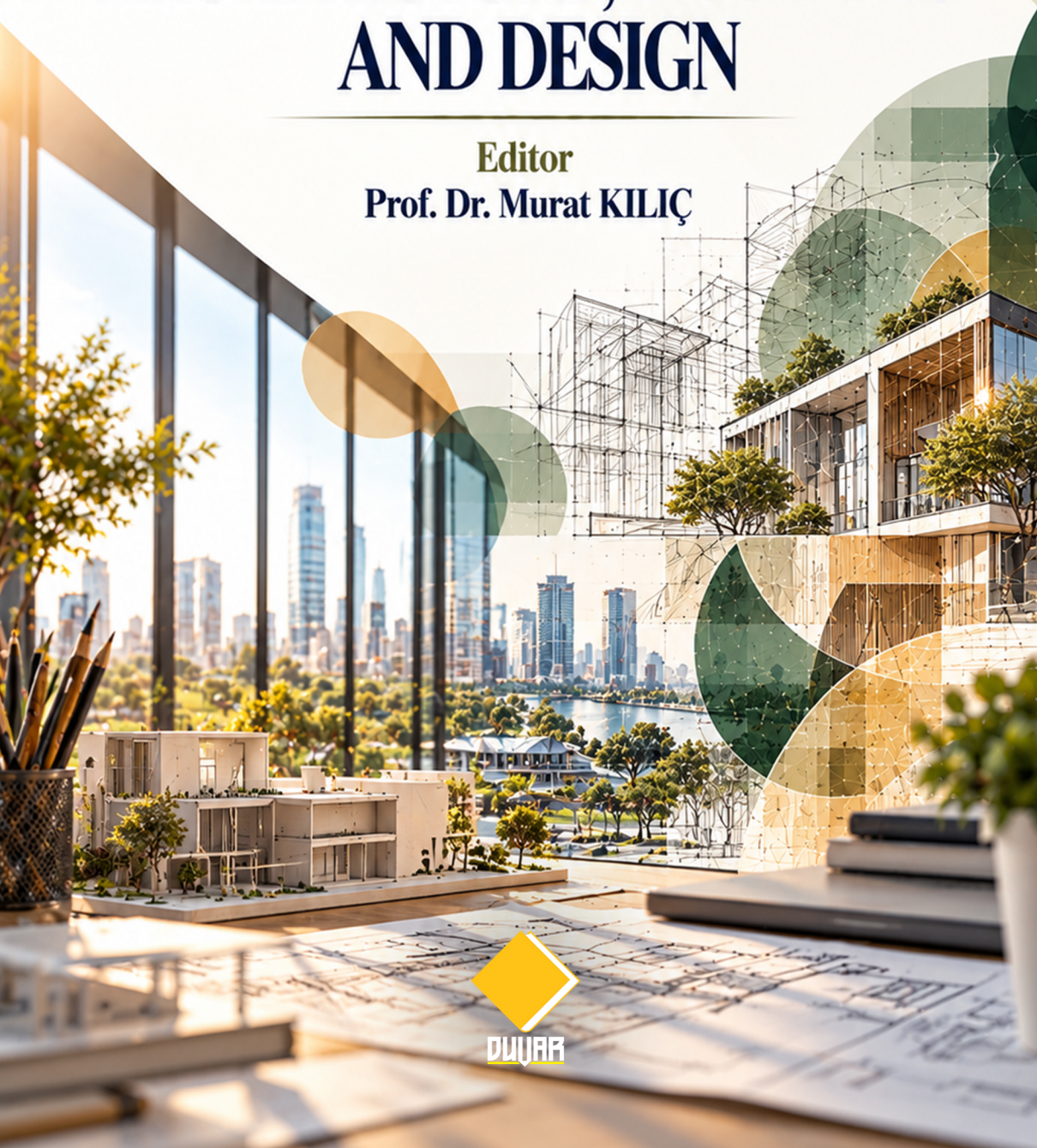
INNOVATIVE APPROACHES AND SCIENTIFIC STUDIES IN ARCHITECTURE, PLANNING AND DESIGN

Editor
Prof. Dr. Murat KILIÇ



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Innovative Approaches and
Scientific Studies in Architecture, Planning and Design

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Chapter 1

University Campuses and Carbon Footprint: An Integrated Framework for Carbon Accounting, Sustainable Mobility, Spatial Planning, and Green Infrastructure

Burçin Burcu VARLIK[1]

Abstract

Universities are increasingly expected to measure and reduce greenhouse gas (GHG) emissions while simultaneously demonstrating leadership in climate action, sustainability education, and institutional innovation. University campuses are particularly suitable settings for carbon management because they function as complex, small-scale urban systems that combine buildings, energy infrastructure, mobility networks, procurement, waste streams, open spaces, and diverse user populations. This chapter presents an integrated framework for understanding and managing the carbon footprint of university campuses. It first reviews the conceptual and methodological foundations of organizational carbon accounting, including carbon dioxide equivalents, organizational and operational boundaries, emission factors, and the Scope 1, Scope 2, and Scope 3 classification. It then examines the principal sources of campus emissions, with particular attention to building energy, commuting, business travel, procurement, waste, and capital goods. The chapter subsequently connects carbon accounting with spatial planning and sustainable mobility, arguing that campus form, accessibility, parking, pedestrian and cycling infrastructure, and integration with public transport can influence travel behavior and associated Scope 3 emissions. Green infrastructure is discussed as a complementary mitigation and adaptation strategy through carbon sequestration, shading, microclimate regulation, stormwater management, and biodiversity benefits. Finally, a step-by-step campus carbon management framework is proposed, linking inventory preparation to hotspot identification, target setting, spatial interventions, implementation, monitoring, and reporting. The chapter emphasizes that carbon accounting is most useful when it moves beyond measurement and becomes a decision-support tool for campus planning and design.

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1. Introduction

Climate change is one of the defining environmental and societal challenges of the twenty-first century. The reduction of anthropogenic greenhouse gas emissions requires action across multiple scales, ranging from international agreements and national policies to cities, organizations, institutions, and individuals. Urban systems are particularly important because the organization of land use, buildings, transport, infrastructure, energy, and consumption influences both direct and indirect emissions (Abdullah et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) emphasizes that integrated urban planning, compact and accessible urban form, low-emission energy systems, improved infrastructure, and green and blue infrastructure can contribute to deep emission reductions while supporting climate-resilient development (IPCC, 2023).

Within this broader transition, higher education institutions occupy a distinctive position. Universities are not only educational and research organizations; they are also large institutional consumers of energy and materials, generators of travel and waste, owners or managers of buildings and open spaces, and influential actors within their surrounding cities. Their campuses therefore provide living laboratories in which climate mitigation strategies can be measured, tested, demonstrated, and communicated. At the same time, the operational complexity of universities makes their carbon footprint difficult to represent through a single indicator unless organizational boundaries and emission sources are carefully defined.

The carbon footprint has become one of the most widely used concepts for quantifying climate-related impacts. At the organizational level, greenhouse gas accounting frameworks allow institutions to identify direct emissions, emissions associated with purchased energy, and a broader range of indirect emissions throughout the value chain (Abdullah et al.,2019). The Greenhouse Gas Protocol Corporate Standard explicitly applies to organizations including universities and provides a widely used structure for preparing institutional GHG inventories (WRI & WBCSD, 2004). Its Scope 3 framework further extends assessment to indirect activities such as commuting, business travel, purchased goods and services, waste, and capital goods (WRI & WBCSD, 2011).

Recent reviews demonstrate that campus carbon assessment is growing, but methodological coverage remains uneven. Qiu and Dong (2024), in a systematic review of 135 campus life-cycle assessment studies, found that buildings and

energy facilities dominated the literature and that Scope 1 and Scope 2 emissions were studied more frequently than Scope 3. Similarly, Paredes-Canencio et al. (2024) reviewed carbon footprint studies in higher education and identified electricity consumption, transportation, and fuel use among the most frequently evaluated sources. These findings indicate both the importance of conventional operational emissions and the need for broader institutional inventories that capture indirect activities.

A particularly important issue for campus carbon management is mobility. Students, academic staff, administrative staff, visitors, service providers, and goods move between campuses and the wider urban system every day. Commuting emissions may therefore represent a substantial component of institutional Scope 3 emissions, especially on automobile-oriented or peripheral campuses (Genta et al., 2022). Yet mobility is not simply a behavioral issue. Travel choices are influenced by campus location, public transport accessibility, distance, parking supply, pedestrian quality, cycling infrastructure, perceived safety, timetable organization, and the spatial distribution of campus functions. This makes transportation-related carbon emissions directly relevant to spatial planning and campus design.

Green infrastructure adds another spatial dimension. Campus trees, vegetated areas, green roofs, rain gardens, permeable surfaces, and other nature-based solutions can contribute to climate mitigation and adaptation through carbon storage, shading, reduced heat exposure, stormwater management, habitat provision, and improved environmental quality (Hussain, 2020). Their direct sequestration contribution may be modest relative to energy or transport emissions in many institutions, but their multifunctional value makes them important components of integrated low-carbon campus strategies. Recent campus research also highlights the potential of tree inventories and landscape planning to connect carbon assessment with biodiversity, education, and participatory sustainability initiatives (Yoon et al., 2025; Waghmare et al., 2026).

This chapter therefore approaches the university carbon footprint not merely as an accounting exercise but as a planning and decision-support framework. Its aim is to connect greenhouse gas accounting with the physical and functional characteristics of university campuses. The chapter explains the methodological foundations of carbon footprint assessment; identifies major campus emission sources; examines the role of mobility, spatial planning, and green infrastructure; and proposes an integrated pathway for moving from inventory preparation to emission reduction. This approach is intended to support researchers, campus planners, sustainability offices, administrators, and design professionals seeking to develop measurable and spatially informed low-carbon campus strategies.

2. Carbon Footprint: Conceptual and Methodological Framework

2.1. Defining the Carbon Footprint

A carbon footprint represents the greenhouse gas emissions associated with a defined subject, such as a person, product, activity, organization, event, building, campus, city, or supply chain (Lou et al., 2022). Although the term refers to "carbon," contemporary carbon footprint assessments generally include multiple greenhouse gases and express their combined climate effect in carbon dioxide equivalents (CO_2e). The value of the concept lies in its ability to translate diverse activities into a common climate-related metric that can be used for baseline assessment, hotspot identification, comparison over time, target setting, and mitigation planning (Hussain, 2020).

The usefulness of a carbon footprint depends strongly on the boundary of the assessment. A narrowly defined footprint may include only fuel burned on site and purchased electricity, whereas a broader footprint may incorporate commuting, air travel, procurement, food, construction, waste, and other value-chain activities. Comparisons between universities are therefore meaningful only when differences in boundaries, data quality, emission factors, campus characteristics, and reporting years are made explicit (Kiehle et al., 2021). Transparency is particularly important because two institutions with similar populations may report very different carbon intensities for methodological as well as operational reasons.

At the organizational level, two key methodological references are the GHG Protocol Corporate Accounting and Reporting Standard and ISO 14064-1. The GHG Protocol provides principles and guidance for developing organizational GHG inventories, while ISO 14064-1 specifies principles and requirements for quantification and reporting of GHG emissions and removals at the organizational level (ISO, 2018; WRI & WBCSD, 2004). These frameworks support consistency, relevance, completeness, transparency, and accuracy, while allowing organizations to define boundaries appropriate to their structure and reporting purpose.

Table 1. Levels of carbon footprint assessment and their relevance to university campuses

Assessment level	Main focus	Typical examples	Campus relevance
Individual	Personal activities and consumption	Travel, household energy, food	Student and staff mobility and behavior
Product	Life-cycle emissions of a product	Construction materials, equipment, food	Procurement and embodied carbon
Activity/Event	A defined activity or event	Conference, field trip, ceremony	Academic travel and campus events
Building	Operational and/or embodied emissions	Electricity, heating, cooling, materials	Teaching, laboratory and administrative buildings
Organization	Institution-wide direct and indirect emissions	Energy, transport, procurement, waste	University GHG inventory
Campus/District	Spatially defined system	Buildings, mobility, infrastructure, landscape	Integrated campus carbon planning
City/Region	Territorial emissions	Transport, buildings, industry, waste	Campus-city relationship and urban context

Source: Author synthesis based on ISO (2018) and WRI & WBCSD (2004, 2011).

2.2. Greenhouse Gases and Carbon Dioxide Equivalents

Organizational GHG inventories may include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3), depending on applicable standards and activities (Kiehle et al., 2020). Because these gases differ in their warming influence, emissions are converted to a common unit using global warming potential values and reported as CO_2e. This conversion makes it possible to aggregate emissions from different gases within a single institutional inventory.

In practical terms, many campus calculations use activity data multiplied by an appropriate emission factor. Activity data may include kilowatt-hours of electricity, cubic meters of natural gas, liters of fuel, passenger-kilometers traveled, kilograms of waste, or monetary/physical quantities of purchased goods. Emission factors translate these activities into GHG emissions. The reliability of the result depends on the quality and representativeness of both the activity data and the selected emission factor. Country-specific electricity factors, for example, can change over time as the generation mix changes.

A simplified calculation can be expressed as: GHG emissions (kg CO_2e) = Activity data × Emission factor. More complex sources may require additional parameters such as vehicle occupancy, distance by mode, refrigerant type and leakage, waste treatment pathway, or life-cycle coefficients. For this reason, documentation of units, sources, assumptions, conversion factors, and reporting periods should accompany the final inventory.

Table 2. Examples of activity data for campus carbon accounting

Emission source	Possible activity data	Typical unit	Illustrative data source
Purchased electricity	Electricity consumed	kWh	Utility bills / energy management system
Natural gas	Fuel consumed	m^3 or kWh	Utility bills
Campus fleet	Fuel use or distance	L, km	Fleet records
Refrigerants	Refrigerant leakage/refill	kg	Maintenance records
Commuting	Distance, frequency, travel mode	passenger-km	Student/staff survey
Business travel	Distance and mode	passenger-km	Travel office / reimbursement records
Waste	Waste by treatment pathway	kg or t	Waste contractor records
Procurement	Purchased goods/services	physical or monetary units	Procurement system
Capital projects	Material quantities or expenditure	kg, t, m^2, currency	Construction/project records

Source: Author synthesis based on GHG Protocol accounting principles.

2.3. Organizational and Operational Boundaries

Before emissions are calculated, a university must determine what organizational units and operations are included. Multi-campus universities, affiliated hospitals, research centers, rented facilities, student housing, foundations, and outsourced services can create boundary challenges (Ridhosari &Rahman, 2020). The selected approach should be stated clearly and applied consistently across reporting periods. Boundary decisions are not merely technical; they determine which emissions appear in the inventory and which units are accountable for data collection and reduction actions.

Operational boundaries then classify emissions according to their relationship with the institution. The Scope 1, Scope 2, and Scope 3 framework is particularly useful because it separates direct operational emissions from purchased-energy emissions and wider indirect emissions. This distinction also helps universities

identify where they have direct control, contractual influence, planning influence, or primarily behavioral influence.

2.4. Scope 1, Scope 2, and Scope 3 Emissions

Scope 1 includes direct emissions from sources owned or controlled by the institution. Typical university examples include combustion of natural gas or other fuels in boilers, fuel consumed by university-owned vehicles, and fugitive emissions from refrigeration and air-conditioning systems (Garcia-Alaminos et al., 2022). Scope 1 sources are often among the most directly manageable because universities can replace equipment, improve maintenance, electrify fleets, retrofit heating systems, or alter fuel choices.

Scope 2 includes indirect emissions from purchased or acquired electricity, steam, heat, and cooling. Universities frequently have large electricity demands because of laboratories, information technology, lighting, ventilation, cooling, libraries, and extended operating hours (Garcia-Alaminos et al., 2022). Scope 2 reduction strategies may therefore combine demand reduction, energy efficiency, on-site renewable energy, procurement of lower-carbon electricity, and improved operational controls.

Scope 3 encompasses other indirect emissions in the value chain. For universities, relevant categories can include purchased goods and services, capital goods, fuel- and energy-related activities not included in Scope 1 or 2, upstream transportation, waste, business travel, employee commuting, and other categories depending on the institution's activities. Scope 3 is methodologically challenging because the university often does not own the emitting source, data may be incomplete, and behavioral or supply-chain assumptions are required. Nevertheless, excluding these emissions may omit important parts of the institutional footprint. Qiu and Dong (2024) found that Scope 3 remained less comprehensively studied in campus LCA research, while Stridsland and Sanderson (2022) noted continuing methodological challenges in higher-education Scope 3 inventories.

Table 3. Classification of major greenhouse gas emission sources in university campuses

Scope	Emission type	Campus source	Examples	Institutional influence
Scope 1	Direct	Stationary combustion	Boilers, generators, on-site fuel use	High
Scope 1	Direct	Mobile combustion	University-owned cars, buses, service vehicles	High
Scope 1	Direct	Fugitive emissions	Refrigerant leakage	High
Scope 2	Indirect energy	Purchased electricity	Buildings, laboratories, lighting, ICT	High–moderate
Scope 2	Indirect energy	Purchased heat/cooling	District or external systems	High–moderate
Scope 3	Other indirect	Student and employee commuting	Car, public transport, motorcycle, rail	Moderate; planning-sensitive
Scope 3	Other indirect	Business travel	Air, rail, road travel	Moderate
Scope 3	Other indirect	Purchased goods/services	Food, office and laboratory supplies	Moderate
Scope 3	Other indirect	Capital goods	Buildings, infrastructure, equipment	Moderate
Scope 3	Other indirect	Waste	Treatment and disposal	Moderate
Scope 3	Other indirect	Upstream transport	Delivery of goods/materials	Low–moderate

Source: Author synthesis based on WRI & WBCSD (2004, 2011).

3. Carbon Footprint Assessment in University Campuses

3.1. Why Campuses Require a Specific Perspective

University campuses differ from conventional commercial organizations because they combine educational, research, residential, recreational, administrative, and public functions. Their populations also fluctuate daily and seasonally. Laboratories may have unusually high energy intensity; commuting patterns may depend on class schedules; residence halls may shift energy and travel profiles; and procurement can include specialized scientific equipment and materials (Genta et al., 2022). These characteristics make campus carbon assessment both analytically rich and methodologically demanding.

A review by Paredes-Canencio et al. (2024) shows that higher-education carbon footprint studies vary considerably in scope and methodology. Electricity, transportation, and fuel consumption are among the most commonly assessed sources. Such variation reinforces the need to report functional indicators alongside absolute emissions. Examples include emissions per student, per full-time equivalent population, per square meter of floor area, or per unit of research/teaching activity. These indicators can help interpret trends, but they should not replace absolute emissions because institutional growth can reduce intensity while total emissions continue to rise.

3.2. Building Energy and Campus Operations

Buildings are often a major component of campus emissions because universities operate large floor areas with diverse occupancy schedules and technical requirements. Heating, cooling, ventilation, lighting, computing, and laboratory processes can all contribute substantially to energy demand. Older buildings may also have inefficient envelopes or mechanical systems, while new high-performance buildings may reduce operational energy but introduce embodied emissions through construction materials (Shi & Yin, 2021).

A campus decarbonization strategy should therefore distinguish between operational efficiency, energy supply, and embodied carbon. Operational measures may include retro-commissioning, insulation, efficient lighting, building automation, demand-responsive controls, temperature set-point optimization, and behavioral programs. Supply-side measures may include electrification, heat pumps, solar photovoltaic systems, renewable procurement, or district-scale low-carbon energy. Capital planning can further integrate life-cycle carbon into renovation-versus-replacement decisions.

3.3. Transportation and Commuting

Transportation is one of the most important interfaces between the campus and the surrounding city. Paredes-Canencio et al. (2024) identified transportation as one of the most frequently evaluated sources in higher-education carbon footprint studies. Student and employee commuting is particularly relevant because large daily populations can generate substantial passenger-kilometers. Roknaldin et al. (2025) emphasize that single-occupant vehicle commuting can be a significant contributor to university carbon footprints and that mode choice is shaped by safety, time, convenience, incentives, and behavioral factors.

A robust commuting inventory should ideally distinguish user group, travel mode, trip distance, trip frequency, occupancy, and—where relevant—vehicle fuel or technology. Surveys can be combined with administrative data,

geographic information systems, transport smart-card data, parking records, or anonymized mobility datasets where legally and ethically appropriate (Paredes-Canencio et al., 2024). Because surveys are subject to response bias and seasonal variation, assumptions and sampling periods should be documented.

Importantly, commuting emissions are not only a matter of individual choice. Peripheral campus locations, fragmented pedestrian networks, poor transit connections, excessive parking supply, long walking distances between functions, or unsafe cycling conditions can structurally favor automobile use. Conversely, accessible public transport, compact land use, safe pedestrian routes, bicycle facilities, and coordinated scheduling can lower barriers to low-carbon mobility. Carbon management therefore benefits from combining emissions data with spatial and behavioral analysis.

3.4. Procurement, Capital Goods, Food, and Waste

Purchased goods and services can create substantial upstream emissions, yet they are often difficult to quantify because universities purchase thousands of different products and services. Spend-based emission factors can provide broad screening estimates, while supplier-specific or process-based data can improve accuracy for high-impact categories (Perez et al., 2021). A practical approach is to begin with screening, identify procurement hotspots, and progressively improve data quality for categories such as construction, laboratory equipment, information technology, food, and frequently purchased consumables.

Capital goods deserve particular attention in expanding campuses. New buildings and infrastructure generate embodied emissions from cement, steel, glass, insulation, finishes, transport, and construction processes. Integrating whole-life carbon assessment into capital planning can reveal trade-offs between new construction, adaptive reuse, renovation, material selection, and service-life extension.

Waste-related emissions depend on waste composition and treatment pathways. Prevention and reduction should generally precede recycling or treatment because avoided purchasing can reduce both upstream production emissions and downstream waste impacts. Food systems similarly connect procurement, dietary choices, packaging, food waste, and logistics, making campus dining a potentially important area for Scope 3 interventions.

Table 4. Major campus carbon hotspots and possible reduction strategies

Hotspot	Typical scope	Key data	Possible interventions
Building heating/cooling	1/2	Fuel and electricity use	Efficiency, controls, electrification, retrofit
Electricity	2	kWh by building/use	Efficiency, solar PV, renewable procurement
Commuting	3	Mode, distance, frequency	Transit, walking/cycling, parking management, carpooling
Business travel	3	Mode and distance	Rail substitution, virtual meetings, travel policy
Procurement	3	Spend/quantity/supplier data	Low-carbon specifications, supplier engagement
Capital projects	3	Material quantities/LCA	Reuse, low-carbon materials, whole-life design
Food	3	Purchases and waste	Menu design, local/seasonal options, food waste reduction
Waste	3	Mass and treatment	Prevention, reuse, separation, recycling

Source: Author synthesis based on campus carbon accounting literature.

4. Spatial Planning and Sustainable Mobility as Carbon Reduction Strategies

4.1. Campus Form, Location, and Accessibility

The relationship between urban form and emissions is well established in climate mitigation literature. The IPCC identifies integrated land-use planning, compact urban form, infrastructure, electrification, and green and blue infrastructure among key urban mitigation approaches (IPCC, 2023). Although a university campus is smaller than a city, similar mechanisms operate at the campus scale. Location relative to housing and public transport, internal connectivity, distribution of functions, and the relationship between buildings and open spaces influence daily movement patterns and energy use.

A compact campus can reduce internal trip distances and support walking, but compactness alone does not guarantee low-carbon mobility. A dense campus located far from residential areas and poorly served by public transport may still

generate high commuting emissions. Conversely, a less compact campus may perform better if it is integrated with high-capacity transit and has strong pedestrian and cycling networks. Carbon-sensitive planning therefore requires attention to both internal form and metropolitan accessibility.

4.2. Public Transport Integration

Public transport accessibility can reduce dependence on private vehicles when services are frequent, reliable, safe, affordable, and well connected to campus destinations (Leal et al., 2024). Planning measures include locating major entrances near transit stops, minimizing walking barriers, providing shaded and universally accessible routes, coordinating service schedules with teaching hours, and supplying real-time travel information. Universities can also work with transport agencies on pass programs, service adjustments, and first/last-mile connections.

4.3. Walking and Cycling

Walking and cycling are zero-tailpipe-emission modes that also provide health and public-space benefits. Their attractiveness depends on network continuity, safety, comfort, topography, climate, secure bicycle parking, end-of-trip facilities, and the spatial distribution of destinations. In hot climates, shade and microclimate design can be especially important. Green infrastructure can therefore support mobility decarbonization indirectly by improving thermal comfort along pedestrian and cycling routes.

4.4. Parking and Travel Demand Management

Parking policy is a powerful but sometimes overlooked planning instrument. Large supplies of inexpensive parking can reduce the perceived cost of driving, while demand-management strategies can encourage alternative modes (Leal et al., 2024). Potential measures include parking pricing, permit reform, preferential spaces for carpooling, peripheral parking linked to walking or shuttle systems, restrictions in pedestrian-priority cores, and reallocation of parking areas to green space or active-mobility infrastructure. Equity considerations are essential because some users may have mobility limitations, caregiving responsibilities, night schedules, or poor transit access.

Table 5. Spatial planning factors affecting campus carbon emissions

Planning factor	Effect on behavior/resource use	Potential carbon effect	Possible strategy
Public transport accessibility	Changes feasibility of transit commuting	Can reduce Scope 3 commuting emissions	Direct pedestrian links, service coordination, transit incentives
Pedestrian connectivity	Supports short trips on foot	Reduces motorized internal/access trips	Continuous, shaded, accessible paths
Cycling infrastructure	Supports bicycle use	Reduces car dependence	Connected routes, secure parking, showers
Parking supply/management	Influences cost and convenience of driving	Can increase or reduce car commuting	Pricing, permits, carpooling, peripheral parking
Land-use mix	Changes distance to daily needs	Can reduce trip length/frequency	Co-locate teaching, services and amenities
Compactness	Can shorten internal distances	May reduce internal motorized travel	Compact development with adequate open space
Transit-oriented campus access	Connects campus to regional networks	Reduces long-distance car dependence	Entrances and high-demand uses near transit
Green/shaded routes	Improves walking comfort	Indirectly supports low-carbon modes	Trees, shade structures, green corridors

Source: Author synthesis informed by IPCC (2023) and campus mobility literature.

5. Green Infrastructure and Carbon Management

5.1. Carbon Sequestration and Campus Vegetation

Green infrastructure should be understood as multifunctional infrastructure rather than simply decorative landscaping. Campus trees and vegetation store carbon in biomass and soils while providing shade, habitat, visual quality, and microclimate benefits. Yoon et al. (2025) highlight the potential of campus tree inventories to quantify carbon storage and support participatory education. In Türkiye, recent campus research has also examined carbon sequestration as part of sustainable campus planning, illustrating the relevance of landscape-based carbon assessment to local contexts (Yildiz & Kahveci, 2026).

The carbon benefit of vegetation should nevertheless be interpreted carefully. Tree sequestration should not be used to justify avoidable fossil-fuel emissions,

and estimates depend on species, age, size, growth, mortality, maintenance, and methodological assumptions. The strongest role of green infrastructure is therefore often its combined mitigation, adaptation, biodiversity, and social value rather than its use as a simple offset.

5.2. Microclimate, Shading, and Energy Demand

Trees and vegetation can influence campus microclimates through shading and evapotranspiration. Strategically placed vegetation may reduce solar exposure around buildings and outdoor spaces, potentially lowering cooling demand while improving pedestrian comfort. However, planting design should account for climate, water availability, building orientation, maintenance, fire risk where relevant, and potential conflicts with solar-energy systems. Climate-responsive landscape planning is therefore preferable to generic greening targets.

5.3. Rain Gardens, Permeable Surfaces, and Nature-Based Solutions

Rain gardens, bioswales, permeable surfaces, green roofs, and related nature-based solutions are primarily associated with stormwater management and climate adaptation, but they can also contribute to integrated low-carbon campus design. Their value lies in combining hydrological performance with vegetation, habitat, reduced heat accumulation, environmental education, and improved public-space quality. The IPCC recognizes urban green and blue infrastructure as part of integrated urban mitigation and climate-resilient development (IPCC, 2023).

Table 6. Green infrastructure functions within a low-carbon campus framework

Intervention	Primary function	Carbon-related contribution	Co-benefits
Campus trees	Shade, biomass, habitat	Carbon storage; possible cooling-energy reduction	Thermal comfort, biodiversity, identity
Rain gardens/bioswales	Stormwater management	Vegetation/soil carbon; indirect resilience benefits	Runoff control, habitat, education
Green roofs	Building/landscape integration	Potential cooling-energy reduction; biomass	Stormwater retention, habitat
Permeable surfaces	Infiltration and runoff reduction	Supports integrated climate-resilient design	Reduced runoff, groundwater support

Intervention	Primary function	Carbon-related contribution	Co-benefits
Green corridors	Ecological and pedestrian connectivity	Supports walking/cycling through comfort	Biodiversity, recreation, connectivity
Native/climate-adapted planting	Lower-input landscape	May reduce irrigation/maintenance demand	Resilience, biodiversity

Source: Author synthesis based on IPCC (2023), Yoon et al. (2025), and Waghmare et al. (2026).

6. A Step-by-Step Framework for Campus Carbon Footprint Assessment

6.1. Step 1: Define Purpose, Base Year, and Boundaries

The university should first define why the inventory is being prepared, the reporting period, the organizational boundary, included campuses, and intended uses. A base year should be selected for future comparison. Boundary changes, mergers, new campuses, or major methodological revisions should be documented.

6.2. Step 2: Map Emission Sources

A source map should identify all potentially relevant Scope 1, Scope 2, and Scope 3 activities. Screening prevents the inventory from becoming limited to data that are merely easy to obtain. The map can also identify responsible administrative units and data owners.

6.3. Step 3: Collect Activity Data

Data collection should prioritize direct meter and administrative records where available. Surveys may be required for commuting or behavior. Each dataset should include unit, period, source, coverage, uncertainty, and responsible office.

6.4. Step 4: Select Emission Factors and Calculate Emissions

Emission factors should be geographically and temporally appropriate. The calculation file should preserve original activity data, conversions, factors, factor sources, and formulas. Where multiple methods are possible, the selected method and its limitations should be stated.

6.5. Step 5: Quality Assurance and Uncertainty Review

Quality assurance should check completeness, unit conversions, double counting, missing months, outliers, survey representativeness, and consistency

with prior years. High-uncertainty categories can be flagged for future data improvement rather than silently omitted.

6.6. Step 6: Identify Hotspots and Spatial Patterns

The inventory should be translated into decision-relevant information. Emissions can be grouped by source, scope, building, user group, or location. GIS can be used to map commuting origins, transit accessibility, parking, pedestrian networks, energy intensity, and green infrastructure.

6.7. Step 7: Develop Reduction Scenarios

Reduction measures should be linked to quantified hotspots. Scenarios may compare building retrofits, renewable energy, fleet electrification, public transport incentives, parking reform, cycling networks, procurement changes, or landscape interventions. Where possible, scenarios should estimate both carbon reduction and implementation cost.

6.8. Step 8: Set Targets, Implement, Monitor, and Report

Targets should be measurable and linked to a defined baseline and scope. Annual or periodic monitoring should distinguish real operational change from methodological changes. Transparent reporting should explain boundaries, exclusions, uncertainty, and progress.

Table 7. Proposed workflow for a university campus carbon inventory

Step	Main task	Key output
1	Define purpose, base year, organizational and operational boundaries	Inventory protocol
2	Map Scope 1, 2 and 3 sources	Emission-source register
3	Collect activity data	Documented dataset
4	Select emission factors and calculate	GHG inventory in tCO_2e
5	Conduct QA/QC and uncertainty review	Validated inventory
6	Identify hotspots and spatial patterns	Priority areas / maps
7	Develop mitigation scenarios	Reduction action portfolio
8	Set targets, implement and monitor	Carbon management plan and progress reports

Source: Author-developed framework based on GHG Protocol and campus sustainability literature.

7. Illustrative Campus Carbon Calculation Framework

The following table provides a simplified calculation structure that can be adapted to a university's available data. It is intentionally generic: actual emission factors should be selected from authoritative and current sources appropriate to the country, energy system, fuel, transport mode, and reporting year. The table is therefore a methodological template rather than a source of default factors.

Table 8. Illustrative calculation template

Source	Activity data	Emission factor	Calculation	Result
Natural gas	Annual gas consumption (kWh or m^3)	kg CO_2e per unit	Activity × factor	kg/t CO_2e
Electricity	Annual electricity (kWh)	kg CO_2e/kWh	kWh × factor	kg/t CO_2e
Fleet fuel	Liters by fuel	kg CO_2e/L	L × factor	kg/t CO_2e
Commuting	Passenger-km by mode	kg CO_2e/passenger-km	Passenger-km × factor	kg/t CO_2e
Business travel	Passenger-km by mode	kg CO_2e/passenger-km	Passenger-km × factor	kg/t CO_2e
Waste	Mass by treatment	kg CO_2e/kg waste	Mass × factor	kg/t CO_2e
Purchased goods	Quantity or spend	Product/spend factor	Activity × factor	kg/t CO_2e

Note: Emission factors must be selected for the relevant geography, technology, and reporting year.

8. From Carbon Accounting to a Low-Carbon Campus Strategy

The central limitation of many carbon inventories is that they end with measurement. A campus may know its annual emissions without having a clear mechanism for changing the systems that generate them. A low-carbon campus strategy should therefore connect each major emission source to an institutional decision pathway (Tsai et al.,2025) . Building emissions connect to facilities management and capital planning; commuting connects to transport and spatial planning; procurement connects to purchasing rules; business travel connects to academic and administrative policy; and landscape-related actions connect to campus planning and grounds management.

An integrated strategy should also distinguish between avoidance, reduction, substitution, and removals. Avoidance reduces the need for carbon-intensive activity; reduction improves efficiency; substitution replaces high-carbon technologies or modes with lower-carbon alternatives; and removals address

carbon uptake (Nunes et al., 2022; Abo-Khalil, 2024). This hierarchy helps prevent overreliance on offsetting while prioritizing structural reductions.

Campus decarbonization is also a governance challenge. Responsibility is distributed across rectorates or presidents' offices, facilities departments, procurement units, transport offices, academic units, students, and external service providers (Brundiers et al., 2021). A cross-functional carbon management group can therefore improve data quality and implementation. Students and researchers can participate through living-lab projects, mobility surveys, tree inventories, building monitoring, and design studios, linking operational sustainability with education and research.

Finally, equity and user experience should be integrated into carbon strategies. Measures that reduce parking, alter travel patterns, or change building operations can affect users differently. Accessible mobility, safety, affordability, disability needs, night-time travel, caregiving, and climate comfort should be considered. The most durable low-carbon strategies are likely to be those that simultaneously reduce emissions and improve campus accessibility, comfort, health, and environmental quality.

Table 9. Integrated low-carbon campus strategy matrix

Domain	Carbon objective	Planning/management action	Possible indicator
Energy	Reduce Scope 1/2	Efficiency, electrification, renewables	kWh/m²; tCO_2e
Mobility	Reduce commuting emissions	Transit, active mobility, parking management	Mode share; kg CO_2e/person
Buildings	Reduce operational/embodied carbon	Retrofit, adaptive reuse, life-cycle design	kg CO_2e/m^2
Procurement	Reduce upstream emissions	Low-carbon specifications, supplier data	tCO_2e/category
Waste	Prevent material loss	Prevention, reuse, recycling	kg waste/person; tCO_2e
Green infrastructure	Increase resilience and ecosystem services	Trees, rain gardens, green corridors	Canopy, stored carbon, runoff metrics
Governance	Institutionalize carbon management	Targets, responsibilities, annual reporting	Inventory completeness; target progress
Education/research	Use campus as living laboratory	Courses, projects, participatory monitoring	Projects/students engaged

Source: Author-developed synthesis.

9. Challenges, Limitations, and Research Needs

Campus carbon accounting faces several methodological limitations. Scope 3 data are often incomplete, inconsistent, or dependent on surveys and spend-based factors. Electricity emission factors change over time. Institutional boundaries may shift. Remote work and hybrid education can transfer emissions outside the campus boundary. Construction and procurement inventories may rely on generic life-cycle databases that do not fully represent local supply chains. These limitations should be treated as reasons for transparent uncertainty reporting and progressive data improvement rather than reasons to avoid assessment.

Comparability across universities is another challenge. Campus size, climate, research intensity, laboratory load, residential population, urban location, transport accessibility, and national electricity systems differ widely. Rankings based on a single carbon-intensity indicator can therefore be misleading. More useful benchmarking compares an institution with its own baseline over time and supplements carbon metrics with contextual indicators.

Future research should further integrate carbon inventories with spatial data. Geographic analysis can help explain why emissions occur, not only how much is emitted. Research opportunities include linking commuting emissions to residential distribution and transit accessibility; examining the relationship between campus morphology and internal mobility; mapping building energy intensity; evaluating shade and green infrastructure along active-mobility routes; and combining carbon reduction scenarios with cost, health, biodiversity, and climate-adaptation outcomes.

There is also a need for stronger treatment of procurement and capital goods in higher-education inventories. As operational electricity becomes less carbon intensive in some regions, embodied and supply-chain emissions may become increasingly visible. Whole-life approaches can help universities avoid shifting emissions from operation to construction or from direct activities to outsourced services.

Finally, universities can contribute methodologically by making inventories reproducible. Publishing boundary definitions, activity data structures, factor sources, uncertainty assumptions, and calculation logic can improve learning across institutions. The current evolution of corporate GHG accounting standards also means that campus methodologies should remain adaptable to future harmonization between GHG Protocol and ISO frameworks.

10. Conclusion

University campuses offer a valuable scale for translating climate goals into measurable operational and spatial interventions. Their carbon footprints emerge

from a combination of direct fuel use, purchased energy, mobility, procurement, construction, waste, and other institutional activities. A credible assessment therefore requires clear boundaries, transparent data, appropriate emission factors, and attention to Scope 3 sources rather than an exclusive focus on building energy.

The chapter has argued that carbon accounting should be linked directly to spatial planning. Campus location, public transport access, pedestrian and cycling networks, parking, land-use organization, building form, and green infrastructure can shape the activities that generate emissions. Sustainable mobility and green infrastructure are consequently not peripheral environmental initiatives; they are components of a broader campus carbon-management system.

An effective low-carbon campus pathway can be summarized as a continuous cycle: define and measure emissions, identify hotspots, understand their spatial and institutional drivers, develop reduction scenarios, implement interventions, monitor outcomes, and revise strategies. When this process is integrated with teaching and research, the campus can function as a living laboratory in which climate mitigation, adaptation, biodiversity, mobility, and institutional learning reinforce one another.

For universities seeking carbon neutrality or substantial emission reductions, the most important transition is therefore from carbon footprint calculation to carbon-informed decision-making. The carbon inventory provides the baseline; planning, design, governance, and behavioral change determine whether that baseline is transformed into meaningful and lasting reductions.

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Chapter 2

Socio-spatial Effects of Urban Sprawl in İncek, Ankara

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Abstract

This chapter examines urban sprawl and its socio-spatial implications in İncek, within Ankara's southwestern development corridor, between 2006 and 2025. The study addresses the transformation of a formerly rural settlement through dispersed residential development, infrastructure investment and differentiated housing environments. The approximately 14.32 km² study area lies within Gölbaşı district. Landsat-based Normalized Difference Built-up Index (NDBI) maps for 2006, 2014, 2020 and 2025 are considered alongside population records for 2007, 2014, 2020 and 2025, historical satellite imagery and field observations. The reported built-up area increased from 103.9 to 399.5 ha, while the population series rose from 3,001 to 19,449. These figures indicate an increase of 284.5% in classified built-up area and 548.1% in population over their respective observation periods. Physical expansion outpaced population growth in the first interval, but this relationship did not persist throughout the study period. Development followed the main transport corridors, particularly İncek and Turgut Özal Boulevards. The typological analysis identifies a traditional settlement fabric, villa areas and gated residential complexes that differ in building form, enclosure and their relationship with public space. These findings indicate substantial morphological fragmentation and differences in physical access conditions. The extent to which these spatial differences correspond to social segregation, however, requires more detailed household-level evidence. The chapter concludes that urban growth management should combine coordinated land-use decisions, continuity of public space and public transport provision with systematic monitoring of land consumption and residential change.

Keywords: urban sprawl; socio-spatial segregation; NDBI; İncek; residential differentiation.

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1 Introduction

Urban sprawl is among the most contested forms of spatial transformation in contemporary metropolitan areas. It is commonly associated with dispersed development, low densities, inadequate infrastructure coordination and socio-economic differentiation. These characteristics create difficulties for sustainable urban development, although the relationship between land consumption and population growth varies across places and periods. Ewing et al. (2002) identify density, the mix of land uses, the strength of activity centres and street connectivity as central dimensions of sprawl. This multidimensional understanding is important because outward growth alone does not adequately describe the organization or social consequences of a metropolitan fringe.

In Türkiye, low-density, decentralized and discontinuous growth has become a persistent issue in metropolitan development (Serdaroğlu Sağ, 2021; Öncel & Meşhur, 2021). Ankara provides a relevant setting in which to examine this process. The expansion of its southwestern corridor, particularly since the 1990s, has transformed peripheral settlements such as Çayyolu, Ümitköy and İncek into major areas of residential development. Research on Ankara documents the conversion of agricultural land along the western and southwestern axes and the influence of metropolitan growth decisions on this transformation (Sezgin & Varol, 2012).

İncek is one of the settlements in which these changes can be observed. An area that retained a predominantly rural character until relatively recently has developed into a residential location associated with gated communities, villa projects and high-rise apartment complexes. This transformation involves more than an increase in built-up land. The juxtaposition of traditional settlement patterns and enclosed housing developments raises questions about spatial hierarchies, access to shared urban facilities and the continuity of public life.

Existing research provides several starting points for examining these questions. Güneş (2021) investigates relationships between urban expansion, sprawl and the property market in Ankara's Alacaatlı, Bağlıca and Dodurga neighbourhoods. Sezgin and Varol (2012) examine the effects of metropolitan expansion on agricultural land. Focusing directly on İncek, Güller (2019) traces the transition from a rural settlement within the green belt of the 1990 Ankara Master Plan to fragmented development shaped by local development plans and subsequent planning interventions. That study gives particular attention to urban land rent and the allocation of development rights. The present chapter complements this planning perspective by bringing together the reported NDBI time series, demographic change and observations of residential morphology. Its contribution is primarily descriptive and interpretive: the available evidence

supports comparison of spatial patterns but does not independently establish causal relationships between individual investments and development outcomes.

International studies also offer relevant points of comparison. Wagistina and Antariksa (2019) combine NDBI analysis, residential typology mapping and qualitative investigation in the western suburbs of Malang, Indonesia. Their approach illustrates the value of considering physical and social differentiation together without treating them as identical. Seevarethnam et al. (2022) examine urban sprawl in Batticaloa, Sri Lanka, by integrating socioeconomic and biophysical factors. These studies inform the analytical framework used here; their findings are not assumed to apply automatically to İncek.

The main research question is how urban expansion in İncek developed between 2006 and 2025, how it related to infrastructure and planning decisions, and what forms of residential differentiation accompanied it. Four subsidiary questions guide the analysis:

• How did the change in NDBI-derived built-up area compare with population growth over the available observation periods?

• In which directions, and along which transport corridors, was development concentrated?

• How were university campuses and transport investments associated with the spatial distribution of new development?

• What differences in housing morphology, physical enclosure and access to public space were observed between gated developments and the traditional settlement fabric?

By considering remotely sensed land-cover change together with demographic records and residential typologies, the chapter provides a spatially grounded account of İncek's transformation. Its contribution lies in connecting the changing extent and distribution of development with the ways in which different residential environments meet, separate and connect to the wider settlement. The findings also provide a basis for discussing planning priorities in Ankara's southwestern corridor.

2 Literature Review

2.1 Understanding Urban Sprawl

Urban sprawl describes an inefficient and fragmented pattern of urban expansion beyond an established built-up area. The concept is not limited to the total amount of land developed. Ewing et al. (2002) operationalize sprawl through low residential and employment density, the separation of land uses, weak activity centres and poor street connectivity.

Shannon's entropy has also been widely used to assess the dispersion of urban development. In Konya, Serdaroğlu Sağ (2021) combines satellite imagery, GIS and entropy analysis to evaluate changes in built-up land and the spatial character of urban growth. This work demonstrates the value of quantitative monitoring for identifying fragmented urbanization.

Urban growth is influenced by the interaction of accessibility, land markets, public investment and environmental conditions. The Batticaloa study by Seevarethnam et al. (2022) incorporates socioeconomic and biophysical factors in modelling sprawl. This provides a useful basis for examining İncek, where university campuses and major boulevards are prominent features of the development context. Their presence does not make topography or ecological constraints irrelevant. Rather, the question concerns how infrastructure and institutional investment interact with these conditions to influence the location and form of development.

Accordingly, the first group of indicators considered in the case study consists of change in classified built-up area, its relationship to population change, and the spatial association between new development and transport corridors. These indicators are interpreted together. A greater increase in built-up area than in population may indicate extensive land consumption during a particular interval, but a rising population does not necessarily eliminate fragmentation or improve the connectivity of an already dispersed settlement.

2.2 Socio-Spatial Segregation and Gated Communities

Lefebvre's (1991) theory of the production of space understands urban space as both an outcome of social relations and a medium through which those relations are reproduced. From this perspective, gated communities in İncek can be examined as more than a housing type. Their boundaries, access arrangements and internal amenity's structure relations between residents and surrounding areas. Soja's (1980) socio-spatial dialectic likewise emphasizes the reciprocal relationship between spatial organization and social processes. These perspectives support an examination of how physical separation may reinforce social distinctions.

Research on gated communities in Türkiye connects their development with changing housing markets, elite identities and urban politics. Geniş (2007), for example, examines the production of elite residential environments in Istanbul and the institutional and cultural practices involved in their formation. Çetin (2012) reviews urban segregation and forms of spatial clustering, providing a broader conceptual basis for distinguishing different kinds of residential

separation. Together, these perspectives direct attention to the organization of access and the social meanings attached to residential space.

Wagistina and Antariksa (2019) examine the separation of planned residential areas from established village settlements in Malang. Their combination of spatial analysis and qualitative inquiry is relevant to İncek, where new residential compounds adjoin an older settlement fabric. The comparison is methodological rather than a claim that identical social outcomes occur in both places. In the Turkish context, land prices, the decentralization of public investment and changing housing preferences have also been identified as factors associated with sprawl (Öncel & Meşhur, 2021). These factors help explain the setting in which enclosed residential developments emerge.

The second group of indicators therefore concerns the presence and intensity of physical barriers, the distribution of housing types and the relationship between residential developments and publicly accessible space. The distinction is maintained throughout the interpretation of the İncek case.

2.3 Monitoring Urban Change through Remote Sensing

Remote sensing enables the repeated observation of urban expansion and land-cover change. Commonly used spectral indices include the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI) and the Normalized Difference Built-up Index (NDBI). The last of these is used in this study to examine surfaces associated with development at selected dates.

NDBI expresses the difference between shortwave-infrared and near-infrared reflectance relative to their sum (Zha, Gao, & Ni, 2003). Built-up surfaces often exhibit higher NDBI values than vegetated surfaces, but the index is not a direct measurement of buildings or impermeability. Bare soil and other sparsely vegetated surfaces can have similar spectral responses. Consequently, an NDBI-based classification requires an explicit threshold, suitable preprocessing and independent accuracy assessment. Satellite imagery is useful for spatial comparison, while interpretation must account for these limitations.

Considering remotely sensed development together with population records allows the temporal relationship between land conversion and demographic change to be explored. It can identify periods in which the two indicators diverge, but it does not independently establish property speculation, vacancy or household demand. Harvey's (1989) account of the relationship between economic restructuring and the built environment offers a framework for discussing such processes. In İncek, this interpretation also draws on the planning and land-rent analysis provided by Güller (2019).

3 Methodology

The study combines quantitative analysis of remotely sensed land-cover change and population data with qualitative interpretation of satellite imagery, residential typologies and field observations. Four observation dates are used to trace physical change, while demographic records provide a complementary account of settlement growth. The analysis concerns an approximately 14.32 km² area rather than the whole of Ankara's southwestern corridor.

Satellite imagery and NDBI analysis. The reported analysis uses Landsat 5 TM and Landsat 8/9 OLI imagery for 2006, 2014, 2020 and 2025. Summer images from June to August were selected to minimize cloud cover. NDBI is calculated as follows:

$$\text{NDBI} = \frac{\text{SWIR} - \text{NIR}}{\text{SWIR} + \text{NIR}} \quad NDBI = (SWIR1 - NIR) / (SWIR1 + NIR)$$

Here, SWIR denotes shortwave-infrared reflectance and NIR denotes near-infrared reflectance. The relevant bands are SWIR1 and NIR: bands 5 and 4 for Landsat 5 TM, and bands 6 and 5 for Landsat 8/9 OLI, respectively (U.S. Geological Survey, n.d.). The Landsat data source is USGS EarthExplorer. The NDBI outputs were analysed in ArcGIS Pro to derive the reported built-up area for each date. Because the classification threshold and accuracy-assessment procedure are not documented in the available material, these areas should be treated as reported estimates rather than independently validated measurements. At a spatial resolution of 30 × 30 m, a full pixel represents 900 m², or 0.09 ha. The maps are interpreted as classified surface-cover estimates, not measurements of floor area or building height.

Population data. The population series is attributed to the Turkish Statistical Institute's Address Based Population Registration System (ABPRS) (ABPRS; ADNKS in Turkish). The neighborhoods of İncek and Kızılcaşar have been selected as the sampling area. Because ABPRS results begin in 2007, the demographic baseline is treated as 2007, following the source study's methodological description, while the first satellite observation is dated 2006. Subsequent observations refer to 2014, 2020 and 2025.

Comparison of historical imagery. Images obtained from Google Earth Pro were used to support the interpretation of the NDBI maps. The four-date comparison examines the distribution of development, the relationship of new construction to transport routes and the changing configuration of open areas. It provides visual context for the numerical series rather than an independent quantitative validation of classified land cover.

Residential typology and spatial differentiation. Field observations and high-resolution imagery were used to distinguish three residential environments: the traditional settlement fabric, villa developments and gated apartment complexes. The analysis considers building types, parcel patterns, boundary treatments and relationships with streets and public space. The qualitative categories are presented in Figure 5 and Table 3.

Integration of indicators. The study relates population change and built-up area through Tables 1 and 2, examines development patterns using the NDBI maps and historical imagery in Figures 3 and 4, and interprets residential differentiation through Figure 5. Percentage changes are calculated from the values reported in the original tables. Comparisons of the first interval use 2006–2014 for built-up area and 2007–2014 for population, so they are indicative rather than perfectly time-matched growth measures.

4 Case Study and Findings

4.1 The İncek Area and Demographic Transformation

İncek lies within the southwestern development corridor that has helped shape Ankara's metropolitan form. The study area is located in Gölbaşı district and covers approximately 14.32 km² (Figure 1). The more established residential areas of Ümitköy and Çayyolu lie to the north, while the Gölbaşı hinterland to the south retains elements of a rural landscape. This position gives İncek the character of an urban–rural transition zone, where the relationship between metropolitan growth and the transformation of peripheral land can be examined.

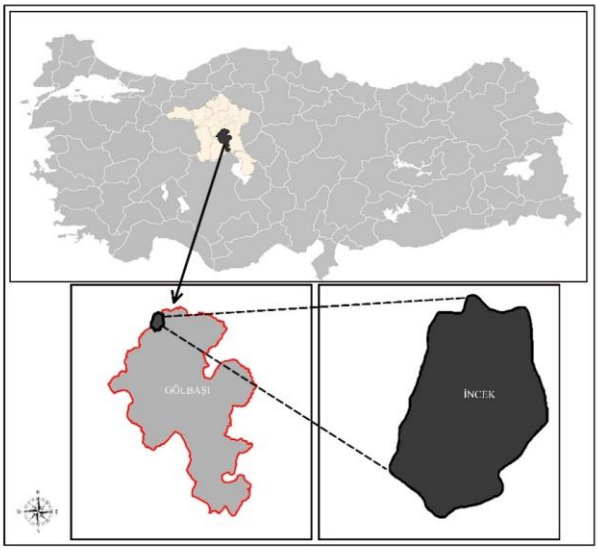


Figure 1. Location of the İncek study area within Gölbaşı district and Ankara province, Türkiye. Source: map prepared by the author. Place names are retained in their original spelling.

Four factors provide the main context for the area's transition from a rural settlement to a location containing villa developments, gated communities and high-rise residential projects.

Transport infrastructure. Improvements to İncek Boulevard and Turgut Özal Boulevard, and their connections with the ring road and the Eskişehir Road corridor, increased the area's accessibility. These changes made İncek more attractive to households able to commute by private car. Güller (2019, p. 105) dates the opening of İncek Boulevard to 2004 and identifies the designation of the urban transformation and development project in 2005 as a further turning point. Transport investment and planning decisions thus formed part of the same development context, rather than representing entirely separate influences.

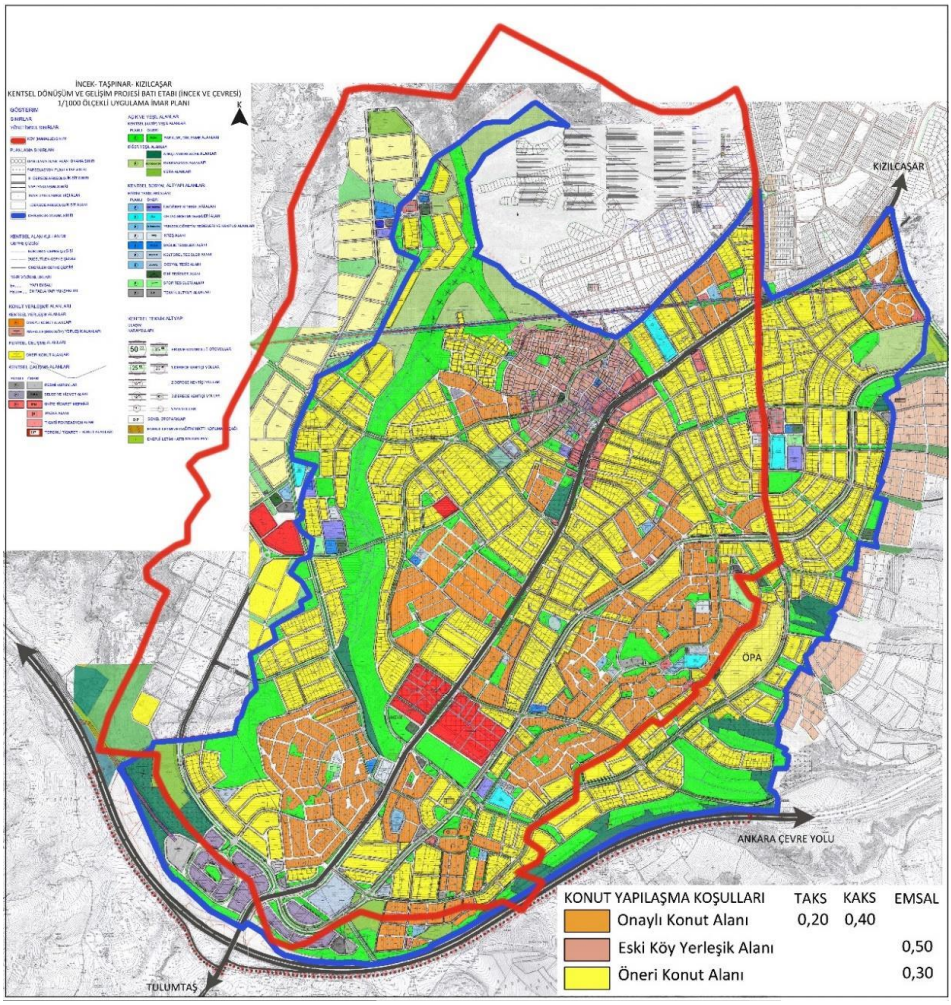


Figure 2. Implementation development plan at 1:1,000 for the western phase of the İncek–Taşpınar–Kızılcaşar Urban Transformation and Development Project. Source: Ankara Metropolitan Municipality archive, reproduced in Güller (2019). English key: orange, approved residential areas (site coverage 0.20; floor-area ratio 0.40); brown, former village settlement (floor-area ratio 0.50); yellow, proposed residential areas (floor-area ratio 0.30). Red line: source study boundary. Blue line: western project-phase boundary. Turkish labels are retained in this historical plan reproduction.

The implementation development plan reproduced in Figure 2 distinguishes different residential conditions. The former village settlement is identified with a floor-area ratio of 0.50, while the approved residential areas are shown with a site coverage ratio of 0.20 and a floor-area ratio of 0.40. Proposed residential areas

have a floor-area ratio of 0.30 in the reproduced key. These designations indicate differentiated development conditions.

The boundary colours require particular care. In the original source, red denotes the study boundary, corresponding to the İncek neighbourhood boundary used there, and blue denotes the western phase of the urban transformation and development project (Güller, 2019, p. 112). Subsequent revisions and parcel-level changes are relevant to the later emergence of high-rise development and are discussed in Güller's historical analysis. The linear arrangement of development along İncek Boulevard is therefore interpreted in conjunction with planning history, rather than as evidence of an absence of planning.

Educational investment. The Atılım and Ufuk university campuses function as institutional activity centres in the area. Their presence is associated with commuting, demand for housing and the provision of services. These investments contribute to the development context, although the present data do not isolate their individual effects on land values or residential growth.

Decentralization of public institutions. The movement of administrative and judicial functions towards Ankara's southwestern corridor is another contextual influence identified in the source study. Such relocation can redirect housing demand among employees and professional groups.

Environmental and topographical characteristics. Uneven terrain, valley views and a historically less densely built environment have provided a setting for projects marketed around spacious housing and proximity to nature. These features influence both residential preferences and the spatial possibilities for development.

These factors correspond broadly to processes identified in other Turkish cities, where transport investment, institutional relocation and changing housing preferences interact with planning decisions to encourage peripheral development (Öncel, 2019; Öncel & Meşhur, 2021). The population series supplied for the İncek area records an increase from 3,001 in 2007 to 19,449 in 2025, a net gain of 16,448 people (Table 1).

The absolute population increments increase across successive intervals. Between 2007 and 2014, the reported population grew by 3,466 people, or 115.5%. Between 2014 and 2020, a further 5,342 people were added, an increase of 82.6%. The largest absolute increment occurred in 2020–2025, when the population increased by 7,640 people, or 64.7%. Thus, the absolute gains became larger while percentage growth over each interval declined.

Table 1. Reported population change in the İncek area, 2007–2025

Year	Population	Change since previous date
2007	3,001	—
2014	6,467	+3,466
2020	11,809	+5,342
2025	19,449	+7,640
Net change	+16,448	—

Source: Population figures attributed to TurkStat ABPRS.

The last interval overlaps with the COVID-19 pandemic, during which demand for gardens, larger dwellings and more spacious residential environments may have influenced housing choices. The available population series does not, however, allow the effect of the pandemic to be isolated.

The demographic changes can be discussed within the broader relationship between investment in the built environment and urban restructuring (Harvey, 1989). The pattern is more differentiated and is examined in the next section.

4.2 Change in Built-Up Area Based on NDBI

The NDBI-derived maps describe changes in the classified built-up footprint between 2006 and 2025, a 19-year interval. Figure 3 shows the spatial distribution of these classifications. Red marks the areas classified as built-up, while the pale yellow shading represents the remaining area within the study boundary. This is a binary land-cover interpretation, and the non-built-up category should not be equated exclusively with vegetation or agricultural land.

The series indicates substantial physical transformation. The reported built-up area increased from 103.9 ha in 2006 to 329.1 ha in 2014 and 418.1 ha in 2020, before declining to 399.5 ha in 2025 (Table 2). The net increase between the first and last observations is 295.6 ha, or 284.5%, meaning that the final classified area is approximately 3.84 times the initial value. The population series, by comparison, increased approximately 6.48-fold between 2007 and 2025. Population growth therefore exceeded built-up area growth over the full, slightly different observation periods.

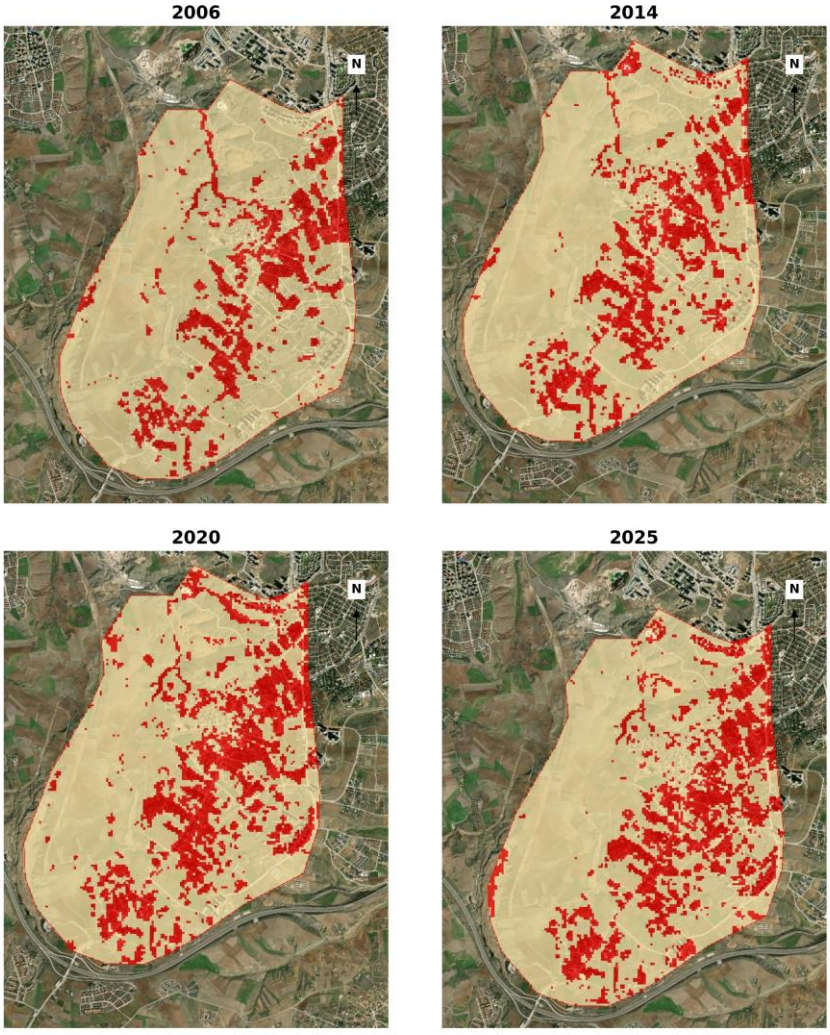


Figure 3. NDBI-derived classifications for 2006, 2014, 2020 and 2025. Source: the author's Landsat-based analysis. Panels retain the original classified pixels and have been cropped around the study area.

The temporal pattern is more informative than the overall increase alone. During 2006–2014, classified built-up area expanded by 225.2 ha, an increase of 216.7%. The corresponding population interval, 2007–2014, records growth of 115.5%. This first interval is therefore consistent with an extensive phase of development in which the expansion of the classified footprint preceded or exceeded demographic growth. Its timing overlaps with the development context

established by transport improvements, planning interventions and institutional investment. The data do not separate the contribution of each factor.

Table 2. Reported built-up area and population at the observation dates

Satellite / population year	Population	Built-up area (ha)	Change in built-up area (ha)
2006 / 2007	3,001	103.9	—
2014 / 2014	6,467	329.1	+225.2
2020 / 2020	11,809	418.1	+89.0
2025 / 2025	19,449	399.5	−18.6
Net change	+16,448	+295.6	—

Source: NDBI-derived area estimates and population figures reported in the original study; changes calculated from those values. Areas are classified surface-cover estimates, not floor-space measurements.

During 2014–2020, built-up area increased by 89.0 ha, or 27.0%, while population grew by 82.6%. Physical expansion continued and the classified footprint reached its highest reported value, but population growth was proportionally stronger. The imagery suggests further development around previously established clusters and along main routes.

During 2020–2025, population increased by 64.7%, whereas the classified built-up area decreased by 18.6 ha, or 4.4%. The contrast may be consistent with more intensive occupation of already developed areas, but NDBI cannot measure building height, housing occupancy or floor space. It therefore cannot establish a transition to vertical development on its own. Differences in image conditions, surface cover, classification thresholds or mixed pixels may also affect the measured area.

Nor does the 2025 figure establish that the area had reached physical saturation. The reported 399.5 ha represents approximately 27.9% of the stated 1,432 ha study area. The remainder is not necessarily land available for construction, since it may include ecological constraints, protected land, agricultural uses or other surfaces. Nevertheless, the area figures alone do not demonstrate that all opportunities for horizontal growth had been exhausted. Evidence on land suitability, plan allocations, vacancies and building intensity would be required for that conclusion.

The spatial arrangement remains relevant despite these qualifications. The classified development is associated with İncek and Turgut Özal Boulevards and

has a pronounced corridor-based pattern. This is consistent with ribbon development and the role of accessibility in directing peripheral growth. The planning history documented by Güller (2019) supports an interpretation in which development rights and land-market expectations contributed to the emerging form. The NDBI series itself, however, does not measure speculation or demonstrate that development was unrelated to housing demand.

4.3 Historical Satellite Imagery and Spatial Expansion

Historical satellite imagery provides a complementary view of the physical changes summarized by the NDBI results. The four panels in Figure 4 illustrate the changing distribution of buildings, roads and open land. Their principal value lies in identifying the spatial configuration of development and its relationship to the surrounding landscape.

The 2006 panel shows extensive agricultural and open land together with a comparatively sparse settlement fabric. By 2014, additional development patches can be observed along and near the main access routes. This pattern is consistent with the comparatively rapid increase in the classified built-up area during the first interval. The difference between physical expansion and population growth is compatible with development taking place in advance of full residential occupation. It does not, without land-market or vacancy evidence, prove that all new construction was speculative. Harvey's (1989) framework and Güller's (2019) case-specific analysis nevertheless provide a basis for discussing how expectations of future value can shape peripheral land development.

The 2020 imagery shows additional construction within and around earlier development clusters. Some previously separate areas appear more connected, while open land remains visible elsewhere. In the 2025 panel, larger residential projects coexist with villa areas and the older settlement. Together with field photographs, this supports a qualitative reading of increasing differentiation in building forms.

Topography also appears relevant to the distribution of development. Valleys and steep terrain can interrupt building patterns, while new roads facilitate access to other locations. The case is best understood through the interaction of environmental conditions and infrastructure investment. The comparison with Seevarethnam et al. (2022) supports attention to both sets of factors, rather than the proposition that economic processes replace or eliminate biophysical constraints. In İncek, the major transport axes provide a visible organizing structure within a terrain that continues to influence the form of development.

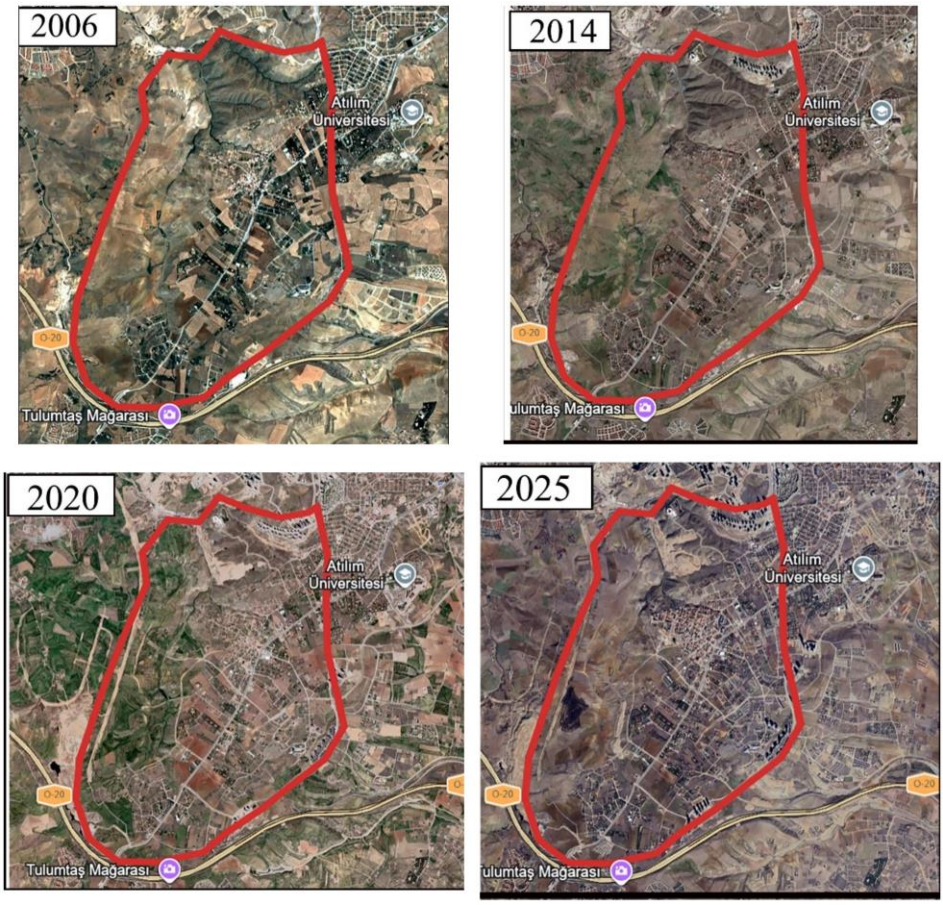


Figure 4. Comparison of historical satellite imagery for 2006, 2014, 2020 and 2025. Source: Google Earth Pro imagery compiled by the author. Red outlines delimit the study area. Place labels: Atılım Üniversitesi, Atılım University; Tulumtaş Mağarası, Tulumtaş Cave.

4.4 Housing Typologies and Socio-Spatial Differentiation

The transformation of İncek also concerns the relationship between different residential environments. Figure 5 presents the typological mapping and photographic material supplied with the field study. Three broad types are distinguished: Zone A, representing the traditional settlement fabric; Zone B, characterized by villa developments; and Zone C, containing gated apartment complexes and high-rise residences. Their principal characteristics are summarized in Table 3.

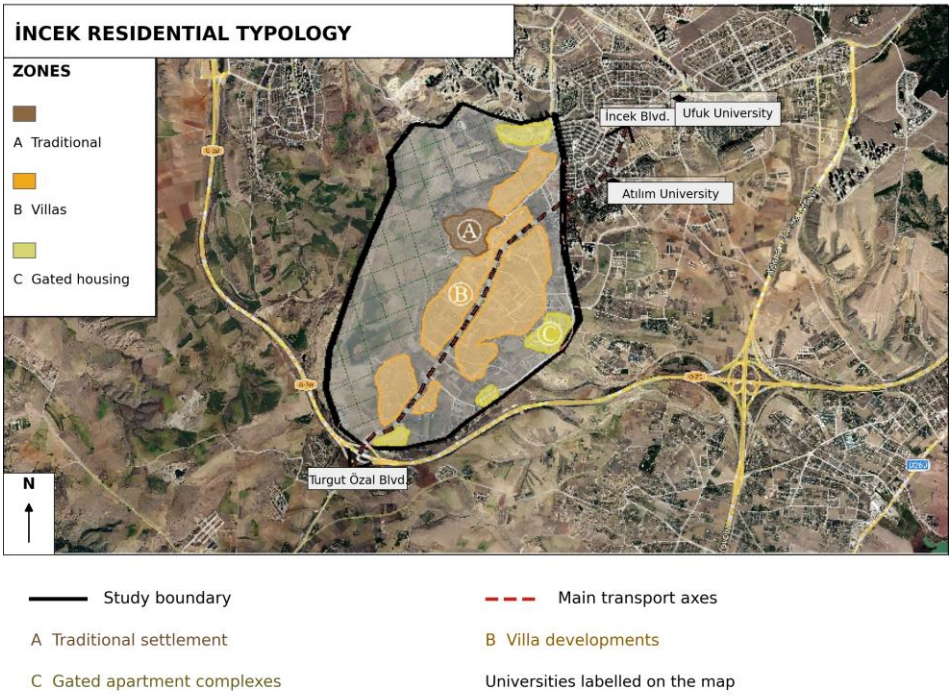


Figure 5a. Residential typology mapping in İncek. A: traditional settlement fabric; B: villa developments; C: gated apartment complexes. Source: the author's original typology map.



Figure 5b. Photographic examples of the three residential environments. Source: photographs reproduced from the author's fieldwork board (2026).

The first distinction concerns the treatment of residential boundaries. In the observed parts of Zone A, low-rise buildings and irregular plots maintain a comparatively direct relationship with local streets. In Zone B, walls and fences provide enclosure at the parcel level. Zone C contains more extensive boundary treatments, including retaining walls, fencing and controlled entrances. These differences create varying degrees of permeability between residential areas and the surrounding street network. They provide direct spatial evidence of separation, although the experience of those boundaries may differ among residents, visitors and workers.

Table 3. Residential typology characteristics reported in the field study

Characteristic	Zone A Traditional fabric	Zone B Villa areas	Zone C Gated housing
Settlement pattern	Organic and irregular	Planned, low-density	Planned, high-density
Relative density	Low	Medium	High
Building type	Traditional detached houses	Detached villas	Apartment blocks and high-rise residences
Parcel pattern	Small, irregular plots	Larger, regular plots	Very large plots
Public-space access	High	Medium	Very low
Physical barriers	None reported	Walls and fences	High walls and security systems
Social interaction	Strong	Moderate	Weak

Source: Access and interaction labels are qualitative assessments supplied by the author, not measured scores. The extent and meaning of social interaction require independent investigation.

The second distinction concerns access to shared space. The source typology classifies public-space access as high in Zone A, medium in Zone B and very low in Zone C. It similarly characterizes social interaction as strong, moderate and weak. These categories are qualitative field interpretations rather than measured access scores or survey results. The evidence supports concern about the continuity of publicly accessible routes and the enclosure of amenities.

Differences in building form reinforce the contrast. The traditional settlement includes low-rise detached buildings and small, irregular parcels, while villa developments generally occupy larger and more regular plots. Gated apartment projects contain substantially larger parcels and taller buildings. The mapping indicates close adjacency between these environments and limited morphological transition in some locations. The result is a fragmented residential landscape in which changes in scale, enclosure and street relationships are readily visible.

The planning context helps explain this juxtaposition. Güller (2019) documents the coexistence of the old village fabric, low-density housing associated with earlier local plans and later development shaped by plan revisions. These historical layers caution against explaining the present pattern solely through individual housing preferences. At the same time, Öncel (2019) and Öncel and Meşhur (2021) identify changing housing provision, parcel dimensions and residential preferences as factors associated with urban sprawl.

The İncek pattern should therefore be understood as the outcome of interacting planning and market processes.

The comparison with Malang is useful at the level of residential differentiation. Wagistina and Antariksa (2019) examine how planned housing areas develop alongside established settlements and investigate the accompanying social relations through qualitative research. In İncek, the available material establishes morphological contrasts and physical enclosure more clearly than it establishes the intensity of social separation. Household interviews, income data and systematic observation of everyday movement would be needed to determine how far the observed physical boundaries correspond to sustained social segregation.

5 Discussion

The findings connect İncek's transformation with wider debates on metropolitan expansion, infrastructure-led development and residential differentiation. They also show why aggregate change must be separated from the processes occurring in particular intervals. The full series records a substantial increase in classified built-up land, but population growth is proportionally greater. The claim that land expansion consistently exceeded demographic growth is supported only for the first, imperfectly time-matched interval. Subsequent periods show stronger demographic growth relative to the classified footprint.

This temporal distinction affects how the case is compared with the literature. Serdaroğlu Sağ's (2021) Konya study demonstrates the usefulness of spatial metrics for diagnosing sprawl, but its findings should not be reproduced as if they were measured outcomes for İncek. The İncek evidence instead suggests an early phase of extensive land conversion followed by stronger growth within a more established development pattern.

The spatial pattern provides a second dimension of interpretation. Development is closely associated with major roads, and the university campuses form part of the institutional setting of the corridor. This is consistent with the importance of accessibility and investment in the location of peripheral growth. However, the evidence does not isolate the causal contribution of each campus or road project. The international comparisons are therefore used to frame questions about growth processes and residential change, rather than to assert that İncek reproduces the same dynamics as Batticaloa or Malang in every respect.

The role of planning is especially important. Güller's (2019) account shows that İncek's transformation involved successive planning interventions. Öncel and Meşhur (2021) likewise emphasize that sprawl in Türkiye can emerge

through formal planning processes. A more accurate interpretation concerns fragmented decisions, changing development rights and limited coordination between individual projects and the wider settlement.

The typology analysis adds a socio-spatial dimension to this interpretation. Differences in boundary treatments and the relationship between buildings and streets suggest that neighbouring developments provide unequal opportunities for movement and access. Geniş's (2007) analysis of elite residential environments is relevant to understanding how enclosure can acquire social and institutional significance. Çetin's (2012) discussion of segregation and spatial clustering also supports attention to the different forms that separation can take. The present observations identify conditions that may support segregation; they do not establish the income composition of every zone or the frequency of interaction across its boundaries.

These distinctions strengthen the planning implications of the study. An increase in population within the existing footprint does not automatically create an integrated urban environment. Infill or taller buildings may coexist with private access systems, disconnected streets and unequal access to amenities. Similarly, retaining open land does not by itself ensure ecological continuity or public accessibility. The quality of urban development depends on the organization of connections, services and rights of access as well as on the amount of land consumed.

6 Conclusions and Recommendations

The İncek case documents a substantial transformation of Ankara's metropolitan fringe between 2006 and 2025. Classified built-up area increased from 103.9 to 399.5 ha, with its highest reported value in 2020. The population series increased from 3,001 in 2007 to 19,449 in 2025. Physical expansion was proportionally greater in the first interval, while demographic growth was stronger in later intervals and over the full observation periods. This changing relationship is more informative than a general claim that construction consistently outpaced population.

Three further findings concern the spatial organization of this growth. Development follows major transport corridors; planning interventions and institutional investments form an important part of its context; and traditional settlement, villa developments and gated apartment complexes coexist in a fragmented residential landscape. The clearest socio-spatial evidence concerns building morphology, enclosure and differences in access. The social consequences warrant further investigation through household and movement data.

Planning and land management. Growth management should establish a coordinated framework for protecting remaining open and ecologically significant land, assessing cumulative development capacity and aligning individual projects with the wider settlement. An urban growth boundary could be considered as part of this framework, subject to an assessment of housing needs, environmental constraints and implementation capacity. The effects of parcel-level plan changes should be evaluated at corridor scale. Land-value taxation or other mechanisms for addressing speculative holding and recovering publicly created land value may also be considered at the appropriate policy level; their feasibility requires a separate institutional and fiscal assessment.

Social integration and urban design. Planning and design measures should improve continuity between the traditional settlement and newer residential areas. Connected pedestrian routes, green corridors and publicly accessible social facilities can reduce spatial separation and broaden opportunities for everyday contact. Mixed-use public centres should serve different residential groups and connect to the surrounding street network. These interventions need to address actual access arrangements and residents' needs, rather than assume that physical proximity alone produces social integration.

Transport and infrastructure. A stronger role for public transport is needed to reduce dependence on corridor-based, car-oriented development. Transit-oriented development offers a framework for concentrating suitable growth around accessible public transport nodes while coordinating land use, pedestrian connections and service provision. Density increases should be linked to infrastructure capacity and public-space quality. This would allow the efficiency of development to be assessed in terms of both land use and access, instead of treating additional construction as an isolated objective.

The case demonstrates the need to manage metropolitan growth through an integrated spatial and social perspective. The recommendations below are planning implications derived from the observed patterns and the reviewed literature; they were not tested as interventions within this study. Monitoring should combine consistent land-cover classifications, comparable population boundaries and information on building intensity and housing occupancy. Field research should also examine how residents use streets, facilities and spaces across residential boundaries. Such evidence would allow Ankara's southwestern corridor to be planned with closer attention to efficient land use, ecological continuity and equitable participation in urban life.

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Chapter 3

Architectural-Structural Integration in Seismic Retrofitting of Prefabricated Reinforced Concrete Industrial Buildings: Damage Mechanisms, Intervention Approaches, and Design Decisions

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ABSTRACT

Industrial buildings made of prefabricated reinforced concrete are commonly used as factory and warehouse rooms for single and multiple storey buildings in Turkey. However, these structures can develop extensive joint damage, joint column bases can collapse, roof systems can fail, façades can come apart, etc. after major earthquakes, regardless of the main advantages of such buildings, i.e., relatively short construction periods and ease of modularity. As one of the effects of a retrofitting strategy is to alter the structural performance but also the spatial layout, the design aspects of the exterior walls, layout of internal facilities, uninterrupted functioning, and the overall life cycle value, the paper presents four types of interventions: upgrading of panel-frame connections, wrapping columns, addition of energy-dissipating braces/dampers, and prestressed complementary frames. The analysis consists of a narrative synthesis of peer-reviewed works, earthquake aftermath data collected in the field and official technical standards. The supporting evidence was grouped into on-site inspections, laboratory studies, simulated models, and specifications, and, methods were analyzed according to damage modes, efficiency indexes, level of architectural changes, and preconditions for the method application. While the literature describes model-specific drift reductions in jacketing as leading to 54-72% and, lead extrusion dampers as to 40-90%, they were not directly translated into an overall ranking of superiority mainly because of different structural configurations and shake characteristics. The outcome of the discussion is also that the architects/structural engineers/clients decision making on the spatial planning aspects of the building, the compatibility of the movements of the building exterior with the interventions

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adopted, the duration of the period of interruption of production, and the accessibility condition for the maintenance personnel should be evaluated simultaneously with the technical matters like the transfer of loads and the security of the joint. The decision framework on architectural-structural issues that has been outlined in this paper was not an instrument to carry out a design verification. On the other hand, it is a form of qualitative assessment to guide more detailed investigations on a case-by-case basis.

Keywords: Prefabricated reinforced concrete; industrial architecture; earthquake resilience; seismic retrofitting; architectural-structural integration; façade systems; adaptability.

1. INTRODUCTION

Precast reinforced concrete (precast RC) structural systems are widely used in industrial, storage, and logistics buildings due to the ability to manufacture structural elements under controlled production conditions, shortened construction times, and the economical creation of large-span spaces. However, the seismic performance of these systems depends not only on the sectional strength of the structural members, but also on the mechanical behaviour of the connections, system integrity, and continuous load transfer. Recent reviews treat the strength, stiffness, ductility, and energy dissipation capacities of beam-column connections as decisive variables in the seismic behaviour of prefabricated buildings (Guaygua et al., 2023; Xiao & Fomin, 2024). Therefore, the evaluation of existing structures must consider not only columns and beams, but also supports, roof diaphragms, and the movement compatibility of heavy façade panels.

Investigations carried out following the August 17, 1999 Marmara and November 12, 1999 Düzce earthquakes in Turkey revealed the impact of connection deficiencies and column base damage on structural system safety in prefabricated industrial buildings (Arslan et al., 2006). Research concerning the 2012 Emilia earthquakes in Italy likewise demonstrated that mechanisms such as inadequate lateral connections, limited support seating lengths, and the detachment of heavy cladding panels can escalate local damage into widespread progressive collapse (Belleri et al., 2015; Savoia et al., 2017). Findings obtained from different seismic regions support that element strength and connection/load-path security are performance controls that cannot substitute for one another.

Post-earthquake fragility studies indicate that buildings of similar appearance may behave differently because of construction period, connection details and ground-motion intensity. Buratti et al. (2017) derived empirical fragility relationships from damage observed after the Emilia earthquakes; Bournas et al.

(2014) subsequently emphasized connection and support deficiencies when discussing strengthening priorities. Damage diagnosis and retrofit selection are thus related but distinct tasks.

The 6 February 2023 Kahramanmaraş earthquakes renewed concern about Türkiye's precast industrial stock. Field reports identified damage mechanisms and potential interruptions to industrial use (Şenel et al., 2025; Demir & Sezen, 2025). Arslan et al. (2024) examined how construction details influence connection response. Avğın et al. (2026) reviewed 595 industrial buildings, while Şişman et al. (2025) analysed more than 4,000 building records to derive empirical fragility curves. Their different samples and outcome definitions do not permit a pooled damage rate.

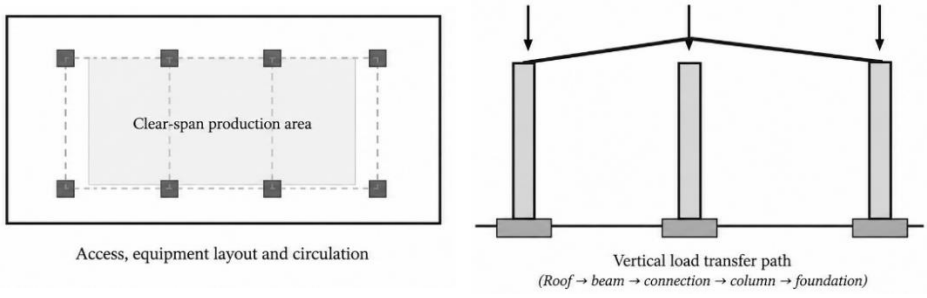
The Turkish Building Earthquake Code provides the regulatory basis for assessing existing structures and designing strengthening interventions (Disaster and Emergency Management Presidency [AFAD], 2018). Its application to precast buildings requires explicit verification of support seating, anchors, roof load transfer and cladding connections. fib Bulletin 43 likewise treats connections as integral structural components throughout manufacture, erection and maintenance (International Federation for Structural Concrete [fib], 2008). Increased member capacity must therefore be checked against redistributed demands at other components.

For industrial architecture, seismic safety extends beyond collapse prevention. Column grids, loading zones, escape routes, services and future changes of use constrain where new structural elements can be placed. Two schemes offering similar structural performance may differ considerably in usable floor area, façade coherence, maintenance access and downtime. Studies integrating structural and envelope renovation underscore the need for interdisciplinary assessment (Banti, 2024; Pohoryles et al., 2022).

Earlier Turkish stock studies have identified structural and geometric variables associated with different vulnerability levels (Yesilyurt et al., 2021), while broader reviews address connection technologies and dissipation mechanisms across several precast typologies (Chang et al., 2023). Their heterogeneous prototypes, loading protocols and response metrics hinder direct comparison of reported gains. A further gap is the explicit connection between these structural findings and the architectural consequences of retrofitting.

This chapter compares four intervention families—panel–frame connection upgrades, reinforced concrete column jacketing, energy-dissipating braces or dampers, and supplemental prestressed frames—according to targeted mechanisms, supporting evidence, structural performance, architectural implications and implementation constraints. Its contribution is a traceable,

qualitative relationship among the identified deficiency, candidate intervention, verification requirement and spatial compatibility. It presents no new experiments or numerical simulations, and does not rank methods using percentages obtained from non-equivalent studies. Figure 1 introduces the spatial layout and gravity-load path of the reference industrial-building typology.



(a) (b)

Figure 1. Architectural and structural organisation of a single-storey precast reinforced concrete industrial building: (a) architectural plan showing the clear-span production area and circulation layout; (b) schematic structural section illustrating the vertical gravity-load transfer from the roof to the foundations. *(Not to scale; original conceptual illustration developed by the authors based on a synthesis of the literature.)*

2. THEORETICAL FRAMEWORK OF ARCHITECTURAL-STRUCTURAL INTEGRATION

2.1. Large-Span, Modular Design, and Spatial Adaptability

The column grid and clear spans of a precast RC industrial building respond to production, storage, equipment and logistics requirements. While large spans create usable and adaptable interiors, pinned beam–column systems may exhibit cantilever-like column response under lateral loading. Displacement demand and connection security must therefore be assessed together with the existing plan, rather than treating a retrofit as an exclusively structural addition.

Walls, braces and supplementary frames may improve lateral resistance but constrain machinery clearances, forklift routes, loading bays or emergency egress. Their position should be coordinated with the architectural plan before detailed design and checked against projected changes in production and circulation.

Spatial adaptability includes the capacity to accommodate future equipment, storage and functional changes without disproportionate construction work. ISO 20887:2020 provides principles for adaptability and disassembly over a

building's life cycle, but is not a seismic bracing design code (International Organisation for Standardization [ISO], 2020b). It is used here solely to inform assessments of reversibility, replaceability and spatial flexibility.

2.2. Façade Envelope Safety, Component Interaction, and Architectural Expression

Precast concrete cladding forms a major part of the industrial building envelope and its architectural expression. Panel geometry affects façade rhythm, openings, daylight and thermal detailing. Under earthquake action, however, panel mass, connection stiffness and in-plane or out-of-plane displacement compatibility also influence the structural response.

Full-scale SAFECLADDING tests identified limitations to complete frame–panel decoupling in certain horizontal-cladding arrangements and investigated controlled, dissipative connections (Lamperti Tornaghi et al., 2022). The resulting lesson is that cladding connections are both architectural details and safety-critical mechanical components.

Controlled panel participation requires checks on anchorage forces and force transfer, whereas decoupled systems emphasize movement capacity and joint clearances. Both approaches affect façade joints, waterproofing, insulation continuity, inspection access and post-earthquake realignment. These consequences should be explicitly documented in retrofit details.

ISO 22502:2020 sets out simplified principles for concrete cladding connections, including mechanical, sliding and dissipative arrangements (ISO, 2020a). Connection strength and relative-displacement capacity therefore require separate verification; the standard is not a universal catalogue of details for every industrial building.

2.3. Post-Earthquake Functionality and Production Continuity

Seismic resilience includes the ability to restore production after an earthquake, not only to prevent collapse. Detached panels, displaced machinery, damaged services or jammed loading doors may interrupt operation even when the main frame remains standing.

FEMA P-58 includes repair costs, repair times and damage to non-structural components in performance-based loss assessment (Federal Emergency Management Agency [FEMA], 2018). This supports the consideration of architectural and service systems alongside the structure; no probabilistic loss or recovery-time calculation is carried out for a particular plant in this chapter.

Retrofit works in an occupied factory also require equipment protection, temporary access, construction phasing and occupational safety. Column

jacketing can temporarily close working areas, while exterior interventions may reduce interior disruption but alter loading areas, fire access and service routes. Such trade-offs require project-specific coordination.

Bal (2026) assessed hybrid strengthening of selected Turkish precast industrial buildings, including implementation considerations; Ostetto et al. (2024) investigated seismic risk and loss implications of retrofit levels. Together they support evaluating operational constraints and consequences alongside structural performance, without suggesting that one solution suits every facility.

Studies on externally integrated structural and envelope retrofits suggest opportunities for coordinating seismic and thermal work (Badini et al., 2022). Because their building typologies differ, their results inform the present discussion conceptually rather than providing design evidence for single-storey industrial frames. Figure 2 compares an open-plan industrial layout with a conceptual bracing arrangement, drawing attention to circulation and equipment-clearance constraints.

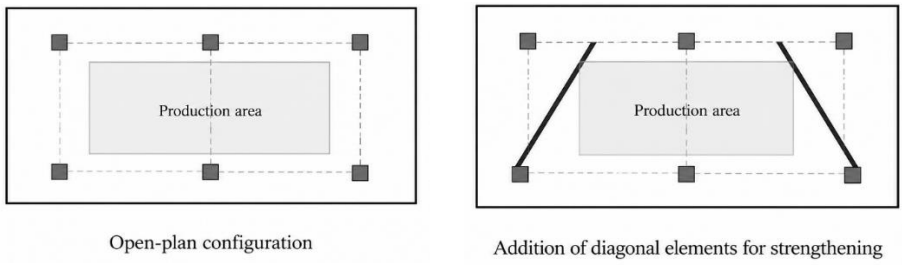


Figure 2. Spatial implications of seismic retrofitting in a precast concrete industrial building: (a) existing open-plan configuration; (b) retrofitted layout illustrating the potential effects of diagonal bracing on circulation and equipment clearance. *(Not-to-scale conceptual illustration prepared by the authors based on the literature synthesis.)*

2.4. Sustainable Renovation and Multi-Criteria Performance

Strengthening an existing industrial building can avoid some material use and demolition waste, yet environmental superiority cannot be assumed without considering new embodied impacts, maintenance, replacement and service life. A defensible choice requires a project-specific life-cycle perspective.

Cavalieri et al. (2023) compared seismic and environmental outcomes of alternative precast retrofit schemes. Research on combined energy and seismic renovation likewise supports coordinating façade and structural works, while

cautioning against treating an improvement in one performance dimension as proof of improvement in another (Ademovic et al., 2022; Pohoryles et al., 2022).

New braces or frames may be visibly expressed as part of an industrial building's architectural character or concealed behind the envelope. Neither strategy is inherently preferable: context, operational needs, reversibility and façade continuity should guide the decision.

Architectural compatibility, adaptability and sustainability are therefore treated as qualitative design considerations—not as measured user responses or the outputs of a life-cycle calculation. Table 1 summarises their relationship with structural checks.

Table 1. Recommended joint performance and design evaluation criteria within the scope of architectural-structural integration.

Evaluation dimension	**Recommended control criteria**	**Correspondence in architectural design**
Structural system safety	Support and anchorage safety; connection capacity; load transfer continuity	Structural axis arrangement, positioning of retrofitting elements, and structural integrity
Spatial use and adaptability	Net spans; equipment layout; circulation and access requirements	Continuity of production areas, operational flexibility, and future functional transformation
Façade and building envelope	Panel-frame movement compatibility; connection safety; joint and maintenance access	Façade organisation, opening arrangement, connection details, and envelope integrity
Operational continuity	Temporary shutdowns; construction phasing; access and maintenance needs	Work sequencing; alternative routes; continuity of production
Lifecycle and sustainability	Embodied impacts; durability; replaceability; disassembly	Reversible interventions; long-term adaptability and reuse

Note: The criteria presented in the table are qualitative evaluation headings developed from the literature synthesis. They do not constitute a validated scoring system or a quantitative performance ranking.

3. MATERIALS AND METHODS

3.1. Research Approach and Selection of Literature

This study uses a structured narrative review of scientific publications, post-earthquake investigations, standards and technical guidance, with emphasis on the 2006–2026 period. It focuses on single-storey precast RC industrial buildings,

while drawing on other typologies only when an intervention mechanism is relevant and transfer limitations can be stated.

Search themes included ‘precast industrial building’, ‘seismic retrofitting’, ‘beam-to-column connection’, ‘cladding panel’, ‘RC jacketing’, ‘dissipative bracing’ and ‘post-tensioned retrofit’, together with Turkish equivalents. Bibliographic identities were checked against journal, institutional and publisher records.

Sources were selected for topical relevance, a sufficiently described method, interpretable performance or implementation findings, and publication in peer-reviewed or authoritative technical outlets. Findings from different structural typologies were not treated as interchangeable design evidence.

Because database-specific retrieval counts and complete exclusion decisions were not retrospectively recorded, the work is neither a PRISMA-compliant systematic review nor a meta-analysis. Its objective is a transparent qualitative synthesis rather than exhaustive retrieval or a pooled effect estimate.

3.2. Classification of Evidence and Comparison Method

Five evidence categories were used: G1, post-earthquake field observation; G2, laboratory or full-scale testing; G3, experimentally calibrated numerical analysis; G4, uncalibrated numerical or parametric analysis; and G5, standards, guidance or reviews. These labels identify the origin and transfer limits of evidence, not a hierarchy of scientific merit.

Field investigations reveal observed failure mechanisms but do not measure retrofit efficiency. Tests clarify component behaviour within specimen and loading limits; numerical analyses explore building-level scenarios subject to model and motion assumptions. Table 2 distinguishes the interpretive strengths and limits of these evidence types.

Table 2. Evidence classes, evaluation possibilities, and generalization limits used in the literature synthesis.

Evidence class	Data or research type	Primary information provided	Interpretation and generalization limit
G1 – Field observation	Post-earthquake damage records, photographs, and building inspections	Identification of actual damage and collapse mechanisms	Does not directly demonstrate the effectiveness of the retrofitting method
G2 – Experimental research	Cyclic loading, laboratory, or full-scale tests	Mechanical behaviour of connections and components	Limited by specimen geometry, scale, and loading protocol
G3 – Calibrated numerical model	Structural analyses supported by experimental data	Evaluation of intervention scenarios at the system level	Dependent on model assumptions, structural properties, and seismic inputs
G4 – Numerical/parametric research	Numerical models and parametric analyses	Examination of potential behaviour and parameter sensitivity	May require independent experimental verification
G5 – Guide, standard, or review	Technical regulations and synthesis of existing research	General design principles and theoretical evaluation framework	Does not directly reflect the realized performance of a single building

For each study, the building typology, intervention, loading scenario, response variable and reference condition were recorded separately. Single-storey industrial frames, multi-storey retrofit frames and isolated connection specimens were not pooled. Thus, a percentage gain in local connection resistance was not equated with building-level drift reduction.

Comparison addressed the targeted weakness, anticipated structural contribution, type of supporting evidence and implementation requirements. An additional architectural layer covered usable spans, cladding, services, operational continuity and adaptability. These dimensions describe trade-offs without producing an unsupported global score.

Numerical findings are reported only in their original contexts. No pooled mean, confidence interval, significance test or method ranking was calculated from non-equivalent studies.

3.3. Reference Building Typology, Performance Criteria, and Methodological Limitations

The reference typology is a wide-span, single-storey precast RC frame with columns, supported roof beams, secondary roof elements and perimeter cladding panels. Depending on detailing, columns may act as cantilevers, supports may have limited seating or restraint, and roof elements may lack diaphragm continuity. These are potential deficiencies requiring a building-specific survey, not universal characteristics of precast construction. Figure 3 depicts the principal possible damage mechanisms: beam unseating, column-base distress, discontinuous roof load transfer and cladding connection failure. Its schemes are conceptual, not details from a surveyed or analysed building.

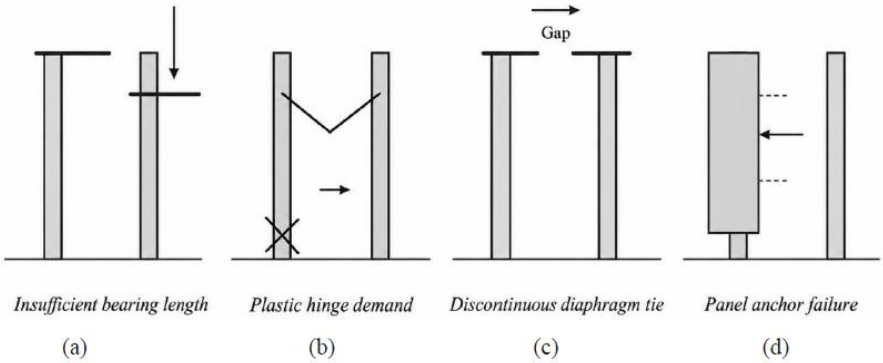


Figure 3. Principal earthquake damage mechanisms in single-storey prefabricated reinforced concrete industrial buildings: (a) unseating of beam from support, (b) column base damage, (c) load transfer discontinuity in the roof plane, and (d) loss of connection of the façade panel. *(Not-to-scale conceptual illustration developed by the authors based on a synthesis of the literature.)*

Response indicators included peak and residual lateral displacement, interstorey drift, column-base moment and curvature demand, connection strength and deformation capacity, support seating, cladding compatibility and hysteretic energy dissipation. Roof-element sliding and local connector deformation must be checked separately from global drift.

For the same building and earthquake input, the percentage change in a positive demand measure D can be reported as [(D_before − D_after)/D_before] × 100. This relationship was not used to recompute values across the reviewed studies because their models, input motions and response definitions differ.

Architectural evaluation considered five qualitative dimensions: production-space continuity, façade–structure interaction, material and visual compatibility,

construction and maintenance access, and adaptability with environmental implications. No expert weighting, user survey or validated optimisation score was produced.

The review is constrained by heterogeneous evidence types and the absence of a fully registered search protocol. Results from other building typologies, particularly supplemental prestressed frames, are discussed as transferable concepts requiring independent verification rather than confirmed solutions for one-storey industrial buildings.

The proposed comparison is therefore a preliminary, evidence-linked screening framework and cannot replace site investigation, structural modelling, design verification or construction inspection.

4. EARTHQUAKE DAMAGE MECHANISMS AND THEIR RELATIONSHIP WITH DESIGN

Post-earthquake studies in Türkiye identified beam–column connection deficiencies, column-base damage and unseating after the 1999 earthquakes (Arslan et al., 2006). Similar failures, together with vulnerable cladding anchors and inadequate lateral ties, were documented after the 2012 Emilia earthquakes (Belleri et al., 2015; Savoia et al., 2017). Their shared lesson is that member capacity cannot substitute for a continuous load path and secure supports.

The 2023 Kahramanmaraş earthquakes provided further field evidence. Şenel et al. (2025) examined damage in industrial areas, raising questions about usability and production continuity. The duration or cost of downtime, however, cannot be inferred directly from the structural damage grade.

Arslan et al. (2024) combined field evaluation with connection-level modelling and reported a 62% increase in out-of-plane lateral resistance for a specific grouted connection model. This is a local, model-dependent capacity result, not a measured building-wide seismic improvement.

Avğın et al. (2026) analysed damage records from 595 industrial buildings, while Şişman et al. (2025) derived empirical fragility relationships from more than 4,000 records, considering construction-era differences. Their populations and methods differ; the observations cannot be pooled or interpreted as retrofit success rates.

Field records document real failure patterns, whereas analytical work tests particular modelling assumptions. Table 3 therefore distinguishes study scope, architectural implications and the limits of transferring each finding to design decisions.

Table 3. Comparative evaluation of findings obtained from post-earthquake field observations and analytical studies in prefabricated reinforced concrete industrial buildings from a design perspective.

Study and evidence	Research scope	Design implication	Transferability limit
Arslan et al. (2006) · G1	1999 Turkish earthquake damage	Check connections, seating and column bases jointly	No retrofit effectiveness quantified
Savoia et al. (2017) · G1	2012 Emilia damage and collapse	Secure supports and cladding anchors	Damage rates not transferable to Türkiye
Şenel et al. (2025) · G1	2023 industrial-building field surveys	Consider functionality alongside damage	No direct production-loss estimate
Arslan et al. (2024) · G1/G4	Connection modelling and field findings	Detailing affects local capacity	62% result applies to one model
Avğın et al. (2026) · G1	Damage data for 595 buildings	Account for construction and detailing	Sample is not the whole stock
Şişman et al. (2025) · G1 + statistics	Fragility analysis, 4,000+ records	Distinguish construction cohorts	Not a retrofit success measure
Minghini & Tullini (2021) · technical	Strengthening after Emilia	Coordinate local and global load paths	No universal construction detail

Note: G1 denotes evidence based on field observations, and G4 denotes evidence based on numerical analyses. Statistical and technical evaluations are indicated as analytical approaches complementing the evidence classes defined in the previous section. Inferences presented in the table are qualitative evaluations developed based on the findings of the source studies.

Minghini and Tullini (2021) assessed implemented retrofit solutions after the Emilia earthquakes and stressed coordination between local connections, members and global force transfer. Consequently, strengthening elements should be located not only for spatial convenience but also for structural load-path continuity.

For architectural coordination, support lengths, column heads, roof ties, panel anchors and required movement clearances should be visible in the relevant detail drawings. Improving panel-fall protection does not prove frame adequacy, just as strengthening a beam–column connection does not establish column-base safety (Belleri et al., 2015; fib, 2008).

Damage diagnosis and intervention design must thus be coordinated across engineering and architecture, including façade integrity, services, circulation and post-earthquake usability.

5. COMPARATIVE EXAMINATION OF RETROFITTING APPROACHES

The reviewed strategies address different weaknesses: connections secure load transfer, jacketing increases member capacity, dampers control response demand, and supplemental prestressed frames can support recentering. Their assessment must consider architectural disruption and compatibility as well as structural effects.

5.1. Improvement of Connections, Façade, and Structural Members

In prefabricated reinforced concrete industrial buildings, connection zones and façade panels rank among the critical components affecting the holistic behaviour of the structural system under seismic effects. Although façade panels are mostly designed as non-structural elements, they can alter the behaviour of the structure under lateral loads due to panel mass, connection stiffness, contact conditions, and their interaction with the frame. Biondini et al. (2013) numerically investigated the interaction between the connection properties of prefabricated wall panels and the structural system, highlighting the significance of panel connections in terms of system-level behavior. Therefore, the retrofitting of existing structures requires evaluating not only the safety of façade panels against falling, but also their mechanical interaction established with the structural frame.

Full-scale experiments carried out within the scope of the SAFECLADDING research program have demonstrated that completely decoupling panel movements from the structural frame in horizontal prefabricated façade panels can create difficulties in certain connection configurations. Lamperti Tornaghi et al. (2022) examined the potential of connection solutions allowing controlled movement and energy dissipation in terms of seismic performance. These findings reveal that panel-frame interaction must be explicitly defined at the initial stage of retrofitting design. In approaches where the panel is targeted to contribute to the structural system in a controlled manner, connection stiffness and force transfer capacity come to the fore, whereas in solutions where panel movement is decoupled from frame behavior, relative displacement capacity and the adequacy of movement clearances become decisive.

In the retrofitting of façade connections, tension and shear capacities of anchorages, concrete edge distances, inertial forces arising from panel mass, in-

plane and out-of-plane movements, and the behaviour of connections under cyclic loads must be evaluated together. Uncontrolled increase in stiffness of connections can alter panel-frame interaction and generate additional force demands in anchorage zones. Consequently, preventing panel detachment and improving the overall seismic performance of the structural system are complementary targets requiring distinct verification criteria. From an architectural perspective, the visibility of connection elements on the façade, panel joints, insulation continuity, and maintenance access are key parameters influencing the applicability of the intervention.

Mechanical retrofitting solutions aiming to increase the local safety of connection zones can reduce the risk of beam unseating without creating a comprehensive change in the sectional stiffness of structural members. Rodrigues et al. (2024) evaluated the retrofitting arrangement they developed for beam-column connections in prefabricated reinforced concrete industrial buildings through cyclic loading experiments. It was reported that the proposed connection solution increased the lateral strength in the most unfavorable loading direction by 49% compared to the friction-based reference connection alone. However, this result pertains to experimental connection capacity and does not demonstrate that an equivalent rate of building-level interstorey drift reduction has been achieved. This distinction necessitates separately analysing the effect of local connection improvements on overall structural system behavior.

Reinforced concrete column jacketing, on the other hand, is a traditional retrofitting method aiming to increase flexural and shear capacity, sectional stiffness, and, under appropriate detailing conditions, confinement effect through the addition of new reinforcement and concrete layers to existing column sections. Soydan and Özkaynak (2019) investigated the effect of reinforced concrete jacketing application on the earthquake performance of a three-dimensional prefabricated industrial building using numerical models calibrated with experimental findings. In the research, a reduction in the range of 54–72% was reported for average maximum and minimum interstorey drift values for the selected earthquake records and building model. However, this result is specific to the building geometry, material properties, numerical model assumptions, and seismic inputs examined in the study; it cannot be interpreted as though the same performance gain will be achieved in the retrofitting of different buildings.

The enhancement of structural system stiffness by column jacketing can alter the vibration characteristics of the structure and the distribution of earthquake forces among members. Therefore, alongside strengthening columns, changing force demands on foundation capacity, column-foundation connections, roof diaphragms, beam supports, and existing anchorage mechanisms must also be

checked. Furthermore, interface behaviour between old and new concrete, reinforcement continuity, transverse reinforcement details, and the adequacy of foundation connections are fundamental technical conditions influencing the success of the application. Merely increasing the flexural capacity of columns does not automatically eliminate the risks of beam unseating or façade panel connection loss.

Evaluated architecturally, reinforced concrete column jacketing can alter net usable dimensions of production areas by increasing existing column dimensions. Particularly, machinery, rack systems, transport equipment, and maintenance routes positioned around columns can be directly affected by the new section geometry. In addition, formwork installation, reinforcement placement, concrete pouring, and the curing process may require specific areas in active production facilities to be temporarily taken out of service. Consequently, the applicability of column jacketing should be evaluated by considering its effects on spatial utilization and compatibility with operational activities, rather than solely through structural performance gains and construction costs.

5.2. Energy-dissipating Systems and Prestressed Auxiliary Frames

Energy-dissipating retrofitting systems aim to reduce displacement and deformation demands that may arise in structural members by ensuring that energy transferred to the structure during earthquake motion is dissipated in specific components in a controlled manner. In these approaches, the energy dissipation mechanism can be created through devices utilizing friction, metallic yielding, or other hysteretic behaviour characteristics. Unlike traditional stiffness-enhancing methods, energy-dissipating systems aim to control the seismic demands of existing structural members and, under appropriate design conditions, concentrate damage in specific replaceable components.

Dal Lago et al. (2021) numerically examined a unidirectional bracing approach that provides friction-based energy dissipation under tensile forces and limits force transfer in the compression direction, for use in the seismic retrofitting of prefabricated industrial buildings. The proposed system aims to mitigate buckling problems that may occur due to compression effects, particularly in long bracing elements, and to contribute to the control of lateral seismic demands. Nevertheless, the results of the research are valid for the examined device model and prototype building, and should not be evaluated as directly verified performance values in different connection details or application conditions.

Soydan et al. (2020) investigated the use of lead extrusion dampers in the retrofitting of existing single-storey prefabricated reinforced concrete industrial

buildings. For the building model and earthquake scenarios examined in the study, reductions of approximately 40–90% in interstorey drifts and improvements reaching up to 70% in certain comparisons for deformation demands at the column base were reported. These findings demonstrate the potential of energy-dissipating devices to reduce structural demands when used in conjunction with an appropriate connection arrangement and load transfer mechanism. Nevertheless, the reported rates cannot be directly compared with percentage gains in different studies concerning reinforced concrete column jacketing. The geometric properties, structural system behaviors, device parameters, earthquake records, and evaluation indicators of the examined buildings differ from one another.

The effectiveness of energy-dissipating systems depends on the reliability of mechanical connections established with the existing structural system, alongside the hysteretic behaviors of the devices. Particularly, anchorage forces, movement capacities, cyclic fatigue behavior, corrosion and temperature effects, and post-earthquake inspection and replacement requirements of the devices must be evaluated during the design process. Di Salvatore et al. (2024) examined the contribution of hysteretic devices used in prefabricated connections to seismic behaviour via numerical dynamic analyses and revealed the significance of the relationship between connection behaviour and energy dissipation. The contribution of such systems to structural performance must be evaluated together with the force transfer continuity among the roof plane, columns, foundations, and other connection components beyond the individual characteristics of the device.

From an architectural design perspective, the positioning of energy-dissipating braces can create a direct impact on existing building axes, production areas, circulation routes, and equipment layouts. Placing new braces into specific spans can restrict production line continuity, forklift access, loading areas, or emergency evacuation routes. Conversely, systems placed around the building perimeter or in specific service zones under appropriate geometric conditions can allow for the reduction of interventions inside the interior space. Therefore, in evaluating energy-dissipating systems, layout arrangement, maintenance accessibility, and post-earthquake replaceability must be treated as design criteria just as much as the technical performance of the devices.

Prestressed prefabricated auxiliary frame systems, on the other hand, constitute an alternative retrofitting approach aiming to limit permanent displacements that may occur post-earthquake alongside increasing the lateral load-bearing capacity of the structure. In these systems, prestressed connections can contribute to re-centering behaviour under appropriate detailing conditions,

making it possible for the structure to approach its initial geometry after an earthquake. Kurosawa et al. (2019) evaluated the use of lightweight pressure-jointed prefabricated prestressed auxiliary frames in the seismic retrofitting of existing reinforced concrete frames through experimental and numerical methods. Favorable results were obtained in the research regarding controlled crack development, limited residual drift, and damage mitigation; however, it was stated that partial retrofitting carried out only on specific floors could lead to deformation concentration on other floors.

The fact that the system examined in the aforementioned research was applied to existing multi-story reinforced concrete frames limits the direct transferability of the obtained results to single-storey prefabricated industrial buildings. Therefore, prestressed auxiliary frames are handled not as a validated retrofitting method for all prefabricated industrial buildings within the scope of the present research, but as an intervention approach that can be evaluated in light of experimental and numerical findings obtained from different building typologies. For such a system to be applicable in single-storey industrial buildings, connection behaviour between new and existing frames, foundation capacity, force sharing with the roof plane, and effects on spatial utilization must be analysed on a project-specific basis.

Another key feature of prestressed systems is that re-centering capacity and energy dissipation capacity are distinct performance components. Reducing permanent displacements does not mean that higher hysteretic energy dissipation is provided in every case. The opening-closing behaviour of connections, prestressing force, friction conditions, and the use of additional energy-dissipating devices can alter the cyclic behaviour of the system. Fang et al. (2024) demonstrated that the cyclic behaviour and repair potential of prestressed prefabricated connections depend on connection details. Consequently, in evaluating prestressed auxiliary frames, strength, stiffness, energy dissipation, and permanent deformation must be treated as separate performance indicators.

The conceptual positions and primary behaviour mechanisms of the four fundamental retrofitting approaches examined on the structural system are comparatively illustrated in Figure 4.

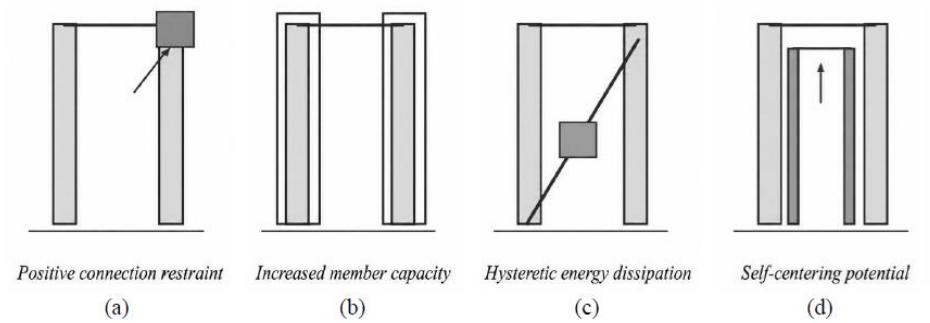


Figure 4. Conceptual representation of four fundamental seismic retrofitting approaches in prefabricated reinforced concrete industrial buildings: (a) connection improvement, (b) reinforced concrete column jacketing, (c) energy-dissipating bracing, and (d) prestressed auxiliary frame. (Not-to-scale conceptual illustration developed by the authors based on a synthesis of the literature.)

5.3. Comparative Evaluation of Retrofitting Approaches

The comparison of the examined retrofitting approaches demonstrates that different methods are not solutions that can be directly substituted for one another to remedy the same structural deficiency. While connection improvements primarily target force transfer continuity and support safety, reinforced concrete column jacketing focuses on increasing member capacity and stiffness. Energy-dissipating systems aim to control displacement and deformation demands occurring during an earthquake, whereas prestressed auxiliary frames aim for low permanent deformation and re-centering behaviour under appropriate system conditions. Therefore, the selection of the retrofitting method must be based not merely on the numerical performance gain reported in a specific study, but on the dominant damage mechanisms of the existing structure and the system behaviour that will change following the intervention.

The existence of multiple structural deficiencies in existing structures may necessitate the combined use of different retrofitting techniques. For instance, increasing the flexural capacity of columns does not automatically ensure the support safety of existing beam-column connections, just as strengthening mechanical connections does not eliminate increasing force demands at the column base. Therefore, it is possible to evaluate local connection improvements together with section strengthening, alongside additional energy-dissipating systems when necessary. Bal (2026), in his case studies conducted on four single-storey prefabricated reinforced concrete industrial buildings in Turkey, evaluated hybrid retrofitting options containing carbon fibre-reinforced polymer (CFRP) wrapping and steel structural components through nonlinear analyses. Such

research demonstrates the importance of jointly addressing interventions targeting different structural weaknesses; however, the findings obtained must be restricted in terms of building geometry, connection conditions, and model assumptions.

Force redistribution that may emerge among structural system components following retrofitting is a key evaluation subject in method selection. While the vibration characteristics of the structure and the distribution of earthquake forces can change with the increased stiffness of columns, the effectiveness of energy-dissipating bracing systems can depend on the roof diaphragm possessing adequate load transfer capacity. Similarly, rigidifying façade panel connections can alter panel-frame interaction and generate additional forces in connection and anchorage zones. In prestressed auxiliary frames, force sharing between existing and new systems must be evaluated together with re-centering and energy dissipation mechanisms. Therefore, positive performance outcomes obtained at the element or connection level should not be accepted as proof of holistic seismic safety without performing necessary analyses at the building level.

From the perspective of the architectural discipline, the comparison of retrofitting methods encompasses, in addition to structural system behavior, the effects of interventions on spatial organisation, the building envelope, operational continuity, and future utilization potential. Reinforced concrete column jacketing can lead to a loss of usable area around columns, whereas the placement of bracing elements can restrict circulation and equipment access in specific axes. Externally added structural systems can alter the existing façade rhythm, the perception of the building mass, and surrounding service areas. Conversely, local connection and panel anchorage improvements can affect the plan schema at a more limited level, yet generate application requirements such as façade dismantling, joint arrangements, and maintenance access. Consequently, the architectural effects of retrofitting methods should be addressed not as secondary problems emerging post-application, but as fundamental decision parameters that must be evaluated during the preliminary design phase.

The environmental impacts of retrofitting decisions must also be evaluated alongside the technical features of the method. Cavalieri et al. (2023) compared reinforced concrete column jacketing with alternatives based on energy-dissipating devices on a single-storey prefabricated reinforced concrete industrial building in terms of seismic performance and lifecycle environmental impacts. Under the examined example building and evaluation conditions, it was determined that the approach based on energy-dissipating devices could provide advantages regarding environmental impacts. Nevertheless, it is inappropriate to evaluate this result as a universal indicator of superiority for different building

typologies, material quantities, and operational conditions. Determining environmental performance requires examining lifecycle components such as material production, assembly, maintenance, replacement, and expected service life together. The primary effect mechanisms, expected structural gains, and conditions requiring validation prior to application for the examined retrofitting approaches are compared in Table 4.

Table 4. Effect mechanisms, expected gains, and design verification requirements of principal retrofitting approaches in prefabricated reinforced concrete industrial buildings.

Retrofitting approach	**Primary effect mechanism**	**Expected performance contribution**	**Critical design and application checks**
Improvement of panel-frame connections	Ensuring force transfer continuity and controlled movement	Panel safety, connection integrity, and controlled damping under appropriate conditions	Anchorage capacity, panel-frame movement compatibility, concrete edge distance, and connection behavior
Reinforced concrete column jacketing	Increasing section capacity, rigidity, and confinement effect	Enhancement of flexural and shear capacity, control of lateral drift demand	Old-new concrete interaction, column-foundation connection, changing earthquake forces, and spatial utilization
Energy-dissipating braces and dampers	Hysteretic energy dissipation and limitation of deformation demands	Potential for reducing relative drift and deformation demands	Device capacity, anchorage safety, roof diaphragm, cyclic fatigue, and replaceability
Prestressed auxiliary frames	Additional lateral load-bearing system and re-centering mechanism	Potential for limiting permanent deformation and controlled damage behavior	Existing-new system interaction, foundation capacity, diaphragm connections, and prestressing conditions
Local mechanical support improvements	Prevention of unseating and connection loss	Reduction of beam falling risk and enhancement of local connection safety	Loading direction, connection strength, deformation capacity, and cyclic behavior

Note: Performance gains indicated in the table represent potential effects targeted by the methods; they are not verified or quantitatively guaranteed results for every building.

Quantitative performance results reported in the literature, on the other hand, rely on different structural models, experimental setups, and loading conditions. Therefore, it is important that the performance indicator utilized and the evidence level of the research are clearly specified when comparing these results. The relative drift reductions reported in the studies of Soydan and Özkaynak (2019) and Soydan et al. (2020) demonstrate the results of different retrofitting approaches on specific building models. The local lateral strength increase reported in the research of Rodrigues et al. (2024) is a performance metric distinct from building-level drift control. The connection capacity increase in the study of Arslan et al. (2024) is likewise limited to a specific numerical model and loading condition. These findings are summarized in Table 5 while preserving the original evaluation contexts of the studies.

Table 5. Selected quantitative retrofitting findings reported in the literature and comparability limitations.

Source and evidence type	**Examined intervention / indicator**	**Reported result**	**Validity and comparison limit**
Soydan & Özkaynak (2019) – G3	Reinforced concrete column jacketing; inter-story drift	54–72% reduction	Limited to a specific three-dimensional building model and earthquake records
Soydan et al. (2020) – G3	Lead extrusion damper; inter-story drift and column base deformation	Approximately 40–90% reduction in inter-story drift, reductions up to 70% in column base deformation demand	Specific to the respective building model, device properties, and seismic inputs
Rodrigues et al. (2024) – G2	Mechanical connection improvement; local lateral strength	49% increase in the most unfavorable loading direction	Pertains to a cyclic connection experiment; is not a building-level inter-story drift reduction
Arslan et al. (2024) – G4	Grout mortar application; out-of-plane load-bearing capacity of the connection	62% increase in the specific numerical model	Limited to connection geometry, model assumptions, and loading direction

Note: G2 denotes experimental research, G3 denotes numerical models calibrated with experimental findings, and G4 denotes numerical analyses. Since percentage results in the table represent different performance magnitudes, a direct superiority ranking among methods has not been made.

No single method addresses every failure mode. Support loss calls for connection safety; column-base deficiencies may require member and foundation checks; excessive drift may motivate stiffness modification or dissipation; and panel detachment requires anchorage and movement compatibility. Prestressed supplemental frames remain a candidate when residual deformation is critical, subject to typological verification.

Accordingly, screening should begin with an as-built structural and connection survey, proceed through project-specific demand–capacity checks, and compare candidate interventions using structural analysis and architectural constraints. The framework guides initial decisions but does not prescribe a universal retrofit.

6. EFFECTS ON ARCHITECTURAL DESIGN DECISIONS

Retrofitting can alter production layouts and access. Braces may obstruct circulation, jacketed columns reduce local clearance, and external frames may affect façade and service zones. Equipment access, fire egress, loading operations and maintenance routes should be checked against the proposed layout, using relevant project standards rather than generic dimensional assumptions.

Structural strengthening must be coordinated with façade joints and anchors, rooflights, smoke extraction and mechanical services. Coordinated envelope work may reduce repeated construction access, but improved seismic response does not automatically imply energy savings (Lamperti Tornaghi et al., 2022; Pohoryles et al., 2022; ISO, 2020a). The principal interfaces are illustrated in Figure 5.

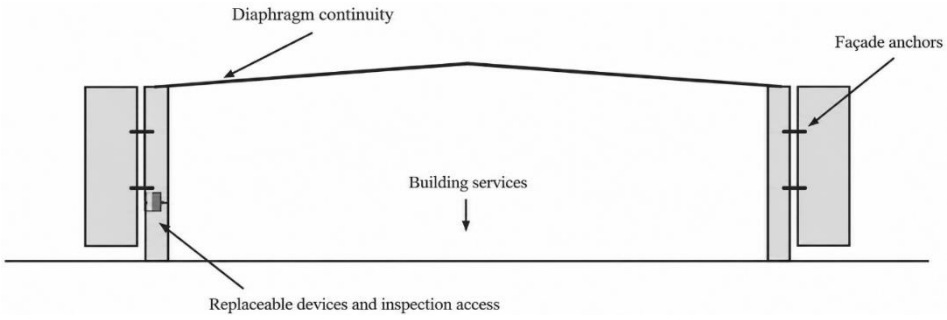


Figure 5. Architectural-structural integration of the roof plane, façade connections, technical installations, and maintenance access in prefabricated reinforced concrete industrial buildings. (Not-to-scale conceptual illustration developed by the authors based on a synthesis of the literature.)

Visible braces may articulate an industrial building's character, while concealed interventions preserve an existing façade rhythm. Decisions should reflect context and reversibility (ISO, 2020b). Where production continues during construction, temporary supports, alternative circulation, equipment protection and work phasing must also be planned. Table 6 summarises the main architectural interfaces.

Table 6. Potential effects of seismic retrofitting approaches on architectural design and coordination requirements.

Retrofitting approach	Potential architectural effect	Priority design check
Improvement of connections and panels	Changes in façade joints and anchorage layout	Panel movement compatibility, insulation, and maintenance access
Reinforced concrete column jacketing	Narrowing in net usable area and around equipment	Machine clearances and circulation safety
Energy-dissipating braces	Transition and access restrictions on specific axes	Evacuation routes and device access
Exteriorly added auxiliary frames	Alteration of façade rhythm and surrounding service areas	New foundation, façade connection, and fire access
Prestressed auxiliary frames	Requirement for additional structural axis and spatial depth	Stressing area, maintenance access, and system compatibility

Note: Effects presented in the table are qualitative architectural evaluations developed from the literature. The applicability of interventions must be verified through project-specific structural analyses and architectural checks.

7. DISCUSSION: FROM EVIDENCE TO DESIGN DECISIONS

7.1. Structural Integrity and Performance Verification in Retrofitting Decisions

The comparison shows that retrofit selection must begin with the governing failure mechanisms rather than a preferred material or nominal stiffness increase. Improving column capacity will not secure an inadequately restrained roof beam; conversely, strengthening a connection will not establish foundation adequacy. The response of supports, columns, roof and cladding must be verified as an interacting system.

Retrofits can redistribute seismic force and deformation demands. Dampers require dependable anchorage and roof transfer, while prestressed systems require separate checks of recentering and dissipation. Consequently, local component improvements must be demonstrated to benefit the whole frame.

Reliable assessment requires surveyed geometry, material and reinforcement properties, support and anchor details, roof stiffness, foundation conditions and seismic demand. Model assumptions and local as well as system-level checks should be documented.

The proposed framework does not assign numerical rankings to alternatives. Instead it links the identified deficiency to required evidence, candidate intervention and verification, with the minimum site information summarised in Table 7.

Table 7. Control criteria for the preliminary evaluation of retrofitting alternatives in prefabricated reinforced concrete industrial buildings.

Evaluation area	**Required existing condition data**	**Significance for decision**	**Verification requirement**
Connection and support safety	Seating length, dowel and anchorage details	Requirement for local connection improvement	Connection capacity and displacement compatibility
Column and foundation capacity	Section, reinforcement, material, and foundation properties	Requirement for member or system retrofitting	Flexural, shear, and foundation checks
Roof diaphragm	Roof layout, connections, and lateral load transfer path	Effectiveness of auxiliary structural systems	In-plane strength and deformation capacity
Façade panels	Panel mass, anchorages, and movement clearances	Panel safety and connection behavior	In-plane/out-of-plane movement and anchorage checks
Architectural use and operation	Production layout, access, maintenance, and application conditions	Spatial and functional applicability of the intervention	Architectural coordination and operational planning

Note: The table is a qualitative preliminary evaluation framework developed from the literature synthesis. It does not replace project-specific engineering calculations or necessary checks within the scope of regulations.

The main stages of the decision-making process can be summarized through the coordinated evaluation of existing conditions, dominant damage mechanisms, candidate retrofitting strategies, and the required structural and architectural verification steps.

7.2. Architectural-Operational Applicability, Application Verification, and Research Limitations

Architectural suitability is a separate condition for retrofitting: usable spans, equipment routes, fire access, downtime and maintenance must be considered after basic structural safety has been established. When a technically promising layout conflicts with production requirements, an alternative location or construction sequence should be assessed.

Construction quality governs the realised behaviour of anchors, jackets, steelwork and energy-dissipating devices. Inspection should document installation tolerances, interface preparation, material tests and the continuity of the completed load path. Maintenance and post-earthquake inspection responsibilities must also be defined.

Life extension may offer environmental benefits, but additional embodied impacts and future replacement needs remain project-dependent (Cavalieri et al., 2023). Multi-criteria decision-making research likewise shows that selecting or weighting evaluation criteria influences preferred retrofit options (Caruso et al., 2023); no weighting was developed or validated here. Table 8 proposes traceable inspection records from survey and design through construction and facility operation.

Table 8. Recommended control stages from design to the operational period in the retrofitting of prefabricated reinforced concrete industrial buildings.

Stage	Primary control subject	Documentation example	Relevant discipline
Preliminary inspection	Existing structure, material, and damage characteristics	As-built drawings, material tests, and damage records	Architecture and structural engineering
Project design	Structural performance, intervention layout, and load transfer	Calculation reports, architectural and engineering projects	Design team
Application	Anchorage, jacketing, steel element, and device installation	Site quality control and test records	Application and inspection teams
Handover	Compliance of the applied system with projects and technical specifications	Post-application drawings and control documents	Project and operations teams
Operation	Maintenance, inspection, and post-earthquake evaluation	Maintenance plan, inspection, and intervention records	Facility management and expert teams

Note: Control stages present a general application framework based on the literature. Responsibilities and mandatory inspections must be determined in line with relevant regulations and project conditions.

The findings arise from a structured narrative synthesis rather than original experiments, numerical modelling or a fully documented systematic search. Evidence from unlike structures and protocols cannot yield a pooled effect size. The architectural decision matrix has not been tested against a real building or independent expert panel and should not be treated as a quantitative optimisation method.

Future research should compare alternatives for the same reference industrial frame and earthquake set while also documenting lost usable space, installation downtime, repairability and life-cycle impacts. Capacci et al. (2026) provide a relevant example of probabilistic assessment of retrofitted single-storey precast archetypes; this chapter performs no new probabilistic analysis.

8. CONCLUSION AND RESEARCH RECOMMENDATIONS

This chapter critically compared seismic strengthening approaches for existing precast RC industrial buildings. The synthesis identifies connection integrity, column–foundation performance, roof load transfer and cladding movement compatibility as interdependent safety requirements; upgrading one component does not resolve deficiencies elsewhere.

Connection upgrades, column jacketing, dissipative devices and supplemental prestressed frames target different response mechanisms. Their published quantitative gains are model- or specimen-specific and do not support a universal ranking across non-equivalent studies.

For architecture, retrofit effectiveness also depends on preserving usable spans, circulation, façade coherence, maintenance access and operational continuity. These demands should be recorded in coordinated plans and details alongside the engineering verification process.

The contribution is an evidence-linked preliminary assessment framework relating damage mechanisms, intervention families and architectural consequences—not a validated design algorithm. Future work should examine common reference frames under equivalent seismic inputs while quantifying spatial loss, downtime and environmental performance. Project-specific design and verification remain essential.

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