

Article

BIM-Integrated Life Cycle Analysis Framework for Sustainable Urban Design Under Climate-Responsive Building Physics

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Abstract

This study presents a BIM-integrated life cycle analysis framework (screening-level) for climate-responsive urban energy performance assessment at district scale. The methodology addresses the need for consistent evaluation of operational energy demand under both design interventions and future climate conditions. A mixed-use district in Milan is used as a case study, where parametric BIM massing models (LOD 200–300) are coupled with building energy simulation to analyze three scenarios: a baseline configuration (S0), an envelope optimization scenario (S1), and a future climate scenario based on CMIP6 morphed weather data (S2). The framework enables comparative assessment of energy performance across consistent geometric, operational, and climatic assumptions. Results indicate that envelope optimization reduces energy use intensity by approximately 15–22% across building typologies. Under future climate conditions, cooling demand increases significantly, while reduced heating requirements result in a total district energy use intensity of 33.6 kWh/m²-year (1.60 GWh/year). An indicative carbon assessment based on simulated energy use highlights cooling-driven electricity as the dominant contributor to operational emissions under future conditions. The findings demonstrate that climate change primarily redistributes energy demand between heating and cooling rather than uniformly increasing total consumption, and confirm the value of BIM-integrated, scenario-based workflows for supporting climate-responsive urban design decisions.

Keywords: building information modeling (BIM); integrated life cycle analysis (LCA); building physics; simulation; energy efficiency

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1. Introduction

The accelerating pace of urbanization, combined with increasingly frequent and severe climate extremes, has intensified the need for urban development strategies capable of reducing carbon emissions while ensuring indoor environmental quality and long-term climate resilience [1]. In this context, early-stage urban design decisions—particularly those concerning urban massing, building envelope configuration, and material selection—exert a disproportionate influence on the operational energy demand and life cycle environmental impacts of the built environment.

Building information modeling (BIM) has become a central platform for digital design coordination, while life cycle assessment (LCA) is widely recognized as a standardized method for quantifying embodied and operational environmental impacts.

However, despite their widespread use, the integration of BIM and LCA in urban-scale design workflows remains limited and methodologically fragmented. In most existing approaches, operational energy simulation, embodied carbon assessment, and urban form analysis are conducted as separate and sequential processes, which restricts the ability to evaluate energy–carbon interactions consistently during early design phases [2]. Furthermore, building physics-based simulations—including energy modeling, hygro-thermal analysis, and climate responsiveness under future weather conditions—are rarely embedded within integrated BIM–LCA environments in a transparent and reproducible manner [3].

Recent international research efforts, including the IEA EBC Annex 91 project, have highlighted persistent interoperability barriers in BIM-to-building energy model (BEM) conversion workflows [4]. These include semantic information loss, inconsistent zoning strategies, geometric simplification issues, and data discontinuities during model translation [5]. Such challenges become even more critical at the district scale, where aggregated building interactions, urban morphology, and shared microclimatic effects significantly influence overall energy and carbon performance.

Despite these advances, three key research gaps remain insufficiently addressed in the current literature: (i) the lack of a unified and transparent BIM–BEM–LCA workflow that enables consistent coupling between geometric, energy, and carbon models at district scale; (ii) insufficient integration of future climate scenarios within early-stage urban energy–carbon assessments; and (iii) limited methodological transparency regarding model validation, data transformation, and assumption traceability in integrated simulation environments.

To address these gaps, this study proposes a BIM–BEM–LCA integrated methodological framework (screening-level) for climate-responsive and low-carbon urban design, and demonstrates its application through a mixed-use district case study in Milan. Milan is selected as a representative Mediterranean-European urban context characterized by a dense mixed-use morphology, high building stock renewal pressure, and increasing exposure to climate-driven overheating and cooling demand. These characteristics make it particularly suitable for evaluating the interaction between urban form, operational energy demand, and embodied carbon under both current and projected future climate conditions.

The proposed framework combines parametric BIM-based massing models (LOD 200–300), building physics-based energy simulations, and life cycle carbon assessment within a unified computational workflow [6]. The selected case enables the assessment of how district-scale design strategies perform under climate variability; however, it does not capture the full diversity of climatic zones, governance frameworks, or construction practices found across European and global cities. This limitation highlights the need for further studies extending the framework to different climatic regions and urban typologies, including colder climates, high-rise-dominated districts, and rapidly developing urban areas.

The framework is designed to support sustainability-oriented decision-making in early-stage urban design by enabling the simultaneous evaluation of operational energy demand, embodied carbon impacts, and climate adaptation performance at district scale. In particular, it allows the explicit assessment of energy–carbon trade-offs under changing climate conditions, thereby contributing to more transparent and evidence-based pathways toward low-carbon and climate-resilient urban development. Future research should expand the application of the framework to multi-city comparative studies, integrate socio-economic indicators such as cost and comfort, and enhance uncertainty analysis related to climate scenarios and material life cycle inventories.

2. Background and Related Work

2.1. BIM and Early-Stage Design Limitations

Building information modeling (BIM) is widely established as a core digital environment for design coordination, documentation, and construction management. However, its application in early-stage urban and architectural design has historically been constrained by the trade-off between model detail, computational effort, and uncertainty associated with low levels of development (LOD). In particular, BIM at LOD 200–300—where geometry is simplified and system properties are partially defined—has often been considered insufficient for robust performance-based environmental analysis.

Recent studies, however, indicate that LOD 200–300 BIM models can effectively support early-stage sustainability assessment when modeling assumptions, abstraction rules, and uncertainty boundaries are explicitly defined [7]. Within this context, simplified massing representations enable rapid exploration of urban form, density, and envelope configurations while maintaining a consistent geometric–semantic structure suitable for computational workflows [8].

Despite these advances, a key limitation remains: early-stage BIM applications are still largely disconnected from integrated environmental assessment frameworks that simultaneously address operational energy demand, embodied carbon, and climate responsiveness [9]. Consequently, early design decisions are frequently evaluated through fragmented and sequential tools, limiting their capacity to support holistic sustainability strategies. This gap highlights the need for integrated BIM-based approaches that connect geometric abstraction with coupled energy and life cycle performance evaluation at district scale [10].

2.2. BIM–BEM Interoperability Challenges

A persistent challenge in performance-driven BIM workflows is the reliable translation of BIM models into building energy models (BEM). The recent literature consistently reports issues related to geometric simplification, thermal zoning inconsistencies, and semantic information loss during model exchange processes [11,12]. These limitations are particularly evident in standardized formats such as IFC and gbXML, where differences in schema interpretation and data structure often result in incomplete or non-equivalent energy representations.

Systematic reviews of BIM–BEM interoperability confirm that the main barriers include inconsistent data mapping, lack of semantic alignment, and difficulties in translating architectural objects into energy simulation entities [13]. The IEA EBC Annex 91 research program further highlights persistent challenges in geometry-to-energy model conversion, particularly related to zoning logic and boundary condition definition in automated workflows.

Recent advances propose hybrid and semi-automated pipelines where BIM models are pre-processed into analytical thermal zones before export to energy simulation tools [14,15]. These approaches reduce conversion errors by enforcing explicit simplification rules while maintaining spatial consistency required for BEM generation. However, scalability issues remain when extending these workflows to district-scale applications, where cumulative geometric and semantic inconsistencies can significantly affect simulation outputs [16].

Building on this perspective, controlled BIM-to-BEM workflows based on parametric massing models and validated IFC-based exchanges are increasingly adopted to improve transparency and reproducibility in performance-driven design environments.

2.3. Integration of LCA and Building Physics

Life cycle assessment (LCA) is widely used to evaluate environmental impacts of buildings, particularly embodied carbon from material production, construction, and end-of-life stages [17–19]. However, BIM–LCA integration approaches remain largely static and inventory-based, with limited coupling to building physics processes that govern operational performance over time.

Energy simulation, hygrothermal behavior, and envelope performance evolution are rarely integrated into LCA frameworks, despite their influence on operational energy demand, maintenance cycles, and service life impacts [20]. This limitation becomes increasingly critical under future climate conditions, where changing temperature and cooling demand significantly alter building performance trajectories [21].

Although recent studies have started to integrate energy modeling with LCA, these approaches remain predominantly focused on single-building applications and simplified climate assumptions. District-scale and climate-responsive urban applications remain underexplored, particularly when dynamic climate scenarios and BIM-based workflows are combined in a unified computational environment.

Despite significant advances in BIM-based design workflows, building energy modeling, and life cycle assessment, current research remains fragmented across disciplinary boundaries. Existing studies typically address either building-scale performance assessment or partial BIM–BEM or BIM–LCA integrations, while fully coupled frameworks remain limited.

Moreover, most approaches rely on static climate assumptions and simplified exchange workflows, limiting their ability to represent dynamic interactions between urban morphology, building physics, and future climate conditions. This gap is particularly critical in early-stage urban design, where decisions on form, density, and envelope systems strongly influence both operational and embodied carbon outcomes.

To address these limitations, this study develops an integrated BIM–BEM–LCA methodological framework for coupled assessment of operational energy demand, embodied carbon, and climate responsiveness under both current and future climate conditions.

3. Materials and Methods

3.1. Framework Overview

The proposed study develops a BIM–BEM–LCA integrated methodological framework for climate-responsive and low-carbon urban performance assessment. The workflow is structured into four sequential modules:

- Parametric BIM for urban massing generation
- Building energy simulation and environmental performance analysis
- Life cycle assessment (LCA) based on operational energy demand (screening-level)
- Scenario-based evaluation of climate and design configurations

The framework ensures consistency between geometric abstraction, energy simulation inputs, and life cycle inventory calculations through a unified computational pipeline. Data exchange between modules is implemented using interoperable formats (IFC and gbXML), supported by parametric processing in Grasshopper (Rhino 7.0).

Building information models are developed at LOD 200–300, representing simplified urban massing geometries with defined spatial envelopes and preliminary zoning assumptions. This level of development is appropriate for early-stage design analysis, where detailed construction specifications are not yet available but comparative performance evaluation is required. To ensure methodological traceability, each BIM model is systematically translated into simulation-ready thermal zoning models. However, it is

noted that the resulting representation corresponds to building-level energy simulation aggregated at multiple buildings, rather than a fully resolved district microclimate or urban airflow model.

3.2. Tools and Software Environment

The computational workflow integrates established and validated simulation tools to ensure reproducibility and methodological transparency:

- BIM authoring environment: Autodesk Revit (LOD 200–300)
- Parametric modeling environment: Rhino + Grasshopper
- Energy simulation engine: EnergyPlus v23.2.0, via OpenStudio v3.7.0 and Honeybee v1.8
- Screening-level embodied carbon assessment

All simulation inputs are derived from a common BIM geometry source to minimize inconsistencies across modeling stages. Standardized tools and interoperable workflows are adopted to reduce dependency on custom or non-replicable computational procedures.

3.3. BIM-to-BEM Conversion and Validation Procedure

To address interoperability limitations in BIM-to-BEM workflows identified in IEA EBC Annex 91, a structured conversion and validation procedure is implemented. The workflow consists of five steps:

Step 1: Geometry generation (Revit/Rhino)

Urban massing models are generated in Revit and simplified for analytical representation.

Step 2: Thermal zoning (Honeybee)

Each building mass is converted into thermal zones consistent with EnergyPlus modeling requirements.

Step 3: Geometric consistency verification

Key geometric parameters are quantitatively compared between BIM and BEM models, including:

- footprint area
- gross floor area (GFA)
- envelope surface area
- building volume

Deviation thresholds are evaluated to ensure geometric preservation after translation.

Step 4: Pre-simulation integrity checks

Exported models are checked for:

- missing or duplicated surfaces
- incorrect surface orientation (flipped normals)
- invalid surface adjacency
- zoning inconsistencies

Step 5: EnergyPlus preprocessing validation

Simulation log files are systematically reviewed to identify geometry-related warnings or errors prior to final simulation execution.

This validation procedure ensures geometric integrity and reduces uncertainty introduced during BIM-to-BEM translation. However, it is acknowledged that the approach does not represent a full automated verification of semantic BIM data preservation (e.g., material stratification or full IFC attribute mapping), which remains a limitation.

3.4. Life Cycle Assessment Scope and Energy–Carbon Coupling

The life cycle assessment follows ISO 14040/44 [22,23] and EN 15978 standards [24], ensuring methodological consistency with established LCA practice. The functional unit is defined as the life cycle environmental impact of the analyzed building system over a 50-year reference study period (RSP). The system boundary includes:

- A1–A3: material production
- A4–A5: transport and construction
- B6: operational energy use
- C1–C4: end-of-life processes

Module B4 (replacement and maintenance) is excluded due to the early-stage LOD 200–300 modeling assumption and the absence of detailed material service-life data. This exclusion is acknowledged as a methodological limitation. This study adopts a screening-level life cycle carbon approach. Embodied carbon is not dynamically modeled from material inventories but is treated as a constant benchmark value to enable comparative scenario analysis focused on operational energy variability.

The assessment adopts principles from ISO 14040/44 and EN 15978 to establish the system boundary and carbon accounting framework. Due to the early-stage design resolution (LOD 200–300), a screening-level life cycle carbon assessment is performed using BIM-derived quantities and literature-based embodied carbon coefficients.

3.5. Operational Carbon Calculation and Emission Factors

Operational energy results obtained from EnergyPlus simulations are converted into carbon emissions using energy carrier-specific emission factors [25]. The annual operational carbon emissions are calculated as:

$$CO_{2,op} = \sum_i E_i \cdot EF_i \quad (1)$$

where

- $CO_{2,op}$: annual operational carbon emissions [kgCO₂e/yr]
- E_i : annual delivered energy for energy carrier i [kWh/yr], directly obtained from EnergyPlus “delivered energy” outputs (not thermal loads)
- EF_i : emission factor for energy carrier i [kgCO₂e/kWh]
- i : electricity, heating fuels, cooling-related electricity, and auxiliary end uses

Emission factors are assumed to remain constant across all scenarios in order to isolate the effects of:

- urban form
- envelope design
- and climatic variation

Future decarbonization pathways of energy systems are excluded from the baseline scenario and are identified as a direction for future work. Emission factors are derived from the Italian national electricity mix and standardized fuel combustion datasets.

4. Case Study Description

4.1. Neighborhood Context

The proposed BIM–BEM–LCA framework is applied to a mixed-use urban district located in Porta Romana, Milan, Italy (Figure 1). The study area includes 18 residential buildings and 3 office buildings within an urban boundary of approximately 23,800 m². The total building footprint is 12,400 m², resulting in a site coverage ratio of approximately 52%.

The final modeled configuration reaches a gross floor area (GFA) of approximately 47,800 m², corresponding to a floor area ratio (FAR) of 2.0. GFA is derived directly from

BIM-based parametric massing without introducing intermediate floor-count assumptions, ensuring consistency between geometric representation and simulation input data. Building footprints are derived from validated GIS-based site geometry and simplified into parametric massing volumes using a LOD 200–300 representation. This level of abstraction is appropriate for early-stage urban analysis, where detailed architectural and construction information is not yet available but comparative performance assessment is required. Each building is assigned a unique identifier and semantic attributes, including:

- functional type (residential or office)
- footprint area
- building height

The district model is generated using a Rhino–Grasshopper parametric workflow, ensuring full consistency between geometric generation and EnergyPlus simulation inputs (Figure 2).



Figure 1. Urban boundary, building footprints, and massing model of the Milan case study, with the highlighted area indicating the selected case study zone [26].

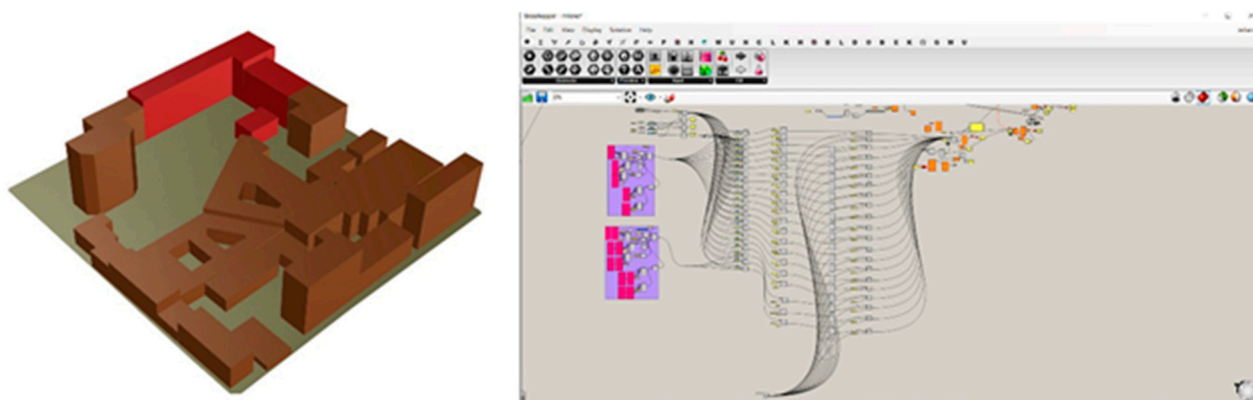


Figure 2. District model in Grasshopper–Rhino (**left**) and corresponding energy simulation algorithm (**right**). On the left side, red and brown indicate building typologies and functionality, where red represents office buildings and brown represents residential buildings included in the study and simulation process. On the right side, purple, pink, yellow, and orange correspond to the programmatic template structure used in Grasshopper and do not indicate any specific case or building type.

4.2. Gross Floor Area Definition

Gross floor area is computed parametrically as the sum of all conditioned floor areas derived from BIM geometry:

$$GFA_i = \sum A_{floor,i} \quad (2)$$

where

- GFA_i : gross floor area of building i
- $A_{floor,i}$: floor area derived from BIM geometry

Floor-count assumptions and fixed floor-to-floor height calculations are not used in the energy or LCA modeling workflow [27,28], in order to avoid introducing additional geometric simplifications unrelated to simulation requirements.

4.3. Design Scenarios and Simulation Assumptions

Three scenarios are defined to isolate the effects of envelope design and climate change on building energy performance:

S0—Baseline Scenario: current envelope under present-day Milan climate

S1—Climate-Adapted Scenario: improved envelope under current climate

S2—Future Climate Scenario: mid-century (2050) climate applied to S1 geometry

All scenarios maintain identical:

- urban geometry (LOD 200–300 massing)
- zoning logic
- internal loads
- occupancy schedules
- HVAC representation

This ensures that differences in results are attributable only to envelope and climate variations, not modeling inconsistencies. Future climate conditions (S2) are generated using a morphing-based EPW dataset derived from CMIP6 projections under SSP2–4.5 (2041–2060). The weather file is modified to reflect projected changes in dry-bulb temperature, humidity, and solar radiation for Northern Italy. Simulation assumptions are summarized in Table 1.

Table 1. Scenario definition and modeling assumptions.

Aspect	S0—Baseline	S1—Climate-Adapted	S2—Future Climate
Climate data	Current Milan EPW	Current Milan EPW	Morphed 2050 EPW
Simulation approach	Building-by-building analysis	Building-by-building analysis	Same buildings under future climate
Energy model	EnergyPlus (Honeybee)	EnergyPlus (Honeybee)	EnergyPlus (Honeybee)
Thermal zoning	One zone per building	One zone per building	One zone per building
Geometry (LOD)	LOD 200–300	Same	Same
Building functions	Residential/Office	Same	Same
Window-to-wall ratio	Res: 35%/Off: 50%	Res: 15%/Off: 30%	Same as S1
U-values (W/m ² K)	Wall 0.259/Roof 0.203/Floor 0.248	Roof improved to 0.11	Same as S1
Shading	None	External shading elements	Same as S1
Internal loads	Standard EN 16798 [29]	Same	Same
Schedules	Standard	Same	Same
HVAC representation	Ideal air loads	Ideal air loads	Ideal air loads
Output type	Thermal loads	Thermal loads	Thermal loads
Operational carbon	Derived from loads	Derived from loads	Derived from loads
Embodied carbon	Not included	Not included	Included (separately in LCA)
Energy–carbon coupling	No	No	Yes

All simulations use the ideal air loads system in EnergyPlus, which computes theoretical heating and cooling loads required to maintain indoor setpoints without representing system efficiencies or HVAC equipment behavior. Therefore, all reported values correspond to thermal loads rather than delivered energy consumption, which is appropriate for early-stage comparative urban analysis.

It is important to note that scenario S1 represents an envelope optimization strategy rather than a novel façade design approach. The objective of this scenario was not to demonstrate the innovation of reducing the window-to-wall ratio (WWR), which is a well-established passive design measure, but to evaluate its impact within the proposed BIM-integrated simulation framework under both current and future climate conditions. The baseline model employed WWR values of 35% for residential buildings and 50% for office buildings, while Scenario S1 adopted reduced values of 15% and 30%, respectively. These values were selected to represent a substantially improved envelope configuration capable of limiting solar heat gains and transmission losses while maintaining functional daylight access and façade transparency. Therefore, the selected WWR values should be interpreted as representative design assumptions for comparative scenario analysis rather than optimized or prescriptive design targets. A comprehensive sensitivity analysis investigating alternative WWR configurations was beyond the scope of the present study and is identified as an important direction for future research.

5. Results (Energy–Carbon Coupling)

This section presents the results of the integrated BIM–LCA workflow across three scenarios: baseline (S0), climate-adaptive design (S1), and future climate conditions (S2). Results are reported at both building and district scales, focusing on energy use intensity (EUI), end-use energy breakdown, and operational–embodied carbon coupling.

5.1. Building-Level Energy Performance (S0–S1)

The building-level analysis compares operational energy performance under the baseline scenario (S0) and the climate-adaptive envelope scenario (S1) (Table 2). Both scenarios use identical assumptions regarding geometry (LOD 200–300 massing), internal loads, schedules, and HVAC representation (ideal air loads), ensuring that performance differences are exclusively driven by envelope modifications [30]. Scenario S1 introduces reduced window-to-wall ratios (WWR), improved roof insulation ($U = 0.11 \text{ W/m}^2\text{K}$), and passive shading strategies.

Table 2. Energy use intensity (EUI) comparison at building level (S0 vs S1).

Building	S0 EUI (kWh/m ² ·yr)	S1 EUI (kWh/m ² ·yr)	Reduction (%)
Residential 1	418.56	323.72	22.7
Residential 2	198.85	161.20	18.9
Residential 3	253.73	204.59	19.4
Residential 4	369.72	288.71	21.9
Residential 5	98.33	85.67	12.9
Residential 6	201.58	165.09	18.1
Residential 7	158.02	129.92	17.8
Residential 8	201.07	163.63	18.6
Residential 9	176.78	145.09	17.9
Residential 10	444.12	336.31	24.3
Residential 11	305.44	240.57	21.2
Residential 12	255.38	205.94	19.4
Residential 13	228.81	180.73	21.0

Residential 14	147.96	124.30	16.0
Residential 15	195.29	158.99	18.6
Residential 16	196.16	161.23	17.8
Residential 17	218.22	175.12	19.7
Residential 18	190.75	155.94	18.2
Office 1	234.68	198.13	15.6
Office 2	221.88	188.69	15.0
Office 3	179.01	150.57	15.9

At the residential scale, scenario S1 achieves an average reduction of ~19%, while office buildings show an average reduction of ~15.5%. The higher sensitivity of residential buildings is attributed to lower internal heat gains and stronger dependence on envelope heat transfer mechanisms.

5.2. Aggregated Multi-Building Energy Performance Under Future Climate Conditions (S2)

Scenario S2 evaluates the performance of the same building stock under projected mid-century climate conditions represented by a morphed 2050 EPW weather file. To ensure consistency with the previous scenarios, identical geometric models, zoning assumptions, occupancy schedules, and envelope characteristics are maintained. The only variable modified is the climatic boundary condition. The results are reported for the aggregated multi-building model and are expressed as annual thermal loads obtained from EnergyPlus simulations. Table 3 summarizes the principal geometric characteristics of the analyzed building stock, while Table 4 presents the annual thermal demand distribution.

Table 3. District geometry and system metrics.

Metric	Value
Gross floor area (GFA)	47,800 m ²
Conditioned volume	195,470 m ³
External wall area	33,847 m ²
Roof area	13,736 m ²
Window area	12,938 m ²

Table 4. District energy breakdown (S2).

End-Use	Energy (kWh/Year)	Share (%)
Cooling	742,483	46.3%
Heating	547,851	34.2%
Electricity (lighting + equipment)	314,105	19.6%
Total	1,604,439	100%

The aggregated model comprises approximately 47,800 m² of gross floor area, 195,470 m³ of conditioned volume, 33,847 m² of external wall area, and 13,736 m² of roof area. Cooling demand represents the largest component of annual thermal demand, accounting for approximately 46.3% of total loads. Heating demand contributes approximately 34.2%, while electricity-related end uses account for the remaining 19.6%. The total annual demand is approximately 1.60 GWh. The corresponding district-level energy use intensity (EUI) is calculated as:

$$EUI_{district} = \frac{1,604,439}{47,800} = 33.56 \text{ kWh/m}^2 \cdot \text{yr} \quad (3)$$

The results reveal a clear shift toward cooling-dominated performance under future climatic conditions. Rising outdoor temperatures substantially increase cooling require-

ments while simultaneously reducing heating demand. Although the balance between end uses changes considerably, the reduction in heating demand partially offsets the increase in cooling loads, resulting in a relatively moderate total annual demand. These findings demonstrate the importance of incorporating future climate projections into urban-scale energy assessments. Evaluating performance solely under present-day climatic conditions may underestimate future cooling requirements and misrepresent long-term building performance.

5.3. Operational Energy and Indicative Carbon Implications

To evaluate the environmental implications of operational energy demand, annual heating, cooling, and electricity consumption were converted into equivalent carbon emissions using standard emission factors [31]. Operational carbon emissions are calculated using energy carrier-specific emission factors with Equation (1).

For comparative purposes, an electricity emission factor of 0.233 kgCO₂e/kWh (Italian grid average) and a heating (natural gas equivalent) emission factor of 0.202 kgCO₂e/kWh were adopted. The annual operational carbon emissions were calculated for cooling, heating, and electricity use (scenario S2) and are summarized in Table 5.

Table 5. Annual operational carbon emissions (S2).

End-Use	Energy (kWh/Year)	EF (kgCO ₂ e/kWh)	Carbon (tCO ₂ e/Year)
Cooling	742,483	0.233	173.0
Heating	547,851	0.202	110.7
Electricity	314,105	0.233	73.2
Total	1,604,439	—	356.9

The results indicate that cooling accounts for the largest share of operational carbon emissions, followed by heating and electricity consumption. This distribution reflects the increasing importance of cooling energy under warming climatic conditions and highlights the need for passive cooling strategies, solar control measures, and adaptive envelope technologies. It should be noted that the EnergyPlus ideal air loads system calculates thermal loads rather than actual delivered energy consumption. Therefore, the resulting carbon emissions should be interpreted as comparative indicators suitable for evaluating design alternatives rather than precise operational carbon inventories.

5.4. Life Cycle Carbon Assessment (Operational + Embodied)

A screening-level life cycle carbon assessment was performed by combining operational carbon emissions with embodied carbon estimates derived from BIM-generated quantities [32,33]. The embodied carbon calculation was based on envelope component areas extracted directly from the BIM model and representative carbon coefficients obtained from the literature [34,35]. The embodied carbon of each envelope component was calculated using the following equation:

$$\text{Embodied Carbon (kgCO}_2\text{e)} = \text{Quantity} \times \text{Embodied Carbon Factor} \quad (4)$$

where

- Quantity represents the BIM-derived area of the building component (m²).
- Embodied Carbon Factor represents the carbon intensity associated with the component (kgCO₂e/m²).

$$EC_{total} = \sum (Q_i \times EF_i) \quad (5)$$

where

EC_{total} = total embodied carbon (kgCO₂e)

Q_i = quantity of component i

EF_i = embodied carbon coefficient of component i .

Table 6 presents the BIM-derived quantities and the embodied carbon factors adopted for the screening-level assessment.

Table 6. BIM-derived envelope quantities and embodied carbon coefficients.

Building Component	Quantity (m ²)	Embodied Carbon Factor (kgCO ₂ e/m ²)
Opaque Walls	20,910	90
Roofs	13,736	80
Windows	12,938	120

Using these values, the embodied carbon contribution of each component was calculated as shown in Table 7.

Table 7. Estimated embodied carbon of envelope components.

Building Component	Quantity (m ²)	Carbon Factor (kgCO ₂ e/m ²)	Embodied Carbon (tCO ₂ e)
Opaque Walls	20,910	90	1882
Roofs	13,736	80	1099
Windows	12,938	120	1553
Total	—	—	4534

The results indicate that the envelope systems contribute approximately 4534 tCO₂e of embodied carbon. Among the evaluated components, opaque wall assemblies account for the largest share of embodied impacts, followed by glazing systems and roof assemblies. To provide context, the estimated annual operational carbon emissions amount to approximately 356.9 tCO₂e/year. Assuming a reference service life of 50 years, cumulative operational carbon emissions can be estimated as:

$$\text{Operational Carbon}_{50\text{-year}} = 356.9 \times 50 = 17,845 \text{ tCO}_2\text{e} \quad (6)$$

Table 8 summarizes the indicative life cycle carbon contributions.

Table 8. Indicative life cycle carbon contributions over a 50-year service life.

Carbon Source	Carbon Emissions (tCO ₂ e)	Percentage (%)
Embodied Carbon	4534	20.3
Operational Carbon (50 years)	17,845	79.7
Total Life Cycle Carbon	22,379	100

The results demonstrate that operational emissions remain the dominant contributor to life cycle impacts over the assumed service life. Nevertheless, embodied carbon represents approximately one-fifth of total life cycle emissions and therefore should be considered during early design stages. Integrating BIM-derived quantities with energy simulation outputs enables designers to evaluate operational and embodied impacts simultaneously and supports more balanced sustainability-oriented decision-making. Because the embodied carbon assessment is based on generic literature coefficients and aggregated BIM quantities, the results should be interpreted as screening-level estimates rather than a comprehensive ISO 14040-compliant life cycle assessment. Future studies should incorporate detailed material inventories, environmental product declarations (EPDs), transportation scenarios, replacement cycles, and end-of-life processes to improve assessment accuracy.

6. Discussion

The results obtained from the BIM-integrated energy assessment framework provide a multi-scale understanding of how envelope design strategies and future climate conditions influence building energy performance and associated operational energy implications. By comparing the baseline scenario (S0), climate-adaptive design scenario (S1), and future climate scenario (S2), the study identifies clear relationships between building envelope characteristics, energy demand patterns, and climate-driven performance shifts at the district scale.

The results of scenario S1 demonstrate that envelope optimization remains an effective strategy for reducing operational energy demand under current climatic conditions. Across the analyzed building stock, reductions in energy use intensity (EUI) ranging from approximately 15% to 22% were achieved through the implementation of climate-responsive envelope measures, including reduced window-to-wall ratios, improved thermal insulation, and external shading systems. Residential buildings exhibit a consistently higher relative reduction in energy demand compared to office buildings. This difference is primarily driven by variations in internal heat gains and occupancy profiles. Residential buildings typically have lower internal gains from equipment and occupants, resulting in a stronger dependence on envelope thermal performance. Consequently, improvements in insulation levels and solar control strategies have a more pronounced effect on total energy demand. In contrast, office buildings are characterized by higher internal gains associated with occupants, lighting, and equipment, which partially offset the impact of envelope improvements.

These findings highlight the importance of considering building typology when developing energy-efficient design strategies. A uniform envelope optimization strategy does not produce equivalent performance improvements across different functional building types. Instead, design interventions should be tailored to the specific thermal and operational characteristics of each typology to maximize energy-saving potential and improve overall system efficiency.

The future climate scenario (S2) reveals a significant transformation in the structure of energy demand rather than a uniform increase in total consumption. Cooling becomes the dominant end-use, accounting for approximately 46.3% of total annual energy demand, while heating decreases to approximately 34.2%, and electricity-related loads remain at 19.6%. This shift reflects the increasing influence of higher ambient temperatures and extended cooling seasons under projected mid-century climate conditions.

Despite the increase in cooling demand, the simulations indicate that total annual energy demand does not increase proportionally. The reduction in heating demand partially offsets the rise in cooling loads, resulting in a modified seasonal energy balance rather than a monotonic increase in consumption. This finding challenges simplified assumptions that climate change inevitably leads to higher total energy demand and instead demonstrates that climate impacts are strongly dependent on local climatic conditions and building thermal characteristics. In temperate climates such as Milan, reductions in winter heating demand can partially compensate for increased summer cooling requirements, particularly in envelope-efficient buildings.

The indicative operational carbon assessment further highlights the environmental implications of these energy shifts. Carbon emissions are derived from simulated energy demands using fixed emission factors; therefore, the results should be interpreted as comparative indicators rather than absolute carbon inventories [36–38]. Within this context, cooling-related electricity emerges as the dominant contributor to operational carbon implications under future climate conditions. This emphasizes the growing importance of passive cooling strategies, solar control measures, and envelope designs that mitigate overheating risk in addition to reducing heating demand.

The study also demonstrates the value of BIM-enabled workflows for early-stage energy performance evaluation. The integration of BIM-based geometric modeling with EnergyPlus simulations enables a consistent and efficient framework for generating and comparing multiple design and climate scenarios within a unified modeling environment. This supports rapid iteration in early design phases and allows for the assessment of climate-responsive strategies before detailed architectural decisions are finalized.

Several limitations should be acknowledged. First, the simulation framework employs simplified thermal zoning, with each building represented as a single thermal zone. While suitable for comparative district-scale analysis, this approach does not capture detailed intra-building thermal variations. Second, urban microclimatic effects such as heat island intensity, wind flow variations, and radiative exchanges between buildings are not explicitly modeled. These factors may influence actual energy performance in dense urban environments.

Third, the EnergyPlus ideal air loads system computes thermal loads rather than actual delivered energy consumption. As a result, the operational carbon estimates presented in this study should be interpreted as indicative comparative metrics rather than precise operational carbon footprints. More detailed assessments would require explicit HVAC system modeling, efficiency assumptions, and time-resolved grid carbon intensity data [39]. Finally, occupant behavior, adaptive comfort responses, and dynamic control strategies are not explicitly included in the simulations, although they may significantly influence real-world energy performance under future climate conditions [40,41].

The findings demonstrate that energy performance in urban districts is governed by a complex interaction between climate conditions, building typology, and envelope design strategies. Envelope optimization remains an effective approach for reducing operational energy demand under current climatic conditions, while future climate scenarios primarily alter the distribution between heating and cooling rather than uniformly increasing total energy consumption. The BIM-integrated workflow developed in this study provides a transparent and reproducible framework for evaluating these interactions and supports climate-responsive design strategies for improving long-term urban energy performance.

7. Conclusions and Policy Implications

This study developed and applied a BIM-integrated LCA framework (screening-level) to evaluate the energy performance of a district-scale building stock under three scenarios: baseline conditions (S0), climate-adaptive design interventions (S1), and future climate conditions (S2). The proposed workflow enables a consistent and traceable assessment of building energy demand across multiple scenarios within a unified parametric modeling environment, supporting comparative evaluation of design- and climate-driven effects at the urban scale.

The results demonstrate that envelope design strategies and climate change influence district energy performance in distinct but interconnected ways. Under the climate-adaptive scenario (S1), improvements in envelope performance—including reduced window-to-wall ratios, enhanced thermal insulation, and passive shading strategies—lead to significant reductions in operational energy demand across all building typologies. Overall, energy use intensity decreases by approximately 15–22%, confirming the effectiveness of passive design measures under current climatic conditions. Residential buildings show greater sensitivity to envelope improvements compared to office typologies, primarily due to lower internal heat gains and stronger dependence on envelope heat transfer processes. The energy savings observed in scenario S1 should be interpreted in relation to the specific envelope assumptions adopted in this study. Because only one alternative WWR configuration was evaluated, the results do not imply that 15% and 30% represent optimal

values for residential and office buildings, respectively. Future studies should investigate a broader range of façade configurations through sensitivity and multi-objective optimization analyses.

Under future climate conditions (S2), the district exhibits a substantial reconfiguration of energy demand rather than a uniform increase. Cooling becomes the dominant end-use, accounting for approximately 46.3% of total annual energy demand, while heating demand decreases significantly due to milder winter conditions. Although cooling loads increase, the reduction in heating demand results in a total annual energy demand of approximately 1.60 GWh (33.6 kWh/m²-year). These results indicate that climate change reshapes the seasonal distribution of energy demand rather than necessarily increasing total consumption in this case study context. Operational carbon implications derived from energy use follow a similar pattern, with cooling-related electricity becoming the dominant contributor under future climate conditions.

The analysis highlights that operational energy demand remains the primary performance indicator within the proposed modeling framework. However, its magnitude and distribution are highly sensitive to both envelope design strategies and climatic boundary conditions. This finding underscores the importance of incorporating future climate scenarios into early-stage urban energy assessments to avoid misinterpretation of performance trends based solely on present-day climatic conditions.

This study contributes to building performance simulation and climate-responsive urban design in three main ways. First, it demonstrates an integrated BIM–EnergyPlus workflow that ensures geometric consistency, scenario control, and reproducible comparative evaluation across multiple design and climate conditions within a single modeling environment. Second, the scenario-based approach enables clear separation between design-driven effects (S1) and climate-driven effects (S2), improving interpretability of energy performance outcomes. Third, the aggregation of multiple heterogeneous buildings at district scale provides a more representative analytical framework than single-building studies, capturing variability in typology, function, and energy behavior.

The findings have several implications for sustainable urban design practice. Envelope optimization remains a highly effective strategy for reducing operational energy demand under current climate conditions, particularly for residential buildings. However, future climate adaptation strategies should place greater emphasis on cooling-dominated performance management, including overheating mitigation, solar control strategies, and summer comfort enhancement, rather than focusing exclusively on heating reduction. In addition, district-scale evaluation provides a more robust basis for understanding energy dynamics in heterogeneous urban environments, where interactions between different building typologies significantly influence overall system behavior.

Operational energy demand remains a key driver of building-related energy performance in the studied system, reinforcing its importance for near- and mid-term energy efficiency and decarbonization strategies. At the same time, the results indicate that climate change primarily alters the structure of energy demand rather than uniformly increasing it, highlighting the need for climate-sensitive approaches in urban energy planning and design decision-making.

Several limitations should be acknowledged. The analysis is based on static emission factors, which do not reflect future changes in electricity or fuel carbon intensity. In addition, occupant behavior, adaptive comfort responses, and dynamic control strategies are not explicitly represented, which may influence real-world energy demand, particularly under future climate conditions. Furthermore, each building is modeled as a simplified single thermal zone, which limits the ability to capture intra-building spatial variations and detailed operational dynamics.

Future research should extend the proposed framework by integrating time-dependent carbon intensity profiles for electricity and heating systems, enabling more temporally resolved operational carbon assessments. The incorporation of occupant behavior models and adaptive comfort algorithms would further enhance the realism of future climate simulations. In addition, multi-objective optimization approaches could be developed to simultaneously evaluate operational energy demand, overheating risk, and design constraints within a unified decision-support framework.

Further work should also explore the applicability and scalability of the proposed framework across different climatic regions and urban morphologies, as well as incorporating uncertainty analysis related to climate projections and simulation parameters. These developments would strengthen the robustness and transferability of BIM-integrated energy assessment methods and support more adaptive and climate-resilient urban design strategies.

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