A MULTI-MODEL FRAMEWORK INTEGRATING CLIMATE PROJECTIONS AND SYSTEM DEGRADATION FOR CLIMATE-AWARE RETROFIT PLANNING

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Abstract

Current building energy simulations often rely on static assumptions, neglecting dynamic factors such as climate change and component degradation, leading to performance gaps and suboptimal retrofit decisions. This research applies a multi-model framework that integrates climate projections with building envelope and HVAC degradation models within an automated workflow. Using an office building case study, the results demonstrate the efficacy of the multi-model framework while also improving understanding of maintenance–retrofit trade-offs under climate uncertainty. The analysis reveals key sensitivities and limitations of dynamic energy modelling, advancing insight into how the multi-model framework can support climate-aware, lifecycle-oriented retrofit decision-making.

Introduction

The global building sector represents a primary driver of energy demand and environmental impact, currently accounting for approximately 40% of total energy use and 36% of greenhouse gas emissions (Farahani et al., 2019). Within the European context, a significant majority of the building stock was constructed before the implementation of stringent energy efficiency standards, with many structures remaining in operation for over 50 years (Feng et al., 2022). Consequently, the pressure on primary energy resources is increasing, necessitating a rapid increase in the rate and effectiveness of energy retrofitting (Roetzel and Tsangrassoulis, 2012). Energy retrofitting, defined as the upgrade of existing building technologies, materials, and features, is essential for reducing operational costs, improving occupant comfort, and achieving long-term sustainability goals (Wang et al., 2014; Asadi et al., 2014).

Despite the importance of these interventions, the planning and scheduling of retrofits are often hampered by inaccurate energy consumption projections. Building energy consumption is a highly dynamic and complex system shaped by an intricate interplay of thermophysical properties, construction quality, local climatic conditions, and the aging of mechanical systems (Delzendeh et al., 2017; Li et al., 2021). Conventional simulation methods frequently rely on static inputs that ignore the degradation of the building envelope or the shifting baseline of future weather patterns driven by climate change (Thomas et al., 2016b). Research indicates that ignoring these factors can lead to discrepancies between predicted and actual energy use of up to 100%, resulting in misdirected investments and policy failures (Thomas et al., 2016b; Delzendeh et al., 2017).

In the domain of computing in construction, the emergence of digital twins and integrated modeling offers a pathway to address these complexities. Digital twins provide virtual abstractions of physical assets, enabling continuous monitoring and scenario-based analysis throughout the building's lifecycle (Lu et al., 2025). However, the integration of heterogeneous models (such as climate projections, material science degradation laws, and mechanical engineering maintenance factors) remains a significant technical challenge (Nikolic et al., 2019). Most existing workflows are either too simplified to capture physics-based volatility or too labor-intensive to scale across large scenario grids (Li et al., 2021; Waddicor et al., 2016).

This paper presents a novel Multi-Model (MM) framework, the Multi-Model Building Energy Consumption Simulator (MM-BECS), designed to automate and integrate the simulation of building energy systems under varying future scenarios. By leveraging the multi-modelling infrastructure (MMI) principles established in the MMviB project, the framework ensures loose coupling between participating models, facilitating the reuse of validated components (Nikolic et al., 2019; Matthijssen et al., 2023). The research question addresses how an integrated multi-model framework can provide high-fidelity annual energy trajectories to inform effective retrofitting and maintenance decisions over a building's entire 60-year lifespan. The primary contribution of this work is the development and demonstration of a containerized, tool-agnostic workflow that bridges the gap between specialised and validated physics-based models and lifecycle investment planning. The novelty of this work lies not in individual sub-models, but in their integration into a fully automated, containerised, and tool-agnostic workflow capable of generating annual energy trajectories over a full 60-year lifecycle.

Background

The scientific literature surrounding building energy simulation has increasingly recognized the limitations of single-model approaches when applied to long-term projections. Traditional decision-support tools often frame building retrofit planning as a life cycle cost optimization (LCO) problem, utilizing Net Present Value (NPV) to identify cost-effective interventions (Wang et al., 2014; Ascione et al., 2015).

While studies by Wang et al. (2014) and Luo and Oyedele (2022) provide valuable economic insights, they frequently treat energy savings as fixed, stable inputs. This assumption is a significant deficiency, as it ignores the reality that insulation performance and HVAC efficiency decline as components age, while climate warming shifts the underlying demand baseline (Eleftheriadis and Hamdy, 2018). Consequently, many LCO and Life Cycle Assessment (LCA) models rely on externally generated, time-invariant energy trajectories that do not endogenously account for combined, time-varying effects. Such simplifications reduce the realism of the guidance provided to facility managers and policy makers.

Prior research has attempted to integrate multiple influencing factors through various coupling methods, yet each approach presents distinct trade-offs. Scripted multi-run approaches, as exemplified by de Wilde et al. (2011), are transparent and tool-agnostic but become computationally and manually burdensome as the scenario space expands. Waddicor et al. (2016) utilized decadal snapshots to evaluate the joint impact of climate warming and system aging on a historic library in Turin, finding that rising temperatures and declining chiller efficiency can double cooling demand. However, the decadal resolution used in such studies is a notable limitation, as it smooths out the inter-annual volatility driven by extreme weather events, which are critical for sizing mechanical systems and assessing resilience. In contrast, runtime co-simulation allows for bi-directional feedback between models, but introduces significant technical challenges in time synchronization and interface validation (Thomas et al., 2016a).

Existing methods also suffer from limitations in temporal horizon and spatial applicability. While Li et al. (2021) produced annual trajectories, their analysis was restricted to a 25-year horizon, which is insufficient for representing a building's full 60-year service life. Furthermore, many current climate-forcing methods rely on statistical extrapolation or morphing techniques that fail to capture the rising frequency of climate uncertainties and extremities such as heatwaves (Rodrigues et al., 2023). Finally, many approaches are geographically constrained due to reliance on local probabilistic datasets, limiting their applicability across regions in the building sector.

The critical research gap identified is the absence of an automated end-to-end methodology capable of generating annual energy consumption series for the entire operational life of a building while accounting for joint trajectories of climate change and envelope degradation. Despite the successful application of multi-modelling infrastructures in other complex energy domains, such as national infrastructure planning (Huang and Nikolic, 2024), this approach has not yet been realized for high-fidelity building energy simulation. There remains a lack of a containerized, tool-agnostic workflow that uses standardized interfaces to execute large scenario ensembles without manual oversight, thereby producing the consistent annual trajectories required for robust lifecycle financial and environmental appraisal.

Method

The methodology adopted in this study follows a structured multi-model framework, focusing on the development of an integrated simulation system that can represent the building energy consumption system as a whole (Matthijssen et al., 2023). In this paper, the term 'multi-model framework' is used consistently to describe the integration of independently developed simulation components. The framework is conceptualized using the XLRM structure, which organizes Exogenous Uncertainties (X), Policy Levers (L), Relationships (R), and Performance Metrics (M) to enable systematic decision analysis (Lempert et al., 2003). The XLRM framework for building energy systems decomposes the complex dynamics of building energy use into manageable components.

The Exogenous Uncertainties (X) include climate change pathways (RCP 2.6, 4.5, and 8.5) alongside the degradation rates of insulation materials and HVAC components. The Policy Levers (L) represent the decision space, encompassing maintenance regimes, the choice of energy-saving measures, and the timing of retrofit interventions. The Relationships (R) are governed by the physics-based energy simulation engine, while the Performance Metrics (M) are the annual values of site energy consumption, heating/cooling loads, and cumulative energy savings.

Case

Figure 1: Office building at Green Village, Delft.

The developed system will be demonstrated using the case of the Office building at Green Village, Delft. This building features XPS polystyrene as insulation and a four-pipe fan coil unit as an HVAC system. Additionally, passive ventilation measures have been integrated into the building's design to enhance energy efficiency. This building was selected as a case study because it represents the implementation of traditional Dutch construction designs and practices. The size of the building was suitable for demonstration purposes.

Model Identification and Formulation

The research identifies validated models for three distinct domains: future weather data generation, building component degradation, and whole-building energy simulation.

Weather Model

Dynamic Downscaling and Bias Correction.
To provide future climate forcing, the study utilizes dynamically downscaled weather data from the Coordinated Regional Downscaling Experiment (CORDEX) archive. For the office building case study in Rotterdam, the MPI-ESM-LR global model and KNMI-RACMO22E regional model were selected. A hybrid bias-correction scheme was implemented using Multivariate Bias Correction (MBCn) for inter-dependent variables (temperature, humidity, wind) and univariate Quantile Delta Mapping (QDM) for shortwave irradiance (Machard et al., 2024).

Ageing Model

Degradation Laws and Maintenance Scenarios.
The degradation of the building envelope is modeled via the thermal conductivity (λ) of insulation materials. For extruded polystyrene (XPS), a polynomial degradation law was applied (Eleftheriadis and Hamdy, 2018):

$$\begin{aligned}\lambda_{\text{age}} = \Big(& -0.000097502(\text{age}-1)^5 + 0.0054(\text{age}-1)^4 \\ & -0.1126(\text{age}-1)^3 + 1.0895(\text{age}-1)^2 \\ & -4.9677(\text{age}-1) + 28.7371\Big)^{-1}\ \mathrm{W\,m^{-1}\,K^{-1}}\end{aligned} \tag{1}$$

For HVAC components, the study utilizes linear and exponential degradation laws for the Coefficient of Performance (COP) as a function of time (t) and maintenance factor (r) (Griffith et al., 2008; Hendron, 2006):

$$\text{COP}(t) = \text{COP}(0)\,(1 - r\,t) \tag{2}$$

$$\text{COP}(t) = \text{COP}(0)\,(1 - r)^{t} \tag{3}$$

Simulation Model

EnergyPlus Configuration.
EnergyPlus was selected as the simulation engine due to its feature-rich capabilities and widespread scientific validation (Crawley et al., 2008; Barbosa et al., 2015). The

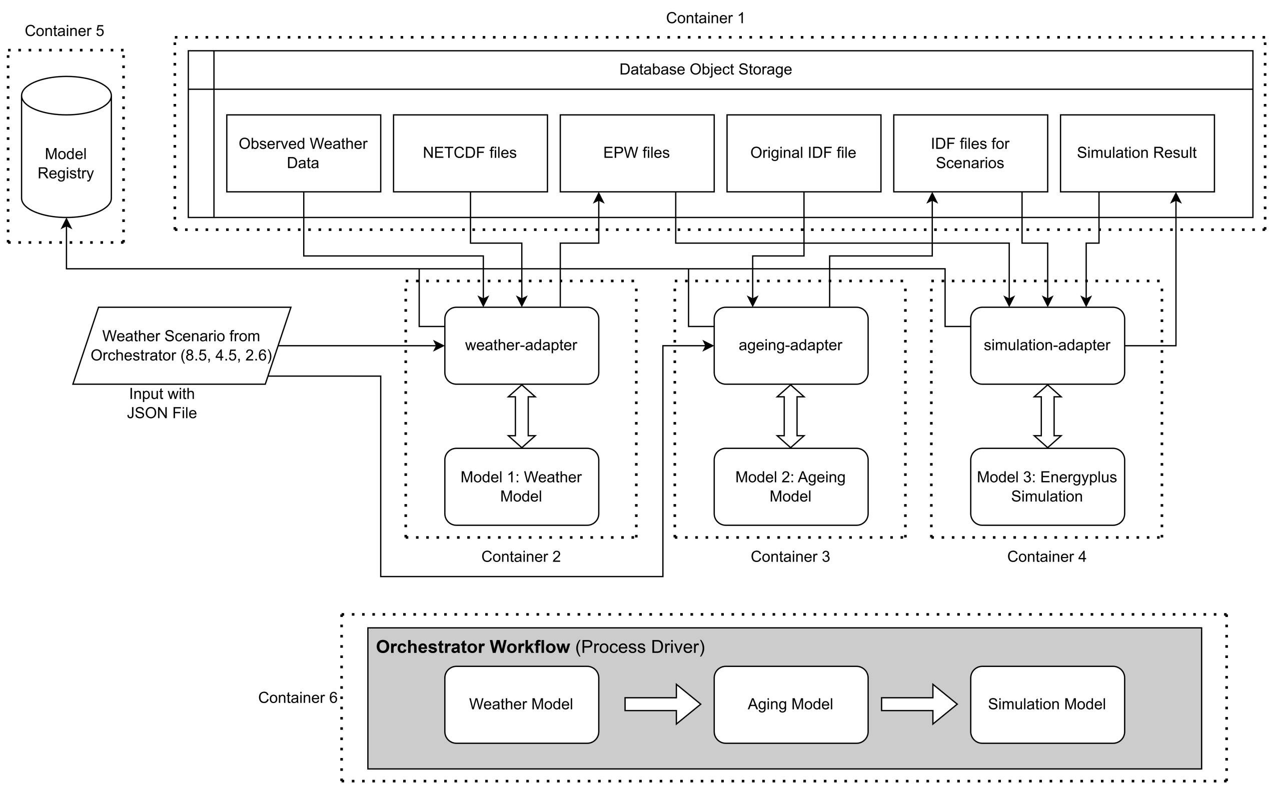

Figure 2: Multi-model Building Energy Consumption Simulator (MM-BECS) system.

engine was configured to run year-by-year simulations by pairing scenario-specific building description files (IDF) with annual weather files (EPW).

Implementation

The technical realization of the MM-BECS system utilizes a containerized architecture to achieve loose coupling and high portability, following the architectural guidelines of the MMviB project (Matthijssen et al., 2023; Nikolic et al., 2019).

Architecture and Service Adapters

Each participating model (Weather, Ageing, and Simulation) is packaged as a Docker container, providing isolation of libraries and dependencies (Matthijssen et al., 2023). Communication is mediated by adapter services, which are lightweight web applications exposing standardized RESTful APIs. These adapters handle the interplay between model-specific inputs and the central object storage service, Minio, which serves as the data repository for the multi-model workflow.

Orchestration and Workflow Automation

A model registry service maintains a catalog of available models and their health status. The orchestrator, implemented as a Directed Acyclic Graph (DAG) in Apache Airflow, automates the sequence of events: (1) preparing future weather inputs, (2) generating scenario-specific building models, and (3) executing the EnergyPlus simulations. This automated execution allows for large scenario grids to run unattended, ensuring computational tractability as the scenario space expands (Huang and Nikolic, 2024).

Results

The MM-BECS system generated annual site energy consumption, cooling load, and heating load for 28 distinct scenarios over a 60-year lifespan (2025–2084) based on the designed simulation configuration. Scenarios E1–E28 represent combinations of maintenance regimes, HVAC replacement timing, and envelope retrofit interventions.

Baseline Performance and Volatility

The baseline scenario (E1) under the RCP 8.5 climate pathway indicates a steady rise in total annual energy consumption, increasing by approximately 43% over the horizon. This trend is driven by the compounding effects of climate warming and the gradual degradation of insulation and mechanical systems. Notably, annual cooling loads nearly double, reflecting rising sensitivity to extreme summer temperatures as chiller performance decays.

Evaluation of Retrofitting and Maintenance Scenarios

A single HVAC replacement in 2055 (Scenario E2) reduces cumulative lifecycle energy consumption by 8.0%. However, implementing regular maintenance without any

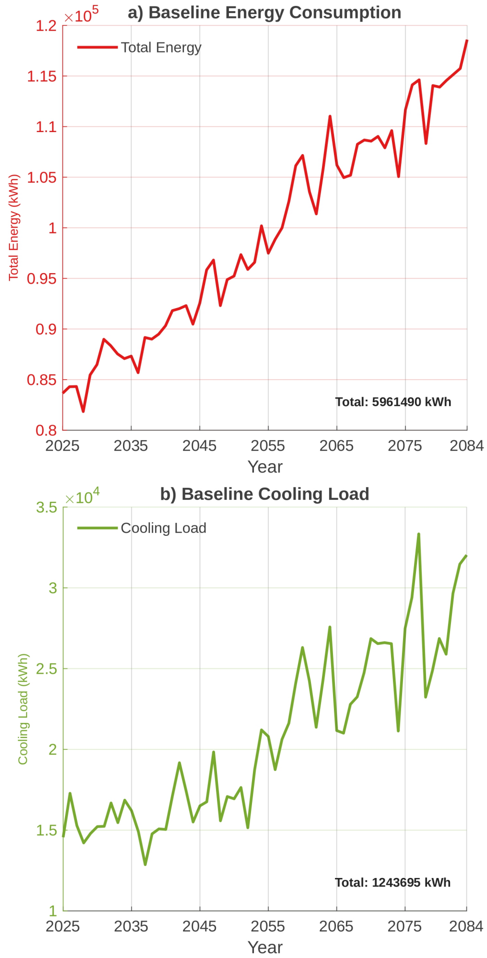

Figure 3: Performance metrics in baseline scenario under RCP 8.5.

HVAC replacement (Scenario E8) achieves lifecycle savings of 10.4%—identical to a dual-replacement scenario (E4) without maintenance. This suggests that a continuous maintenance policy can be as effective as capital-intensive retrofits if initiated early.

Integrated Policy Pathways

Scenario E28, combining dual HVAC replacements, an envelope retrofit in 2055, and regular maintenance, reduces total energy use by 13.6%. While this represents the maximum savings, Scenario E3 demonstrates that a single HVAC retrofit in 2055 followed by regular maintenance still captures 75% of these maximum savings, offering a balanced approach for resource-constrained asset management.

Discussion

The results generated by the MM-BECS system underscore the critical need for integrating dynamic factors into building energy assessments. Traditional methods relying on static models fail to capture the long-term trends and intra-decadal volatility revealed by this multi-model framework (Waddicor et al., 2016; Li et al., 2021).

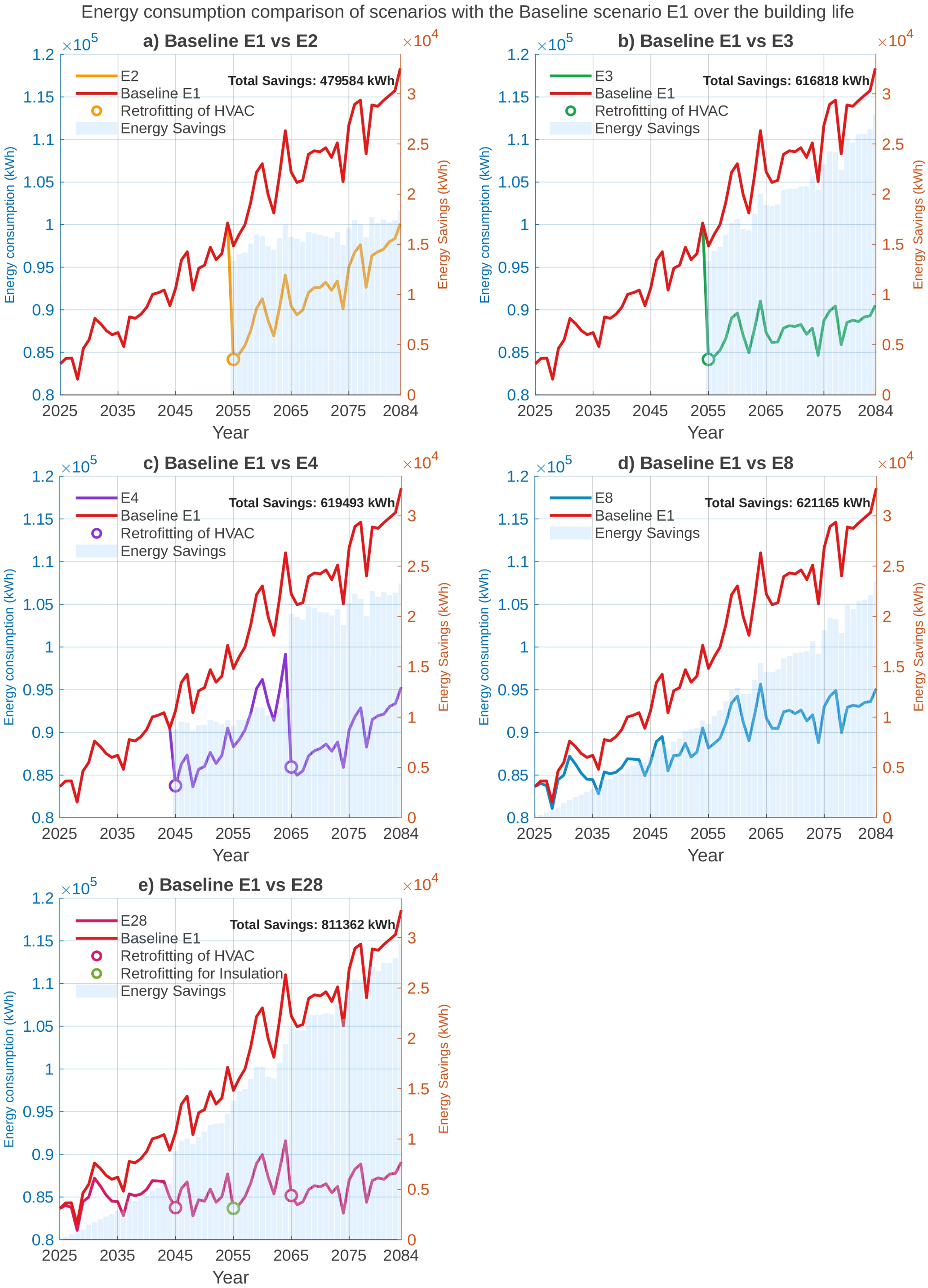

Figure 4: Comparison of energy consumption pathways under RCP 8.5 for different retrofit scenarios

The comparative analysis demonstrates that the value of an intervention is highly dependent on its timing relative to climate forcing and equipment aging (Farahani et al., 2019). Maintenance acts not only to reduce efficiency loss but also to dampen the volatility of cooling loads. For facility managers, this suggests that investment in regular maintenance can defer the need for expensive capital retrofits while ensuring performance stability.

Methodologically, the containerized architecture addresses interoperability challenges that plague bespoke simulation scripts (Huang and Nikolic, 2024). The use of RESTful adapters and centralized object storage allows for a ‘‘plug-and-play’’ environment where sub-models can be updated as new data becomes available. Furthermore, the automation of these workflows significantly reduces human labor; while traditional practice for building energy modeling can take 8 to 32 hours per case, automated pipelines like MM-BECS (and comparative frameworks like Data2BEM) can execute large-scale analyses in minutes (Lu et al., 2025). The MM-BECS framework is transferable to other building types and regions, provided appropriate climate datasets, degradation parameters, and building models are available. The modular architecture facilitates substitution of sub-models without altering the overall workflow.

Despite its advantages, the current system treats occupant behavior as a static schedule. Future iterations should integrate agent-based occupancy models to capture socio-technical feedbacks (Delzendeh et al., 2017; Thomas et al., 2016a). Additionally, moving toward stochastic ensembles would allow for the generation of probabilistic energy trajectories, providing risk-aware guidance for investment (de Wilde et al., 2011). Furthermore, each sub-model (climate forcing, degradation, and energy simulation) is based on previously validated approaches in the literature. However, the integrated system has not been empirically validated against long-term measured datasets, which remains an area for future work. Also, this study is limited to a single office building archetype and a specific climatic context (Delft, NL). While the framework is generalisable, quantitative results are case-specific. Additionally, occupant behaviour is represented using static schedules, and uncertainty is explored through scenario variation rather than probabilistic ensembles.

Conclusions

This research has demonstrated a multi-model framework for building energy simulation that successfully integrates the dynamic, interdependent influences of climate change, envelope degradation, and HVAC aging. By operationalizing the Multi-Model Building Energy Consumption Simulator, the study has addressed the critical performance gaps inherent in conventional static energy assessments relying on fixed assumptions, neglecting dynamic factors such as climate change and component degradation. The research successfully identified and validated modular sub-models for climate forcing, envelope degradation, and system aging (linear/exponential efficiency loss). These were integrated into a containerized architecture that leverages loose coupling, enabling tool-agnostic execution across large scenario grids. Through the demonstration of a 60-year analysis horizon for an office building, the framework proved capable of generating annual site energy consumption series that capture both long-term trends and intra-decadal volatility. The systematic comparison of 28 scenarios highlighted the efficacy of strategic maintenance as a policy lever, showing that early and consistent maintenance can deliver energy savings comparable to capital-intensive retrofits while damping demand fluctuations caused by extreme weather events.

Methodologically, the study advances the state-of-the-art by moving from decadal snapshots to continuous annual trajectories, providing the high-fidelity data required for sophisticated lifecycle assessments and financial appraisals. The use of standardized interfaces and orchestration logic (Apache Airflow) ensures that the workflow is scalable, reusable, and reproducible—a significant improvement over the bespoke, labor-intensive scripts common in current professional practice. Practically, the findings empower facility managers to optimize the timing of interventions, showing that clustering or splitting retrofits based on divergent heating and cooling load trajectories can significantly improve the cost-effectiveness of energy transition strategies.

Currently, the annual trajectories produced by MM-BECS require manual export for financial evaluation. Future development should focus on the direct integration of lifecycle cost and lifecycle assessment models into the automated pipeline to provide real-time economic and environmental performance indicators. Additionally, the incorporation of a monitoring and calibration layer—utilizing real-time sub-metering and local weather observations—would transform the framework into a climate-responsive digital twin. Such a cognitive system could iteratively update degradation parameters and occupant behavior patterns, allowing for adaptive management that ensures long-term building resilience and sustainability in an increasingly volatile climatic context. This work provides a foundational template for the next generation of data-driven, portfolio-scale decision-support tools in the built environment.

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