Balancing Smart Building Automation and Energy Consumption through a Model-Driven Framework for Electrical Systems Design

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***Abstract*—Smart buildings increasingly adopt distributed microcontroller-based devices to reduce wiring complexity and improve automation flexibility. However, embedded electronics introduce standby energy consumption and automation overhead that are rarely considered during early design stages. This paper presents an ongoing extension of an existing Domain-Specific Language (DSL) for smart building electrical system design, originally aimed at minimizing cable usage and actuator deployment. The proposed extension introduces appliance energy profiles, standby power, controller types, and communication protocols to support energy-aware modeling and multi-objective analysis of architectural trade-offs between wiring complexity, actuator count, operational energy, and automation overhead. We outline the extended meta-model, illustrate a representative scenario, and discuss future directions toward automated Pareto-optimal design space exploration.**

***Index Terms*—Model-Driven Engineering, Domain-Specific Language, Smart Building, Electrical System Design, Energy-Aware Modeling, Multi-Objective Optimization**

I. Introduction

The design of electrical systems in smart buildings involves complex trade-offs among wiring infrastructure, control hardware, and automation capabilities. Traditional approaches rely on centralized electrical panels with dedicated cabling to each load point, resulting in extensive copper usage but minimal electronics overhead. Conversely, modern smart building architectures employ distributed microcontroller-based actuators (e.g., KNX, Zigbee, or Wi-Fi-enabled relays) that reduce cabling by enabling bus-based or wireless communication, yet introduce non-negligible standby power consumption across potentially hundreds of embedded devices [1].

Current optimization efforts in smart buildings predominantly target operational energy, such as HVAC scheduling, lighting control, and building energy management systems (BEMS) [2], [3]. Very few approaches address the design-time trade-off between wiring topology, actuator deployment strategy, embedded electronics overhead, and the resulting standby energy footprint. This gap is particularly relevant as the proliferation of always-on microcontrollers in distributed architectures can aggregate into significant baseline consumption that is seldom accounted for at the architectural design stage.

In prior work [1], we proposed a DSL [5] and a Model-Driven Engineering (MDE) framework for smart building electrical systems, enabling designers to model rooms, appliances, switchboards, cables, and actuators, and to automatically evaluate cable length reduction and actuator count. This paper presents an early-stage extension of that DSL toward *energy-aware model-driven electrical system design*. The goal is to enrich the modeling language with concepts that capture energy profiles, standby power, controller classifications (smart vs. non-smart), and communication protocol characteristics, thereby enabling future multi-objective optimization across competing design dimensions.

II. Background and Motivation

Our previous contribution [1] introduced a DSL grounded in MDE principles, allowing designers to specify building topologies, electrical loads, and wiring strategies. Model-to-model transformations can suggest optimized configurations that minimized total cable length and reduced actuator proliferation by identifying alternative cabling configurations. The approach demonstrated measurable savings in residential and tertiary building scenarios but did not consider the energy implications of different control architectures.

Modern smart building devices (i.e., smart relays, dimmers, motorized blinds controllers) typically embed ARM Cortex-M or ESP32-class microcontrollers that consume 0.5–3 W in standby [4]. In a building with 80–200 such devices, aggregated standby consumption can reach 100–600 W continuously, translating to 876–5,256 kWh/year. Traditional fixed-function electronics (e.g., impulse relays, digital timers without microcontrollers) achieve equivalent switching functionality with near-zero standby ($<$0.1 W per device) but lack remote programmability and bus communication.

The trade-off between *automation flexibility and standby overhead* is currently invisible at the design modeling level. Designers choose architectures based on functional requirements without quantitative feedback on the energy cost of smartness. An energy-aware DSL would make this trade-off explicit and analyzable.

III. DSL Extension for Energy-Aware Modeling

Figure 1 presents the key extensions to the original DSL meta-model. The core additions are: a) **EnergyProfile**: captures standby power and duty cycle for each device or controller. b) **Controller**: classifies controllers as `Smart` (microcontroller-based, programmable, bus-connected) or `Fixed` (digital or electromechanical, no MCU, minimal standby). c) **CommunicationProtocol**: models bus characteristics (wired: KNX, DALI; wireless: Zigbee, Wi-Fi) including per-node power overhead. d) **ControlArchitecture**: distinguishes `Centralized` (single controller, star wiring) from `Distributed` (per-zone controllers, bus/wireless) topologies. e) **Appliance**: extended with nominal power, energy class, operational profile, and controllability requirements.

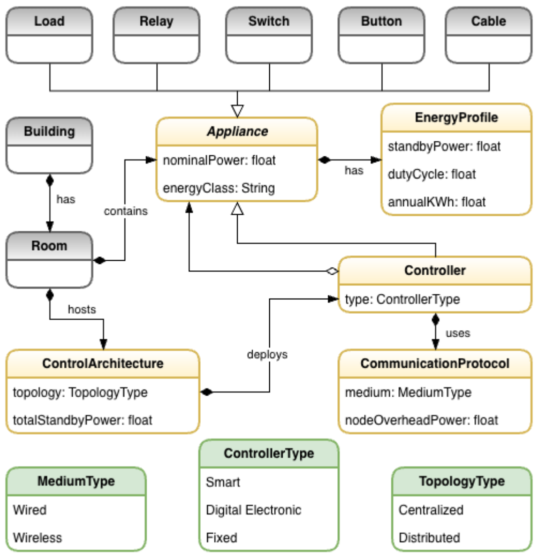

Fig. 1. Extended DSL meta-model: energy-aware concepts (simplified view). Coloured classes represent new or significantly extended entities and features.

The extended meta-model preserves backward compatibility with the original DSL, assuring existing models to remain valid; energy-aware attributes default to unspecified, enabling incremental adoption. Each `Controller` instance is annotated with the standby power $P_{standby}$ (inherited from its `EnergyProfile`) and the associated communication protocol energy overhead $P_{protocol}$ (`nodeOverheadPower`). A model-level aggregation rule computes the total automation energy overhead as:

$$E_{auto} = \sum_{i=1}^{N} (P_{standby,i} + P_{protocol,i}) \times 8{,}760 \text{ h} \qquad (1)$$

where N is the number of deployed controllers. This metric becomes a first-class objective alongside cable length (L_{cable}) and actuator count (N_{act}) from the original DSL, and used in a Pareto-based exploration to find the optimal system configuration.

IV. Conclusion and Future Work

As an example, we consider a representative residential apartment of approximately $120\,\text{m}^2$ comprising 6 rooms with 40 controllable load points: 18 light switches, 6 shutters, 12 sockets, and 4 HVACs. Cable lengths are estimated from a core switchboard with 12–18 m average radial distances; bus topologies reduce runs to shared trunk lines.

TABLE I
Architectural Trade-Off Comparison.

Metric	**Traditional (Fixed)**	**Distributed (Smart)**	**Hybrid (Mixed)**
Cable length (m)	∼580	∼190	∼350
Control units	10	40	20
Standby power (W)	∼3	∼80	∼32
Est. annual standby (kWh)	∼26	∼700	∼280
Automation flexibility	Low	High	Medium–High
Remote updatability	None	Full	Partial

Table I[1] compares results: i) the *Traditional* architecture employs 10 multi-channel (4–6 loads) relay modules using ∼580 m cables to wire each load through a star layout and consuming a negligible standby power of ∼0.3 W per module; ii) the *Distributed* one employs 40 individual smart node (e.g., KNX actuator, Zigbee relay), reducing cabling to ∼190 m, but drawing a total standby power of ∼80 W continuously. iii) the *Hybrid* one employs smart nodes for remote programmable loads only, yielding 15 points in average, resulting in a moderate cable reduction (∼350 m), and standby power of ∼32 W.

Importantly, real building electronics span a *gradual technology spectrum* through intermediate solutions (i.e., X10-class power-line devices or MCU-less configurable components) that achieve low standby power consumption and medium flexibility. The scenario confirms that no single architecture dominates in absolute terms.

This work targets *design-time architectural trade-off analysis* but has limitations: the current meta-model extension is not yet fully formalized, and the reported estimates require validation against real building audits. Current efforts focus on (i) completing the Ecore/EMF formalization, (ii) implementing model validation rules for energy profile completeness, and (iii) developing model-to-analysis transformations for multi-objective evaluation. Future work will integrate constraint-based Pareto exploration to identify non-dominated configurations automatically, supporting energy-conscious architectural decisions at early design stages.

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[1]Values are preliminary design-stage estimates.