Kennedy, E., Cai, Y., Aryal, A., and Hartell, J. (2026). Digitalization Over Prescription: A Lean Design Case Study for Target Value Design and Off-Site Construction's Conflict with Prescriptive Energy Codes. *Lean Construction Journal* 2026 Special Issue CRC-CSCE pp 52-78
https://doi.org/10.60164/ky4tlud1y (Submitted 10Jan2026; Accepted 28Aug2026) www.leanconstructionjournal.org

Digitalization Over Prescription: A Lean Design Case Study for Target Value Design and Off-Site Construction's Conflict with Prescriptive Energy Codes

Evan Kennedy[1], Yilin Cai[1], Ashrant Aryal[1], and Julie Hartell[1]

Abstract

Question: This systematic simulation approach functions as Set-Based Concurrent Engineering (SBCE), suggesting where investment in energy reduction provides maximum value and where it becomes wasteful, underscoring the necessity of Target Value Design (TVD) to find true value.

Purpose: The need for research into regulatory efficiency is indicated through growing energy demand from residential buildings, particularly during summer months in Texas environments due to increased frequencies of climatic disasters. Such metrics have prompted this study which investigates the conflict between Lean design processes (TVD) advanced Digitalization techniques (simulation), and Off-Site Construction against the baseline, prescriptive mandates of the 2021 International Energy Conservation Code. This research's core capability rests upon the digitalization and repetition of 180 comparative energy simulations, which identified the optimal energy reduction and energy generation Target Value aimed at the greatest energy reduction capabilities for five major Texas city centers across three distinct climate zones (2A, 3B, and 4A).

Research Method: The simulation-derived single component substitutions, optimized scenarios, and the real-world performance of six companies utilizing Off-Site Construction (prefabricated and manufactured units) as their Production System Design for project delivery were benchmarked against the current 2021 IECC metrics.

Findings: Although the International Code Council (ICC) codes are effective in ensuring public safety, our analysis suggests that high-performing case studies often fail prescriptive requirements, yet their energy performance has been thought to exceed code minimums when simulated. This oversight is not a flaw, rather a possible Lean trade-off. In this case study, it was found that companies strategically mitigate resources to certain envelope sectors because of over-performance in others.

Limitations: Continued research will aim to harness calibrated digital models to better

[1] Department of Construction Science, Texas A&M University, 574 Ross St., College Station, Tx

estimate true value saved through off-site means of construction.

Implications & Value for practitioners: This research exposes a gap that forces builders to engage in non-value-adding work (Waste), demonstrating that prescriptive regulation can functions against Lean principles by impeding efficient product development and optimal resource allocation aided by performance-based code compliance.

Keywords: Energy Efficiency; Housing Regulations; LEAN Construction; Performance-Based Codes

Paper type: Full paper

Introduction

Energy Fragility, Grid Strain, and the Imperative for Resilience

The stability of the national energy grid, particularly in high-demand, thermally intense regions such as Texas, has been called into question by a series of recent extreme weather events (Stone et al., 2021). These events have exposed a systemic fragility that extends beyond the domain of power generation and transmission, reaching into the very efficiency and performance of the built environment. As the frequency and intensity of climatic disasters rise, manifesting as prolonged, record-breaking heat waves, severe and unexpected freezes, and hydrological extremes, the residential building stock faces unprecedented strain (NOAA, 2023). Residential buildings constitute the largest single sector of energy consumption in the United States, and this demand is not static; it spikes dramatically during extreme weather events, creating a feedback loop that further destabilizes the grid (EPA, 2025; Stone et al., 2021).

This is not only a matter of infrastructure engineering or utility management; it is an issue of public safety. The concept of passive survivability, defined as the ability of a dwelling to maintain habitable internal conditions for its occupants during prolonged power outages without active mechanical heating or cooling, has transitioned from a theoretical niche in architectural discourse to a critical performance metric for life safety (Stone et al., 2021). Recent research investigating compound climate and infrastructure events, such as the simultaneous occurrence of severe heat waves and wide-area electrical grid failures, suggests that the thermal performance of a building's envelope is a determining factor in human survival rates during such crises (Stone et al., 2021). In addition, a high-performance envelope, although often lowering thermal comfort in a building, offers increased performance under extreme heat loads on the structure (Baniassadi et al., 2019).

The urgency of this situation is underscored by the stark economic reality facing American households. A comprehensive survey conducted in 2023 indicated that 81% of Americans report that extreme weather events have directly increased their energy consumption, resulting in higher monthly financial burdens that strain household budgets (Gillespie & Rubloff, 2024). This energy vulnerability is exacerbated during summer months, particularly in the southern United States (Climate Zones 2A and 3B), where cooling loads drive peak demand that strains power grids. The Environmental Protection Agency (EPA) notes that residential energy use is a primary driver of greenhouse gas emissions, creating a cyclical problem where inefficient homes contribute to the very climate change that threatens them

(EPA, 2025). Consequently, the overarching objective of modern residential construction must shift from merely meeting static safety baselines, which assume a functioning grid (Vaughan & Turner, 2012), to achieving dynamic energy resilience that ensures safety even when infrastructure fails. However, the path to this objective is currently obstructed by a regulatory framework that, while historically well-intentioned, has been observed as an impediment to the very innovation required to solve the matter (Gyourko & Molloy, 2015).

Prescriptive Regulatory Friction and Economic Inefficiency

The fundamental conflict inhibiting the wide-scale adoption of resilient, high-performance housing is rooted in a systemic dissonance between modern construction capabilities and, rigid compliance mechanisms. Current energy codes, exemplified by the 2021 International Energy Conservation Code (IECC), predominantly rely on a prescriptive path for compliance (IECC, 2021). This approach mandates specific material inputs, such as defined R-values for insulation, specific glazing U-factors, and rigid assembly techniques, effectively dictating the requirements for construction rather than the desired performance outcome.

While prescriptive codes have historically served as a necessary baseline for ensuring public safety and establishing minimum standards of habitability (Vaughan & Turner, 2012), they inherently lack the flexibility to accommodate the rapid advancements in digital design, material science, and off-site construction and manufacturing. In the context of Lean Construction philosophy, this rigidity generates waste (*Muda*); first described in *Taiichi Ohno's* seminal work *"The Toyota Production System"* (Ohno, 1988). It forces builders to adhere to a static checklist that may not represent the optimal solution for a specific climate, building orientation, or integrated system. For instance, increasing insulation thickness beyond a certain point, a common mechanism for code updates, often yields diminishing returns in operational energy savings while increasing embodied carbon and material costs (Iqbal & Al-Homoud, 2007). Yet, under a prescriptive regime, builders are compelled to comply with these specific thickness mandates to secure permits. Even given indications that a thinner, higher-performing material (like a structural insulated panel) could achieve a higher efficiency under a thermal load (Jannat et al., 2020).

This regulatory friction is not an operational nuisance for contractors; it has been perceived as an economic constraint with macroeconomic implications. Comprehensive economic reviews of land-use and building regulations have long demonstrated that such rigidities systematically constrain housing supply and inflate costs, reducing the elasticity of the construction market (Gyourko & Molloy, 2015). By mandating adherence to a recipe rather than a result, prescriptive codes force builders to engage in over-processing, a core tenet of Lean waste, requiring redundant documentation (such as ResCheck compliance reports that are procedural) or the installation of components that add cost without adding commensurate value to the homeowner (NAHB, 2020).

Furthermore, this operational inconsistency can discourage the adoption of industrialized construction methods, such as off-site construction and prefabrication. These modern methods rely on standardized, factory-optimized systems that deliver superior precision and thermal performance but may not align neatly with the site-built assumptions of traditional codes (Tommelein & Ballard, 2016). A factory-built wall assembly might have a different layer structure than what is depicted in the code book's reference tables, leading to rejection by inspectors despite superior performance.

The failure to address this regulatory barrier is not for lack of awareness or political will. For over fifty years, federal efforts have attempted to reduce regulatory barriers to housing affordability and innovation (Blumenthal, 2023). From the "Housing in the Seventies" report in 1974 to commissions in 1982, 1991, and 2003, the U.S. government has recognized that local regulations impede affordability, yet these barriers have persisted and even calcified (Blumenthal, 2023). The friction remains: a high-performance, factory-built home that utilizes advanced composite materials (like Structural Insulated Panels (SIPs)) may vastly outperform a code-compliant stick-built home in rigorous energy simulation yet fail a prescriptive audit because its wall assembly does not match the specific thickness or layering mandates of the code. This paradox, where a superior product is deemed non-compliant while an inferior one is approved, represents a systemic failure in the regulatory mechanism that this study seeks to expose, analyze, and resolve

A Tripartite Framework of Lean Design, Digitalization, and Off-Site Construction

To resolve the deep-seated conflict between static prescription and dynamic performance, this research proposes a comprehensive tripartite methodology that integrates Lean design, digitalization, and off-site construction. This approach moves the industry beyond a passive method, toward an active, accountability-driven verification of value.

First, Lean design is operationalized through the methodology of Target Value Design (TVD). Unlike traditional design-bid-build processes where cost and performance are estimated *after* the design is complete, often leading to value engineering that strips out quality, TVD sets the performance target (in this context, specific energy reduction goals) at the very outset of the project (Zimina et al., 2012). The design team then steers the project toward this target, eliminating any component, process, or material that does not contribute directly to the goal. In this context, value is redefined: it is not just economic cost, but energy resilience, thermal autonomy, and long-term operational efficiency (Lee et al., 2012).

Second, digitalization serves as the essential enabler of Lean principles in the 21st century by means of integration of Information Technology systems (Fitch, 2006). By employing Information Technology practices such as Building Performance Simulation (BPS) as a digital twin, designers can validate decisions computationally before physical resources are committed. This study utilizes a set-based concurrent engineering (SBCE) approach, running 180 distinct energy simulations to computationally test widespread design alternatives across multiple climate zones (Ballard, 2020). This digital process identifies the precise point of diminishing returns for various interventions, exposing exactly where prescriptive code requirements effectively mandate waste. Digitalization provides the accountability mechanism that has been missing from traditional performance-based routes; it offers empirical, data-driven proof that a proposed design meets or exceeds the energy target, rendering the prescriptive recipe obsolete (Sacks et al., 2010).

Third, off-site construction acts as the delivery mechanism for this optimized value. Prefabricated systems, such as SIPs and modular assemblies, offer the precision, airtightness, and quality control necessary to execute high-performance designs that are difficult to achieve in the uncontrolled environment of a construction site (Windle et al., 2019). However, these systems are often the primary casualties of prescriptive discrepancies. By validating their performance through digital twins, this research advocates for a codification shift that recognizes the quality and energy metrics of industrialized construction (Tommelein & Ballard, 2016). As Fikru (2019) notes, efficiency measures must precede renewable adoption to maximize return-on-investment (ROI), supporting this strategy of optimizing the envelope first (Fikru, 2019).

Research Objectives

This study aims to catalyze a dialogue on identifying specific code constraints within the current 2021 International Energy Conservation Code (IECC) that hinder the market availability of innovative housing solutions. Having identified the prescriptive mandates necessary for permitting, the case study simulation findings and vendor data will be compared for prescriptive-based and performance-based code compliance. This aim will be achieved by the following specific research objectives:

Use digitalization to identify the optimal energy reduction target value achievable through passive envelope components in five major Texas city centers (Houston, Austin, Dallas, El Paso, and Amarillo). This objective seeks to demonstrate that better performance is possible than the baseline 2021 IECC code through specific, data-driven interventions rather than guesswork (Pennanen et al., 2011). Demonstrate how the IECC 2021 prescriptive code systematically contradicts this optimal target, creating waste by forcing redundant requirements (Tommelein & Ballard, 2016). The study will show that waste reduction is only partially achievable through current compliance checklists (like REScheck), which are often performed too late in the process to influence design. Validate this operational inefficiency using real-world case studies of eight companies employing advanced Off-Site Construction techniques (specifically SIPs and modular advancements). The study will benchmark their real-world performance against the prescriptive mandates to highlight the gap where innovation is stifled (Windle et al., 2019). And furthermore, provide evidence that the simulation-derived single component substitutions and optimized scenarios offer a superior, more flexible, and more accurate method of ensuring energy resilience than the static tables of the IECC (Sacks et al., 2010).

Literature Review: Defining Waste

The theoretical foundation of this research rests on the convergence of distinct but complementary academic domains: Lean Construction Philosophy, Computational Building Science (Digitalization), Off-Site Construction Dynamics, and Regulatory Policy Theory. While these fields are often studied in isolation, Lean experts focus on process, scientists on physics, and policy analysts on law, their intersection provides the necessary framework to understand how current energy codes can generate waste and how digital tools stand a chance to eliminate it. This review reviews the state-of-the-art in each domain, identifying gaps that necessitate a shift from prescription to digitalization.

Lean Design: Defining Value and Eliminating Waste

The principles of Lean Construction are derived from the Toyota Production System (TPS), which revolutionized manufacturing by relentlessly focusing on the elimination of *Muda* (Waste) and the maximization of value (Zimina et al., 2012). In the context of the built environment, value is a subjective term defined by the customer's requirements. Historically, this was interpreted strictly as financial cost, delivering a building for the lowest possible price.

Zimina et al. (2012) argues that the fundamental challenge of value generation in construction lies in shifting the focus from cost reduction to value optimization. In traditional project delivery, value engineering is a process that occurs late in the design phase, often leading to the removal of high-performance features (like advanced insulation or glazing) to meet budget constraints (Zimina et al., 2012). Lean Design flips this dynamic. By defining the target value at the project's inception, the design process becomes a vehicle for delivering that value efficiently (Zimina et al., 2012).

TVD is the primary Lean tool for executing this value-centric approach. Ballard (2020), a foundational figure in Lean Construction, describes TVD as a management practice that drives design to deliver customer values within project constraints (Ballard, 2020). Rather than estimating cost after design, TVD sets the cost (or energy) target first and designs to it. This constraint-based approach fosters creativity, as the team must innovate to meet the target rather than simply accepting standard solutions.

Crucially, Lee et al. (2012) extended the application of TVD beyond financial costs to energy efficiency investments. Their research demonstrated that TVD is the optimal methodology for identifying the optimal energy solution mixture, or the specific combination of envelope components and systems that delivers the highest energy savings for the lowest investment (Lee et al., 2012). This supports the methodology of the current study, which uses simulation to find the target value of energy reduction.

This analogy suggests that the resilience of the energy grid would be better served by a system that manages performance (TVD) rather than one that checks material thickness (prescription). The regulatory friction creates what Lean practitioners call over-processing, doing work that adds no value. When a builder must install R-49 attic insulation to meet a prescriptive code, even though simulations show that R-38 coupled with better air sealing achieves the same thermal performance at lower cost and carbon, the difference is pure waste first (Baechler et al., 2012). These solutions often are not applied in silos, as Baechler et al. (2012) contends that wasteful spending can occur if other issues of air leakage are not addressed first (Baechler et al., 2012).

Digitalization: Exposing Waste through Simulation

Digitalization can be the engine that makes Lean methodologies actionable in complex systems. Sacks et al. (2010), in their work on the interaction of Lean and energy simulation tools defined the "matrix of interaction" between these two fields. They argued that simulation tools enable Lean principles by reducing cycle times, enhancing visualization of flow, and providing immediate feedback on design decisions (Sacks et al., 2010).

In the context of this study, Building Performance Simulation (BPS) functions as the verification arm of TVD. Without the ability to rapidly simulate energy outcomes, TVD would rely on manual calculations or heuristics, which are too slow to support the iterative nature of Lean design (Sacks et al., 2010). The use of BPS allows for "design steering," a concept described by Pennanen et al. (2011) where rapid feedback loops steer the design toward the target trajectory. This digital steering mechanism allows the design team to navigate the complex trade-offs between different building components (e.g., window U-factor vs. wall R-value) in real-time.

A critical component of the Lean-Digital workflow is Set-Based Concurrent Engineering (SBCE). Traditional design follows a point-based approach, where a single solution is selected early and refined. If that solution fails, the team must backtrack (iteration waste). SBCE, conversely, keeps multiple sets of options open for as long as possible, narrowing the field only as data confirms performance (Ballard, 2020).

The methodology of running 180 comparative energy simulations, as conducted in this study, is a practical application of SBCE. By simultaneously testing permutations of wall systems, glazing, and heating, ventilation, air conditioning (HVAC) configurations, the solution space is explored exhaustively. This aligns with the work of Ballard (2020) and Lee et al. (2012), proving that the optimal design is found not by guessing, but by systematically filtering sets of alternatives based on performance data. This method avoids the negative iterations common in traditional design, where late discovery of energy failure forces a redesign.

The concept of the digital twin, a virtual replica of the physical building, provides the "accountability" necessary to replace prescriptive codes. May (2003) analyzed the "Leaky Building Crisis" in New Zealand, a catastrophic failure of early performance-based codes. They concluded that performance-based regulation fails when there is insufficient verification (May, 2003). Flexibility without proof leads to negligence and failure.

However, the technology landscape has shifted dramatically since the early 2000s. Dacquisto and Rodda (2006) long advocated for the use of Information Technology to streamline regulatory processes (Dacquisto & Rodda, 2006). Today, advanced BPS tools (like EnergyPlus) provide the rigorous verification that was missing in previous decades. This study suggests that there is now "digitalization over prescription" as a means of compliance where the simulation becomes the "digital audit."

Off-Site Construction: The Operational Antidote to Waste

Off-site construction, encompassing prefabrication and modularization, represents the industrialization of the building process. It shifts construction from a chaotic, variable site environment to a controlled factory setting, embodying the Lean goal of flow efficiency (Tommelein & Ballard, 2016). Research by the Windle et al. (2019) highlights the critical role of factory-built housing in disaster response, noting that off-site methods offer superior speed and quality control, which are essential for resilience.

The resilience argument is further supported by the material properties often used in off-site manufacturing. structural insulated panels (SIPs), for example, are a staple of high-performance prefabricated homes. Schiavoni et al. (2016) provided detailed comparative analyses of insulation materials, demonstrating that the composite nature of SIPs (typically expanded polystyrene (EPS) foam sandwiched between oriented strand board (OSB)) offers superior thermal resistance and air tightness compared to conventional fiberglass batt insulation.

The efficiency of Off-Site Construction relies on a tightly integrated supply chain. Zeng et al. (2025) analyze the coordination required in modular construction, describing a four-stage coordination flow that spans the factory and the site. This flow is highly sensitive to disruption (Zeng et. al., 2025).

When a prescriptive code enforcement officer rejects a modular component on-site because it does not match a standard wood framed code checklist, this could cause disruptions that ripples back through the entire factory supply chain (Zeng et al., 2025). This is not just a localized delay; it is a systemic failure of the Lean production system. Tommelein & Ballard (2016) specifically addresses "building code compliance for off-site construction," identifying the mismatch between traditional codes and modular assembly as a primary barrier to industry adoption (Tommelein & Ballard, 2016). This forces off-site manufacturers to create workarounds or to produce code-compliant modules that are less efficient than their standard product, to satisfy the regulatory framework (Tommelein & Ballard, 2016).

The Regulatory Impediment

Regulation is not an abstract legal concept; it is a market force. Gyourko and Molloy (2015) provide a comprehensive review of how regulation affects housing supply, concluding that strict building codes and land-use regulations act as a supply constraint, reducing the elasticity of the market and driving up prices. In the context of the Texas housing market, where demand is surging, these regulatory constraints exacerbate affordability crises (Gyourko & Molloy, 2015).

Blumenthal (2023) chronicles "*Fifty Years of Efforts to Reduce Regulatory Barriers*," revealing a sobering history of failure. Since the 1974 "Housing in the Seventies" report, the federal government has recognized that local regulations impede affordability, yet these barriers have only grown (Blumenthal, 2023). This historical context suggests that policy papers and commissions are insufficient to solve the problem. A technical, process-driven solution, like the one proposed in this study, is required to bypass the deadlock.

The core of the regulatory conflict in this context lies in the distinction between Prescriptive and Performance-Based regulation. Coglianese, C. (2016) and the Inter-jurisdictional Regulatory Collaboration Committee (IRCC) (2010) provide the theoretical definitions for this debate. Prescriptive Regulation dictates *means*: "Install R-13 insulation." It is easy to enforce but rigid and innovation averse while Performance-Based Regulation dictates *ends*: "Achieve an energy rating of X." It encourages innovation but requires sophisticated measurement (Coglianese, C., 2016; Meacham, 2010).

Foliente (2000) notes that the global trend has been moving toward performance-based codes for over two decades, driven by the need for trade and innovation. However, the U.S. residential sector, governed largely by the prescriptive path of the IECC and other International Code Council (ICC) codes, remains a laggard. When the code demands a specific material thickness, it implicitly bans, by means of prescription, any material that achieves the same insulation value with a thinner profile (e.g., aerogels or high-performance foam), creating a technological lock-in that is antithetical to Lean innovation.

A critical critique of the prescriptive path is that it does not guarantee performance. Visscher et al. (2016) describe the "performance gap," where code-compliant buildings frequently underperform because the regulations focus on design compliance (the checklist) rather than outcome verification (Visscher et.al., 2016). Yu et al. (2024) further highlights the discrepancy between theoretical U-values (used in code tables) and "in-situ" measured performance, particularly for novel or bio-based materials (Yu et.al., 2024).

This disconnect is exacerbated by enforcement challenges. Fakunle et al. (2020) identify complexity and a lack of technical understanding as major barriers to code enforcement globally. A prescriptive code that becomes increasingly complex does not necessarily lead to better buildings; it often leads to unintentional non-compliance. In contrast, a digital compliance path, verified by simulation, simplifies enforcement by reducing the complex physical audit to a verified digital output. This shift from physical inspection of inputs to digital verification of outputs is a potential path to closing the performance gap.

Building Physics, Material Science, and Resilience

Iqbal and Al-Homoud (2007) confirmed a non-linear finding of increased insulation thickness by 50% increase in polyurethane yielded only a 2% energy reduction. In hot/humid climates, Jannat et al. (2020) demonstrated that solar gain through glazing drives energy use more than conductive wall heat, supporting a Lean approach that redirects resources from excessive

Kumar et al. (2020) emphasize that thermal resistance is only one factor of performance alongside placement, air tightness, and moisture management. Schiavoni et al. (2016) noted that advanced materials like aerogels outperform traditional mineral wool. Jannat et al. (2020) found that bio-based and composite walls often outperform masonry in the tropics due to lower thermal diffusivity.

Aynur et al. (2009) demonstrated that Variable Refrigerant Flow (VRF) systems offer 17-57% energy savings over traditional VAV systems. Rezaie et al. (2011) and Koskela et al. (2019) discuss optimizing PV and battery sizing for cost and peak load management. While solar is common, simulation results indicate wind turbines are effective in specific high-wind zones like Amarillo (Zone 4A). A Lean, digital approach allows for integrating such site-specific generation technologies, whereas uniform prescriptive codes ignore local resource variations.

Stone et al. (2021) identifies "passive survivability" as the critical intersection of infrastructure failure and envelope performance. While Fikru (2019) explored renewable energy integration, they emphasized that efficiency must precede generation to ensure economic viability. Consequently, the target value shifts from utility reduction to extending habitable time during outages, necessitating another scenario for dynamic simulation over static prescriptive tables.

Synthesis: The Gap in Research

The review of literature reveals a distinct convergence of needs and capabilities, yet a glaring gap in application. A housing stock that is affordable, resilient to climate disasters, and energy-efficient is urgently required (Stone et al., 2021; Gyourko & Molloy, 2015). Lean Design (TVD) and Digitalization (BPS/BIM) provide the advanced tools to design and verify these homes with extreme precision (Ballard, 2020; Sacks et al., 2010). Prefabricated and manufactured construction methodologies offer the industrial capacity to build them at scale with high quality (Windle et al., 2019). The regulatory framework (IECC prescriptive path) remains stuck in a pre-digital, means-based paradigm that can block the integration of these solutions (Tommelein & Ballard, 2016).

While significant research exists in each of these silos, Lean experts study TVD, Building Scientists study BPS, and Policy analysts study regulation, there has been found to be a lack of consolidated research that uses digitalization to explicitly work to remove the waste generated by prescriptive codes in the specific context of prefabrication/modularization and explicit focus on alternative materials and means of construction. This study fills that gap. By using digital twins, it provides the empirical evidence necessary to argue for a regulatory shift: digitalization over prescription.

Methodology

This study employs a sequential, three-phase research design following the precise operational steps taken to identify inconsistencies in the code's execution. To investigate points of potential regulatory friction, the methodology shifts from a linear comparative analysis to a mixed-methods design rooted in Lean Construction philosophy.

To begin, the study focused on five Texas cities, Houston, Austin, Dallas, El Paso, and Amarillo, as illustrated in Figure 1. Each city was selected to represent distinct geographical locations and climate characteristics while also providing regional insights for five diverse major population centers within Texas. Houston, Austin, and Dallas fall under the IECC 2A climate zone, characterized as hot and humid. El Paso is categorized as 3B, warm and dry, while Amarillo falls within the 4A climate zone, which is mixed humid (IECC, 2021).

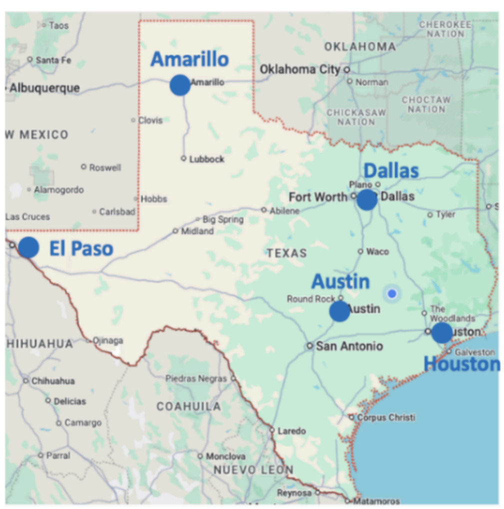

Figure 1. Texas Cities Used for Energy Modeling

Phase 1: Regulatory Deconstruction and Digital Baseline

The research began with a forensic deconstruction of the 2021 IECC, specifically Chapter 4 (Residential Energy Efficiency). This analysis extracted specific prescriptive parameters (Table 1), such as R-values for envelopes and U-factors for fenestration, and air-tightness flow rates, mandated for the selected climate zones to establish the prescriptive metrics for baseline compliance among the case studies.

Table 1: 2021 IECC Chapter 4 Baseline Prescriptive Metrics of Interest for Code Compliance for Texas Climate Zones 2A, 3B, and 4A

Texas Climate Zone	**2A**	**3B**	**4A**
Fenestration U factor	0.4	0.3	0.3
Skylight U factor	0.65	0.55	0.55
Glazed fenestration SHGC	0.25	0.25	0.4
Ceiling R value	49	49	60
Wood Frame Wall R Value	13 or 10ci	20 or 13+5ci or 15ci	30 or 20+5ci or 13+10ci or 20ci
Mass Wall R Value	4/6	8/13	8/13
Steel Frame R Value	Refer to Table R4.2.2.6		
Floor R Value	13	19	19
Air infiltration (ACH50)	5	3	3

*Note- (SHGC)- Solar Heat Gain Coefficient / (ci)- Continuous Insulation

A typical 2-bedroom, 2-bathroom unit (2B2B) model with a total area of 1,297 sq ft as shown in Figure 2 was developed for energy simulation purposes. The model utilized for simulations came from the Department of Energy (DoE) Prototype Building Model (USDOE, 2021). The model geometry accounts for three occupants and a range of household electronic devices. Operational use cases were set to a standard residence for proper energy use intensity simulations across all alternatives observed. Specifications for individual building components were adjusted according to regional climate variations. Components within each category to be supplemented were chosen from FEMA Technical Bulletin 2's acceptable materials for resilient materials (FEMA, 2020). It should be noted that no additional calibration was necessary, as the baseline model used for this study consistently aligned with the U.S. Energy Information Administration's (EIA) metrics for the average annual household consumption in the United States (EIA, 2025). Acceptable alternatives to be substituted were classified classes 4 or 5 in Table 2 of FEMA Technical Bulletin 2 (FEMA, 2020). The baseline energy consumption for the model across five Texas cities—Amarillo, Austin, Dallas, El Paso, and Houston, is shown in Figure 3. Energy consumption values range from 37.26 GJ/year (El Paso) to 41.94 GJ/year (Dallas). Notably, Dallas exhibits the highest energy consumption. These baseline figures highlight regional variations influenced by climate, forming the foundation for further energy efficiency analysis. Additionally, detailed building construction compositions are listed in Table 2 to address the baseline operating levels and prescribed resource allocations from the 2021 IECC.

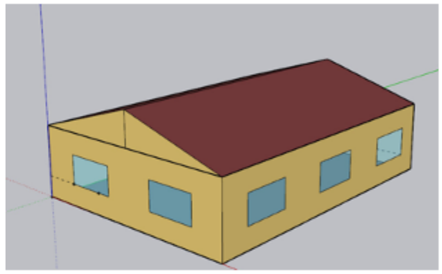

Figure 2. Building Model Geometry of Simulations Conducted (2B2B) (USDOE, 2021)

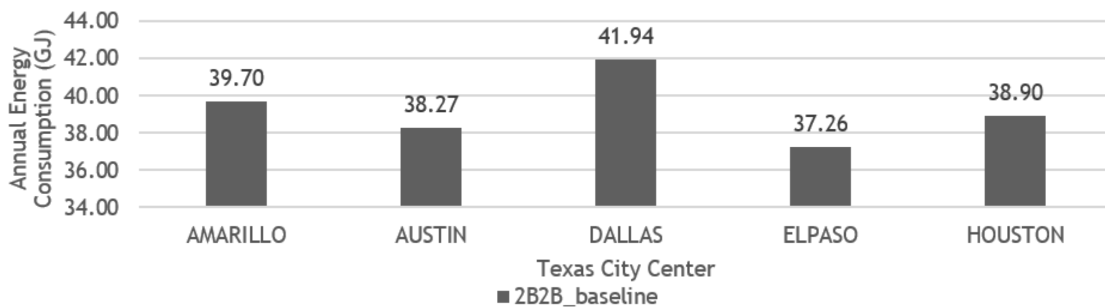

Figure 3. Yearly Energy Consumption for Baseline Models (GJ/Year)

Table 2: Baseline Model Parameters for Climate Zone 2A Cities-Austin, Dallas, and Houston

Building items	Construction composition*	Thickness(mm)*	Conductivity(W/m·K)*
Foundation-slab	Concrete	100.00	0.90
Floors	Plywood 3/4in	19.05	0.12
	Carpet Padding	25.40	0.06
Walls-Exterior	Synthetic Stucco	3.05	0.09
	Sheathing Layer	12.701	0.091
	OSB 7/16in	11.11	0.12
	Wall Insulation Layer	88.902	0.062
	Drywall 1/2in	12.70	0.16
Ceiling	Ceiling Insulation Layer	444.46	0.06
	Drywall 1/2in	12.70	0.16

Building items	Construction composition*	Thickness(mm)*	Conductivity(W/m·K)*
Attic-Roof	Asphalt Shingles	6.34	0.08
	OSB 1/2in	12.70	0.12
Windows	Glass	-	U-2.27
Doors	Consolidated Door	31.703	0.073

Note: *All layer values came from the Department of Energy (DoE) Prototype Building Model in compliance with the 2021 IECC in reference to Chapter 4 (Residential Energy). The specific material was unknown, but the recommended insulative value was achieved.

1. For climate zone 3B (El Paso), the sheathing layer thickness and conductivity were 12.70 mm & 0.09 (W/m K) respectively. For climate zone 4A (Amarillo), the sheathing layer thickness and conductivity were 31.12 mm & 0.04 (W/m K) respectively.
2. For climate zone 3B (El Paso) & 4A (Amarillo), the wall insulation layer thickness and conductivity were 139.70 mm & 0.06 (W/m K) respectively.
3. For climate zone 3B (El Paso) & 4A (Amarillo), the consolidated door layer thickness and conductivity were 42.27 mm & 0.07 (W/m K) respectively.

Phase 2: Digital Simulation for Target Value Identification

Utilizing Set-Based Concurrent Engineering (SBCE), the study conducted 180 independent computational simulations utilizing materials listed in Table 3. This was conducted by simply replacing a single baseline material parameter with alternative values for testing (e.g. market available insulated foundation parameters replaced the baseline model foundation values) while no other changes were made to the energy model for each corresponding simulation. This methodology assured uniform simulation conditions to gain comparative data for analysis. In total, 180 independent energy simulations were conducted to systematically assess individual component impact against the baseline model. From here, a review of each model performance was conducted.

Table 3: Alternatives Simulated in Substitution to the Baseline

Components	Building Components Alternative			
Alternative Energy Generation	PV1	Solar Roof	Solar Window	Wind Turbine
	PV + Battery	Solar Roof + Battery	Solar Window + Battery	Wind Turbine + Battery
Roofing	High Albedo			
Siding	Brick	Fiber Cement Board	Aluminum (metal)	
Flooring	Wood	Tile	Carpet	
Windows	Double Pane Low-E[3]	Triple Pane	FEFA[6], Low-E Triple-Pane	

Components	Building Components Alternative			
Alternative Energy Generation	PV1	Solar Roof	Solar Window	Wind Turbine
	PV + Battery	Solar Roof + Battery	Solar Window + Battery	Wind Turbine + Battery
Doors	1-Hour Fire Rated	Glass Pane	Steel Plated	
Insulation	High Density Fiber Glass	Closed Cell Spray Foam	EPS[5]	
Foundations	Insulated SoG[2]	Crawl Space		
Drywall	Mold & Moisture Resistant	Fire Resistant (Type C)	High Impact	
SIPs[7]	Wood SIPs	Steel SIPs	MgO[8] SIPs	
HVAC	Window AC	High SEER[4] Rating		

1 - Photovoltaic (PV) / 2 – Slab-on-Grade / 3 – Low emissivity / 4 - Seasonal energy efficiency ratio / 5 – Expanded Polystyrene / 6 - Foam Enhanced Frame & Argon / 7 – Structural Insulated Panels / 8 – Magnesium Oxide

The best performing alternative from each building component category was then substituted collectively within a model to simulate the combined effects of each building component substitution. These new simulation values were integrated based on their ability to net the least yearly purchased energy in each climate zone. It is important to note that not all alternatives implemented on the new model were the same for each climate zone. This decision to nonuniformly implement alternatives across all climate zones was derived from their varying ability to reduce net energy consumption within each climate zone further supporting the focus on climate specific resilient solutions. The following diagram (Figure 4) illustrates the macro-level progression of the research phases in relation to each Energyplus simulation.

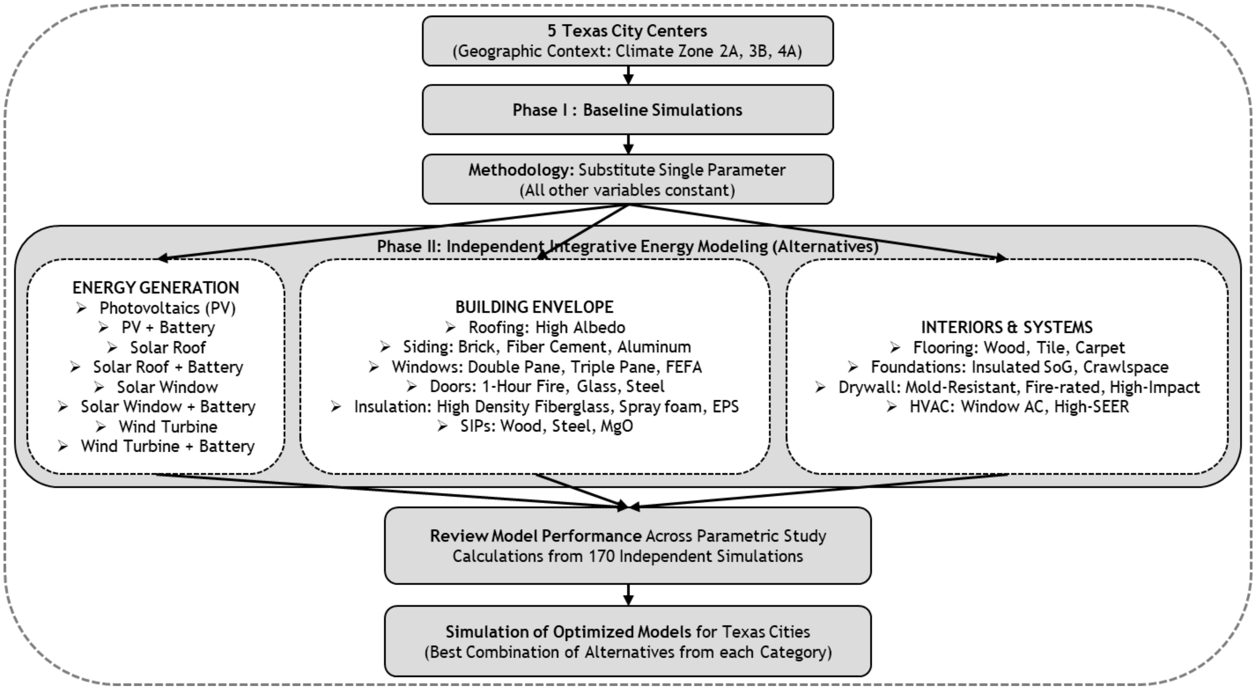

Figure 4. Systematic Progression of Independent Integrative Energy Simulations

A strict methodological distinction was maintained between energy reduction (demand side) and energy generation (supply side). While generation technologies like PV and wind turbines were simulated as an overlay, the primary Lean analysis focused on the passive building envelope. This aligns with the principle that "waste" must be minimized through efficiency before optimizing supply via generation (Fikru, 2019).

Following the component isolation, the best-performing avoidance components were compiled into an Optimized Digital Twin for each climate zone. This combinatorial synthesis defined the target value, the theoretical performance ceiling or highest equivalent neutral target for energy reduction achievable with current market technology.

Phase 3: Off-Site Case Study and Comparative Gap Analysis

The study utilized a purposive sampling strategy to collect technical data from six alternative housing unit (AHU) companies, including manufactured, prefabricated, kit built, and 3D printed vendors capable of demonstrating market viability currently. These vendors were selected based on their utilization of prefabrication/modularization and explicit focus on alternative materials and means of construction. Data points harvested included wall assembly U-factors, glazing specifications, and air tightness ratings as extracted from Chapter 4 of the 2021 IECC (IECC, 2021).

A binary compliance audit of the six vendors against the IECC 2021 prescriptive tables was then performed. The necessary information called out in Table 1 for comparison to the initial DoE models was extracted and categorically associated with anonymizing metrics. The metrics were denoted by "Does not meet all Texas climate zone requirements (N/M)", "meets all Texas climate zone requirements(M)", "exceeds all Texas climate zone requirements (E)."

The final step involved mapping the simulation results (Phase II) against the audit results (Phase III) to create an understanding of potential waste streams in the design of the IECC code structure. This analysis justified deviations from the code not as risks, but as Lean decisions. Figure 5 displays the methodological process employed to increase the digitalization and automation that arises through the implementation of available compliance data and reliable energy simulation tools.

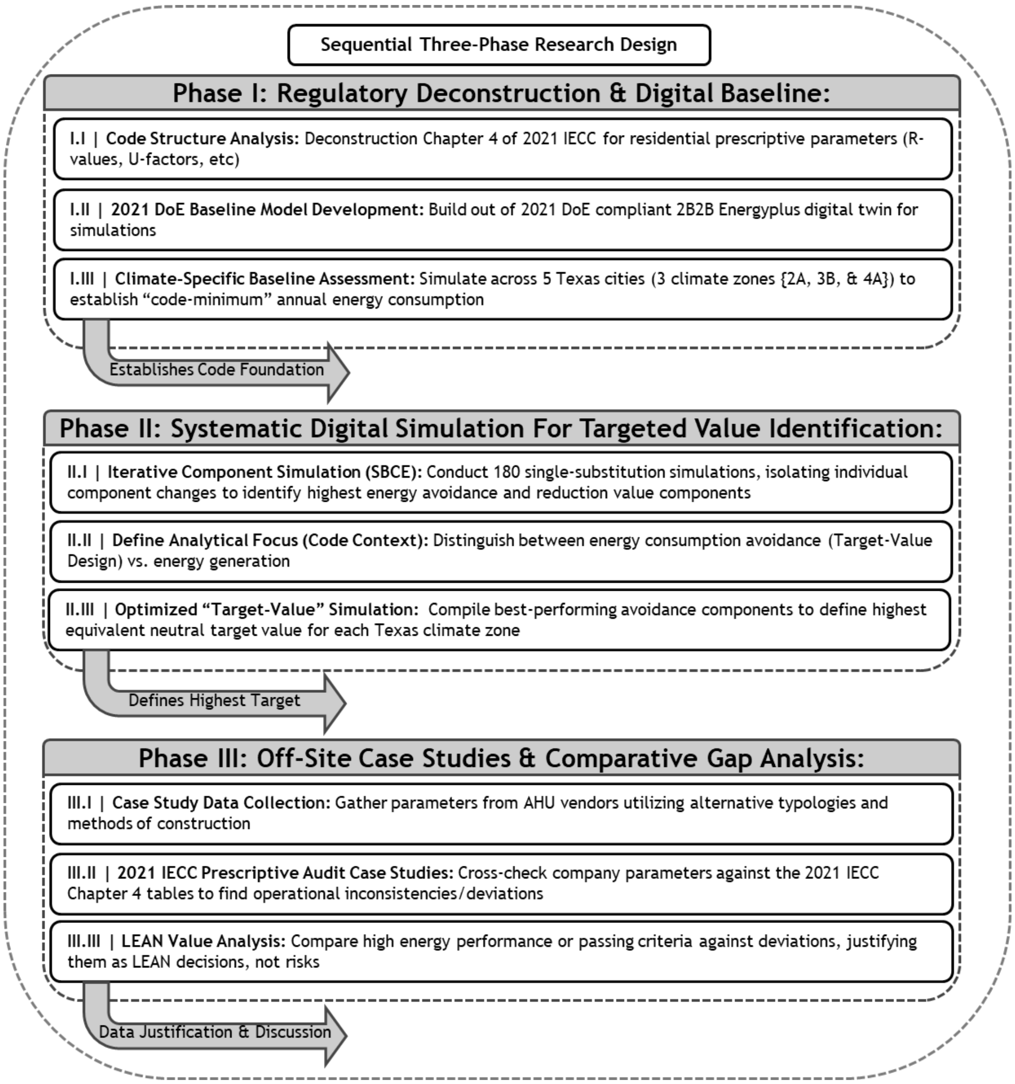

Figure 5. Sequential Three Phase Research Design for Adhering Case Studies to a Prescriptive Audit of the 2021 IECC for Extraction of LEAN Design Viability

Results

Digital Simulation Results

The final component of this study involved simulating the combined impact of multiple building modifications rather than evaluating materials and technologies in isolation. The optimal alternative for each category specific to each city center is outlined in Table 4. The results confirmed that the integration of multiple energy-efficient strategies led to greater reductions in energy consumption compared to implementing individual measures alone. These findings support the growing body of research advocating for targeted design approaches that optimize energy savings thus increasing energy resilience of homes. Such design approaches point to savings through implementation of resilient material and system choices.

Table 4: Optimized Building Components for the Combined Case Study

Building Components	Texas City Center				
	Amarillo	**Austin**	**Dallas**	**El Paso**	**Houston**
Alt. Energy	Wind Turbine + Battery	Solar Roofing + Battery	Solar Roofing + Battery	Solar Roofing + Battery	Solar Roofing + Battery
HVAC	High Efficiency HVAC	High Efficiency HVAC	High Efficiency HVAC	High Efficiency HVAC	High Efficiency HVAC
Roof	High Albedo Roof	High Albedo Roof	High Albedo Roof	High Albedo Roof	High Albedo Roof
Insulation	Wood-SIP	Wood-SIP	Wood-SIP	Wood-SIP	Wood-SIP
Siding	Brick	Aluminum Siding	Aluminum Siding	Aluminum Siding	Aluminum Siding
Dry Wall	High Impact	High Impact	High Impact	High Impact	High Impact
Window	FEFA LOW-E Triple-Pane	FEFA LOW-E Triple-Pane	FEFA LOW-E Triple-Pane	FEFA LOW-E Triple-Pane	FEFA LOW-E Triple-Pane
Floor	Wood	Wood	Wood	Wood	Wood
Door	1-Hour Fire Rated	1-Hour Fire Rated	1-Hour Fire Rated	1-Hour Fire Rated	1-Hour Fire Rated
Foundation	Insulated Foundation	Insulated Foundation	Insulated Foundation	Insulated Foundation	Insulated Foundation

The Energyplus simulations confirmed that optimizing the building envelope and HVAC systems are the most prominent contributors to energy use avoidance. The results of individual component substitutions, detailed in Table 5, highlight the variance in energy reduction capabilities across the five targeted Texas city centers.

Substitutions of insulation type alone were found to yield diminished energy savings compared to a more comprehensive wall system such as SIP's. SIPs were identified as a viable alternative solution for increasing energy efficiency. Compared to conventional framing methods, greater energy savings were achieved due to minimized heat loss and increased R-values through the utilization of expanded polystyrene (EPS) within the SIP core.

Additionally, it was observed that interior components, such as advanced drywall materials or specific foundation choices, had a relatively minor impact on overall energy consumption when compared to building envelope improvements. While these materials may offer benefits in terms of disaster resilience and indoor comfort, their role in reducing heating and cooling loads was found to be limited. This finding highlights the importance of prioritizing exterior interventions, such as high-performance insulation, advanced glazing, and air-tight construction techniques, when seeking to improve a home's energy efficiency.

Furthermore, it was demonstrated that not all alternative materials and technologies were equally effective across all climate zones. Some energy-efficient solutions performed well in a more heating-dominated region (Climate Zone 4A), but they provided less substantial benefits in cooling-dominated climates (Climate Zones 2A & 3B), and vice versa. This finding underscores the importance of a climate-driven approach when selecting materials and technologies, as broadly applied strategies might not yield optimal results leading to an inefficient source of waste in the design.

Specifically, Structural Insulated Panels (SIPs) were identified as a viable solution for envelope efficiency, yielding energy reductions ranging from 2.25% (Steel SIPs in Amarillo) to 6.99% (Wood SIPs in Dallas) compared to baseline construction methods. Advanced window technologies also demonstrated notable impacts, with reductions observed between 1.86% and 6.57% for FEFA & Low-E triple-pane configurations across all simulated climate zones. Additionally, alternative forms of insulation including expanded polystyrene (EPS), was found to only yield a 0.03% reduction in energy use when substituted to the baseline, highlighting insulation techniques as the widest range of potential net benefits. These avoidance techniques see a range of 0.03% (EPS in Amarillo) to 6.99% (wood SIPs in Dallas). Table 6 defines the net ranges observed for each energy use avoidance and alternative energy generation category.

Table 5: Net Energy Consumption of Alternative Building Components Substituted to Baseline by Percentage

Alternative Building Components	City Center				
	Amarillo	Austin	Dallas	El Paso	Houston
High Albedo Roof	-0.79%	-1.79%	-1.34%	-2.07%	-1.95%
High Density Fiber Glass	1.44%	-2.27%	-2.99%	1.01%	-2.27%
Closed Cell Spray Foam	0.37%	-3.25%	-4.40%	-0.24%	-3.24%
EPS	0.03%	-3.41%	-4.57%	-0.52%	-3.40%
Brick	-1.57%	-2.88%	-2.78%	-2.58%	-2.94%
Fiber Cement Board	-0.43%	-1.32%	-1.08%	-1.11%	-1.49%
Aluminum (metal)	-1.11%	-3.90%	-3.22%	-3.05%	-4.11%
Mold/Moisture Resistant	0.28%	0.26%	0.27%	0.30%	0.25%
Fire Rated (Type C)	0.27%	0.28%	0.30%	0.29%	0.27%
High Impact	-0.70%	-1.52%	-2.04%	-0.99%	-1.55%
Wood SIPs	-2.97%	-5.69%	-6.99%	-3.75%	-5.47%
Steel SIPs	-2.25%	-4.99%	-6.47%	-2.86%	-5.00%
MgO SIPs	-2.34%	-4.88%	-5.73%	-3.01%	-4.67%
Double Pane Low-E	-5.99%	-1.56%	-3.29%	-1.23%	-1.29%
Triple Pane	-4.45%	0.17%	-1.69%	1.16%	0.56%
FEFA & Low-E triple-pane	-6.57%	-2.11%	-3.84%	-1.92%	-1.86%
Wood	-4.87%	-6.19%	-5.50%	-5.97%	-6.50%
Tile	-4.20%	-5.18%	-4.57%	-5.05%	-5.42%
Carpet	-1.72%	-2.01%	-1.76%	-2.00%	-2.11%
1-Hour Fire Rated	-0.12%	-0.13%	-0.10%	-0.06%	-0.11%
Glass Panel	-0.30%	-0.12%	-0.36%	0.02%	-0.10%

Alternative Building Components	City Center				
	Amarillo	Austin	Dallas	El Paso	Houston
Steel Plated	-0.61%	-0.46%	-0.53%	-0.45%	-0.43%
Insulated SoG	-0.50%	-0.38%	-0.84%	-0.29%	-0.44%
Crawl Space	0.04%	-1.58%	-1.34%	-1.03%	-2.23%
Window AC	19.46%	8.47%	14.47%	7.57%	6.70%
High SEER HVAC	-12.68%	-12.05%	-13.81%	-10.68%	-11.44%

Table 6: Net Energy Consumption of Selected Building Components Substituted for the Combined Case Study Against the Baseline by Percentage

Building Components	Range of Net Reduction	Texas City Center				
		Amarillo	Austin	Dallas	El Paso	Houston
Alt Energy	66.07%-73.51%	-72.33%	-70.61%	-66.07%	-73.51%	-70.63%
HVAC	10.68%-13.81%	-12.68%	-12.05%	-13.81%	-10.68%	-11.44%
Roof	0.79%-2.07%	-0.79%	-1.79%	-1.34%	-2.07%	-1.95%
Insulation	0.03%-6.99%	-2.97%	-5.69%	-6.99%	-3.75%	-5.47%
Siding	1.57%-4.11%	-1.57%	-3.90%	-3.22%	-3.05%	-4.11%
Dry Wall	0.70%-2.04%	-0.70%	-1.52%	-2.04%	-0.99%	-1.55%
Window	1.86%-6.57%	-6.57%	-2.11%	-3.84%	-1.92%	-1.86%
Floor	4.87%-6.50%	-4.87%	-6.19%	-5.50%	-5.97%	-6.50%
Door	0.06%-0.13%	-0.12%	-0.13%	-0.10%	-0.06%	-0.11%
Foundation	0.29%-0.84%	-0.50%	-0.38%	-0.84%	-0.29%	-0.44%

Although noticeable energy resilience increases can be observed in this study by substituting only one alternative as also stated by Fikru (2019), the compounded effects for overall residential resiliency as seen in Table 7 are displayed through the combined simulation conducted here. Dallas showed the lowest net reduction in energy consumption of 83.77%, while El Paso boasted an 88.29% net reduction in energy consumption. By prioritizing energy efficiency, resilience, and cost-effectiveness, informed choices can be made to contribute to the long-term sustainability and affordability of residential construction.

Table 7: Net Energy Consumption of the Combined Case Study Against the Baseline by Percentage

Simulation Type	City Center				
	Amarillo	Austin	Dallas	El Paso	Houston
Combined Case	-86.86%	-85.55%	-83.77%	-88.29%	-84.77%

Off-Site Construction Case Study Performance

This section presents the comparative analysis of six case studies utilizing Off-Site Construction methods. The audit examined how these vendors met or exceeded the IECC 2021 baseline performance. Table 8 indicates each of the proposed six vendors' current ability to meet compliance with the current baseline model metrics consistent with the 2021 IECC.

These abilities represent compliance in the 2021 IECC defined climate zones for the respective zones where each unit could be deployed in each of the three Texas climate zones defined in the 2021 IECC. For the intents of the study, no modifications were made from their existing climate zone compliance checklist. One finding from this audit is that while these companies reportedly utilize high-performance envelope assemblies and high efficiency HVAC units (value), they frequently indicated prescriptive non-compliance when audited strictly against the IECC prescriptive path although each system provided data consistent with overperformance in multiple other categories (pointing to a possible source of waste).

Table 8: Suggested Vendor enhancements against current Baseline Metrics for Energy Efficiency for the State of Texas based on the Building Materials Report

Components	Vendor(A)	Vendor(B)	Vendor(C)	Vendor(D)	Vendor(E)	Vendor(F)
Glazing U-Factor	E	N/M	E	E	E	N/M
Glazing SHGC	E	E	E	E	E	M
Ceiling	N/M	N/M	N/M	N/M	N/M	N/M
Wall	E	N/M	E	E	N/M	E
Floor	E	E	N/M	N/M	E	N/M
Air tightness	E	N/M	E	D/S	D/S	N/M

Note[1]:Did not specify (D/S)", "Does not meet all Texas climate zone requirements (N/M)", "meets all Texas climate zone requirements(M)", "exceeds all Texas climate zone requirements (E)"

This cross-check identified operational inconsistencies where thermodynamic systems (e.g., SIP roofs) failed to meet specific thickness or R-value mandates, resulting in a "Not Met" (N/M) classification despite documenting commensurate or exceeding energy performance when checked by third party systems such as RESCheck, local county inspectors, or architects. This suggests that strictly adhering to prescriptive parameters could generate waste, while strategic deviations (such as using thinner but higher-performing SIPs) deserve further research into implementation.

Discussion: Conflict of Digital Value vs. Prescriptive Waste

Target Value Identification via Digitalization

The primary objective of this research was to utilize digitalization to identify the optimal energy reduction target value for Texas climate zones, moving beyond the static baselines of the 2021 IECC. To achieve this, the study operationalized BPS as a generator of value rather than a post-design verification tool as seen using US. DoE RESCheck compliance pathways. The execution of 180 independent simulations functioned as a SBCE workflow. This aligns directly with Ballard (2020), who posits that SBCE avoids negative iterations by keeping sets of design alternatives open until data confirms the optimal path.

The study simulation data definitively identified the "optimal energy bundle" through this iterative filtering, a methodology consistent with Lee et al. (2012), who established that TVD is an efficient mechanism for maximizing energy efficiency investments. The results demonstrated a clear hierarchy of value: systemic envelope changes (such as SIPs) yielded reductions up to 6.99% and HVAC systems demonstrating energy avoidances up to 13.81% in climate zone 3B, whereas isolated material substitutions, specifically increasing the thickness of standard insulation (EPS), yielded negligible returns of only 0.03%.

By identifying this saturation point through simulation, this study established a target value based on data-driven performance. This confirms that the most effective route to energy reduction in Texas climates is not the "more is better" approach of prescriptive tables, but the "system is better" approach of Lean design.

The Regulatory Hurdle: Optimal Design vs. IECC 2021 Prescription

Once the Target Value was established, the comparison against the 2021 IECC prescriptive tables revealed a fundamental operational inconsistency. While Vaughan and Turner (2012) argue that codes provide essential safety and energy baselines, our analysis suggests that in the context of high-performance materials, the prescriptive baseline acts as a barrier to innovation.

The audit revealed that high-performance off-site construction assemblies, specifically those utilizing composite SIPs, were frequently deemed "non-compliant" (N/M) despite the simulation showing they exceeded the energy performance of the code-compliant baseline. This finding empirically validates Tommelein and Ballard (2016) who identified that regulatory frameworks designed for stick-built construction create significant compliance burdens for off-site manufacturing.

Furthermore, these findings highlight an inversion of the performance gap described *by* Visscher et al. (2016). While Visscher et al (2016) noted that code-compliant buildings often underperform, this study found that "non-compliant" off-site case studies overperformed the U.S. DoE Energyplus simulation baseline. This discrepancy indicates that the regulatory friction described by Burby et al. (2000) is not a procedural nuisance but a source of systemic waste.

The regulatory lag forces builders to expend resources on redesign and redundant documentation to satisfy a prescriptive table.

Lean in Practice: Case Study Trade-offs in Energy Reduction

The analysis of the six case studies demonstrates the potential operational inefficiency of the current code structure and the necessity of Lean trade-offs. The vendors analyzed operate with a Lean production system design, making intelligent trade-offs among components to achieve the target value. For instance, companies prioritized investments in high-impact components, such as air-tight SIP envelopes and high-efficiency HVAC systems, while reducing effort on lower-impact components, such as specific glazing metrics.

This behavior aligns with the "efficiency first" principle advocated by Fikru (2019), which prioritizes envelope optimization over other interventions. From a Lean perspective, defined by Zimina et al. (2012) as the maximization of value, these trade-offs are rational and efficient.

However, the prescriptive code's inability to recognize this value leads these vendors into operational inconsistency. By demanding upgrades to components that the simulation indicated provide only marginal value (e.g., upgrading a window SHGC when the wall system already compensates for the load), strict code adherence grows the potential for waste generation.

Conclusions

This study offers insights into digitalization (simulation) to possibly enable accurate Target Value Design for energy reduction, and off-site construction. By operationalizing digitalization to test 180 distinct simulations, the research achieved its first objective: identifying an optimal energy reduction target value for Texas climate zones that is shown to exceed the static baselines of the 2021 IECC.

Furthermore, the operational inconsistencies identified across five Texas city centers demonstrate that the IECC 2021 prescriptive path can unknowingly impede the execution of Lean principles, leading to potential waste in both design and material usage. The second and third research objectives were met by showcasing that high-performing off-site vendors, despite utilizing superior thermodynamic assemblies, were observed to fail sections binary compliance audits due to rigid definitions of value definitions from the prescriptive codification pathway. This finding contends that the current regulatory framework exhibits functions that if left unresolved, could present as a barrier to innovation, forcing manufacturers to engage in non-value-adding work to secure permitting.

Consequently, to achieve robust energy resilience, regulation must evolve to accept the performance proof that can be provided by digitalization across climate zones while actively incentivizing companies to work towards a target value rather than a prescribed recipe of energy compliance, aligning code compliance with the efficiency principles of Lean. The study successfully showed evidence that simulation-derived scenarios can offer a more flexible and accurate method of ensuring resilience than static tables, fulfilling the final research objective.

Alternative veins of research to be explored can be seen in the current findings, such as the marginally greater energy efficiency of the selected window types over other window alternatives (e.g., double pane Low-E windows versus triple pane foam-enhanced frame, Argon, and Low-E windows). Other occurrences of this include the performance of crawl-space foundations in Houston and the comparison of solar roofing versus solar panels across climate zones 2A and 3B. These findings reiterate the need for further cost/benefit analysis on proposed energy-efficient alternatives. Currently, many of the alternative case studies presented herein are novel in their design approach. As these emerging technologies and construction methods continue to evolve and gain market share, further financial analyses will be essential to better inform occupants about which solutions are most viable for broad, sustainable implementation. As such, further research investigating a pay-back period analysis should be conducted for each of the alternatives discussed in this study. Finally, as research around both energy-efficient and resilient building materials gains prevalence, a more robust reliance on statistical analysis to determine significance regarding the impact on energy reduction should be explored.

Through energy simulation models and data gathered from manufacturers and scientific literature, the necessity of integrating multiple solutions to create sustainable, energy-efficient homes capable of withstanding both environmental and economic challenges was discussed. While no single solution was identified as universally optimal, the findings highlighted the importance of selecting technologies and materials that align with regional climate conditions. By prioritizing energy efficiency, resilience, and cost-effectiveness within the codification pathway through digitalization and minimizing waste, informed choices can be made to contribute to the long-term sustainability and affordability of residential construction.

Acknowledgements

Data collection for this research was conducted under the sponsorship of the Texas General Land Office (GLO). The views expressed are those of the authors and may not reflect those of the agency. The data and analysis provided herein should not represent a continuation of the research conducted under the sponsorship of the Texas GLO but the independent research of the authors. Express permission for anonymous publication from each company whose data was discussed has been received.

References

Aynur, T. N., Hwang, Y., and Radermacher, R. (2009). "Simulation comparison of Vav and VRF Air Conditioning Systems in an existing building for the cooling season." *Energy and Buildings*, 41(11), 1143 1150.

Baechler, M., Adams, K., Hefty, M., Gilbride, T., and Love, P. (2012). "Energy renovations - volume 17: Insulation - A guide for contractors to share with homeowners." *Technical Report: Energy Renovations: Insulation*, 17.

Ballard, G. (2020). "Target Value Delivery: Lean Construction." *Taylor & Francis Online*, Routledge.

Baniassadi, A., Sailor, D. J., Krayenhoff, E. S., Broadbent, A. M., and Georgescu, M. (2019). "Passive survivability of buildings under changing urban climates across eight US cities." *Environmental Research Letters*, 14(7), 074028.

Blumenthal, P. M. (2023). "Fifty years of efforts to reduce regulatory barriers: Hud User." Fifty Years of Efforts to Reduce Regulatory Barriers | HUD USER, *United States Department of Housing and Urban Development | Office of Policy Development and Research*.

Burby, R. J., May, P. J., Malizia, E. E., and Levine, J. (2000). "Building code enforcement burdens and central city decline." *Journal of the American Planning Association*, 66(2), 143–161.

Coglianese, C., Nash, J., and Olmstead, T. (2003). "Performance-Based Regulation: Prospects And Limitations In Health, Safety, And Environmental Protection." *UPenn Law Scholarship*, Penn Carey law: Legal Scholarship Repository.

Dacquisto, D. J., and Rodda, D. T. (2006). "Housing Impact Analysis." *Huduser.org*, U.S. Department of Housing and Urban Development: Office of Policy Development and Research.

EIA. (2025). "Frequently asked questions (FAQS) - U.S. energy information administration (EIA). Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA), U.S. Energy Information Administration.

EPA. (2025). "Climate Change Indicators: Residential Energy Use." *EPA*, Environmental Protection Agency.

Fakunle, F. F., Opiti, C., Sheikh, A. A., and Fashina, A. A. (2020). "Major barriers to the enforcement and violation of building codes and regulations: a global perspective." *SPC Journal of Environmental Sciences*, 2(1), 12-18.

FEMA. (2020). "Flood Damage-Resistant Materials Requirements." *FEMA.gov*, Federal Emergency Management Agency.

Fikru, M. G. (2019). "Electricity bill savings and the role of Energy Efficiency Improvements: A case study of residential solar adopters in the USA." *Renewable and Sustainable Energy Reviews*, 106, 124-132.

Fitch, C. (2006). "Guide to more effective and efficient building regulatory processes through information technology." *Guide to More Effective and Efficient Building Regulatory Processes Through Information Technology | HUD USER*, U.S. Department of Housing and Urban Development | Office of Policy Development and Research.

Foliente, Greg. (2000). Developments in performance-based building codes and standards. *Forest Products Journal*. 50. 12-21.

Gillespie, L., and Rubloff, T. (2024). "Survey: 81% of Americans say higher energy costs or extreme weather have impacted their wallets." *Bankrate-Homeowners Insurance*, Bankrate.

Gyourko, J., and Molloy, R. (2015). "Regulation and housing supply." *Handbook of Regional and Urban Economics*, 5, 1289–1337.

IECC, (2021). "Chapter 4." *2021 International Energy Conservation Code (IECC)*, International Code Council (ICC).

Iqbal, I., and Al-Homoud, M. S. (2007). "Parametric analysis of alternative energy conservation measures in an office building in hot and humid climate." *Building and Environment*, 42(5), 2166–2177.

Jannat, N., Hussien, A., Abdullah, B., and Cotgrave, A. (2020). "A comparative simulation study of the thermal performances of the building envelope wall materials in the Tropics." *Sustainability*, 12(12), 4892.

Koskela, J., Rautiainen, A., and Järventausta, P. (2019). "Using electrical energy storage in residential buildings – sizing of battery and photovoltaic panels based on electricity cost optimization." *Applied Energy*, 239, 1175–1189.

Kumar, D., Alam, M., Zou, P. X. W., Sanjayan, J. G., and Memon, R. A. (2020). "Comparative analysis of building insulation material properties and performance." *Renewable and Sustainable Energy Reviews*, 131, 110038.

Lee, H. W., Tommelein, I. D., and Ballard, G. (2012). "Application of target value design to Energy Efficiency Investments." *Escholarship.org*, UC Berkeley.

May, P. J. (2003). "Performance-Based Regulation and Regulatory Regimes: The Saga of Leaky Buildings." *Law & Policy*, 25(4), 381-401.

Meacham, B. J. (2010). "Performance-based building regulatory systems principles and experiences." *ircc.info*, Inter-Jurisdictional Regulatory Collaboration Committee (IRCC).

NAHB. (2020). "FEMA study shows Resilience Value of building codes but understates cost impact." *NAHB.org*, National Association of Home Builders: Codes and Standards, Accessed December 2025.

Ohno, T. (1988). *Toyota production system*. Productivity Press, New York, New York.

Pennanen, A., Ballard, G., and Haahtela, Y. (2011). "Target costing and designing to targets in construction." *Journal of Financial Management of Property and Construction*, 16(1), 52–63.

Rezaie, B., Esmailzadeh, E., and Dincer, I. (2011). "Renewable energy options for buildings: Case studies." *Energy and Buildings*, 43(1), 56–65.

Sacks, R., Koskela, L., Dave, B. A., and Owen, R. (2010). "Interaction of Lean and building information modeling in construction." *Journal of Construction Engineering and Management*, 136(9), 968–980.

Schiavoni, S., D׳Alessandro, F., Bianchi, F., and Asdrubali, F. (2016). "Insulation materials for the building sector: A review and comparative analysis." *Renewable and Sustainable Energy Reviews*, 62, 988 1011.

Stone, B., Mallen, E., Rajput, M., Gronlund, C. J., Broadbent, A. M., Krayenhoff, E. S., Augenbroe, G.,O'Neill, M. S., and Georgescu, M. (2021). "Compound climate and infrastructure events: How electrical grid failure alters heat wave risk." *Environmental Science & Technology*, 55(10), 6957- 6964.

Tommelein, I., & Ballard, G. (2016). "Target Value Design Introduction, Framework, and Current Benchmark." *In Target Value Design Introduction, Framework, and Current Benchmark*.

USDOE. (2021). "US Department of Energy (USDOE). "Residential Prototype Building Models," *Building Codes Energy Program*. 2021.

Vaughan, E., and Turner, J. (2012). "The value and impact of building codes." *Insurance Institute for Business and Home Safety*, Insurance Institute for Business and Home Safety (IBHS).

Visscher, H., Meijer, F., Majcen, D., and Itard, L. (2016). "Improved governance for energy efficiency in housing." *Building Research & Information*, 44(5–6), 552–561.

Windle, M., Quraishi, S. & Goentzel, J. (2019). "Disaster housing challenges in America: exploring the role of factory-built housing." MIT Humanitarian Supply Chain Lab, MIT Center for Transportation & Logistics. Cambridge, MA.
Yu, J., Dong, Y., Wang, T.-H., Chang, W.-S., and Park, J. (2024). "U-values for building envelopes of different materials: A Review." *Buildings*, 14(8), 2434.
Zeng, N., Liu, Y., Wang, C., Chen, Q., Liu, Y., and Li, Q. (2025). "On- and off-site coordination in a modular construction supply chain: Domain-spanning production flow framing and evaluation." *Journal of Construction Engineering and Management*, 152(2).
Zimina, D., Ballard, G., and Pasquire, C. (2012). "Target value design: Using collaboration and a lean approach to reduce construction cost." *Construction Management and Economics*, 30(5), 383–398.