

# Research Methodology for Passive Energy-Saving Design Strategies Buildings for Cold Climate Regions in China

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## ABSTRACT

Passive and high-performance buildings consistently outperform conventional designs in energy efficiency, indoor environmental quality, and long-term economic value, particularly in cold-climate regions. Yet, adoption across northern China remains uneven despite strong policy support. This study examines Zhangjiakou as the primary target region and uses Chengde, Harbin, and Xi'an as comparative cases to assess the transferability and cost-effectiveness of passive design strategies within local construction and climatic conditions. Persistent gaps remain between policy ambition and practical cost planning, including perceived capital expenditure (CAPEX) premiums, uncertain operational expenditure (OPEX) savings, and inconsistent replacement cycles. To address these barriers, this paper outlines a research methodology for developing and validating an integrated Elemental + Life-Cycle Cost (ECA + LCC) Model as a decision-support tool for feasibility analysis. The methodology combines Elemental Cost Analysis with forty-year Life-Cycle Costing and is structured using Saunders' Research Onion, a pragmatic-post-positivist philosophy, and Design Science Research (DSR) complemented by Model Verification and Validation (V&V). Case studies from the three comparative regions calibrate the model and assess its transferability to Zhangjiakou. Data collection includes structured document review, expert consultation, and validation. The resulting methodological framework provides a transparent and replicable basis for quantifying cost-performance relationships at the elemental level, supporting feasibility evaluation, cost optimisation, and strategic decision-making for passive-design implementation in China's cold-climate construction sector.

**Keywords:** Elemental Cost Analysis (ECA); Life-Cycle Costing (LCC); Passive Building; Cold Climate; Model Validation; Research Onion; China.

## INTRODUCTION

China's commitment to achieving carbon neutrality by 2060 necessitates the development of buildings that integrate high energy performance with economic feasibility [1], [2]. In northern cold-climates, where heating constitutes the largest portion of energy demand, passive design strategies have become a strategic imperative for reducing long-term energy consumption and carbon emissions [3]. A growing body of research confirms that passive and high-performance buildings outperform conventional designs in energy efficiency, indoor environmental quality, and life-cycle economic value [1], [4], [5]. Nevertheless, adoption across North China remains uneven despite clear policy support and the presence of pilot projects [6]–[8].

A key barrier lies in the fragmented nature of China's construction cost management system [9], [10], in which developers estimate construction expenditures while operational costs are separately recorded by local governments. This disjunction prevents a holistic understanding of life-cycle performance and limits effective policy development [6]–[10].

To address these gaps, the research develops an Elemental + Life-Cycle Cost Model (ECA + LCC) capable of quantifying both construction and operational costs for passive and active buildings in cold-climate contexts. The methodology follows Saunders' (2016) Research Onion [11]–[13] to structure philosophical and procedural

decisions, replacing PRISMA's review-based approach with Design Science Research (DSR) and Model Verification and Validation (V&V) frameworks.

## Research Philosophy

The research follows a pragmatic-post-positivist philosophy. Pragmatism is appropriate for practice-oriented research seeking effective solutions to complex real-world problems [11]–[13]. Post-positivism recognises that although cost data are quantitative, they remain probabilistic due to market variability. Together, they allow theoretical grounding and empirical flexibility.

Ontologically, the study views buildings as socio-technical systems shaped by design decisions, material behaviour, and climate [14], [15]. Epistemologically, it privileges applied knowledge production through artefact construction, consistent with Design Science. Thus, the cost model itself becomes an embodiment of knowledge, bridging theory and practice [16]–[18].

## Research Approach

The study adopts an abductive research approach, which combines deductive reasoning derived from established theories of passive building design with inductive reasoning emerging from empirical cost observations [11]–[13]. Unlike purely deductive approaches that move from theory to data or purely inductive approaches that generalise from observation, abduction allows for a recursive dialogue between theory and evidence [19], [20]. This characteristic is essential for construction economics research, where cost and performance variables are dynamic, context-dependent, and influenced by both technical and behavioural factors.

Abduction provides a methodological bridge between conceptual modelling and empirical verification. At the outset, the research draws upon theoretical constructs from life-cycle costing (LCC), elemental cost analysis (ECA), and passive design principles to formulate initial expectations about how design strategies influence cost structures. This deductive stage defines the conceptual framework and cost-performance relationships as informed by literature, policy, and precedent studies [12].

Subsequently, through an inductive stage, data are collected and analysed from selected case studies in Harbin, Xi'an, and Chengde, regions representing distinct climatic, construction, and policy contexts within northern China. These data include elemental construction costs, operational energy expenditures, and maintenance profiles. Patterns emerging from the empirical evidence are examined against the theoretical assumptions to refine the model's cost parameters and relationships.

Finally, the study enters a model inference cycle, where both sets of reasoning converge. Here, iterative testing and refinement of the Elemental + Life-Cycle Cost Model ensure that simulation outputs align with observed cost behaviours while remaining theoretically consistent. The abductive process therefore does not seek linear confirmation but rather a progressive alignment between conceptual validity and empirical adequacy.

This cyclical reasoning ensures the model's adaptability to diverse regional and project conditions, a necessity in China's heterogeneous cold-climate zones. It also reinforces theoretical integrity by allowing the model to evolve through successive validation and recalibration stages. Through this abductive logic, the study maintains a balance between explanatory rigour and practical relevance, enabling the development of a cost model that is both grounded and generalisable [21], [22].

## Research Methodology for This Paper

This paper adopts a qualitative analytical approach to justify the methodological framework employed in examining cost-modelling strategies for passive energy-saving buildings in cold-climate regions. The focus is on meta-methodological reflection, articulating how the research design ensures coherence, transparency, and scientific rigour rather than presenting empirical simulations [12], [16]–[18], [21], [22].

Grounded in an interpretivist–pragmatic philosophy, the approach recognises that methodological selection is both an interpretive and practical process shaped by contextual realities and the need for effective outcomes

[11]–[13]. The interpretivist dimension values reflective reasoning and contextual understanding, while the pragmatic orientation emphasises methodological functionality in addressing real-world construction and policy challenges.

A descriptive narrative analysis synthesises three key frameworks, Saunders' Research Onion, Design Science Research (DSR), and Model Verification and Validation (V&V), to structure the methodological justification. The Research Onion provides philosophical and procedural alignment; DSR establishes the iterative process of model creation and evaluation; and V&V ensures technical accuracy and reliability.

## Research Strategy

The Design Science Research (DSR) cycle adopted consists of six stages [23]:

1. Problem identification: Recognising fragmented cost accounting in China's building sector.
2. Objective definition: Integrating Elemental Cost Analysis (ECA) and Life-Cycle Costing (LCC) into a unified decision-support tool.
3. Design and development: Defining variables, cost elements, and calculation routines.
4. Demonstration: Applying the prototype model to case studies in Harbin, Xi'an, and Chengde.
5. Evaluation: Conducting verification, validation, and sensitivity testing.
6. Communication: Disseminating methodological and policy implications.

This DSR cycle ensures a systematic and iterative structure, aligning theoretical reasoning with practical validation. Alternative frameworks, such as PRISMA, were evaluated but deemed unsuitable, as the study focuses on model development and validation rather than literature synthesis. DSR and V&V together provide the flexibility and traceability necessary for quantitative model-based inquiry in construction economics [16]–[18], [21]–[23].

## Comparative Case Study and Simulation modelling strategies

The study integrates comparative case study and simulation modelling strategies. The case studies, Harbin, Xi'an, and Chengde, represent diverse cold-region typologies and provide actual cost and operational data. Simulation extends these data to Zhangjiakou, testing the transferability of passive design cost advantages. The strategy enables triangulation: case studies ground the model empirically, while simulations generalise its applicability.

The justification follows a document-based analytical pathway, reviewing established methodological literature and cost-modelling practices to align each layer, from philosophy to validation technique, with the study's objective: developing a verifiable and transferable cost model for passive design strategies.

In essence, the research method for this paper functions as a meta-methodological justification, integrating interpretivist–pragmatic philosophy, narrative analysis, and artefact-based validation frameworks to ensure methodological integrity and replicability for future research in sustainable passive-design building construction cost modelling.

## Time Horizon

This study adopts a hybrid time horizon, combining cross-sectional data collection with longitudinal cost projection. Baseline construction and energy data are collected at a single point in time but are projected over a forty-year life cycle, corresponding to the minimum statutory lifespan of China residential property rights. This approach captures both the immediacy of construction-phase investments and the long-term economic implications of building operation and maintenance.

The total life-cycle cost (LCC) is estimated using the following expression:

$$LCC = C_i + \sum_{t=1}^{40} \frac{(C_{om,t} + C_{rep,t})}{(1+r)^t}$$

1. LCC : Life-Cycle Costing
2.  $C_i$  : Initial Investment Cost
3.  $C_{om,t}$  : Operations and maintenance costs in year  $t$
4.  $C_{rep,t}$  : Replacement costs in year  $t$
5.  $r$  : Discount rate
6.  $t$  : Time in years, from 1 to 40
7.  $\sum$  : The summation symbol, which indicates the sum of the present value of all future costs over the 40-year period.

This temporal framework integrates short-term capital expenditure (CAPEX) with long-term operational expenditure (OPEX), enabling a holistic evaluation of cost efficiency over the building's service life.

By simulating the cumulative effects of inflation, depreciation, and discounting, the model reflects the real economic performance of passive versus active design buildings building strategies within cold-climate contexts.

### Elemental Cost Analysis (Eca)

Elemental Cost Analysis (ECA) forms the methodological core of this research, providing a structured mechanism to decompose, quantify, and compare construction cost components between passive and active buildings. By translating building functions into discrete cost elements, ECA links design strategy directly to financial outcomes and serves as the foundation for life-cycle cost integration.

### Analytical Rationale

Conventional cost estimation tends to aggregate expenditures, obscuring how specific design decisions influence cost distribution. ECA addresses this by disaggregating total construction cost into functionally homogeneous elements, enabling analysis of how passive design interventions shift expenditure patterns. The approach follows Ashworth and Perera (2015) and the China GB 50500-2013 Standard for Bill of Quantities, ensuring compatibility with both international and domestic practices. Within this framework, ECA quantifies all construction and installation engineering costs (CAPEX), the initial component of the broader life-cycle cost model.

### Element Classification and Yardsticks

Each case study building is decomposed into standard elemental groups, as shown below.

Major Group	Example Sub-Elements	Yardstick	Design Influence
Substructure	Foundations, basement works	RMB/m <sup>2</sup>	Design-neutral
Superstructure	Columns, beams, slabs	RMB/m <sup>2</sup>	Design-neutral
Envelope	Wall & roof insulation, glazing, airtightness	RMB/m <sup>2</sup>	Passive enhancement
Finishes	Flooring, wall and ceiling finishes	RMB/m <sup>2</sup>	Neutral
Services (M&E)	HVAC, ventilation, lighting, renewable systems	RMB/item or RMB/kW	Active dominance
External Works	Landscaping, paving, external lighting	RMB/m <sup>2</sup>	Neutral

Unit rates (yardsticks) are obtained from consultant databases and feasibility estimates, normalised to 2024 price levels using regional Tender Price Indices. This ensures comparability across different project and regional contexts.

## Element Ratios and Benchmarking

The relative cost weight of each element  $i$  is expressed as:

$$E_i = \frac{C_i}{\sum_{j=1}^n C_j}$$

Where  $C_i$  = cost of element  $i$ , and  $n$  = total number of elements.

The ratio  $E_i$  reflects the proportion of each element within total construction cost, enabling direct comparison between passive and active designs. A higher  $E_i$  for the envelope in passive schemes indicates greater investment in insulation and glazing, while a lower  $E_i$  for services reflects downsized mechanical systems.

## Integration with Life Cycle Costing (LCC)

ECA results provide the **construction cost component** within the overall life-cycle cost model, expressed as:

$$LCC_{total} = \sum_{i=1}^n E_i + C_{O\&M}$$

where  $\sum E_i$  represents initial construction cost and  $C_{O\&M}$  denotes discounted operational and maintenance expenditure. This integration clarifies how up-front capital investments influence total life-cycle economy, offering a transparent linkage between design decisions and long-term financial outcomes.

## Comparative Elemental Profiles

The comparative analysis of elemental cost distributions reveals three dominant cost-behaviour patterns that define the economic dynamics between conventional, passive, and smart-integrated housing designs. These patterns not only describe how cost is allocated across building elements but also expose the underlying trade-offs between upfront investment and lifecycle efficiency.

**Front-loaded envelope investment** – Higher costs in insulation and glazing yield long-term reductions in heating demand.

The first pattern concerns a front-loaded investment in the building envelope, specifically, higher spending on insulation materials, high-performance glazing, airtight façade systems, and external shading devices. While these elements elevate the initial capital cost, they function as cost-mitigating assets over the building's lifecycle. Enhanced thermal performance reduces heat transfer, thereby lowering the demand on mechanical cooling and heating systems. This shift from operational to capital expenditure represents a strategic redistribution of costs: developers and designers allocate more budget to passive design measures that deliver long-term energy savings and improved indoor environmental quality. The data thus affirm that early-stage investment in the envelope is a predictive indicator of energy efficiency and cost resilience.

**Reduced mechanical-service costs** – Smaller HVAC systems and simplified controls decrease both capital and maintenance expenditures.



The second pattern highlights the inverse cost relationship between passive-envelope enhancement and mechanical-service expenditures. As the building envelope becomes more thermally efficient, the demand for large-scale HVAC systems and complex control mechanisms diminishes. The result is smaller plant sizes, simplified ductwork, and reduced system redundancy, collectively lowering both the capital and maintenance costs associated with mechanical services. This pattern underscores a synergistic cost behaviour, whereby passive design optimisation directly offsets mechanical dependency, leading to a net reduction in lifecycle expenditure. From a modelling perspective, this relationship forms an essential input for elasticity calibration within the elemental cost model, showing how one element's improvement yields compensatory savings in another.

**Stable neutral elements** – Substructure, structure, and finishes exhibit minimal cost variation across design types.

The third pattern pertains to elements that demonstrate cost neutrality across all design typologies. Substructure, superstructure, and internal finishes display minimal variance in cost per square metre, primarily because these components are governed by structural integrity and compliance requirements rather than design-intent innovation. Their costs remain relatively stable regardless of whether the building adopts passive, or active design features. This stability provides a baseline reference for normalising cost comparison, ensuring that the observed differences in overall expenditure genuinely stem from Passive versus active design buildings design buildings interventions rather than from core construction fundamentals.

Together, these three profiles articulate a quantifiable cost–performance continuum between passive and active strategies. They confirm that Passive versus active design buildings design buildings cost efficiency arises not from isolated technological upgrades but from systemic equilibrium allocating resources toward high-impact envelope features while achieving compensatory reductions in mechanical systems. This empirical insight provides the foundation for model sensitivity testing and calibration.

### **Sensitivity and Calibration**

The subsequent sensitivity and calibration phase strengthens the model's robustness, adaptability, and predictive reliability across diverse contexts. Each elemental cost input, spanning substructure, superstructure, envelope, services, and finishes, is tested through present and future net value adjustments, incorporating an assumed 6 per cent annual inflation rate to simulate material-price volatility and labour-productivity fluctuations. This dual-timeframe evaluation captures the temporal elasticity of cost behaviour, identifying high-sensitivity components (passive and active design features) versus low-sensitivity components (such as structural concrete and brickwork).

Following sensitivity assessment, regional calibration is conducted to harmonise elemental ratios across the reference cities of Harbin, Xi'an, and Chengde before extending the model to Zhangjiakou. This step standardises cost differentials arising from climatic variation, construction practices, material supply, and labour conditions. For example, insulation and heating costs receive heavier weighting in colder northern regions, while structural elements remain relatively constant.

Cross-referencing these calibrated cost indices achieves internal consistency within the dataset and external validity beyond the sample region. The process verifies that the elemental cost model remains stable, scalable, and contextually transferrable, capable of predicting passive versus active design buildings design building under differing climatic and economic conditions. In doing so, it substantiates the model's credibility as both a validation mechanism and a decision-support instrument for future Passive versus active design buildings design buildings cost simulations and policy applications.

### **Analytical Output**

The Elemental Cost Analysis (ECA) framework yields three interrelated analytical outputs that underpin the quantitative comparison of passive and active building design typologies in cold-region environments. These outputs consolidate cost data, performance metrics, and calibration parameters into a cohesive structure capable of informing both project-level and policy-level decision-making [24]–[26].

First, the ECA establishes a standardised Elemental Cost Breakdown Structure (ECBS) specifically adapted for cold-climate construction. The ECBS organises substructure, superstructure, envelope, services, and finishes into a hierarchical taxonomy that aligns with the elemental classification principles of the RICS (2020) and SMM 2nd Edition frameworks. By disaggregating total building cost into functional elements, it facilitates cross-comparative benchmarking between projects of varying design intensity and construction technology. The standardisation ensures data interoperability across regional datasets, reducing the stochastic variance introduced by differing measurement conventions and enhancing the replicability of cost analytics across case studies.

Second, the framework quantifies cost differentials between passive and active design elements, expressing them through normalised ratios and differential indices that capture the redistribution of capital and operational expenditure. Passive envelope enhancements, such as high-performance glazing, multi-layer insulation, and thermal-bridge mitigation, exhibit higher initial investment but produce proportionate reductions in mechanical-service capacity, maintenance frequency, and energy-consumption profiles. These quantified relationships confirm the economic elasticity between design categories and reveal the marginal cost-performance efficiency ( $\Delta C/\Delta E$ ) inherent in passive systems. In essence, the ECA converts qualitative design intentions into a numerically verifiable trade-off matrix, providing empirical grounding for cost-performance optimisation models.

Third, the ECA produces a validated and regionally calibrated dataset suitable for integration into life-cycle cost (LCC) simulations and dynamic sensitivity analyses. Each elemental input undergoes temporal adjustment via present- and future-value factors incorporating an assumed 6 % inflation rate, capturing potential fluctuations in material pricing and labour productivity. Regional calibration, applied across Harbin, Xi'an, and Chengde before extrapolation to Zhangjiakou, normalises climatic and economic variability, achieving both internal consistency within the dataset and external validity for model generalisation. The resulting database functions as a robust empirical substrate for subsequent LCC modelling, scenario testing, and policy simulation.

Collectively, these outputs establish the ECA as the analytical nucleus of the study, operationalising the interface between construction-phase economics and sustainability assessment. By quantifying the interdependence of elemental costs, performance outcomes, and regional factors, the model supports evidence-based decision-making for cost-optimised, energy-efficient building development, advancing the methodological bridge between traditional cost modelling and sustainability-driven design economics.

## Research Techniques and Data Analysis

### Data Collection

Two complementary data streams underpin the analysis:

- Secondary evidence. Feasibility reports and investment estimates from ongoing passive-design projects in Harbin, Xi'an, and Chengde, consolidated into a standardised ECBS to ensure cross-project comparability.
- Primary validation. Expert questionnaires and semi-structured interviews with cost engineers and policy stakeholders to confirm element selection, yardsticks, and price assumptions; interview notes were thematically coded to resolve discrepancies and calibrate element ratios.

### Life-Cycle Cost (LCC) Simulation

Operational and maintenance (O&M) costs are extrapolated from year-one expenditure using escalation  $g$  and discount  $r$ :

$$C_{om} = \sum_{t=1}^{40} \frac{C_{om,1}(1+g)^{t-1}}{(1+r)^t}$$

Sensitivity ranges:  $r = 3\text{--}7\%$ ,  $g = 1\text{--}3\%$ . Integration of ECA and O&M data generates total 40 years of LCC values for both design scenarios.

## Verification and Validation (V&V)

Verification and validation procedures were implemented to ensure the reliability, transparency, and computational soundness of the Elemental + Life-Cycle Cost (ECA + LCC) Model. Verification focused on testing the mathematical accuracy and software logic of the model. All formulae, discounting operations, and indexation routines were validated through controlled test runs, while aggregated elemental costs were cross-checked against source feasibility estimates to confirm internal consistency.

Validation assessed the model's empirical accuracy by comparing simulated outputs with realised cost data from the reference projects in Harbin, Xi'an, and Chengde. Model fit was evaluated using the Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE), expressed both in RMB/m<sup>2</sup> and as percentages of mean values. Deviations exceeding  $\pm 10$  per cent prompted targeted recalibration of the corresponding elements to restore precision [27]–[29].

Sensitivity testing further examined the model's robustness under variable assumptions, including discount rate ( $r$ ), escalation rate ( $g$ ), energy-price trends, and climate severity (heating degree-days). These iterative tests verified that cost–performance relationships remained stable across plausible parameter ranges. Collectively, the V&V procedures replace PRISMA's document-based rigour with quantitative transparency and reproducibility suitable for model-driven construction-economics research.

## Model Application and Comparative Simulation

Upon completion of the verification and validation phases, the calibrated model was applied to Zhangjiakou, a key cold-climate city targeted for passive-building development. Local construction indices, labour coefficients, and climatic degree-days were integrated to adjust cost parameters derived from the comparative regions. The simulation generated a comprehensive output set comprising:

1. initial elemental investment costs (ECA),
2. forty-year discounted operational and maintenance (O&M) costs, and
3. total life-cycle cost (LCC) differentials between passive and active building scenarios.

These outputs enabled identification of the break-even period and calculation of marginal cost–performance efficiency ( $\Delta C / \Delta E$ ) associated with passive-design interventions. Cross-regional benchmarking confirmed a pattern of cost–performance convergence, illustrating where passive design achieves cost parity or long-term economic advantage over conventional active systems. The comparative simulation thus provides practical evidence to guide municipal investment prioritisation, design-standard development, and low-carbon policy formulation within China's cold-climate construction sector.

## Reliability, Validity, And Ethics

Reliability was achieved through the use of standardised data templates, reproducible formulae, and version-controlled computation files, ensuring traceability and consistency throughout all modelling stages [30]. Construct validity was strengthened via triangulation among case-study datasets, expert judgement, and simulation outputs, while face validity was established through consultation with practitioners involved in passive-building cost planning. External validity was confirmed through regional replication across Harbin, Xi'an, and Chengde before application to Zhangjiakou, demonstrating the model's transferability across differing climatic and economic contexts.

Ethical compliance was upheld by obtaining informed consent from expert participants and ensuring anonymisation and secure storage of all proprietary cost data. The dataset is used exclusively for academic purposes, safeguarding confidentiality while promoting transparency and methodological replicability. Together, these measures reinforce the research's integrity and support its contribution to evidence-based cost-modelling practice.

## Limitations

The study's scope is constrained by its reliance on a limited set of comparative case studies from Harbin, Xi'an, and Chengde. While these regions represent northern China's cold-climate contexts, they do not capture the



broader diversity of construction practices, climatic conditions, and economic environments across the country. Consequently, the model's generalisability to other cold-climate regions or to different building typologies may be limited. Data completeness and parameter sensitivity remain key limitations. LCC outputs depend on assumptions for discount rate, energy escalation, and maintenance intervals, which may vary over time. Regional cost indices also fluctuate. Nonetheless, the model's probabilistic structure allows recalibration as new datasets become available, ensuring continuing relevance.

### Future Recommendation

Although the model achieves acceptable accuracy across the selected case regions, further validation using a wider range of cold-climate contexts in China would strengthen external generalisability. Future research should incorporate a broader range of empirical case studies from additional cold-climate regions across China. Expanding the dataset would enable further validation and refinement of the model to reflect regional variation in construction methods, climatic severity, and cost behaviour. Additionally, simplifying the model for practical use, such as through user-friendly tools or decision-support interfaces, would improve accessibility for practitioners and policymakers who may not have expertise in construction economics. Presenting results in clear and interpretable formats would further enhance the model's usability and practical value.

## CONCLUSION

This study formulates a comprehensive research methodology for developing and validating an Elemental + Life-Cycle Cost Model suited to passive energy-saving buildings in China's cold climate regions. Rooted in pragmatic-post-positivist philosophy and guided by abductive reasoning, the methodology integrates quantitative simulation with qualitative validation under the Design Science framework. Replacing PRISMA with Model Verification & Validation (V&V) and Design Science Research (DSR) ensures methodological rigour for artefact-based inquiry. The inclusion of Elemental Cost Analysis (ECA) provides the essential analytical granularity linking design decisions to financial outcomes, while Life-Cycle Costing (LCC) extends those insights over time. Collectively, these methods deliver a transparent, verifiable, and transferable tool for assessing the economic viability of passive construction in northern China. Beyond its academic contribution, the framework offers practical policy value: it equips planners and developers with a structured basis for low-carbon investment decisions and strengthens the cost-performance evidence required to mainstream passive design in China's sustainable building agenda.

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