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Intelligent Computation and Analysis of Mechanical Behaviour in Piezoelectric Metamaterials Based on Physics-Informed Neural Networks

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Abstract: Piezoelectric metamaterials, serving as critical functional media in high-end equipment, face significant design challenges due to the mesh bottlenecks of traditional finite element methods and the interpretability shortcomings of purely data-driven models. Physical Information Neural Networks (PINNs) establish a robust scientific machine learning paradigm by embedding physical equations, offering an innovative solution to these predicaments. This paper systematically reviews recent advancements of PINNs in piezoelectric metamaterial analysis and design: drawing upon multiscale modelling theory, it elucidates PINNs' mesh-free advantages in handling high-dimensional parameters and their exceptional capability in solving small-sample inverse problems; subsequently, it explores their application paradigms in constructing high-fidelity forward surrogate models and accelerating efficient topology optimisation. Finally, this paper summarises key computational challenges in multi-physics coupling scenarios and outlines potential pathways towards achieving high-fidelity intelligent design, aiming to bridge the existing gap between theoretical modelling and engineering practice in piezoelectric metamaterials.

Keywords: Piezoelectric Metamaterials; Physical Information Neural Network; Multi-scale Modeling; Multiphysics Coupling; Topology Optimization

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1. Introduction

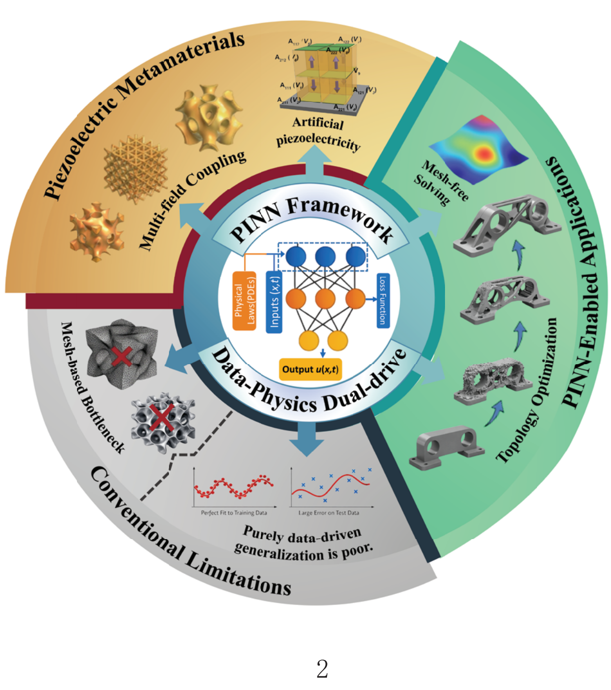
Piezoelectric metamaterials achieve artificial customisation of electromechanical coupling effects by overcoming the physical limitations of natural materials through sophisticated topological design and periodic arrangement of microscopic unit cells [1]. This novel intelligent medium exhibits exceptional properties including all non-zero piezoelectric coefficients, broad bandgap tunability, and negative Poisson's ratio [2-4], holding significant engineering value in fields such as aerospace vibration suppression, self-powered MEMS sensing, and structural health monitoring[5]. As engineering demands evolve towards extreme and precision requirements, the design specifications for piezoelectric metamaterials have expanded from simple mechanical load-bearing to complex "force-electricity-heat" multi-field coupling and anisotropic customisation. This significantly increases the complexity of microstructure topology optimisation design.

For a considerable period, mesh-based numerical methods such as the finite element method (FEM) and boundary element method (BEM) have been the mainstream tools for analysing piezoelectric structures. Whilst these methods demonstrate maturity in conventional problems, they face significant challenges when handling piezoelectric metamaterials due to the high-dimensional parameter space and strong multi-field coupling calculations. On one hand, the piezoelectric effect involves strong bidirectional coupling between stress and electric fields. The disparity in magnitude between physical fields readily leads to deterioration in the condition number of the stiffness matrix, thereby compromising computational convergence. On the other hand, the introduction of intricate microstructures—such as triple-periodic minimal surfaces (TPMS) or fractal structures [6]—to pursue extreme performance renders high-fidelity meshing a computational bottleneck. Particularly in multiscale analysis and topology optimisation scenarios[7,8], computational load increases exponentially with degrees of freedom, rendering traditional numerical methods inadequate for real-time simulation and rapid iterative design requirements.

In recent years, deep learning techniques have offered novel avenues for alleviating the aforementioned computational bottlenecks[9]. Data-driven surrogate models have demonstrated application potential in accelerating structural response prediction and aiding additive manufacturing(AM) [10,11]. However, existing purely data-driven models, such as Convolutional Neural Networks (CNNs), typically lack physical interpretability and do not explicitly incorporate physical governing equations as constraints. This results in models being highly dependent on high-quality labelled data. In piezoelectric metamaterial research, acquiring high-fidelity ground truth datasets covering multi-field coupling and complex geometries is costly and challenging. Furthermore, the absence of embedded physical constraints means predictions from purely data-driven models cannot guarantee strict adherence to energy conservation or boundary conditions. Consequently, their generalisation performance beyond the training sample domain (out-of-distribution) is limited, hindering direct application in engineering design requiring high reliability.

To address these limitations, Raissi et al. proposed the Physical Information Neural Network (PINN), establishing a scientific machine learning (SciML) framework that integrates physical principles for solving complex partial differential equations (PDEs) [12]. By embedding the residuals of the partial differential equations governing the physical system as a regularisation term within the loss function, PINN achieves high-accuracy solutions for multi-physics problems without mesh generation and relying solely on sparse observational data. This dual ‘data-physics’ driven characteristic confers significant advantages in handling complex boundary conditions of piezoelectric metamaterials, multi-field coupled inverse problems, and parameter identification[13,14], and has been extensively validated for effectively resolving diverse engineering PDE problems[15]. In recent years, topology optimisation methods based on PINN have also seen progressive development and application[16]. This paper aims to provide a systematic review of the latest research advances in PINNs for analysing the mechanical behaviour of piezoelectric metamaterials, multi-physics coupling modelling, and topology-optimised design. The complete framework is illustrated in Fig. 1.

Figure1: Current status of computational studies on piezoelectric metamaterials within the PINN framework



To present the research trajectory of this emerging field with logical clarity, the subsequent sections of this paper are organised as follows: Section 2 elaborates on the physical modelling theory of piezoelectric metamaterials, establishing the necessity of introducing deep learning by analysing the multiscale computational bottlenecks of traditional methods; Section 3 systematically constructs the theoretical framework of PINNs, thoroughly comparing their advantages over finite element methods (FEM) and purely data-driven models; Section 4 focuses on core application strategies and cutting-edge developments of PINN in performance forward prediction and structural inverse design; Section 5 outlines future research directions for PINN.

2. Modelling the Mechanical Behaviour of Piezoelectric Metamaterials

The design and application of piezoelectric metamaterials hinge upon a profound understanding of their complex mechanical behaviour, with the core challenge lying in accurately describing the interaction between multi-physics coupling effects and multi-scale geometric features. This section aims to establish a systematic physical modelling theoretical framework spanning from microscopic mechanisms to macroscopic responses. Building upon the derivation of multi-field coupled governing equations using linear piezoelectric theory and continuum mechanics, alongside the establishment of physical conservation laws, this framework further elaborates on the representative volume element (RVE)-based equivalent medium theory and homogenisation methods. This addresses the unique periodic microstructural characteristics of metamaterials, thereby establishing a theoretical bridge mapping microscopic topological parameters to macroscopic effective material properties. Concurrently, addressing numerical bottlenecks arising from strong multi-physics coupling and complex geometries, this work thoroughly examines critical challenges such as ill-posed stiffness matrices and mesh distortion. This aims to establish a robust theoretical foundation for subsequent efficient analysis and topological optimisation.

2.1 Control Equations for Piezoelectric Dielectrics and Multi-Field Coupling Mechanisms

The macroscopic mechanical response of piezoelectric metamaterials is fundamentally governed by the bidirectional interaction between elastic and electric fields. This intrinsic electromechanical coupling effect manifests as the reciprocal processes of mechanical deformation inducing electrical polarisation (direct piezoelectric effect) and external electric fields exciting mechanical strain (reverse piezoelectric effect), endowing the material with exceptional performance in wave field manipulation and energy conversion. To quantitatively characterise this intricate dynamic physical process, a comprehensive mathematical model must be established within the framework of continuum mechanics and linear piezoelectric theory. Under the assumptions of small deformation and quasi-static electric fields, its physical behaviour is governed by the combined action of geometric equations, constitutive equations, and equilibrium equations. This yields a closed system of partial differential equations describing the mechanical behaviour of piezoelectric media[17].

Consider a piezoelectric continuum occupying spatial region Ù $\subset \mathbb{R}^3$, whose boundary is

$$\partial\Omega = \Gamma_u \cup \Gamma_t = \Gamma_\phi \cup \Gamma_q \tag{1}$$

The displacement and potential are specified at Γ_u, Γ_ϕ, with natural boundary conditions applied at Γ_t, Γ_q.

Based upon the assumptions of a continuous medium, small deformations, and a quasi-static electric field, the geometric kinematics equations establish a consistent relationship between fundamental field variables and their gradient fields. Within the Cartesian coordinate system, for a given mechanical displacement vector u_i and electric potential scalar ϕ, the linear strain tensor ε_{ij} and electric field intensity vector E_i are respectively defined as:

$$\begin{cases} \varepsilon_{ij} = \dfrac{1}{2}(u_{ij} + u_{ji}) \\ E_i = -\phi_{,i} \end{cases} \tag{2}$$

The subscript comma denotes the partial derivative with respect to spatial coordinates. The symmetry of ε_{ij} reflects that rigid-body rotation does not induce strain, while the negative sign of E_i indicates that the electric field direction points from higher to lower potential.

The electromechanical coupling behaviour of piezoelectric materials is derived from the second-order expansion of the thermodynamic potential function. To facilitate the independent treatment of strain and electric field variations, $G(\text{å}, \mathbf{E})$ is selected as the fundamental thermodynamic potential, expressed as:

$$G(\boldsymbol{\mathring{a}},\mathbf{E})=\frac{1}{2}C_{ijkl}\varepsilon_{ij}\varepsilon_{kl}-e_{kij}E_k\varepsilon_{ij}-\frac{1}{2}\kappa_{ij}E_iE_j \tag{3}$$

The respective components correspond to elastic potential energy, electromechanical coupling energy, and dielectric energy. By taking partial derivatives of this potential function with respect to strain and electric field, the thermodynamic conjugates can be obtained:

$$\sigma_{ij}=\frac{\partial G}{\partial\varepsilon_{ij}},\quad D_i=-\frac{\partial G}{\partial E_i} \tag{4}$$

Constitutive equations serve as the link between force fields and electric fields, profoundly revealing the thermodynamic mechanisms of energy conversion within materials. Based on the above expression utilising Gibbs free energy or electric enthalpy density functions, linear equations in stress-charge form can precisely express the dependence of the stress tensor σ_{ij} and electric displacement vector D_i upon the independent variables of strain and electric field:

$$\begin{cases}\sigma_{ij}=C_{ijkl}\varepsilon_{kl}-e_{kij}E_k\\ D_i=e_{ikl}\varepsilon_{kl}+\kappa_{ik}E_k\end{cases} \tag{5}$$

This formulation simultaneously describes both the direct and inverse piezoelectric effects, ensuring the system satisfies energy conservation and the second law of thermodynamics.To systematically derive the control equations, an energy-based variational principle is introduced. For piezoelectric dynamics, the actual trajectory of the system should maximise the following functional:

$$\delta\int_{t_1}^{t_2}(T-\Pi)\mathrm{d}t=0 \tag{6}$$

Here, the system's kinetic energy is defined as:

$$T=\frac{1}{2}\int_{\Omega}\rho\dot{u}_i\dot{u}_i\mathrm{d}\Omega \tag{7}$$

Internal Energy (Electrical-Mechanical Coupling):

$$U=\int_{\Omega}G(\varepsilon_{ij},E_i)\mathrm{d}\Omega \tag{8}$$

External Forces and Electric Potential Energy:

$$W=\int_{\Omega}f_iu_i\mathrm{d}\Omega+\int_{\Gamma_t}\overline{t}_iu_i\mathrm{d}\Gamma+\int_{\Gamma_q}\overline{q}\phi\mathrm{d}\Gamma \tag{9}$$

Total potential energy:

$$\Pi=U-W \tag{10}$$

The internal energy is obtained by integrating the Gibbs free energy density over the entire domain, whilst the external work includes that performed by physical forces, surface forces, and surface charges. This constitutes a complete potential energy functional, providing a unified starting point for subsequent variational derivations.

By applying independent variational formulations to the displacement field and potential field respectively, and incorporating the variational relationship between strain and electric field, the variational representation of the energy functional can be expressed as an integral with respect to δu and $\delta\phi$. Applying Gauss's theorem to the spatial integral terms transfers the first-order derivatives from the variational function to the stress and electric displacement terms, thereby naturally introducing the corresponding boundary terms.

Displacement Variational:

$$\begin{aligned}\delta T&=\int_{\Omega}\rho\dot{u}_i\delta\dot{u}_i\mathrm{d}\Omega\\ \delta U&=\int_{\Omega}\left(\sigma_{ij}\delta\varepsilon_{ij}-D_i\delta E_i\right)\mathrm{d}\Omega\end{aligned} \tag{11}$$

Use:

$$\delta\varepsilon_{ij}=\frac{1}{2}(\delta u_{i,j}+\delta u_{j,i}),\quad \delta E_i=-\delta\phi_{,i} \tag{12}$$

Integration by parts in space (Gauss's theorem).

Stress term:

$$\int_{\Omega}\sigma_{ij}\delta u_{i,j}\mathrm{d}\Omega=-\int_{\Omega}\sigma_{ij,j}\delta u_i\mathrm{d}\Omega+\int_{\Gamma_t}\overline{t}_i\delta u_i\mathrm{d}\Gamma \tag{13}$$

Electrical displacement term:

$$\int_{\Omega} D_i \delta\phi_{,i} \mathrm{d}\Omega = -\int_{\Omega} D_{i,i} \delta\phi \mathrm{d}\Omega + \int_{\Gamma_q} \bar{q} \delta\phi \mathrm{d}\Gamma \tag{14}$$

Ultimately yielding the weak form of the piezoelectric dynamics problem:

$$\begin{aligned} &\int_{\Omega} \rho \ddot{u}_i \delta u_i \mathrm{d}\Omega + \int_{\Omega} \sigma_{ij} \delta\varepsilon_{ij} \mathrm{d}\Omega = \int_{\Omega} f_i \delta u_i \mathrm{d}\Omega + \int_{\Gamma_t} \bar{t}_i \delta u_i \mathrm{d}\Gamma \\ &\int_{\Omega} D_i \delta E_i \mathrm{d}\Omega = \int_{\Gamma_q} \bar{q} \delta\phi \mathrm{d}\Gamma \end{aligned} \tag{15}$$

The ultimate equilibrium state of the system is governed by physical conservation laws. For dynamical problems incorporating inertial effects, the mechanical field must satisfy the law of conservation of momentum (namely Newton's Second Law), whilst the electric field, under the assumption of an insulating medium, must satisfy the law of conservation of charge (namely Gauss's law from Maxwell's equations). Excluding physical forces and internal free charges, the governing equations may be expressed as:

$$\begin{aligned} &\sigma_{ij,j} + f_i = \rho \\ &\ddot{u}_i D_{i,i} = 0 \end{aligned} \tag{16}$$

Here, ρ denotes the material density, while $\ddot{u}_i$ represents the second derivative of displacement with respect to time. The aforementioned governing equations, coupled with the constitutive relationship and supplemented by corresponding mechanical boundary conditions (such as Dirichlet or Neumann boundaries) and electrical boundary conditions, constitute a complete boundary value problem for solving the wave dynamics and vibration characteristics of piezoelectric metamaterials.

In FEM, introduce interpolation:

$$\mathbf{u} \approx \mathbf{N}_u \mathbf{d}, \quad \phi \approx \mathbf{N}_\phi \varphi \tag{17}$$

Obtain a semi-discrete system:

$$\begin{bmatrix} \mathbf{M} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{d}} \\ \ddot{\boldsymbol{\varphi}} \end{bmatrix} + \begin{bmatrix} \mathbf{K}_{uu} & \mathbf{K}_{u\phi} \\ \mathbf{K}_{\phi u} & -\mathbf{K}_{\phi\phi} \end{bmatrix} \begin{bmatrix} \mathbf{d} \\ \varphi \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{q} \end{bmatrix} \tag{18}$$

Where:

$$\mathbf{K}_{u\phi} = \int_{\Omega} \mathbf{B}^T e^T \mathbf{B}_\phi \mathrm{d}\Omega \tag{19}$$

2.2 Equivalent Medium Theory

he macroscopic properties of piezoelectric metamaterials are not solely determined by the intrinsic characteristics of the host material, but are primarily governed by the topological structure and periodic arrangement of their microscopic unit cells. This artificially engineered heterogeneity enables metamaterials to exhibit extraordinary electromechanical coupling properties at the macroscale that are difficult to achieve in natural materials[18-20]. To efficiently analyse extensive array structures at the engineering scale, the theory of equivalent media must be employed, approximating the microscopic non-uniform periodic lattice as a macroscopically homogeneous continuous medium [21]. The following sections introduce this approach through the definition of equivalent mechanical properties and the homogenisation principle.

Equivalent mechanical properties denote a set of averaged constitutive parameters capable of reproducing the physical response of microstructures at the macroscopic scale. For piezoelectric metamaterials, this process is commonly termed "homogenisation". Its theoretical foundation is established within a multiscale analysis framework and has been extensively applied to periodic composite materials[22,23].

The Representative Volume Element (RVE)-based volume averaging method combined with finite element analysis (RVE/FEM) is the most commonly employed homogenisation technique in engineering. It directly solves the unit cell response by applying periodic boundary conditions, offering advantages of intuitiveness and high accuracy[24]. The macroscopic mean stress $\bar{\sigma}ij$, mean strain $\bar{\varepsilon}ij$, mean electric displacement $\bar{D}_i$, and mean electric field $\bar{E}_i$ may be defined by integrating microscopic field quantities over the unit cell volume V:

$$\bar{\sigma}_{ij} = \frac{1}{V} \int_V \sigma_{ij} d\Omega , \quad \bar{\varepsilon}_{ij} = \frac{1}{V} \int_V \varepsilon_{ij} d\Omega \tag{20}$$

By applying periodic boundary conditions (PBCs) at the cell boundaries and solving the boundary value problem, an equivalent constitutive relationship describing the macroscopic behaviour can be obtained:

$$\begin{cases} \bar{\sigma}_{ij} = C_{ijkl}^{\text{eff}} \varepsilon_{kl} - e_{ijk}^{\text{eff}} E_k \\ \bar{D}_i = e_{ikl}^{\text{eff}} \varepsilon_{kl} + \kappa_{ik}^{\text{eff}} E_k \end{cases} \tag{21}$$

Among these, , and denote the equivalent elastic stiffness tensor, equivalent piezoelectric coupling tensor, and equivalent dielectric tensor respectively. These parameters constitute core metrics in metamaterial design—for instance, through microstructural engineering, one may achieve negative equivalent parameters unattainable in nature or significantly enhanced electromechanical coupling coefficients[25].

As computational complexity increases, so too does computational cost. To address this challenge, academia has developed multiple homogenisation strategies. Among these, Asymptotic Homogenisation (AH) offers the most rigorous mathematical foundation based on two-scale asymptotic expansion theory, capable of capturing higher-order correction terms. However, its derivation is cumbersome and struggles with extremely complex topologies[26,27]. In recent years, data-driven approaches have advanced rapidly, giving rise to new paradigms based on PINN and deep homogenisation frameworks. Such approaches achieve mesh-free, rapid prediction by learning mappings from microscopic structures to macroscopic equivalent properties, proving particularly suitable for complex topologies and inverse design [28, 29]. They provide efficient tools for optimising piezoelectric metamaterials and conducting multiphysics coupling analyses.

2.3 Multi-scale Structures and Computational Challenges

Piezoelectric metamaterials achieve customisation of macroscopic electromechanical properties through the periodic arrangement of microscopic topologies. While this cross-scale synergistic characteristic endows the material with extraordinary physical properties, it also poses significant challenges to conventional numerical computations. On the one hand, high-fidelity characterisation of microscopic geometric details leads to an exponential increase in computational degrees of freedom (DoFs) across the entire system. On the other hand, the inherent strong electromechanical coupling readily induces severe numerical ill-conditioning in the stiffness matrix. Consequently, overcoming computational scale explosion and convergence issues while maintaining physical fidelity has become the core bottleneck in current analysis and design.

2.3.1 Unusual physical properties arising from periodic structures

Periodic arrangements represent more than mere geometric repetitions of microscopic units. Wave dynamics analysis grounded in the Bloch-Floquet theorem demonstrates that such ordered structures can induce a series of singular dynamic responses. Firstly, these structures can form acoustic bandgaps, wherein elastic wave propagation is prohibited within specific frequency ranges. This property holds critical significance for broadband active vibration suppression in aerospace structures [30]. Secondly, through topological designs such as re-entrant or rotating rigid bodies, metamaterials exhibit negative Poisson's ratio effects, manifesting lateral expansion under tensile stress [31]. Research confirms that this counterintuitive kinematic behaviour significantly alters internal stress distributions, amplifying local effective strain on micro-piezoelectric elements by several orders of magnitud, thereby substantially enhancing macroscopic electromechanical conversion efficiency and energy harvesting power [32].

However, these complex microstructures are often accompanied by the phenomenon of local field enhancement, where the stress or electric field is highly concentrated at the interfaces of multiphase materials, forming "hotspots". Although previous studies have effectively alleviated the computational bottleneck and accuracy contradiction in piezoelectric fracture simulation by traditional finite elements through the adaptive isogeometric analysis framework based on PHT splines and other optimization methods[33], which improved the local mesh refinement technique (Fig2(a)), they are still fundamentally limited by the grid-based discretization solution path. When dealing with tasks such as real-time prediction, reverse design, or parameter inversion, they still face high costs of stiffness matrix reassembly and repetitive iterations. Such drastic gradient changes require numerical methods to have extremely high spatial resolution; otherwise, it is difficult to capture the true physical response.

2.3.2 Discretisation Bottlenecks in Complex Microstructure Topologies

To achieve high specific strength and multifunctional integrated performance, the unit cell configurations of modern piezoelectric metamaterials have evolved from simple truss structures to highly complex biomimetic continuous topologies. Typical examples include Triple-Period Minimal Surfaces (TPMS) and Hierarchical/Fractal Structures [34]. Such structures are often described by implicit level-set functions, featuring smooth, continuous surfaces and excellent topological properties. For these complex configurations, Wang et al. proposed a hybrid optimization framework integrating machine learning (ML) and evolutionary algorithms (EA) [35], demonstrating outstanding performance in the inverse optimization of biomimetic stress-strain curves for fractal metamaterials (Fig. 2(b)).

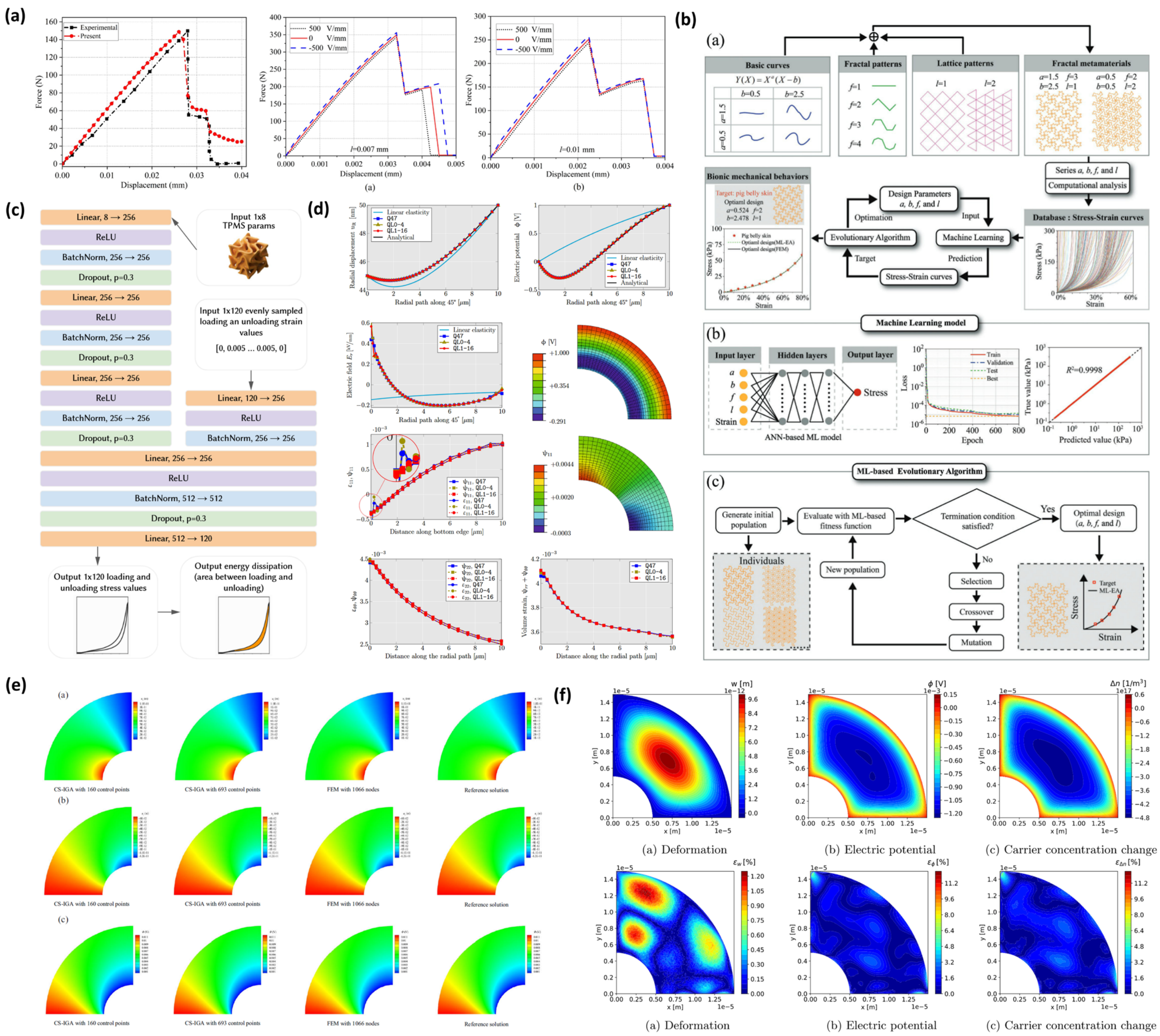
Despite the excellent mechanical potential of the aforementioned geometric design, its complex continuous topological features pose significant challenges for discrete numerical simulations. When employing traditional finite FEM, capturing surface curvature features with precision necessitates the generation of extremely dense unstructured tetrahedral meshes. Upon scaling up single cells to macroscopic arrays, mesh sizes grow exponentially into the tens of millions, frequently triggering out-of-memory errors [36] and resulting in extremely costly simulations and convergence issues (Fig. 2(c)). More critically, mesh distortion at complex surfaces readily induces singular Jacobian matrices and computational divergence, rendering high-fidelity topology optimization based on meshes impractical for engineering applications [37].

2.3.3 Multiphysics Strongly Coupled Stiffness Pathology

The analysis of mechanical behaviour in piezoelectric metamaterials confronts severe numerical stability challenges arising from strong multiphysics coupling. Unlike purely elastic problems involving single fields, piezoelectric analysis necessitates the coupled solution of momentum conservation equations and Maxwell's equations within a unified framework. However, these two physical fields exhibit a vast inherent disparity in energy and parameter scales: the elastic stiffness matrix typically reaches magnitudes of $10^9 \sim 10^{11}$ Pa, whereas the dielectric constant is merely $10^{-9} \sim 10^{-11}$ F/m. This parameter difference spanning nearly 20 orders of magnitude directly results in the global system stiffness matrix, after discretisation, exhibiting extreme ill-conditioning, where the matrix condition number approaches infinity [38]. In traditional finite element method (FEM) analysis, such extremely poor condition numbers not only significantly amplify truncation errors in floating-point operations, causing conventional linear solvers to stagnate, but also induce severe volume locking or shear locking phenomena [39], necessitating supplementary optimization strategies (Fig. 2(d)).

Addressing this long-standing challenge, subsequent research has converged on a dual-track approach combining algorithmic reconstruction with data-driven methods. On one hand, discrete techniques based on smoothing or higher-order geometry have been shown to inherently suppress numerical locking caused by strong coupling at the mesh topology level (as illustrated in Fig. 2(e)), significantly reducing reliance on complex preprocessing techniques [40, 41]. On the other hand, with the emergence of PINNs, researchers began employing neural networks to solve piezoelectric partial differential equations. However, they also discovered that the aforementioned multiscale coefficient variations could lead to severe gradient singularities during optimization. To address this, recent work introduced a dimensionless normalization and adaptive loss weighting strategy [42], successfully achieving high-accuracy solutions for high-contrast multiphysics problems (Fig. 2(f)) without explicitly assembling massive stiffness matrices.

Figure 2: Addressing multiscale structures and numerical computation challenges. (a) An adaptive isogeometric analysis framework for PHT splines, alongside other optimisation methods, effectively mitigates computational bottlenecks and accuracy trade-offs in traditional finite element simulations of piezoelectric fracture by enhancing local mesh refinement techniques [33]. (b) A hybrid optimisation framework combining ML and EA demonstrates superior performance compared to traditional finite elements in inverse optimisation of biomimetic stress-strain curves for fractal metamaterials[35]. (c) A single multilayer perceptron model architecture within deep ensemble models resolves the extremely costly simulations and non-convergence issues associated with self-contact and large deformations [36]. (d) Experiment-driven Bayesian optimisation circumvents simulation bottlenecks for large deformations in complex structures, rigorously validated through physical experiments, analytical solution comparisons, or high-fidelity simulation data matching[39]. (e) Capability to resolve local accuracy loss issues caused by 'multiphysics strongly coupled ill-posed problems' through isogeometric analysis and smoothed finite elements[40]. (f) PINN resolves numerically ill-posed challenges arising from multi-field coupling, achieving high-precision solutions[42].



3. Overview and Comparative Analysis of the PINN Method

3.1 An Overview of the Fundamental Theory of PINN

With the introduction of the Physical-based Neural Network (PINN) by Raissi, Karniadakis et al.[12,14], a mesh-free computational framework integrating physical mechanisms was established by explicitly embedding physical governing equations into the deep learning optimization process (Fig. 3(c)). Unlike traditional purely data-driven approaches, PINNs directly map spatial and temporal coordinates to physical field variables. They utilise automatic differentiation (AD) to precisely compute derivative information, constructing loss functions with PDE residuals, boundary conditions, and initial conditions as regularisation constraints. This mechanism approximates continuous physical fields without requiring mesh discretisation, thereby supporting both forward multi-physics simulation and inverse parameter identification based on sparse observations within a unified mathematical framework.

Within the PINN framework, deep neural networks (DNNs) serve as generalised function approximators for the physical field under investigation. For spatio-temporally dependent physical problems, the network constructs a nonlinear mapping $\mathcal{N}: \mathrm{x} \mapsto \mathrm{u}$ from spatio-temporal coordinates $\mathrm{x} = (x, y, z, t)$ to physical state variables (such as displacement u or potential ϕ).

Unlike early universal approximation theorems, modern deep learning theory focuses more on the expressive advantages brought by “depth.” Yarotsky’s[43] error bound theory demonstrates that for physical functions with sufficient smoothness, deep networks can achieve equivalent approximation accuracy with far fewer parameters than shallow networks, explaining their efficiency in handling high-dimensional physical problems. Furthermore, to overcome the limitation of traditional piecewise linear activation functions like Rectified Linear Unit (ReLU)—whose second derivatives are zero, rendering them unsuitable for describing physical processes involving higher-order derivatives—PINNs typically employ smooth nonlinear activation functions such as the hyperbolic tangent function[44]. This not only ensures the continuity of physical residuals but also effectively mitigates spectral bias in high-frequency problems, providing a mathematical foundation for simulating complex force-electric coupling fields.

Although DNNs possess formidable approximation capabilities, the network itself remains physically agnostic. At this juncture, it becomes necessary to introduce PDE that comply with physical laws to physically drive the DNN, thereby constraining and guiding its behaviour. For general nonlinear PDE systems:

$$\mathcal{F}(u) = \frac{\partial u}{\partial t} + \mathcal{N}[u] - f(\mathrm{x}, t) = 0 \tag{22}$$

The key technology distinguishing it from traditional FEM lies in AD. PINN abandons mesh-based finite difference approximations. Instead, it utilises computational graphs and the chain rule to compute arbitrary-order partial derivatives of network outputs with respect to input coordinates directly at machine precision. This property confers a genuinely mesh-free nature upon PINN: it requires no laborious mesh partitioning for complex geometries such as TPMS, instead establishing physical constraints through random sampling of configuration points within the computational domain. Shin et al. [37] theoretically demonstrated that under certain conditions, this sequence based on continuous functions converges to the strong solutions of linear elliptic and parabolic PDEs, establishing the theoretical completeness of PINN as a rigorous numerical solver. The precise and efficient computational results obtained through the AD method lay the groundwork for subsequent correction of DNNs driven by loss functions.

The training process of PINN involves solving a multi-objective optimisation problem, where the total loss function is typically composed of a data matching term, a boundary condition term, and a weighted physical residual term:

$$\mathcal{L}(\theta) = w_{\mathrm{data}}\mathcal{L}_{\mathrm{data}} + w_{\mathrm{PDE}}\mathcal{L}_{\mathrm{PDE}} + w_{\mathrm{BC}}\mathcal{L}_{\mathrm{BC}} \tag{23}$$

Where, $\mathcal{L}_{data}$: Data matching term, used to assimilate sparse experimental observations or high-fidelity simulation solutions, formulated as mean squared error. $\mathcal{L}_{BC}$: Boundary/initial condition term, enforcing the network to satisfy Dirichlet or Neumann boundary constraints (soft constraints). $\mathcal{L}_{PDE}$: Computed physical residual term, which constitutes the core of PINN. The network continuously updates its parameters via backpropagation algorithms until the physical residual approaches zero, thereby ensuring the DNN's output satisfies the physical constraints of the PDE.

3.2 Comparison of PINN with Traditional Methods

This section aims to dissect the fundamental differences in physical representation logic between PINNs and traditional FEM alongside purely data-driven models (such as CNNs). FEM relies on geometric discretisation, with accuracy constrained by mesh quality; purely data-driven models focus on statistical mapping, exhibiting strong data dependency and lacking physical induction bias. In contrast, PINN achieves a profound integration of physical mechanisms and data observations by embedding governing equations within the loss function. The following sections elucidate PINN's unique computational advantages across three dimensions: geometric representation scalability, forward-inverse problem solving paradigms, and physical consistency. These enable PINN to overcome mesh distortion, break through the small-sample bottleneck, and achieve multi-field coupled parameter inversion.

3.2.1 Scalability of Geometric Discretisation Constraints and High-Dimensional Computation

As a standard tool in structural mechanics, the accuracy of FEM solutions is strictly constrained by the quality of mesh discretisation. While it performs reliably in two-dimensional plane problems, FEM faces severe mesh generation bottlenecks when handling complex three-dimensional topologies. Firstly, computational costs become disproportionate: to approximate smooth surfaces, the reconstruction (re-meshing) of unstructured meshes frequently consumes over 70% of the entire simulation cycle. Secondly, numerical stability risks arise, as intricate geometric features readily induce mesh distortion, subsequently triggering singular Jacobian matrices and computational divergence.

Traditional CNN models are constrained by voxelization strategies, facing computational barriers and geometric scaling effects. To overcome this bottleneck, Ren et al. [10] and Sharma et al. [11] shifted toward more efficient low-dimensional feature-driven approaches. Utilizing explicit parameter mapping (PSMNN) and graph-based representations respectively, they successfully achieved high-fidelity reconstruction of complex metamaterials within low-dimensional spaces (Fig. 3(a,b)). However, these approaches remain fundamentally data-driven. While they address the efficiency issues of geometric characterization, model training still heavily relies on massive finite element simulation labels, failing to overcome the fundamental constraint of high data acquisition costs.

By contrast, the breakthrough of PINN lies in its adoption of a continuous sampling mechanism based on coordinate points (x, y, z, t). As a mesh-free approach, the network size of PINN scales linearly with input dimensions rather than exponentially. This inherently enables PINN to circumvent geometric errors and cubic computational bottlenecks associated with mesh partitioning when handling three-dimensional solid piezoelectric metamaterials. Consequently, it achieves infinite-resolution approximations of physical fields across continuous domains at comparatively low computational expense. This characteristic naturally accommodates the implicit representation of complex structures such as TPMS[45], whilst loss function weighting facilitates multi-physics field balancing [46].

3.2.2 The Paradigm Shift in Solving Positive and Negative Problems

In the engineering applications of metamaterial design, material parameter identification and topology optimisation are often more critical than forward prediction. In this task, the solution paradigms of the three approaches exhibit fundamental differences.

Traditional FEM solutions to inverse problems inherently constitute a “black-box” optimisation process. Due to the inability to directly compute derivatives, an outer optimisation loop is typically required, involving repeated invocations of the forward solver and updates to the geometric mesh. Each parameter iteration necessitates a complete finite element simulation, and this high-frequency re-analysis leads to an exponential explosion in computational cost during multi-parameter space searches.

Although CNNs exhibit extremely rapid inference speeds, they face severe data dependency and lack of generalisation capability in inverse problems: training a high-precision inversion network requires vast amounts of ‘geometry-response’ labelled data, whose generation often still relies on costly FEM simulations due to offline data generation bottlenecks. Simultaneously, purely data-driven models merely provide statistical fits to physical laws, lacking physical constraints. Should the parameters to be inverted fall outside the distribution range of the training set, the model’s predictive capability deteriorates sharply, with no guarantee that results satisfy fundamental physical conservation laws.

PINN proposes a transformative solution paradigm: within this framework, unknown material or geometric parameters may be treated as trainable variables, updated concurrently with network weights during the same backpropagation iteration. This enables PINN to simultaneously predict forward physical fields and identify reverse constitutive parameters at the cost of a single training run. This physically driven self-supervised mechanism not only eliminates reliance on external labelled data but also significantly accelerates the iterative cycle of metamaterial design. Table 1 provides a comparative analysis of traditional finite element methods, purely data-driven neural networks, and PINN from multiple perspectives.

Table 1: Comparative analysis of FEM, CNN and PINN frameworks

Feature	Finite Element Method (FEM)	Pure Data-Driven DL (CNN)	Physics-Informed NN (PINN)
Discretization	Mesh-based (Dependent on mesh quality; prone to distortion)	Grid/Voxel-based (Limited by resolution; cubic complexity)	Mesh-free (Continuous coordinate sampling; infinite resolution)
Physics Enforcement	Intrinsic (Variational principles/Weak form)	Absent (Statistical correlation only; “Black-box”)	Constraint-based (PDE residuals embedded in loss function)
Data Requirement	Minimal (BCs & constitutive parameters only)	High (Requires massive labeled datasets from FEM/Exp)	Minimal (Physics-driven; capable of zero-shot learning)

Feature	Finite Element Method (FEM)	Pure Data-Driven DL (CNN)	Physics-Informed NN (PINN)
Scalability	Exponential (Suffers from "Curse of Dimensionality")	Cubic ($O(N^3)$) (Restricted by voxelization scaling barrier)	Linear (Scales linearly with input dimension)
Inverse Problem	Iterative Re-analysis (High cost due to re-meshing loops)	Fast Inference (Poor extrapolation beyond training data)	Unified Optimization (Parameters updated via back-propagation)
Generalization	High (Within continuum mechanics assumptions)	Low (Poor Out-of Distribution performance)	High (Guaranteed by physical laws)

3.3 Model Improvement and Evolution of PINN

Despite demonstrating considerable potential in solving general partial differential equations, standard PINNs often exhibit convergence stagnation or insufficient accuracy when confronted with the multiscale wave propagation, strongly coupled stiffness singularities, and complex periodic topologies characteristic of piezoelectric metamaterials. To address these challenges, the academic community has proposed a series of improvement strategies encompassing feature embedding, loss weighting, regional decomposition, and operator learning.

Regarding the high-frequency fluctuations and bandgap characteristics commonly observed in the dynamic analysis of piezoelectric metamaterials, standard multi-layer perceptrons (MLPs) exhibit significant spectral bias, wherein the network tends to prioritise fitting low-frequency components while neglecting high-frequency details. To overcome this limitation, Tancik et al. [47] introduced Fourier Feature Embeddings. By mapping input coordinates to a high-dimensional sinusoidal feature space, this approach substantially enhances the network's ability to resolve stress concentrations at microstructural edges and propagate short-wavelength phenomena. Building upon this foundation, the SIREN architecture employs periodic activation functions to further ensure computational accuracy for higher-order derivatives[48].

To address the parameter disparity and stiffness ill-posedness spanning up to 20 orders of magnitude between force-electric coupling fields, adaptive weighting mechanisms have been widely adopted [49]. Unlike traditional methods involving manual adjustment of fixed weights, this mechanism dynamically balances the residual contributions from the momentum equation and Maxwell's equations during training by utilising gradient statistical information. This effectively prevents numerically dominant mechanical terms from dictating the optimisation direction, thereby ensuring synchronous convergence across multiple physical fields.

When confronted with highly complex bionic topological structures such as TPMS, a single network struggles to capture global geometric features. Extended PINN and conservative PINN introduce the concept of domain decomposition [50], partitioning complex macroscopic arrays into multiple subdomains. By employing several sub-neural networks to solve problems in parallel and exchanging information through interface conditions, this approach not only reduces training complexity but also inherently aligns with the demands of high-performance parallel computing.

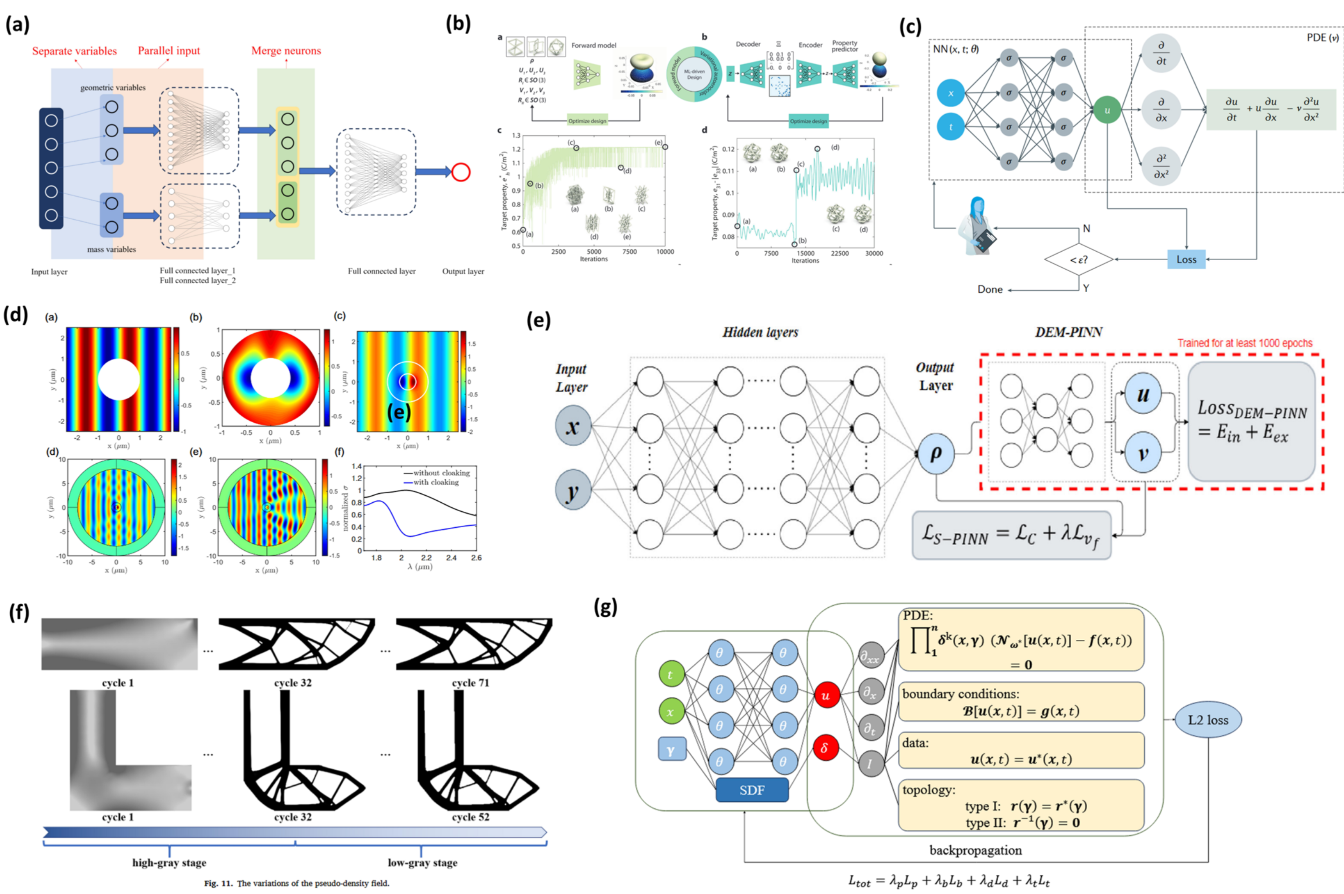
To overcome the efficiency bottleneck of PINNs' one-time training and support real-time inverse design, research focus is progressively shifting towards neural operator learning. Novel architectures such as DeepONet[51] and Fourier Neural Operators[52] no longer confine themselves to solving equations for single operating conditions, but instead strive to learn nonlinear operator mappings from microstructural parameters to macroscopic response fields. Once trained, such models enable millisecond-scale real-time inference, providing a revolutionary tool for rapid topological optimisation and parameter scanning of piezoelectric metamaterials. Table 2 summarises PINN advancements in metamaterial applications.

Table 2: Development of PINN

Year	Research Content	Key Technical Iterations	Key Progress
2020	Physics-informed neural networks for inverse problems in nano-optics and metamaterials[53]	Fundamental PINN framework, meshless inverse scattering	First determination of the effective dielectric constant for finite-size scattering systems, surpassing effective medium theory (Fig. 3(d))

Year	Research Content	Key Technical Iterations	Key Progress
2023	Recent advances in metasurface design with PINNs[54]	PINN combined with topology optimisation	Emphasising physical accuracy and computational efficiency to enhance the versatility of reverse engineering
2023	PINN for for structural topology optimization[55]	A mesh-free topology optimisation framework has been established.	The improved DEM-PINN not only enables prediction but also replaces sensitivity analysis, achieving automatic structural evolution (Fig. 3(e))
2024	Dynamically configured PINN for topology optimization[16]	Dynamic Subnet Configuration and Active Sampling	Enhance optimization efficiency, replacing finite element analysis (Fig. 3(f))
2025	PINNs for topological metamater- ial design[56]	Pre-training + Inverse Design Model + Physically Equivalent Integration	Low-frequency broadband performance, flexible waveguide manipulation, sixfold expansion of bandgap
2025	LT-PINN: Lagrangian topology-conscious PINN[57]	Lagrange Boundary Focusing + Hard Constraint	Processing multi-scale hierarchies to enhance the accuracy of complex geometries (Fig. 3(g))

Figure 3: Data-Driven frameworks and the advancement of PINNs. (a) Data-driven framework based on parallel separated multi-input neural networks (PSMNN) [10]. (b) Machine learning-based optimisation design of piezoelectric metamaterials[11]. (c) Foundational model framework of PINN[14] . (d) Scattering data framework established via PINN framework, enabling novel dielectric devices with significantly reduced scattering performance (e) Schematic of the CPINNTO architecture, where the output density of S-PINN undergoes forward propagation via the DEM-PINN loss [55] .(f) Design of advanced piezoelectric metamaterials through integrated topology and shape optimisation [16] . (g) Lagrangian Topology-Aware PINN (LT-PINN) framework for boundary-directed engineering optimisation [57].



4. Applications of PINN in Metamaterials and Multiphysics

This section broadens the perspective from pure algorithmic theory to the cutting edge of complex engineering applications. We systematically review the latest developments in PINNs for handling strong multiphysics coupling mechanisms, constructing parametric surrogate models for metamaterials, and driving complex microstructure inverse topology optimisation. The emphasis lies in analysing how PINNs overcome the limitations of traditional FEM concerning mesh dependency and multi-field interface interpolation. We further explore the theoretical challenges and technical pathways involved in migrating these generalised multiphysics solution strategies to the domain of piezoelectric metamaterials.

4.1 Method Transfer in Multiphysics Coupling Scenarios

Prior to the extensive exploration of force-electric coupling in piezoelectric effects by PINN, this methodology had already demonstrated its unique advantages in solving classical multiphysics problems such as thermal-mechanical and fluid-structure interactions. However, this represents not a simple superposition of physical equations, but rather a fundamental shift in the underlying numerical computational paradigm.

In the classical thermo-mechanical coupling problem, the heterogeneity of physical fields already poses significant challenges. When an electric field is introduced to form a thermo-electro-mechanical three-field coupling, the complexity of the problem increases exponentially. For instance, Zhang et al. [58,59] recently demonstrated in their study of functionally graded piezoelectric plates that the nonlinear interaction between the temperature field and a strong electric field can induce highly complex dynamic responses. When addressing such multi-physics systems, traditional PINNs are highly susceptible to "Gradient Pathology" in multi-objective optimization due to the vastly different decay scales and energy levels typically exhibited by temperature, stress, and electric potential fields. To address this common challenge, recent work successfully balanced differences among control equations in transient 3D problems and large-scale ratio structures by introducing adaptive weighting strategies and mixed variable formulations [60], effectively resolving network convergence stagnation caused by stiffness mismatch (Fig. 4(b)).

In the more complex domain of fluid-structure interaction, PINN demonstrates flexibility surpassing traditional mesh-based methods. A domain decomposition framework combined with the Immersed Boundary Method has been proven capable of accurately simulating convective heat transfer and fluid stress transfer at moving interfaces [61]. Unlike traditional FEM, which is often constrained by cumbersome and error-prone data interpolation mapping between heterogeneous physical fields (e.g., fluid and solid), PINN's continuous domain coordinate sampling eliminates this limitation entirely. As demonstrated by Rezaei et al. [62], by introducing hybrid variable formulations, PINN can directly construct and solve coupled equation systems on the same set of spatial grid points, effectively circumventing mesh compatibility issues at interfaces. This unique advantage enables the network to simultaneously approximate velocity, pressure, displacement, and potential fields within a unified coordinate system, achieving high-precision multiphysics coupling solutions without requiring mesh mapping.

This "meshless, unified coordinate system" feature holds revolutionary significance for piezoelectric metamaterial research. In piezoelectric composites, the electric field concentration effect typically occurs within an extremely narrow region at the two-phase interface, requiring extremely high-density mesh refinement in traditional FEM. PINNs, however, employ residual-driven adaptive sampling to automatically identify regions of rapid change in the electric-force coupling gradient. This approach eliminates meshing compatibility issues at multi-field interfaces, offering a novel strategy for high-fidelity simulation of interfacial polarization behavior in piezoelectric microstructures [63].

4.2 Forward prediction of metamaterial mechanical behaviour

In solving forward problems, PINN is increasingly becoming the preferred tool for constructing efficient parametric surrogate models for metamaterials. Traditional data-driven deep learning models rely on massive amounts of FEM simulation data as labels, representing "black-box" interpolation. In contrast, the PINN approach directly embeds control equations into the loss function, eliminating the need to pre-generate large discrete datasets. In the field of mechanical metamaterials, existing research has leveraged this mechanism to handle complex linear elastic and elastoplastic constitutive relations [64]. Furthermore, it has established nonlinear mappings between microscopic lattice configurations and macroscopic dispersion relations (as shown in Fig. 4(c)), enabling sub-second predictions of band structures [56].

Extending this paradigm to the field of piezoelectric metamaterials holds immense engineering value but also presents formidable computational challenges due to the high-dimensional parameter space. Unlike purely elastic media, piezoelectric response involves not only the intrinsic coupling of fourth-order elastic tensors and third-order piezoelectric tensors but is also significantly modulated by the impedance characteristics of external shunt circuits. Under extreme operating conditions, this predictive complexity is further amplified. As demonstrated by Zhang et al. [65-67] in their recent studies on piezoelectric shells, flexible cables, and membrane structures, neglecting nonlinear constitutive relationships under the combined effects of strong electric fields and geometric nonlinearity leads to substantial errors in dynamic response prediction. Maintaining accuracy necessitates the use of computationally expensive numerical techniques. This scenario of strong nonlinear coupling, where traditional computational costs surge dramatically, powerfully underscores the urgency of developing efficient PINN-based surrogate models to achieve rapid, high-fidelity predictions.

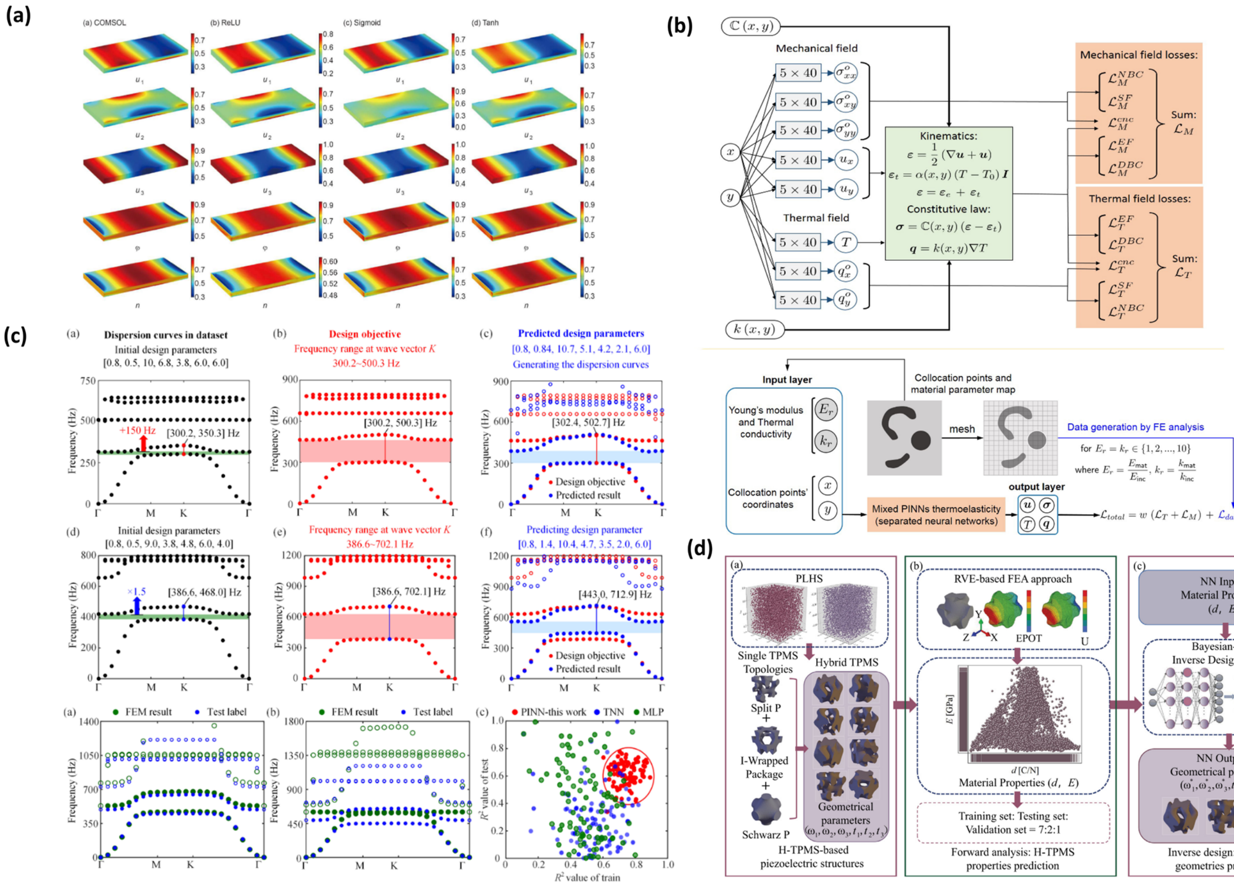
For such prediction challenges involving complex circuits and multi-field coupling, recent breakthroughs have demonstrated promising solutions. For instance, by constructing a hybrid PINN architecture incorporating circuit topology constraints, researchers successfully integrated geometric parameters, material polarization directions, and circuit loads as network inputs, achieving direct mapping to macroscopic voltage outputs or impedance spectra[68]. Similarly, in more intricate piezoelectric semiconductor studies, as illustrated in Fig. 4(a), PINN has also proven effective in tackling the nonlinear prediction challenge of the thermo-deformation-polarization-carrier (TDPC) quadruple field coupling [13], further demonstrating its exceptional generalization capability within high-dimensional multi-physics parameter spaces.

4.3 Reverse Engineering and Topology Optimisation

Reverse design, as the core approach for achieving on-demand customization of metamaterials, has long been constrained by the high computational cost of forward solutions and the difficulty in obtaining gradients. Unlike traditional Solid Isotropic Material Penalty (SIMP) or Level Set Method approaches, PINN-driven topology optimization introduces a Neural Implicit Representation mechanism. This eliminates direct dependence on discrete mesh cell density through fully connected function approximation. Within this framework, geometric evolution is reformulated as an iterative update of neural network weights. This parameterization fully leverages automatic differentiation, effectively circumventing the cumbersome sensitivity analysis inherent in traditional adjoint methods. This “meshless” or “weakly meshed” characteristic enables PINNs to drive geometric configurations to evolve autonomously within a continuous design space while satisfying control equations, thereby pioneering a novel mathematical solution pathway for structural optimization[56].

In the field of piezoelectric metamaterials, PINN demonstrates exceptional advantages, primarily manifested in its capability to solve inverse problems under multi-physics coupling constraints. Due to the bidirectional strong coupling between force and electric fields in the piezoelectric effect, traditional optimization methods often get stuck at local optima when pursuing maximization of piezoelectric coupling coefficients or sensing sensitivity in specific directions, primarily due to multi-objective conflicts and the enormous computational demands of the Jacobian matrix [69]. In contrast, PINNs can directly embed complex force-electric coupling equations as soft constraints within the loss function, enabling the network to inherently satisfy physical conservation laws while seeking optimal microstructure parameters. Although direct PINN-based topology optimization for piezoelectric metamaterial microstructures remains exploratory, pioneering work has demonstrated its immense potential for handling complex geometries [70]. Particularly for microstructures like TPMS or hierarchical structures—which exhibit outstanding piezoelectric-mechanical properties but possess complex geometries—PINN holds promise to overcome computational barriers of traditional numerical methods. It enables direct inverse derivation of optimal topologies based on target piezoelectric responses (as shown in Fig. 4(d)), providing novel mathematical tools and theoretical foundations for designing next-generation smart metamaterials with breakthrough performance metrics [71].

Figure 4: Applications of PINNs in metamaterials and multi-physics fields. (a) The high agreement between the DDPINNs-TD model based on three-dimensional theory and the COMSOL structure demonstrates its reliability under complex multi-field coupling [13]. (b) Investigation of thermal-mechanical coupling through network architecture and loss functions tailored for multi-physics problems, integrating data and physical models with transfer learning-based input and loss functions [60]. (c) Inverse design outcomes under diverse objectives demonstrated exceptional accuracy in predicting dispersion bandgaps, robustly validating its superior performance in metamaterial design [56]. (d) A deep learning-based inverse design framework offers a promising and viable approach for designing composite TPMS structures [71].



Conclusion

This paper provides a systematic review of the latest research advances in PINNs for analysing the mechanical behaviour of piezoelectric metamaterials, multi-physics coupling modelling, and topology-optimised design. By thoroughly analysing the computational bottlenecks of traditional numerical methods (such as FEM) when handling complex microstructures, alongside the generalisation limitations of purely data-driven deep learning models, we demonstrate the unique advantages of PINN as a SciML framework that integrates physical principles. This framework proves particularly effective in addressing high-dimensional, multi-field coupling, and inverse problems. Through a comprehensive review of existing literature, the principal conclusions and perspectives drawn in this paper are summarised as follows:

(1)Mesh-free properties overcome geometric complexity constraints: Unlike traditional finite element methods reliant on high-fidelity mesh partitioning, PINN employs a mesh-free solution strategy based on coordinate points. This characteristic entirely eliminates computational burdens arising from mesh distortion and reconstruction when handling complex topologies common in piezoelectric metamaterials, thereby providing a benchmark for multiphysics simulations under extreme geometric configurations.

(2)The physically embedded mechanism ensures prediction reliability: PINN successfully overcomes the issues of interpretability and physical inconsistency faced by purely data-driven models by explicitly embedding piezoelectric constitutive equations, geometric equations, and boundary conditions as regularisation terms within the loss function. Even under sparse or unlabelled data conditions, PINN ensures predictions strictly adhere to energy conservation and thermodynamic laws, significantly enhancing the model's generalisation capability.

(3)The inherent advantages of inverse problem solving and parameter identification: In the inverse design of piezoelectric metamaterials, PINN demonstrates superior robustness compared to traditional gradient-based optimisation algorithms. It enables the simultaneous optimisation of unknown material parameters or damage fields as trainable variables alongside network weights, thereby accurately identifying anisotropic parameters and microstructural defects within noisy experimental data. This achieves integrated solution for both direct and inverse problems.

(4)A marked improvement in topology optimisation efficiency: Integrating PINNs into the topology optimisation loop to construct physics-based surrogate models effectively resolves the issues of costly Jacobian matrix computations and slow iterative convergence inherent in traditional methods. This approach not only accelerates multi-objective optimisation processes but also provides real-time gradient information for designing metamaterials with specific bandgap characteristics or maximised electromechanical coupling coefficients.

In summary, the PINN framework effectively balances computational efficiency and physical fidelity by integrating physical mechanisms with data-driven approaches, thereby establishing its leading position in the analysis of piezoelectric metamaterials. To bridge the gap between theoretical modelling and engineering implementation, future research should focus on developing adaptive weighting strategies to overcome optimisation pathologies arising from multi-field coupling, whilst leveraging neural operators to address real-time inference bottlenecks in large-scale systems. With breakthroughs in these key technologies, this methodology holds promise to evolve into a robust computational strategy for tackling complex coupled problems, providing core theoretical support for the precise design of next-generation high-end intelligent equipment.

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Conflict of Interests

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Practical Research on Multi-Objective Collaborative System in Architectural Engineering CAD

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Abstract: Driven by the dual forces of high-quality development in vocational education and the digital transformation of the construction industry, the traditional single-skill training model for architectural CAD in higher vocational engineering majors can no longer meet the industry's demand for versatile talent. Based on synergy theory, systems theory, and the outcomes-based education philosophy, this study constructs a multi-objective collaborative teaching system for architectural CAD in higher vocational engineering majors. By reviewing theoretical foundations and analyzing current teaching practices, it clarifies the core logic of multi-objective collaboration. The study explores practical pathways through system restructuring, teaching model innovation, evaluation mechanism optimization, and resource platform development, while validating the feasibility and effectiveness of the system through pilot teaching trials. This provides theoretical reference and practical paradigms for teaching reform in higher vocational engineering disciplines.

Keywords: Architectural CAD; Multi-Bbjective Coordination; Practical Research

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1. Introduction

Vocational education, as a type of education, has the core mission of cultivating high-quality technical and skilled talents to meet the demands of industrial development. Its development quality directly impacts industrial transformation and regional economic and social progress. Currently, the construction industry is accelerating its transition toward digitalization and intelligence, with the widespread application of new technologies and paradigms driving profound changes in production models[1], management concepts[2], and job requirements[3], thereby imposing higher demands on the comprehensive professional competencies of practitioners. As a core technical component in higher vocational engineering education[4-5], Building CAD serves as a crucial bridge connecting theoretical knowledge with engineering practice and plays a pivotal role in fostering students' engineering thinking and practical abilities. The quality of its teaching directly influences the specifications of talent cultivation and industry adaptability.

Under the policy guidance of high-quality development in vocational education, the reform of high vocational CAD teaching in architecture has been continuously advancing but still faces numerous bottlenecks[6]. The teaching objectives focus on software operation skills training while neglecting the synergistic cultivation of engineering thinking, innovation capabilities, and professional qualities, leading to a disconnect between talent development and industry needs[7]. Teaching content updates lag behind industry technological advancements, with prominent issues of fragmented resources, making it difficult to establish a systematic knowledge and skill framework. The teaching model remains dominated by traditional lectures, lacking interactivity and practicality, with insufficient depth in school-enterprise collaborative education. The evaluation mechanism is singular and rigid, emphasizing outcome-based assessments, which fail to comprehensively measure students' comprehensive abilities and quality development. Based on this, constructing a multi-objective collaborative teaching system to break the limitations of single-skill training and achieve integrated cultivation of knowledge, skills, and qualities has become a key pathway to advancing CAD teaching reform and improving talent development quality[8]. This paper systematically explores the construction and implementation strategies of a multi-objective collaborative teaching system through teaching practice, providing referenceable ideas and methods for teaching reform in high vocational engineering disciplines.

2. Theoretical Foundations of the Multi-Objective Collaborative Teaching System

2.1 Synergy Theory

Synergy theory serves as the core theoretical foundation for the construction of a multi-objective collaborative teaching system. Its essence lies in the formation of an ordered structure and the optimization of overall functionality through the interaction and coordination of various elements within the system. This theory emphasizes the integrity, interconnectivity, and dynamism of systems, asserting that no system is merely a simple aggregation of components but rather generates new collective efficacy through synergistic interactions among elements. In architectural CAD teaching, multiple objectives do not exist in isolation but form an interconnected and mutually supportive organic whole, collectively constituting a complex teaching system.

2.2 Outcome-based Education Concept

Outcome-based education centers on learning outcomes, emphasizing that teaching activities should revolve around predefined training objectives. It prioritizes the actual achievement of student competencies and their alignment with job requirements, with its core logic being reverse design and forward implementation. This approach breaks away from traditional knowledge-centered teaching models by making student competency development the starting point and ultimate goal of instruction, ensuring the entire teaching process serves preset learning outcomes. To integrate this concept into architectural CAD education, it is essential to orient teaching around the professional competency demands of the construction industry, reverse-engineering teaching objectives, content, methods, and assessment approaches to ensure precise alignment between teaching activities and talent cultivation goals.

2.3 Taxonomy of Educational Objectives

The classification theory of educational objectives provides a scientific basis for the setting and division of multiple goals. This theory divides teaching objectives into three dimensions: knowledge, skills, and literacy, forming a hierarchical and interrelated system that clarifies the focus and pathways for cultivating objectives in each dimension. In architectural CAD instruction, the knowledge dimension focuses on core content such as software operation principles, architectural drafting standards, and industry technical specifications, requiring students to not only master "how to do it" but also understand "why it is done," thereby solidifying theoretical foundations. The skills dimension emphasizes abilities like software application, drawing creation, technical integration, and project practice, highlighting the practicality, comprehensiveness, and flexibility of skills to ensure students can translate knowledge into practical operational capabilities. The literacy dimension encompasses innovation awareness, teamwork, engineering thinking, and professional responsibility, prioritizing the shaping of students' values and the enhancement of their comprehensive literacy, fostering sustainable competencies to adapt to industry development.

3. Construction of Multi Objective Collaborative Teaching System for Architectural CAD in Higher Vocational Education

3.1 Clarify the core logic of multi-objective collaboration and construct a goal system

Based on the positioning of vocational education types and industry needs, and based on the theory of educational goal classification, a clear hierarchical and collaborative multi-objective system is constructed to ensure that each goal supports and works in the same direction. The knowledge objectives focus on core content such as the operating principles of architectural CAD software, architectural drawing specifications, and industry technical standards. Students are required to master the working principles of software core functions, understand the basic rules and industry standards of architectural drawing, be familiar with the core requirements of industry technological development, and lay a solid theoretical foundation for skill and literacy cultivation.

The skill objectives cover software operation, drawing, technical application, project practice and other abilities, highlighting the practicality and comprehensiveness of the skills. Students are required to proficiently operate software to complete the drawing and modification of various architectural drawings, use cutting-edge technologies to carry out modeling and design work, apply skills to practical projects and solve practical problems, and achieve effective transformation and practical application of knowledge. The literacy goals include innovation consciousness, teamwork, engineering thinking, professional responsibility, etc., to strengthen students' comprehensive professional literacy. Require students to have an innovative consciousness of active exploration and be able to break through the limitations of traditional thinking in design; Having efficient teamwork skills, actively participating in team projects and exerting their own effectiveness; Having systematic engineering thinking and being able to carry out design work based on practical engineering situations; Having a rigorous sense of professional responsibility, strictly adhering to industry norms and professional ethics.

By sorting out the inherent connections between each goal and clarifying the collaborative logic: based on knowledge goals, providing theoretical support for skill and literacy cultivation; Taking skill objectives as the core, realizing the transformation and application of knowledge, and promoting the cultivation of literacy; Guided by the goal of literacy, promote the deep integration of knowledge and skills, and enhance the comprehensive quality of talent cultivation. At the same time, based on the characteristics of vocational education and industry development trends, establish a dynamic adjustment mechanism for goals, regularly investigate industry demand and technological development trends, optimize the training focus and connotation of each goal, and ensure the scientificity and adaptability of the goal system.

3.2 Refactoring modular content system and strengthening multi-objective fusion

Based on the demand for multi-objective collaboration and industry technology development trends, break the traditional content arrangement mode centered on knowledge points, reconstruct a modular and project-based content system, and achieve deep integration of knowledge, skills, and literacy. According to the progressive logic, the content is divided into three levels: basic module, technical module, and comprehensive module. Each module is closely related to the multi-objective training needs, interconnected and synergistically promoted, forming a complete knowledge, skills, and literacy training chain.

The basic module focuses on knowledge objectives and basic skill development, covering software operation basics, architectural drawing recognition, drawing standards, and other content. Through this module, students will master the basic operation methods of software, be able to read various architectural drawings, understand and comply with architectural drawing standards, consolidate theoretical foundations and basic skills, and lay a solid foundation for subsequent module learning. The technology module connects with cutting-edge industry technologies, integrates new technologies and methods, cultivates students' technical application ability and innovation awareness, and achieves the coordinated cultivation of skill goals and literacy goals. Through this module, students will master the core application methods of cutting-edge technologies, be able to integrate new technologies with traditional CAD skills, and enhance their technical sensitivity and innovative thinking.

The comprehensive module takes real engineering projects as carriers, integrates multidisciplinary knowledge, conducts project practical training, cultivates students' engineering practice ability, teamwork ability, and problem-solving ability, and comprehensively implements multi-objective collaborative education. This module selects real projects that meet industry needs, guiding students to carry out the entire process design work as a team, from project analysis, scheme design, drawing to result optimization, and deeply participate in project practice throughout the process. In content arrangement, breaking the limitations of fragmented traditional knowledge points, integrating various module contents through projects, and integrating literacy cultivation into the entire process of knowledge transmission and skill training. By introducing real industry projects, we can achieve precise alignment between content and job requirements, and enhance students' career adaptability; By integrating interdisciplinary knowledge, students can broaden their knowledge horizons and cultivate their ability to solve problems comprehensively.

3.3 Innovate the dual teaching mode of school enterprise and promote collaborative implementation

Based on the theory of collaboration, a teaching model with dual leadership of schools and enterprises and deep integration of theory and practice is constructed, clarifying the responsibilities and division of labor of both schools and enterprises in teaching, and forming a collaborative force for educating students. The school is responsible for theoretical teaching, basic skills training, and teaching organization management, focusing on the implementation of knowledge goals and basic skills goals; Enterprises provide real projects, technical support, and practical venues, participate in content design, practical teaching, and evaluation assessments, and focus on cultivating skills and literacy goals. Both parties establish a regular communication mechanism to jointly develop teaching plans, optimize teaching content, and promote teaching implementation, ensuring that the teaching process is accurately aligned with industry demands and job standards.

Adopting task driven teaching methods, designing three-level teaching tasks to achieve hierarchical training and collaborative promotion of multiple objectives. The basic skills training stage is mainly taught by school teachers, through case teaching, demonstration teaching and other methods, to teach basic theories and software operation skills, and implement knowledge goals and basic skills goals. Teachers use typical cases to explain knowledge points and operational methods, guiding students to consolidate their learning through imitation exercises. At the same time, they focus on cultivating students' self-learning abilities and encourage them to actively explore software functions. In the practical stage of the innovation project, the school enterprise collaborative teaching mode is adopted, with school teachers responsible for theoretical guidance and enterprise technical personnel participating in teaching. Cutting edge technologies and project cases are introduced to guide students to engage in exploratory learning and innovative practice, cultivating students' innovation ability and technological application ability. Teachers from both sides jointly design innovative projects, guide students to conduct exploration and practice in groups, encourage students to break through traditional thinking, and use new technologies and methods to solve design problems.

3.4 Build a diversified teaching resource platform to provide support and guarantee

Build a diversified teaching resource platform that integrates resource development, sharing, and application around the needs of multi-objective collaborative teaching, providing strong support for teaching implementation. The resource platform adopts cloud computing architecture to achieve dynamic updates and collaborative sharing of resources, breaking the limitations of time and space, and meeting different teaching and learning needs. The platform covers various types of resources such as teaching courseware, micro lesson videos, virtual simulation projects, case libraries, exercise sets, etc., forming a complete and systematic teaching resource system. Teaching courseware and micro lesson videos are produced around modular content, highlighting key and difficult points, supporting students' pre class preparation, in class consolidation, and post class review; The case library includes real project cases and typical teaching cases in the industry, providing rich practical materials for teaching; The exercise set is designed for each module's knowledge and skill points to enhance students' knowledge mastery and skill improvement.

Build a collaborative resource sharing channel between schools and enterprises to achieve bidirectional flow of enterprise technology resources, project resources, and school teaching resources. The enterprise synchronizes the latest project cases and technical materials to the teaching resource platform, providing fresh materials for teaching; The school will provide feedback on teaching achievements and student design works to enterprises, providing reference for talent selection and technological innovation in enterprises. At the same time, the platform has set up resource interaction functions, allowing teachers, students, and enterprise technicians to exchange and discuss resource content, promote the deep integration of teaching and production practice, and provide rich resource support for multi-objective collaborative teaching.

3.5 Optimize the multi-dimensional dynamic evaluation mechanism and strengthen feedback regulation

Following the results oriented education philosophy, we will establish a dynamic evaluation mechanism that covers multiple dimensions, multiple subjects, and multiple stages, comprehensively measuring students' knowledge mastery, skill proficiency, and literacy development, and providing timely feedback for teaching optimization. Establish a three-dimensional evaluation index system, with knowledge dimensions focusing on theoretical knowledge and mastery of norms, including core content such as software operation principles, architectural drawing standards, industry technical standards, etc; The skill dimension focuses on software application, project practice, and technological innovation ability, including drawing quality, software operation proficiency, technical application rationality, project completion effect, etc; The dimensions of literacy include innovation consciousness, teamwork, engineering thinking, professional responsibility, etc., including innovative design ideas, proactive teamwork, logical problem-solving, and standardized professional behavior. The indicators of each dimension complement each other, forming a complete evaluation system that comprehensively reflects students' comprehensive abilities.

Adopting a combination of process evaluation and outcome evaluation, process evaluation focuses on the entire teaching process, covering classroom performance, homework completion, project stage achievements, self-directed learning, etc., comprehensively tracking the process of students' ability improvement. Teachers record students' participation, interactive performance, and thinking state through classroom observation, analyze students' knowledge mastery and skill application through homework grading and project stage evaluation, and monitor students' self-directed learning progress and effectiveness through online platform data. Consequential evaluation focuses on the final comprehensive project assessment, testing students' achievement of comprehensive abilities, requiring them to independently or in groups complete complete the project design task, and comprehensively evaluate their knowledge application, skill operation, innovative thinking, and teamwork abilities.

Introduce multiple evaluation subjects and construct an evaluation model that combines student self-evaluation, peer evaluation, teacher evaluation, and enterprise evaluation. Student self-evaluation cultivates self-reflection and evaluation abilities, guiding students to actively summarize the strengths and weaknesses in the learning process, and develop self-improvement plans; Student peer evaluation promotes communication and learning among students, cultivates the ability to objectively evaluate others, and creates an atmosphere of mutual motivation and common progress; Teacher evaluation focuses on professional guidance and comprehensive analysis, and provides comprehensive evaluation and improvement suggestions based on process performance and outcome quality; Enterprise evaluation focuses on job suitability and practical ability, combined with students' internship and training performance and project achievements, providing evaluation opinions from an industry perspective to ensure the comprehensiveness and objectivity of the evaluation results. Develop intelligent evaluation tools, establish a student learning behavior analysis model, and achieve dynamic monitoring and accurate feedback on students' achievement of multiple goals through analysis of online learning data, homework completion data, project achievement data, etc. Teachers adjust teaching strategies in a timely manner based on evaluation results, optimize teaching content and methods, provide targeted guidance for students' weak links, and ensure the effective implementation of the multi-objective collaborative teaching system.

4. Conclusion

This article is based on the collaborative theory, achievement oriented education concept, and educational goal classification theory to construct a multi-objective collaborative teaching system for architectural CAD in higher vocational engineering majors, covering goal system, content system, teaching mode, resource platform, and evaluation mechanism. This system is centered around multi-objective collaboration, and by clarifying the logic of multi-objective collaboration, it solves the problem of traditional teaching objectives being singular and lacking in collaboration; By restructuring the modular content system, precise alignment between teaching content and industry demands can be achieved; By innovating the dual teaching model between schools and enterprises, we aim to strengthen the deep integration of theory and practice; By building a diversified resource platform, provide strong support for teaching implementation; By optimizing the multi-dimensional dynamic evaluation mechanism, ensure comprehensive measurement and continuous optimization of teaching effectiveness.

This system breaks the limitations of traditional single skill training and achieves integrated training of knowledge, skills, and literacy. The teaching pilot verification shows that the system can effectively enhance students' comprehensive vocational abilities, optimize teaching effectiveness, and enhance the adaptability of talent cultivation to industry needs. The construction and implementation of a multi-objective collaborative teaching system not only enriches the theory of vocational education teaching and provides a new perspective for vocational education teaching reform, but also provides specific operational guidelines for vocational colleges to carry out teaching reform, which has important theoretical value and practical significance.

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Conflict of Interests

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A Review of Risk Identification & Risk Assessment on Urban Utility Tunnel Construction

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Abstract: With the rapid development of urban utility tunnel construction in China, the risks encountered during construction are becoming increasingly prominent, necessitating more robust and systematic risk-assessment. This study aims to improve the risk assessment system for the construction of urban utility tunnels and provide theoretical support for engineering practice.

This study critically examines current practices in risk identification and risk assessment in both China and international contexts by reviewing existing literature from year 2013 to 2023. The review reveals that existing research and engineering applications predominantly rely on traditional risk-assessment models, which are generally static and expert-driven. These approaches exhibit notable limitations, particularly in their inability to support dynamic risk monitoring, multi-source data integration, and intelligent early-warning functions. Furthermore, the current risk-assessment systems demonstrate insufficient interdisciplinary integration, limited real-time performance, and constrained practical operability in complex construction environments. Based on these findings, there is the need for a paradigm shift towards dynamic and data-driven risk-assessment approaches which focus on integrating big-data analytics, artificial intelligence, and intelligent sensing technologies to enhance the adaptability, timeliness, and predictive capability of risk management systems. Such advancements are essential to promote the intelligent and systematic development of risk control strategies and to improve the overall effectiveness and foresight of risk management in urban utility tunnel construction.

Keywords: Underground Engineering; Urban Utility Tunnel; Risk Assessment; Risk Indicators; Research Status

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1. Introduction

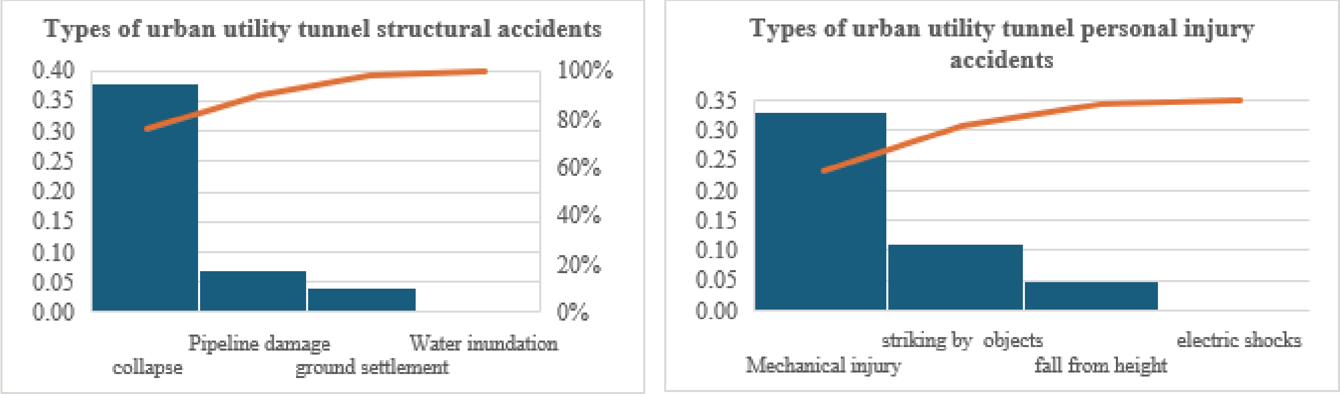
Urban utility tunnels, are an advanced form of infrastructure network. These tunnels are used as an important measure for utilizing underground space and promoting sustainable urban development. In China, the construction of urban utility tunnels has entered a stage of rapid development with the strong campaign on national policies in 2015 (Zhao Yongzhi, 2019). However, due to the complex structure of utility tunnels and high requirements for construction technologies, various risk factors interact with each other during construction, resulting in great difficulties in safety management and control.

Currently, more than fifty cities across China are promoting construction of urban utility tunnels. With the cluster and network development of projects, construction risks are further amplified and aggravated. The overlapping of multiple operation faces and the mutual influence of underground spaces make the risk situation more complex. Through an investigation into the number of accidents involving China's urban utility tunnels over the past decade (2013-2023), the study finds that with the annual expansion of tunnel construction volume, risk accidents have shown an overall upward trend. From 2020 to 2022, due to the global COVID-19 pandemic, construction projects were largely suspended and the number of accidents dropped accordingly. It was not until 2023, when projects resumed successively, that the number of accidents rose again, as detailed in Figure 1.

Figure 1: Statistical Table of Accidents in utility tunnel over the past decade

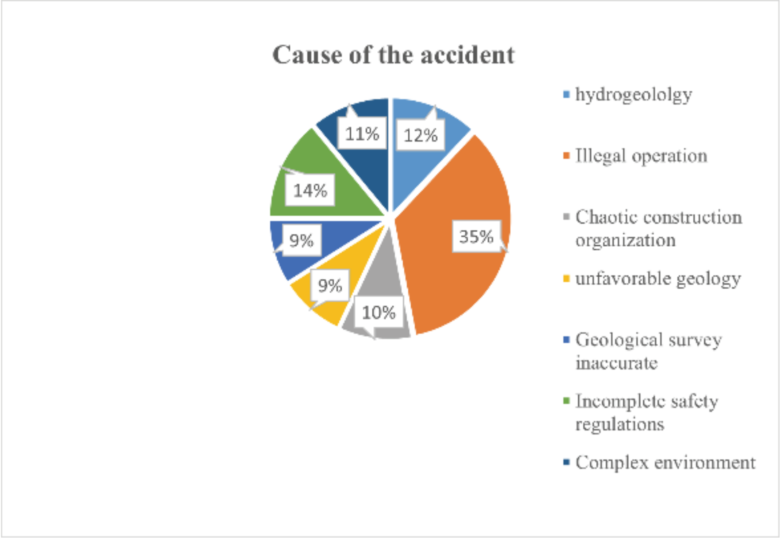
Urban utility tunnel construction involves a variety of accident types. Further analysis reveals that structural accidents such as collapses, pipeline damage, ground settlement and water inundation cause massive property losses. Personal injury accidents including mechanical injuries, falls from height and striking by objects frequently occur during construction, leading to severe casualties. Specific accident types are shown in Figure 2.

Figure 2 Types of utility tunnel accidents



Based on the accident type, an in-depth analysis of its underlying causes was conducted. The accident was mainly attributed to improper personnel operation, complex geological conditions, inadequate safety management and other factors. Specific causes are shown in Figure 3.

Figure 3 Analysis of the Causes of utility tunnel Accidents



It can be seen from Figures 1 to 3 that systematic identification and evaluation of construction risks of utility tunnels, as well as proper risk management, are of great significance to improving the construction safety of utility tunnels.

Construction risks in urban utility tunnels permeate every stage, and the type and severity of these risks dynamically change with variations in personnel, environment, processes, and management measures. The construction of utility tunnels in China started relatively late, and the relevant theoretical system is not yet perfect. Especially in terms of risk assessment, a systematic and scientific methodological system has not been formed. At present, research on risk evaluation of utility tunnels mainly focuses on the operation and maintenance stage, with few studies conducted for the construction stage（Chen Kan, 2021）.

How to construct a risk assessment model suitable for practical engineering projects, and how to effectively classify and control construction risks through appropriate risk identification and evaluation methods, has become a critical issue urgently needing resolution in current engineering practice.

Therefore, this study first systematically analysis the current state of research on risk assessment in urban utility tunnel construction, summarizes existing identification and assessment methods and systems, and points out the shortcomings and development trends of existing research, thus laying a theoretical foundation for constructing a more reasonable risk assessment model.

2. Risk Identification in Utility Tunnels Construction

Risk management can be divided into three parts: risk identification, risk analysis, and risk assessment (Li Chunhua, 2023).

Risk identification refers to the analysis and research of the time, location, quantity, and type of risk occurrence from multiple perspectives, including premonition, identification of risk symptoms, analysis of risk sources, and determination of risk events. Usually, risk analysis and identification are collectively referred to as risk identification（Li Chunhua, 2023）.

Risk assessment refers to the judgment of the probability of risk occurrence, the expected degree of loss, and the ability to withstand the risk through risk analysis, in order to evaluate the possibility of risk occurrence and the harm it brings, and to formulate strategies to reduce risks and losses based on the situation（Yan Lixin, 2024）.

The goal of risk identification in utility tunnel construction is to establish a suitable risk indicator system. At present, most scholars adopt the method of initial knowledge and screening.

2.1 Conventional Risk Identification Frameworks

The most common method for initial identification of risks in utility tunnel is to use the 4M1E method to identify indicators based on existing literature, national standards and regulations, and utility tunnel construction accident cases (Anon, 2020).

4M method is a commonly used tool in problem solving and change management, which is based on four core elements: man, machine and material, management, and method for analysis. Usually, it also includes “1E”: environments. So, it is collectively referred to as the 4M1E method. That is to say, the five elements of man, machine and material, management, method, and environments are commonly referred to.

This method serves as a basic qualitative framework for risk identification with clear logic and ease of application, yet it is inclined to qualitative description and unable to quantify the correlation among risk factors.

Later, researchers combined the 4M1E method with other theories to form a new risk identification technique in order to make the identified indicators as comprehensive as possible.

The basic idea of the Hierarchical Holographic Model (HHM) is to identify risks in a system by analyzing it from multiple perspectives and dimensions based on the fundamental principles of systems engineering (Liu Yukexin, 2022). Firstly, determine the HHM framework of the research object. The HHM framework can collect information through various channels and continue to decompose and derive new sub model graphs through continuous improvement. After the risk identification work of all levels and subsystems is completed, an overall risk list of the project can be generated.

This method is a systematic integration approach suitable for complex systems, which can explore the relationships between different system levels. However, it requires strong support from basic data, involves complex modeling and heavy workload, is not applicable to preliminary risk identification, and generally needs to be used in conjunction with other methods.

In addition, some scholars have applied new theories from other disciplines to the risk identification of utility tunnel construction.

2.2 Integration of Project Decomposition and Causal Analysis Methods

The Work Breakdown Structure-Risk Breakdown Structure(WBS-RBS） is to break down the project into WBS tasks and use RBS to classify potential risks（Li Fangzhen, 2017）. This can systematically identify the risk categories that each work package may face, such as technical risks, management risks, external risks, etc.

This method enables comprehensive and non-omissive risk identification and accurate localization of specific risk occurrence nodes. However, it focuses on process flows and is insufficient in identifying non-technical risks such as management and economic ones, thus it is generally not used alone.

Fishbone analysis method, also known as causal analysis method, is a method of discovering the “root cause” of problems. It was developed by Japanese management master Mr. Ishikawa Shinobu and is therefore also known as Ishikawa diagram. It can also be called a ‘ cause and effect diagram’（Liu Lei, 2020）.

This method is result-oriented, tracing the root causes layer by layer with strong visualization, which facilitates team discussion. However, it is not applicable to preliminary risk identification and only suitable for the cause analysis of well-defined risk problems.

2.3 Data-Driven and Interdisciplinary Identification Approaches

Grounded Theory (GT) was jointly proposed by Anselm Strauss and Barney Laser from Columbia University, it is a method of using a systematic process to induce a phenomenon layer by layer to guide the theory (Chen Wei, 2022). Its main purpose is to abstract new concepts and ideas from empirical data through inductive analysis and comparison. The GT research method achieves hierarchical induction through coding, with the most critical step being the step-by-step coding of the data, which includes three levels: open coding, spindle coding, and core coding. The purpose of open coding is to discover conceptual categories from data and form initial categories. Spindle coding is used to discover and establish various connections between conceptual categories and based on these relationships, encode them again on the basis of the initial category to form the main category. Core coding refers to the discovery of core categories based on comparative analysis of the main category, and the concatenation of all other categories into a whole to construct a theory (Chen Wei, 2022).

This method is a research approach based on data coding and analysis. It has high data requirements and is time-consuming for coding and analysis, making it unsuitable for projects with tight schedules and limited data.

Nowadays, scholars generally use a combination of Expert investigation method and data statistical software for secondary screening based on initial identification of indicators.

The Expert investigation method, was founded and implemented by the Rand Corporation in 1946 (Xu Jingwei, 2020). Essentially, it is a feedback anonymous inquiry method. The general process is to obtain the opinions of experts on the problems to be predicted, organize, summarize, and statistically analyze them, and then anonymously provide feedback to each expert.

After soliciting opinions again, the process is concentrated, and feedback is given again until a consensus is reached.

Statistical Package for the Social Sciences (SPSS) is a statistical analysis software used for data processing, data analysis, and data visualization(Chen Bo, 2020）. It provides a range of statistical analysis tools that facilitate researchers and analysts in extracting information, making decisions, and discovering patterns from data. While this combination improves indicator reliability and consensus, it does not fundamentally resolve the issue of subjectivity, as expert judgment remains the dominant source of decision-making.

The research results of nearly 10 years in this study have been summarized and organized, as shown in Table 1.

Table 1: Research Progress on the Construction of Risk Indicator System

Author / time	Initial identification of risk factors	Risk factor screening	Risk factor database
Liu Yukexin（2022）	HHM 4M1E method Fishbone diagram	Expert investigation method SPSS	5 level 1 indicators 24 level 2 indicators
Wei Haimin（2017）	Work Experience HHM	Expert investigation method Risk probability impact matrix	4 level 1 indicators 18 level 2 indicators
Chen Shengfa（2023）	Fishbone diagram 4M1E method HHM	Expert investigation method	5 level 1 indicators 33 level 2 indicators
Chen Wei（2022）	Grounded Theory	Expert investigation method SPSS	5 level 1 indicators 22 level 2 indicators
Zhang Shuai（2022）	4M method	Expert investigation method	4 level 1 indicators 25 level 2 indicators
Duan Leting (2022)	4M1E method	Expert investigation method	5 level 1 indicators 28 level 2 indicators
Liu Keru（2018）	Expert investigation method		3 level 1 indicators 15 level 2 indicators
Qiu Shi（2019）	4M1E method		4 level 1 indicators
Ruan's Zhizhuang（2019）	4M1E method		3 level 1 indicators
Zhang Xiaolong（2020）	Expert investigation method		4 level 1 indicators
Zhao Hui（2020）	Expert investigation method		5 level 1 indicators 18 level 2 indicators
Cai Menglong（2020）	Expert investigation method		5 level 1 indicators
Zhang Yong (2020)	4M1E method		5 level 1 indicators 28 level 2 indicators
Liu Lei（2020）	4M1E method Fishbone diagram		3 level 1 indicators
Xu Haiyan（2020）	4M1E method Expert investigation method		3 level 1 indicators 12 level 2 indicators 57 level 3 indicators
Jiang Hao（2023）	4M1E method		6 level 1 indicators 31 level 2 indicators
Zhang Zhicheng（2024）	4M1E method		5 level 1 indicators 18 level 2 indicators
Li Fangzhen（2017）	WBS-RBS matrix	Expert investigation method	2 level 1 indicators 6 level 2 indicators 23 level 3 indicators
Chen Bo（2020）	Risk impact mechanism	Expert investigation method SPSS	5 level 1 indicators

Author / time	Initial identification of risk factors	Risk factor screening	Risk factor database
Ma Huigan （2021）	4M1E method	Expert investigation method	5 level 1 indicators 25 level 2 indicators
Hu Yihuan （2023）	Expert investigation method	Field research	5 level 1 indicators 25 level 2 indicators
Huang Huijun （2020）	Fishbone diagram 4M1E method	Expert investigation method SPSS	5 level 1 indicators 18 level 2 indicators
Chen Zeming （2020）	4M1E method	Expert investigation method	5 level 1 indicators 18 level 2 indicators
Han Yuhong （2024）	4M1E method	Expert investigation method	5 level 1 indicators 17 level 2 indicators
Xu Jingwei （2020）	4M1E method	Expert investigation method	5 level 1 indicators 20 level 2 indicators
Qin Huali （2022）	4M1E method	RF Random Forest	5 level 1 indicators 22 level 2 indicators

2.4 Critical Evaluation and Research Gaps

As shown in Table 1, current risk analysis is primarily based on the 4M1E method of accident causation theory. The risk identification process still relies heavily on qualitative descriptions from available documents, standards, and accidents, neglecting in-depth exploration of the engineering substance of the constructed indicator system. This leads to a disconnect between risks and the specific technological, geological, and management scenarios of utility tunnel construction, resulting in risk indicator databases that are more general than specific.

Based on the systematic identification and preliminary analysis of risk factors in utility tunnel construction, the core decision-making step in risk management becomes how to scientifically assess and prioritize the potential impact of these risks. Therefore, the following section will focus on examining the application logic, evolution path, and inherent limitations of various risk assessment methods.

3. Research Progress of Risk Assessment

In recent years, the construction risks of urban utility tunnels have become a focus of attention for scholars. Researchers have conducted a series of studies on the proactive prevention, risk assessment, and management of construction risks in urban utility tunnels, establishing various improved risk assessment models, as detailed in Table 2.

This study summarizes existing construction risk assessment methods into three main categories: qualitative, quantitative, and comprehensive evaluation, in order to further promote the application of construction risk assessment systems in the construction of urban utility tunnels.

Seo et al. (2019) conducted accident scenario analysis on potential hazards during the construction process, providing a theoretical basis for reducing the occurrence of fire accidents during the construction of urban utility tunnel.

The qualitative method played a crucial role in the initial stages of utility tunnel risk assessment, particularly in complex engineering scenarios where data was scarce. However, their limitations have become increasingly apparent with the development of practice. These methods rely heavily on expert experience, and their evaluation results are easily influenced by the composition of the expert group, cognitive biases, and “groupthink,” leading to subjective uncertainties that are difficult to quantify and control.

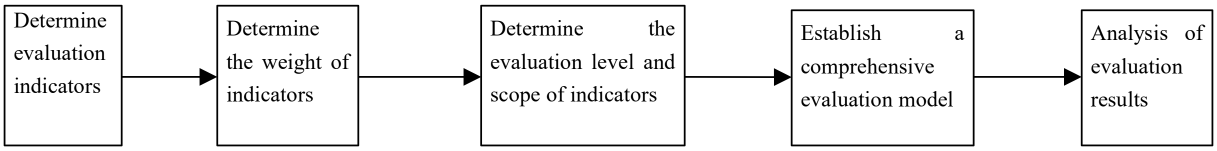
Seong J H (2018) et al. derived hazards related to the utility tunnel, screened key safety hazards, and conducted risk assessment using matrix method.

While risk matrices are intuitive, simply dividing the probability of risk occurrence and the severity of its consequences into a finite number of levels and then discretely combining them often obscures the subtle differences within a continuous risk spectrum, potentially leading to an underestimation of key risks or resource misallocation. Most studies of this kind stop at risk ranking, failing to further reveal the complex coupling and transmission mechanisms between risk factors, thus weakening the predictability and targeted nature of management strategies.

Recognizing the respective shortcomings of qualitative and quantitative methods, comprehensive methods have become the current mainstream research trend, attempting to achieve complementary advantages through method hybridization.

In recent years, Chinese scholars have mostly used the comprehensive evaluation method in the risk assessment research of integrated utility tunnel, and its general process is shown in Figure 4.

Figure 4: General Process of Comprehensive Evaluation



3.1 Weight Calculation

There are various methods for calculating weights, and the most commonly used method by scholars is the Analytic Hierarchy Process (AHP), which mainly conducts importance analysis through expert scoring. With the deepening of research, various evaluation methods have emerged to avoid the subjective judgment of experts affecting the results, making the weights closer to the actual situation.

AHP, refers to a decision-making method that decomposes elements related to decision-making into levels such as objectives, criteria, and plans, and conducts qualitative and quantitative analysis based on these levels (NGUYEN Thi Thuy Trang ,2019). This method is a hierarchical weight decision analysis method proposed by Professor Sati of the University of Pittsburgh, an American operations researcher, in the early 1970s when researching the topic of “electricity distribution based on the contribution of various industrial sectors to national welfare” for the US Department of Defense.

G1 weighting method is based on the AHP for improvement, allocating weights by quantifying the relative importance of different indicators (Zhao Hui, 2020).

Decision making Trial and Evaluation Laboratory (DEMATEL) was conducted by scholar from Battelle Laboratory in the United States Gabus (Duan Le ting ,2020). This method starts with the mutual influence between factors, identifies causal relationships between factors, and can obtain causal and outcome factors. By establishing a direct impact matrix, the influence degree, affected degree, cause degree, and centrality of each factor are calculated to determine the causal relationship between risk factors and the importance of risk factors in the indicator system.

Information entropy is also known as entropy weight method. According to the definition of information entropy, for a certain indicator, the entropy value can be used to determine the degree of dispersion of the indicator (Zhang Shuai, 2022). The smaller the information entropy value, the greater the degree of dispersion of the indicator, and the greater the impact of the indicator on the comprehensive evaluation. If the values of a certain indicator are all equal, then the indicator does not play a role in the comprehensive evaluation.

Criteria Importance Through Intercriteria Correlation is also known as CRITIC. It is an objective weight weighting method proposed by Diakoulaki (Zhao Hui, 2022). Determine the weight of each indicator by comprehensively considering its comparative strength and degree of conflict.

Combination Ordered Weighted Averaging is also called COWA. The OWA operator is the most fundamental research on information integration methods, proposed by American scholar Yager. Its purpose is to weaken the negative effects of extreme values to a certain extent by reordering and weighting the original data. There are numerous changes to the OWA operator, and Chinese scholars have conducted research from the perspective of improving data aggregation forms, believing that COWA can process data more efficiently and simply (Cai Menglong, 2020).

Combination weighting in game theory is a commonly used method for analyzing game problems. It transformed the game problem into a combinatorial problem, and then introduced weights based on the combinatorial problem to reflect the interests and strategies of each participant in the game (Han Yuhong, 2024). Also known as Method of Least Squares combined weighting.

3.2 Evaluate Model

At present, the most commonly used method by scholars is the fuzzy comprehensive evaluation method, on which many models have been developed.

In 1965, Professor L.A. Zadeh, an American expert in automatic control, proposed fuzzy sets concept to express the uncertainty of things. It is a comprehensive evaluation method based on fuzzy mathematics (Chen Wei, 2022). This comprehensive evaluation method transforms qualitative evaluation into quantitative evaluation based on the membership theory of fuzzy mathematics, that is, using fuzzy mathematics to make an overall evaluation of things or objects that are constrained by multiple factors.

The coupling degree model is a model that represents the interaction dependencies of system components. Charles Perrow proposed the concept of risk coupling in the 1970s and pointed out that the cause of accidents is the uncertainty and coupling of two vulnerable points in the system (Zhang Shuai, 2022). It describes the relationships between system components and the tasks they are responsible for. The coupling degree model is divided into three types: coupling type, coupling degree, and coupling details. Coupling type refers to the relationship type between components in a system, which can be classified as cohesive, strongly coupled, lightly coupled, and uncoupled. Coupling degree refers to the interdependence between system components, manifested as low coupling degree, medium coupling degree, and high coupling degree. Coupling details refer to the detailed associations between different components of a system. If there are many coupling details, it indicates that there are more connections between the components in the system, while if there are fewer, it indicates that there are fewer connections between the components in the system.

Grey Relational Analysis is a type of grey system analysis method. It is a method of measuring the degree of correlation between factors based on the similarity or dissimilarity of their development trends (Liu Ruke, 2018), also known as “grey correlation degree”.

Matter element extension method is a powerful tool for resolving secondary contradictions, primary contradictions, and critical problems in complex systems (Zhao Hui, 2020). It is based on the comparison and optimization of multiple known general decisions, by grasping key strategies and maximizing the conversion of incompatible contradictions into compatible relationships, thus achieving the global optimal decision-making goal.

In 1995, Support Vector Machine (SVM) was proposed by Corinna Cortes and Vapnik to solve pattern recognition problems. Based on statistics, it is used to handle classification and regression problems (Chen Bo, 2020). The selected training set is trained continuously to obtain the corresponding relationships between variables for prediction and classification.

System dynamics simulation model (SD) is a model that applies the principles of system dynamics to analyze the structure, behavior, and causal relationships of a system, and simulates the dynamic changes of the system (Duan Leting, 2020). The model establishes a structural model and performs computer simulation operations under different assumptions to predict the dynamic behavior of the system in various situations.

The uncertain measurement evaluation model is a mathematical model proposed to quantify the true quantitative relationships in a system and solve the problem of uncertain information (Zhang Shuai, 2022). By making judgments about the uncertainty contained in uncertain state things by decision-makers and converting this level of cognition into proportional magnitude.

Convolutional Neural Networks is also called CNN. The research began in the 1980s and 1990s, and it is a type of feedforward neural network that includes convolutional computation and has deep structure (Qin Huali, 2022). It is one of the representative algorithms of deep learning.

Interaction matrix analysis method is also known as cross probability method. A method of using the mutual influence matrix to solve the problem of interaction and mutual influence among various predicted events, in order to make accurate predictions (Jiang Hao, 2023). This law was first studied by the United States in the 1960s.

Social Network Analysis (SNA) is a quantitative analysis method developed by humanities and social scientists based on graph theory and other related theoretical foundations. Thomas first applied this method as a tool for describing social relationships between people, used as a research method for analyzing the relationship structure and attributes of social networks (Chen Shengfa, 2023). Compared to traditional analysis methods, social network analysis focuses more on the relationship characteristics of individuals in the network.

Bayesian Network model (BN) is a probability graph model that uses directed acyclic graphs to represent random variables and their conditional dependencies (Zhang Zhicheng, 2024). Nodes represent variables, edges represent conditional dependencies, and unconnected nodes represent conditional independence. Each node is associated with a probability function, which gives the probability of the node based on the variable values of the parent node.

Genetic Algorithm-Back Propagation is also called GA-BP. The GA-BP algorithm refers to the use of genetic algorithms to optimize backpropagation neural networks for improving their performance and efficiency. This method combines the evolution of genetic algorithms and the learning ability of backpropagation neural networks to achieve better optimization results (Xu Jingwei, 2020). Through this process, genetic algorithms can search the parameter space of neural networks, find the optimal parameter combination, and optimize the performance and generalization ability of neural networks. This method is commonly used to handle complex optimization problems, especially when neural networks have a large number of parameters.

Cloud model theory is a concept proposed by Li Deyi, academician of the CAE Member in 1995, is an uncertainty transformation model that deals with qualitative concepts and quantitative descriptions. It can represent the process from qualitative concepts to quantitative representations (forward cloud generator), or it can represent the process from quantitative representations to qualitative concepts (reverse cloud generator). The cloud model represents the primitives in natural language - language values, and uses the numerical features of clouds - expected Ex, entropy En, and super entropy He-to represent the mathematical properties of language values (Liu Yukexin, 2022). The research progress in the past 10 years has been investigated and summarized in Table 2.

Table 2: Summary of Research Progress on utility tunnel Risk Assessment Model

Reference / Time	**weight**	**assessment**
Chen Wei （2022）	DEMATEL Direct impact matrix	Fuzzy comprehensive evaluation
Li Fangzhen （2017）	AHP	Fuzzy comprehensive evaluation
Xu Hanyan （2020）	AHP	Fuzzy comprehensive evaluation
Ma Huigan （2021）	AHP	Fuzzy comprehensive evaluation
Hu Yihuan （2023）	Fuzzy analytical hierarchy process	Fuzzy comprehensive evaluation
Chen Bo （2020）	AHP Entropy method Minimum deviation and Combination weighting	Improving SVM Theory
Han Yuhong （2024）	AHP Entropy method Game theory	Bayesian network model
Cai Menglong （2020）	C-OWA	D-S synthesis algorithm
Zhao Hui （2020）	CRITIC GI weighting method	Improved Extended Matter Element Theory
Qiu Shi （2019）	Entropy method	coupling model
Zhang Yong （2020）	Entropy method DEMATEL	coupling model Vensim PLE software
Zhuang Shuai （2022）	Entropy method	uncertainty measurement theory
Huang Huijun （2020）	C-OWA	Grey correlation degree
Jiang Hao （2023）	C-OWA	interaction matrix

Reference / Time	weight	assessment
Chen Zeming (2020)	AHP	Grey correlation degree
Chen Shengfa (2023)	Social Network Analysis Method	Net draw software Ucinet6.0 software
Huang Ping (2020)	Static subtree Dynamic Accident Tree	Meta decision diagram markov chain model
Liu Yukexin (2022)	AHP	Cloud model Fuzzy comprehensive evaluation
Liu Keru (2018)	Grey correlation degree	
NGUYEN Thi Thuy Trang (2020)	AHP	
Qin Huali (2022)	1D-CNN	
Zhang Zhicheng (2024)	Bayesian network model	
Xu Jingwei (2020)	GA-BP	

3.3 Critical Synthesis and Methodological Limitations

As shown in Table 2, to overcome the subjectivity of qualitative analysis, quantitative models such as Bayesian Networks, and fuzzy mathematics have been introduced into the field of utility tunnel risk assessment. This combination of qualitative and quantitative methods significantly improves the objectivity of the assessment process and the accuracy of the results. However, the overemphasis on these methods has also brought new problems.

Some methods have extremely high requirements for the quality and quantity of basic data. Given the current reality of insufficient standardization of engineering data and incomplete historical databases, their complex calculations may simply be "precisely calculating inaccurate data," leading to a "garbage in, garbage out" dilemma.

Methods such as While Bayesian Networks can dynamically update probabilities and express causal relationships, the construction of their network structure and the assignment of conditional probability tables still largely depend on expert judgment, failing to completely eliminate subjectivity. Furthermore, the model complexity increases exponentially with the increase of risk factors, leading to decreased interpretability.

Therefore, while this type of research makes significant methodological contributions, a large amount of literature exhibits a technology-oriented phenomenon of "synthesis for the sake of synthesis." Many studies focus on improving weight calculations or membership functions, but neglect to delve into the engineering essence of the constructed indicator systems. This leads to a disconnect between the evaluation models and the specific technological, geological, and management scenarios of utility tunnel construction. There are more generalized models than specialized ones, and their foundations still cannot completely escape subjective qualitative inputs. Furthermore, most comprehensive models remain 'static snapshots,' failing to simulate the dynamic process of construction risks evolving as the project progresses.

Conclusion

In recent years, with the continuous expansion of the scale of integrated utility tunnel construction, construction safety accidents have occurred frequently, and construction risks have increasingly become a focus of attention for academic circles both domestically and internationally. Regarding risk assessment methods, an increasing number of studies are attempting to introduce new assessment models into the risk assessment system for utility tunnel construction. Some of these studies have built risk assessment models based on qualitative and quantitative indicators, demonstrating good results in engineering risk prediction and prevention.

However, overall, existing risk assessment models for utility tunnel construction still largely rely on qualitative descriptions of engineering geology, hydrology, and construction conditions, lacking in the quantitative processing of evaluation factors and the analysis of interaction mechanisms between indicators.

Overall, current research has made phased progress in promoting the development of risk assessment from qualitative to quantitative methods, but significant shortcomings remain in dynamic risk monitoring, multi-source information fusion, intelligent early warning, and interdisciplinary system integration. Future research needs to further integrate big data and artificial intelligence technologies to develop a more real-time, interactive, and operable dynamic risk assessment system to comprehensively improve the scientific rigor and proactiveness of integrated utility tunnel construction risk management.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Interface Physical Regulation and Performance Optimization of Solid-State Electrolytes and Perovskite Photovoltaic Devices

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Abstract: Facing the industrial demands of the "Dual Carbon" strategy and the development of a new generation of optoelectronic energy storage devices, all-solid-state lithium batteries (ASSLBs) and perovskite solar cells (PSCs) have emerged as international research frontiers in the field of advanced new energy materials and devices. Excessively high interfacial impedance, severe non-radiative recombination of defects, insufficient lattice stability, and poor consistency in large-scale fabrication are the common scientific bottlenecks restricting the performance breakthrough of these two types of devices. Based on the fundamental theories of materials physics, this paper systematically elucidates the ion transport mechanisms of solid-state electrolytes and the dynamic laws of photogenerated carriers in perovskites. Focusing on the key scientific issues including solid-solid interfacial charge transport, interfacial barrier modulation, defect passivation, and lattice stabilization, we review the cutting-edge regulation strategies such as element doping, interfacial modification, in-situ composite fabrication, and the construction of low-dimensional heterostructures. Combined with the industrial practices of Wuhan East Lake High-tech Development Zone (Optics Valley) in the fields of solid-state batteries, perovskite photovoltaics, sodium-ion energy storage, and interfacial regulation equipment, we analyze in depth the technical pathways and practical bottlenecks for the transformation of frontier materials from laboratory research to industrialization. The research results indicate that atomic-level precise interfacial regulation, multi-scale defect engineering, and the integrated fabrication of optoelectronic energy storage devices are the core directions for the future performance breakthrough of such devices. This work can provide theoretical references and research ideas for the study of interfacial physics of new energy materials, the design of high-performance devices, and regional industrial technological innovation in the new energy field.

Keywords: New Energy Materials; Solid-State Electrolyte; All-Solid-State Lithium Battery; Perovskite Solar Cell; Interfacial Regulation; Materials Physics; Wuhan Optics Valley

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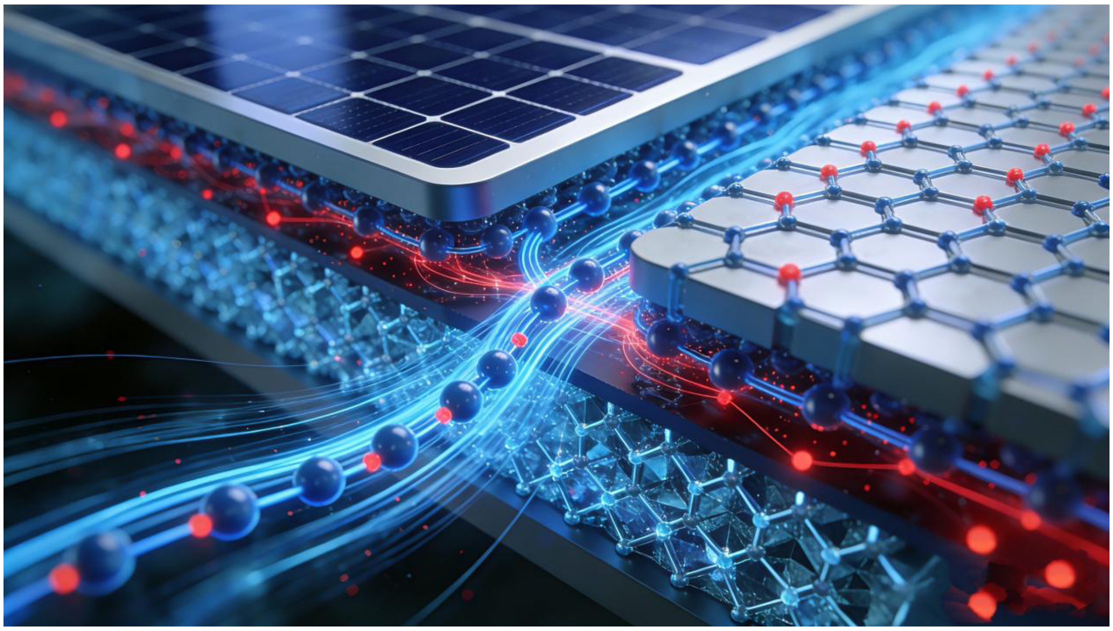
1. Introduction

With the accelerated transformation of the global energy structure towards low carbonization, electrification, and intellectualization, high-efficiency energy storage and advanced photovoltaic devices have become the key carriers supporting the global energy revolution. Traditional lithium-ion batteries are limited by the flammability of liquid electrolytes and the approaching upper limit of energy density, making it difficult to meet the high-safety and high-specific energy requirements of next-generation power batteries and grid energy storage [1]. All-solid-state lithium batteries replace flammable organic liquid electrolytes with inorganic or polymer solid-state electrolytes and can be matched with metallic lithium anodes, with a theoretical energy density exceeding 500 Wh kg^{-1}. This technology fundamentally solves the risk of thermal runaway and is recognized as the most promising technical route for industrialization in the field of new energy storage [2].

In the photovoltaic field, the photoelectric conversion efficiency of crystalline silicon batteries is gradually approaching the theoretical limit, while perovskite solar cells have achieved a rapid efficiency breakthrough by virtue of their inherent advantages, such as a high light absorption coefficient, long carrier diffusion length, tunable band gap, and low-temperature solution processability. The efficiency of perovskite-based tandem solar cells has exceeded 33%, making them the mainstream direction of next-generation high-efficiency photovoltaic technology [3]. However, both solid-state batteries and perovskite devices are plagued by a core bottleneck: the interfacial issue. The solid-solid interface between the electrode and electrolyte of ASSLBs contains contact voids, space charge layers, and side reaction layers, leading to high interfacial impedance and low lithium-ion transport efficiency [4]; a large number of defect states exist at the grain boundaries and surfaces of perovskite films, triggering severe non-radiative recombination and ion migration, which results in a sharp attenuation of device efficiency and long-term stability [5]. Essentially, these two types of problems all belong to the research scope of interfacial transport, defect dynamics, and lattice matching in the field of materials physics.

Fig. 1 Schematic diagram of the integrated structure of perovskite photovoltaic-solid-state energy storage devices



In Fig. 1, the upper layer is the perovskite photovoltaic panel, which is responsible for light energy capture and initial electric energy output; the middle layer is the two/three-dimensional solid-state electrolyte lattice structure, where the large blue spheres represent mobile ions (e.g., Li^{+}), the small red spheres represent photogenerated carriers or defect sites, and the particle flow indicates the direction of energy/ion transport; the lower layer is the supporting substrate and composite electrolyte network, with the blue and red particle flows representing the transport paths of photogenerated carriers and ions, respectively. This diagram intuitively demonstrates the energy conversion and interfacial regulation mechanism of the optoelectronic energy storage integrated device, reflecting the structural stability and unobstructed ion transport channels of the device.

As a national highland of the optoelectronic information and new energy materials industry in China, Wuhan East Lake High-tech Development Zone (Optics Valley) has gathered a number of cutting-edge enterprises, including Solid-state Ion Energy Technology (Wuhan) Co., Ltd, Dongfeng Yuechuang Technology Co., Ltd, Flexible Electronic Technology Co., Ltd, Wandu Photovoltaics Co., Ltd, Jiuyao Optoelectronics Co., Ltd, Yongjia Photovoltaics Co., Ltd, and Qina New Energy Co., Ltd. A complete innovation chain from core materials and interfacial regulation equipment to photovoltaic/energy storage devices has been formed [6-11], which provides an important practical scenario for the basic research and engineering transformation of new energy materials and devices.

Fig. 2 Panoramic layout of the new energy optoelectronic energy storage integrated industrial park in Wuhan East Lake High-tech Development Zone

In Fig. 2, the new energy industrial park takes "perovskite photovoltaics" and "solid-state batteries" as its two core development sectors. The perovskite photovoltaic array on the right side of the figure represents the third-generation new photovoltaic technology, symbolizing a clean energy acquisition approach with high photoelectric conversion efficiency; the solid-state battery energy storage unit on the left side represents the new generation of energy storage technology with high safety and high energy density, which effectively solves the intermittency problem of photovoltaic power generation. Fig. 2 intuitively presents the complete energy application chain, from the photoelectric conversion of photovoltaic modules and electric energy storage by solid-state batteries to intelligent scheduling and distribution in the park, fully reflecting the leading advantages of Wuhan Optics Valley in the research and development and large-scale industrial implementation of advanced energy materials.

Combined with the international cutting-edge research progress from 2023 to 2026 and the industrial technology development direction of Wuhan Optics Valley, this paper systematically discusses the interfacial physical regulation mechanisms, material design strategies, and device performance optimization methods of solid-state electrolytes and perovskite photovoltaic devices, with an emphasis on precise interfacial regulation and collaborative innovation of optoelectronic energy storage systems.

2. Interfacial Physical Mechanism of Solid-State Electrolyte Materials and All-Solid-State Lithium Batteries

2.1 Classification and Ion Conductivity Comparison of Solid-State Electrolytes

Solid-state electrolytes are mainly divided into four major systems: oxide-based, sulfide-based, polymer-based, and composite solid-state electrolytes, each with distinct structural characteristics and electrochemical performance.

Sulfide-based electrolytes exhibit the optimal ionic conduction capacity, polymer-based electrolytes have prominent flexibility but relatively low ionic conductivity at room temperature, and composite solid-state electrolytes can achieve balanced comprehensive performance by combining the advantages of different electrolyte systems. In fact, garnet-type $Li_7La_3Zr_2O_{12}$ (LLZO) and NASICON-type LAGP oxide-based electrolytes possess excellent chemical stability and a wide electrochemical window but suffer from low ionic conductivity at room temperature and poor interfacial contact with electrodes [12]. Sulfide-based electrolytes feature ultra-high ionic conductivity and good mechanical ductility, enabling cold pressing forming, and have become the mainstream industrialization route for ASSLBs at present. However, such electrolytes have prominent problems of high sensitivity to water and oxygen and severe interfacial side reactions with electrodes [13]. Polymer-based electrolytes have excellent flexibility and strong interfacial adaptability with electrodes, but their ionic conductivity at room temperature is limited by the segmental motion of polymer chains and thus needs to be improved through inorganic-polymer composite modification [14].

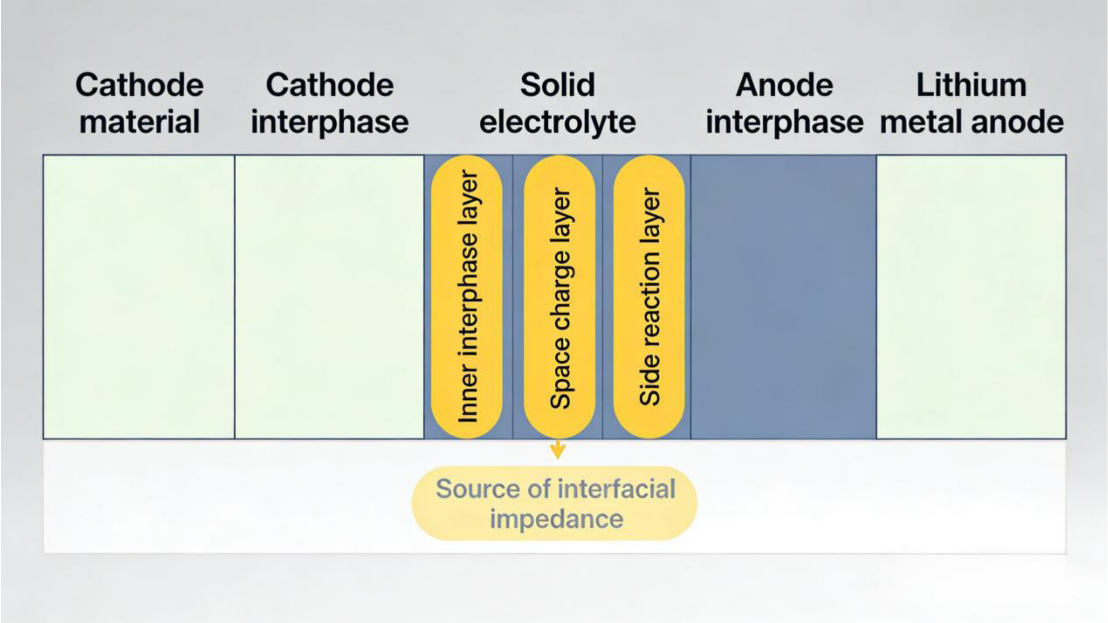
From the perspective of materials physics, lithium ions are mainly transported in solid-state electrolytes through lattice vacancy diffusion and interstitial diffusion, and the grain boundary impedance and defect distribution in the electrolyte bulk directly determine the overall ion transport efficiency [15]. Relying on the achievement transformation of Huazhong University of Science and Technology, Solid-state Ion Energy Technology (Wuhan) Co., Ltd has realized the pilot-scale mass production of polymer-based composite solid-state electrolytes, which provides important material support for the interfacial adaptation of high-performance all-solid-state lithium batteries [16].

2.2 Origin of Interfacial Impedance and Physical Model of All-Solid-State Lithium Batteries

The interfacial impedance of all-solid-state lithium batteries is the core bottleneck restricting their ion transport efficiency and comprehensive device performance. Clarifying the formation origin, distribution characteristics, and action mechanism of interfacial impedance is an important prerequisite for conducting research on interfacial regulation strategies. Different from the liquid-phase contact interface of traditional liquid lithium-ion batteries, the solid-solid multiphase interface formed by the cathode, solid-state electrolyte, and metallic lithium anode in ASSLBs forms multiple types and multi-level impedance sources due to lattice mismatch between different materials, differences in electrochemical potential, and uneven contact caused by fabrication processes. Various impedance causes are intertwined and interact synergistically at the interface, further aggravating the hindrance to lithium-ion transport.

To intuitively analyze the impedance composition of the electrode-electrolyte interface of ASSLBs and clarify the corresponding relationship between each component and impedance sources from the microstructural level, this paper constructs a visual model through the method of interfacial impedance decomposition, which clearly presents the formation and distribution law of impedance in the interfacial region. The specific interfacial impedance decomposition characteristics are shown in Fig. 3.

Fig. 3 Schematic diagram of interfacial impedance decomposition at the electrode-electrolyte interface of all-solid-state lithium batteries



The interfacial impedance of ASSLBs mainly originates from three key factors: poor physical contact, space charge layer barriers, and interfacial side reaction products. Micron-scale voids exist at the solid-solid interface between electrodes and electrolytes, leading to a significant decrease in the effective ion transport area; the electrochemical potential mismatch between electrodes and electrolytes causes the redistribution of lithium ions at the interface, forming a high-barrier space charge layer that hinders ion migration; irreversible chemical reactions occur between the electrode and electrolyte during charge-discharge cycles, generating an insulating interfacial side reaction layer that further blocks the ion transport path [17]. Electrochemical impedance spectroscopy (EIS) is an effective characterization method for interfacial behavior, which can decompose the total interfacial impedance into bulk impedance, grain boundary impedance, and interfacial transfer impedance, realizing the quantitative characterization of the dynamic behavior of lithium ions in different interface regions [18].

2.3 Interface Regulation Strategies for Solid-State Batteries

Interfacial regulation is the core technical path to improve the electrochemical performance of all-solid-state lithium batteries, and the key strategies mainly include element doping and lattice stabilization, interfacial buffer layer modification, in-situ solid-state reaction, and composite electrolyte structure design [19-20]. Flexible Electronic Technology (Wuhan) Co., Ltd has independently developed powder atomic layer deposition (ALD) equipment, which can realize atomic-level conformal coating on the surface of cathode materials and solid-state electrolytes, effectively passivating the interfacial defect sites, significantly reducing the interfacial impedance, and achieving domestic substitution of core equipment [21]. Dongfeng Yuechuang Technology Co., Ltd has built a pilot production line of all-solid-state lithium batteries with a high energy density of 350 Wh kg^{-1}, which has promoted the transformation of solid-state battery technology from laboratory material breakthrough to actual vehicle application [22].

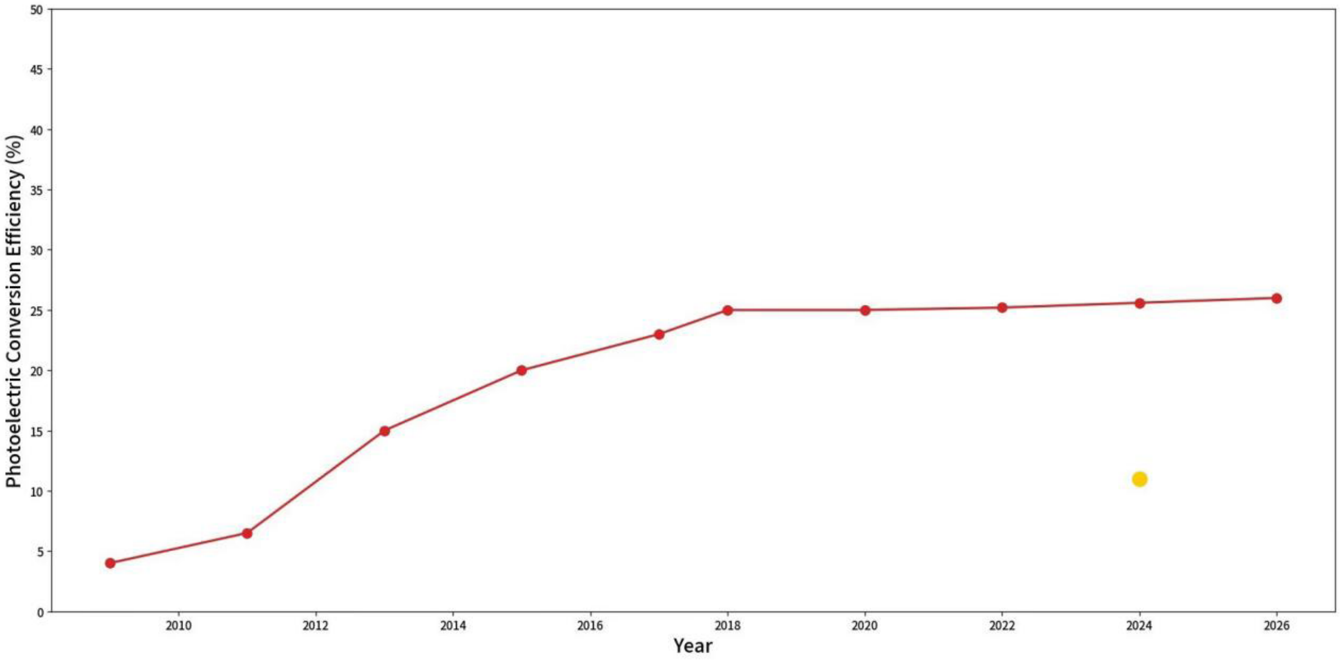
3. Physical Characteristics of Perovskite Photovoltaic Materials and Devices

3.1 Efficiency Development Curve of Perovskite Solar Cells

Relying on their unique intrinsic material advantages, perovskite solar cells have become one of the fastest technical iteration directions in the global photovoltaic field. Since the first report of perovskite solar cells with a photoelectric conversion efficiency of 3.8% in 2009, their efficiency has achieved a leap-forward improvement through continuous research and innovation, making them the most promising technical route for industrialization among third-generation photovoltaic technologies. Through a series of materials physics optimization methods such as component regulation, defect passivation, and interfacial engineering, researchers have continuously broken through the device efficiency bottleneck. The efficiency of single-junction perovskite solar cells has been continuously refreshed, and perovskite-based tandem solar cells have even broken the efficiency limit of single-junction photovoltaic devices, showing excellent development prospects for industrial application.

As of 2026, the certified photoelectric conversion efficiency of single-junction perovskite solar cells has risen rapidly from 3.8% in 2009 to 26.1%, and the efficiency of perovskite/silicon tandem solar cells has even reached 33%, as shown in Fig. 4.

Fig. 4 Trend curve of photoelectric conversion efficiency improvement of perovskite solar cells from 2009 to 2026



Due to their excellent photoelectric characteristics, the efficiency of perovskite solar cells has achieved a leap-forward improvement in more than a decade, far exceeding the development speed of traditional photovoltaic technologies such as crystalline silicon. Perovskite materials have a typical ABX_3-type crystal structure, with inherent advantages such as high defect tolerance, a high light absorption coefficient, and a long carrier diffusion length. Their band gap can be continuously adjusted over a wide range through component regulation, which makes them suitable for the fabrication of both single-junction and tandem high-efficiency photovoltaic devices [23]. The formamidinium-caesium-based mixed cation perovskite system can effectively inhibit the phase transition of perovskite crystals and the generation of intrinsic defects during fabrication and operation, and has become the mainstream structure of current high-efficiency and stable perovskite photovoltaic devices [24].

3.2 Defect Physics and Interfacial Recombination Mechanism of Perovskite Devices

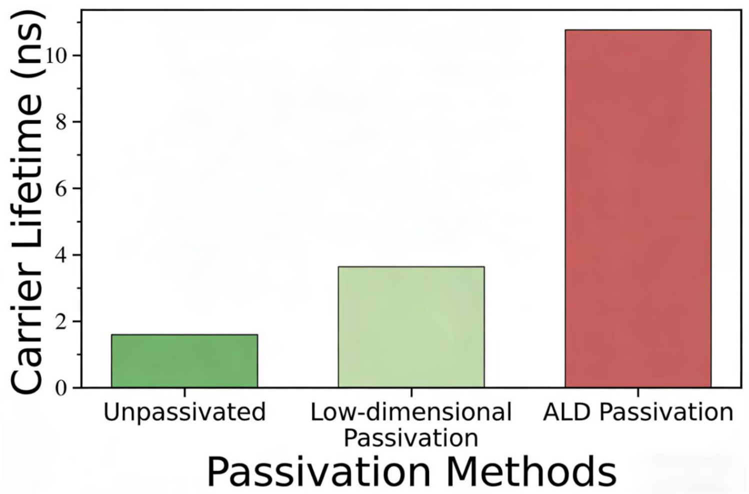
Perovskite materials are typical ionic crystals, and the solution-based fabrication process widely used in industrial production is prone to generate a large number of intrinsic defects such as iodine vacancies, lead vacancies, and surface dangling bonds in perovskite films. These defects act as non-radiative recombination centers, which significantly reduce the open-circuit voltage and fill factor of perovskite solar cells [25]. In addition to the intrinsic defects in the perovskite bulk, the energy level mismatch at the interface between perovskite films and charge transport layers further aggravates the non-radiative recombination of photogenerated carriers, which is a key factor restricting the further improvement of device efficiency and long-term stability [26].

3.3 Interface Passivation and Performance Optimization of Perovskite Solar Cells

Interface passivation, crystallization regulation, band engineering, and advanced packaging technology are the core means to improve the photoelectric performance and long-term stability of perovskite photovoltaic devices [27-28]. Among them, interfacial passivation strategies such as low-dimensional perovskite passivation, inorganic oxide interfacial bonding, and self-assembled monolayer modification can effectively passivate the defect sites at the surface and grain boundaries of perovskite films, significantly reduce the defect density, and improve the hydrothermal stability of perovskite devices [29].

Carrier lifetime is a key parameter to measure the photoelectric performance of perovskite films, and its length directly reflects the degree of non-radiative recombination of photogenerated carriers in the films, which is also a core index to verify the effectiveness of interfacial passivation strategies. To quantitatively compare the passivation effects of different interfacial passivation technologies on perovskite film defects, this study takes the unpassivated perovskite film as a blank control and selects two cutting-edge passivation methods widely used in the photovoltaic field, namely low-dimensional perovskite passivation and atomic layer deposition (ALD) passivation, to carry out comparative experiments. The carrier lifetime of perovskite films under different treatment methods is accurately tested and analyzed to intuitively present the actual efficiency of various passivation technologies in inhibiting defect recombination and improving carrier transport characteristics. The specific test results are compared as shown in Fig. 5.

Fig. 5 Histogram of carrier lifetime comparison of perovskite films before and after defect passivation with different methods



Effective interfacial passivation can significantly inhibit the non-radiative recombination of photogenerated carriers in perovskite films and improve the long-term stability and photoelectric conversion efficiency of devices. Wuhan Optics Valley has currently formed the most complete perovskite industrial ecosystem in China: Wandu Photovoltaics Co., Ltd has built a GW-level production line relying on the original mesoporous perovskite photovoltaic technology; Jiuyao Optoelectronics Co., Ltd has realized the low-cost mass production of large-area perovskite photovoltaic modules; Yongjia Photovoltaics Co., Ltd has developed all-perovskite tandem solar cells with a photoelectric conversion efficiency exceeding 40%; Yaohua Laser Co., Ltd, Aijiang Technology Co., Ltd, and Yuanlu Optoelectronics Co., Ltd provide core equipment support for the industrialization of perovskite photovoltaic technology [30-35].

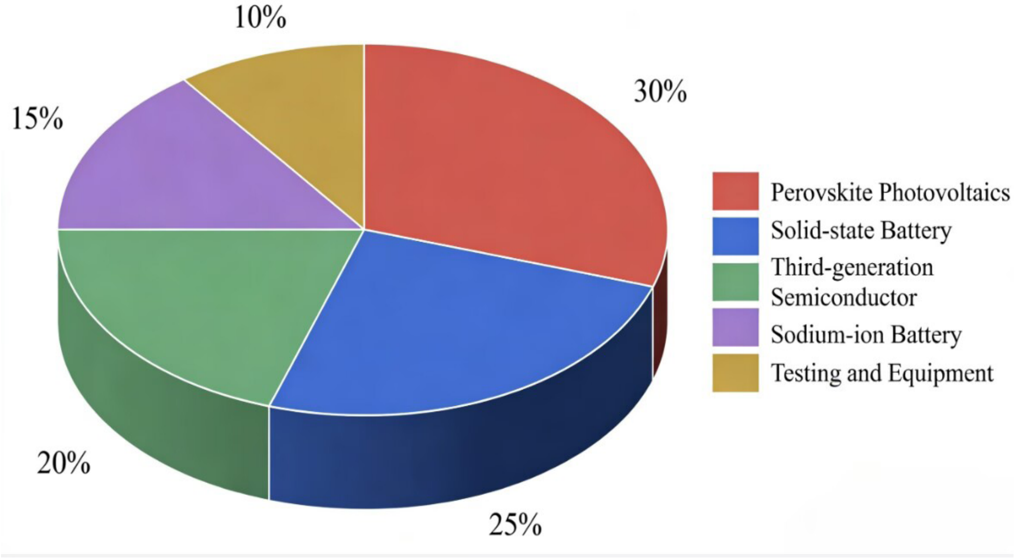
4. Analysis of New Energy Materials Industrial Structure in Wuhan Optics Valley

4.1 Industrial Distribution of New Energy Materials in Wuhan Optics Valley

Wuhan East Lake High-tech Development Zone (Optics Valley) has formed a diversified and clustered development pattern in the field of new energy materials industry, and the market-dominant sectors are mainly perovskite photovoltaics, solid-state batteries, third-generation semiconductors, sodium-ion batteries, and testing & core equipment manufacturing for new energy devices.

Relying on the core advantages of the optoelectronic information industry with complete industrial chains and strong technological innovation capabilities, Wuhan East Lake High-tech Development Zone has completed the full industrial chain layout in the field of new energy materials and devices, forming a distinctive industrial pattern with photovoltaic energy storage as the core and multi-technical route coordinated development. The industrial proportion and development focus of each subdivision field show distinct differentiation and synergy characteristics, which fully reflect the scientific industrial layout and technological innovation advantages of Wuhan Optics Valley in the field of new energy materials. The specific industrial structure distribution is shown in Fig. 6.

Fig. 6 Pie chart of the industrial structure of new energy materials and devices in Wuhan East Lake High-tech Development Zone



Perovskite photovoltaics and solid-state batteries are the core development directions of the new energy materials industry in Wuhan Optics Valley, forming a highly coordinated industrial layout of “core materials - key devices - high-end equipment”. Adhering to the development concept of “cutting-edge materials + high-end equipment + scenario application”, Wuhan Optics Valley has formed a synergistic development layout in the key directions of solid-state batteries, perovskite photovoltaics, sodium-ion batteries, and third-generation semiconductors. Qina New Energy Co., Ltd has developed high-performance cobalt-free nickel-iron-based sodium-ion cathode materials, reducing the raw material cost by 30% compared with traditional sodium-ion cathode materials; Changfei Advanced Technology Co., Ltd has laid out the research and production of silicon carbide power devices, which provide important device support for high-voltage energy storage and new energy vehicles; Huagong Technology Co., Ltd has promoted the industrialization of green hydrogen production equipment and built a complete photovoltaic-storage-hydrogen integrated energy system [36-38]. These key technical directions are highly consistent with the research content of interfacial physics, advanced material design, and device integration in this paper, which provides important industrial implementation scenarios for the transformation of academic research achievements in the field of new energy materials.

5. Summary and Research Prospect

5.1 Summary

All-solid-state lithium batteries and perovskite solar cells, as the core devices of next-generation energy storage and photovoltaic technology, face four common scientific problems in the process of performance improvement and industrialization: interfacial transport and barrier regulation, defect physics and lattice stability, microstructure-performance structure-activity relationship, and uniformity in large-scale fabrication. All these problems require in-depth mechanism research and innovative method exploration from the fundamental perspective of materials physics [39-41].

Based on the systematic research on the above scientific problems, this paper first systematically compares the core bottlenecks of solid-state batteries and perovskite devices from a unified perspective of interfacial physics, revealing the common physical mechanisms of interfacial problems in the two types of devices; then it deeply combines the industrial practice of Wuhan Optics Valley, realizing the effective integration of basic theoretical research on new energy materials and regional industrial technological innovation; finally, it puts forward constructive ideas on the future breakthrough path of "atomic-level interfacial regulation + optoelectronic energy storage integration", which can provide certain reference for subsequent research on advanced new energy materials and high-performance devices.

5.2 Future Development Trends

Driven by the global "Dual Carbon" strategy and the demand for high-performance new energy devices, new energy materials will develop towards high stability, low cost, large-area fabrication, and integrated integration in the future. Based on the current research status and industrial demand, atomic-level precise interfacial regulation, in-situ characterization technology of interfacial dynamic behavior, green lead-free perovskite systems, and high-efficiency optoelectronic energy storage coupling devices will become the research focuses in the field of new energy materials and devices.

Located in Wuhan, a national central city with strong scientific and technological innovation capabilities and a complete industrial chain of new energy materials, we can rely on industrial highlands such as Wuhan Optics Valley to accelerate the transformation of cutting-edge scientific research achievements to industrialization, further promoting China to take the leading position in the global research and development and industrialization of the new generation of high-performance new energy devices.

6. Conclusion

Taking all-solid-state lithium batteries and perovskite solar cells as the core research objects, this paper systematically discusses the ion transport mechanisms of solid-state electrolytes, the formation mechanism of interfacial impedance, the dynamic laws of photogenerated carriers, and the defect regulation rules of perovskite materials based on the basic theories of materials physics. The key regulation strategies for improving the performance of the two types of devices are summarized, including doping modification, interfacial passivation, heterostructure construction, and in-situ composite fabrication. Combined with the industrial innovation practice of the new energy materials industry in Wuhan Optics Valley, the technical bottlenecks and future development directions in the process of translating frontier new energy materials from laboratory research to industrialization are analyzed in depth.

The research results show that the in-depth analysis of interfacial physical mechanisms and atomic-level precise interfacial regulation are the core keys to breaking through the performance bottleneck of all-solid-state lithium batteries and perovskite solar cells. The research ideas and regulation strategies proposed in this paper can provide important theoretical reference and technical support for the design of high-performance new energy devices and the technological innovation of the new energy materials industry.

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No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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A Review on Construction Quality Management of Prefabricated Housing in Xi'an

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Abstract: China's construction industry, despite over 30 years of development since the reform and opening-up period, remains largely traditional, characterized by outdated construction methods and labor-intensive practices. However, with the gradual disappearance of the "demographic dividend," the industry is facing a growing labor shortage. To adapt to the demands of new urbanization, industrialization, and informatization, as well as to align with the "dual carbon" development strategy and promote construction industrialization, China has been vigorously developing prefabricated residential projects. While significant progress has been achieved under supportive policies, the industry is still in a transitional phase from traditional to industrialized construction methods, with construction quality requiring further improvement. Considering the potential of contractor's perspectives to enhance construction quality management, this study explores the evaluation of construction quality management in prefabricated residential projects through the lens of contractors.

This study systematically reviews the fundamental theories of construction quality management evaluation for prefabricated residential projects and identifies initial evaluation indicators based on the characteristics of these projects through a literature analysis method. Subsequently, expert surveys are employed to finalize the evaluation indicators, establishing a contractor-based evaluation indicator system for construction quality management. The study then applies the Analytic Hierarchy Process (AHP) to calculate the weights of indicators at both the criterion and indicator levels and develops a construction quality management evaluation model using the fuzzy matter-element analysis method.

The research results of this article provide an important basis for contractors to conduct quality management evaluations.

Keywords: Prefabricated Residential Buildings; Construction Quality Management Evaluation; Evaluation Indicators; Evaluation Model

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1. Introduction

1.1 Research Background and Importance

Prefabricated construction has been recognized as a transformative approach to address inefficiencies, environmental pollution, and labor shortages in China's traditional construction industry. Since the release of "The Action Plan for Promoting Prefabricated Building Development (2021–2023)", Xi'an—capital of Shaanxi Province and a key node in the

"Belt and Road Initiative"—has set a target of 30% prefabricated housing in new urban residential projects by 2025 [1]. Unlike cast-in-situ construction, prefabricated housing relies on off-site production of standardized components and on-site assembly, which places higher demands on quality coordination across the supply chain [2].

Contractors act as the "integrator" of prefabricated projects: they coordinate component suppliers, manage on-site assembly teams, and ensure compliance with quality standards [3]. However, existing studies on prefabricated quality management have mostly focused on technical aspects or owner/consultant perspectives, with limited attention to contractors' practical challenges [4]. This gap hinders the formulation of targeted quality management optimization strategies that align with industry practice.

1.2 Research Objectives

To improve the overall construction quality of prefabricated housing projects and promote the sustainable development of prefabricated housing, it is essential to have a clear understanding of the on-site quality management level and identify weaknesses in on-site quality management. The study aims to answer the following questions:

(1) What are the critical factors influencing the reliability and performance of prefabricated residential projects in Xi'an?

(2) How can a comprehensive evaluation framework for construction quality management in prefabricated housing projects be developed for Xi'an?

2. Literature Review

2.1 Framework and Research Logic

This study focuses on three core dimensions: prefabricated housing construction quality management, the contractor-centric perspective, and the regional specificity of Xi'an. The review follows a logical structure of theoretical foundation → thematic focus → regional contextualization → gap identification, systematically organizing domestic and international literature to lay a solid basis for constructing a contractor-oriented evaluation system for prefabricated housing construction quality management and conducting empirical research in Xi'an. Specifically, it first clarifies the theoretical connotation and global development context of prefabricated housing quality management; then narrows the focus to the contractor's role and management practices; further anchors the analysis to Xi'an's unique regional characteristics; and finally identifies the research gaps to define the innovation points of this dissertation.

2.2 Connotation, Characteristics, and Global Development of Prefabricated Housing

Prefabricated housing (off-site/modular construction) entails factory prefabrication of components (precast concrete, steel, wood) for on-site assembly [5], with core metrics of prefabrication and assembly rates. It features standardized design and factory production, aligning with green and industrialized construction trends, differing from traditional cast-in-place methods.

Globally, it has evolved through three phases: initial exploration (1950s–1980s), mature development (1990s–2010s), and intelligent upgrading (2010s–present). Europe's Germany leads in precast concrete; the UK uses MMC for housing and carbon goals (2021). East Asia's Japan pioneered housing industrialization [6], while South Korea excels in steel prefabrication.

Southeast Asia's Singapore targets 80% public housing prefabrication (2022), but Malaysia faces industrial chain/talent gaps [7].

In China, prefabricated buildings hit 30% of new starts by 2023. Xi'an mandates 25% prefabrication in key areas (2022), with projects in emerging zones but lags eastern cities in industrial chain maturity and talent [8].

Construction quality management spans design, construction and acceptance to meet standards, rooted in TQM, PDCA, Six Sigma, Lean Construction and 5M1E [9].

Prefabricated housing quality management has an extended chain and diverse risks covering component production, transportation, on-site assembly and strict acceptance. Core pain points include component deviation, poor hoisting accuracy, node leakage and incomplete traceability, requiring full-chain control [10].

2.3 Construction Quality Management from the Contractor's Perspective

Contractors' quality management roles have evolved with construction modes. In traditional cast-in-place projects, they served as "construction executors" focused on on-site process control. For prefabricated housing, they have become "full-chain coordinators" linking component factories, teams, and stakeholders, overseeing component production, transportation, and on-site assembly.

Their lifecycle responsibilities include: pre-construction design review and quality plan formulation; strict component incoming inspections; on-site control of hoisting, grouting, and waterproofing; rapid defect response and rectification tracking [11]; and acceptance coordination with owners and supervisors. Cross-stakeholder collaboration is also critical: resolving design interface issues, joint factory supervision, and closed-loop reporting.

Existing studies have identified three primary quality management modes for contractors undertaking prefabricated housing projects, each with distinct advantages and limitations. The EPC integrated management mode enables the unification of quality control across design, procurement, and construction processes, as demonstrated by the successful full-cycle quality oversight in Shanghai's Lingang prefabricated housing project, which earned national demonstration project recognition; however, this mode imposes stringent requirements on contractors' comprehensive capabilities, thereby restricting its adoption among small and medium-sized enterprises (SMEs). The specialized quality management team mode delivers targeted quality control, with one Beijing-based contractor's dedicated team cutting component rejection rates from 5.2% to 1.8% by developing customized acceptance manuals and assembly checklists, though this approach incurs substantial labor costs that can strain project budgets. Meanwhile, the supply chain collaboration mode leverages information platforms to enhance the efficiency of quality defect resolution—for instance, a Guangzhou contractor improved defect handling efficiency by 30% through a joint quality information platform with local component factories —yet its widespread promotion is impeded by low levels of supply chain informatization and insufficient willingness to collaborate among participating enterprises.

Contractors deploying digital tools for prefabricated housing quality management face a trade-off between technological benefits and practical constraints across three primary solutions. Building Information Modeling (BIM) supports critical workflows including component detailing, hoisting simulation, and full-cycle quality traceability [12], yet its widespread adoption is hampered by high implementation costs and a shortage of skilled professionals, with penetration rates below 20% among contractors in Xi'an specifically. Radio Frequency Identification (RFID) technology enables real-time tracking of prefabricated component logistics, but its effectiveness is undermined by electromagnetic interference at construction sites and elevated equipment maintenance expenses. Meanwhile, smart construction site systems provide real-time monitoring of key construction parameters such as hoisting precision and grouting density; however, most contractors using these systems only achieve basic data collection, failing to translate the gathered information into actionable, data-driven quality management decisions [13].

2.4 Influencing Factors and Evaluation Systems for Contractors' Quality Management

Internal factors include technical capability, management level, personnel quality, and financial strength. In Xi'an, only 35% of contractors' technical teams hold prefabricated construction qualifications [14], and many small contractors lack standardized quality manuals, relying on experience-based construction.

External factors include policies, market environment, supply chain collaboration, and technical standards. Xi'an has only 12 component manufacturers, mostly in suburban areas, causing communication delays and quality standard inconsistencies. Additionally, outdated local standards increase management difficulties.

Existing evaluation systems mostly adopt regulator or owner perspectives. For example, China's Prefabricated Building Evaluation Standard (GB/T 51129-2017) focuses on assembly rate and green performance, ignoring contractors' construction control effectiveness. Some academic systems include indicators like "component acceptance rate" and "one-time hoisting success rate" but exclude Xi'an's regional characteristics and contractors' cost considerations.

2.5 Regional Specificity of Prefabricated Housing Quality Management in Xi'an

Against the backdrop of robust prefabricated housing industrial bases in eastern hubs like Shanghai (annual component capacity >5 million m^3) and Shenzhen (prefabricated project ratio >40%), Xi'an lags significantly with a 2023 component output of just 800,000 m^3, concentrated on small components. Large panels and slabs must be imported from other regions, driving up costs and causing delivery delays.

Xi'an's prefabricated housing policies have two distinct local traits: first, climate adaptation measures mandate integrated external wall insulation and -10°C node crack resistance for the cold Guanzhong climate, stricter than southern standards; second, 32% of 2021–2023 urban village redevelopment projects adopted prefabrication, though tight schedules and limited space added quality hurdles.

For local contractors, two key pain points persist: winter low temperatures slow grout solidification, leading to strength deficits and cracking, with contractors lacking specialized plans facing a 15% node rework rate; meanwhile, only 20% of contractors master the "precast pile + raft foundation" technique needed for Xi'an's collapsible loess, with most relying on incompatible traditional methods.

Current Xi'an-focused research prioritizes policy and macro-technology but overlooks contractors' micro-quality management challenges. Local practices yield mixed results: a state-owned contractor cut component rejection from 8% to 2% via dual factory-site inspections (2023), but the high-cost model is unfeasible for SMEs, while a private firm's three component collisions exposed SME storage management flaws.

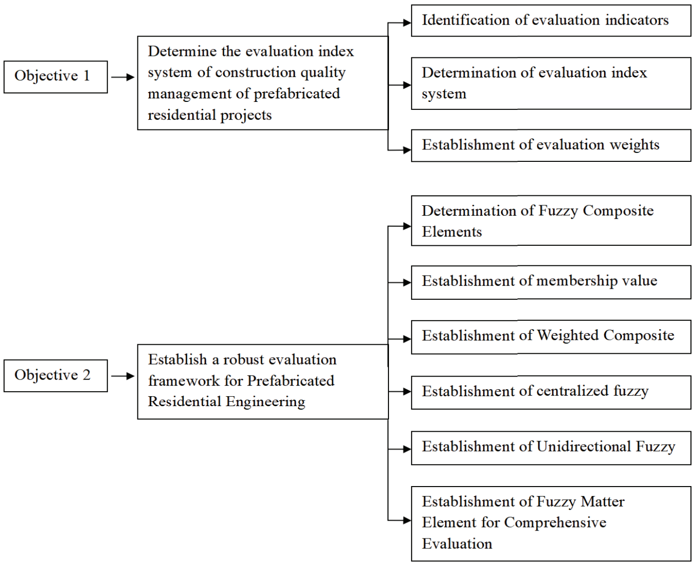
Despite the progress made in prefabricated construction, several gaps remain in the current literature that warrant further investigation. One of the most significant gaps is the lack of region-specific studies that address the unique challenges faced by different cities in China, such as Xi'an, where infrastructure and skill levels may not be as advanced as in coastal cities like Shanghai and Beijing. Existing research does not pay enough attention to the main actors in the construction execution process and does not consider the contractor's dual role as "executor-coordinator". Another gap identified is the insufficient focus on the human factors in quality management, particularly the role of training and skill development in ensuring consistent quality across all stages of the prefabrication process. Additionally, while the integration of digital technologies such as BIM and AI into quality management has been widely discussed, there is a "lack of research" focused on the practical integration of these technologies into quality management systems. Addressing these gaps is crucial for developing more tailored and effective strategies for enhancing the quality and performance of prefabricated residential projects in diverse urban settings.

3. Methodology

Based on the theories of construction quality management and evaluation, combined with the characteristics of prefabricated residential projects, the initial evaluation indicators are identified through literature analysis. The initial indicators are screened and optimized using the expert survey method, and the weight of each indicator is determined by AHP to form a complete evaluation index system.The fuzzy matter-element analysis method is used to construct the construction quality management evaluation model of prefabricated residential projects based on the index weights obtained from AHP.

The overall research design of this study is shown in Figure1:

Figure1 research design

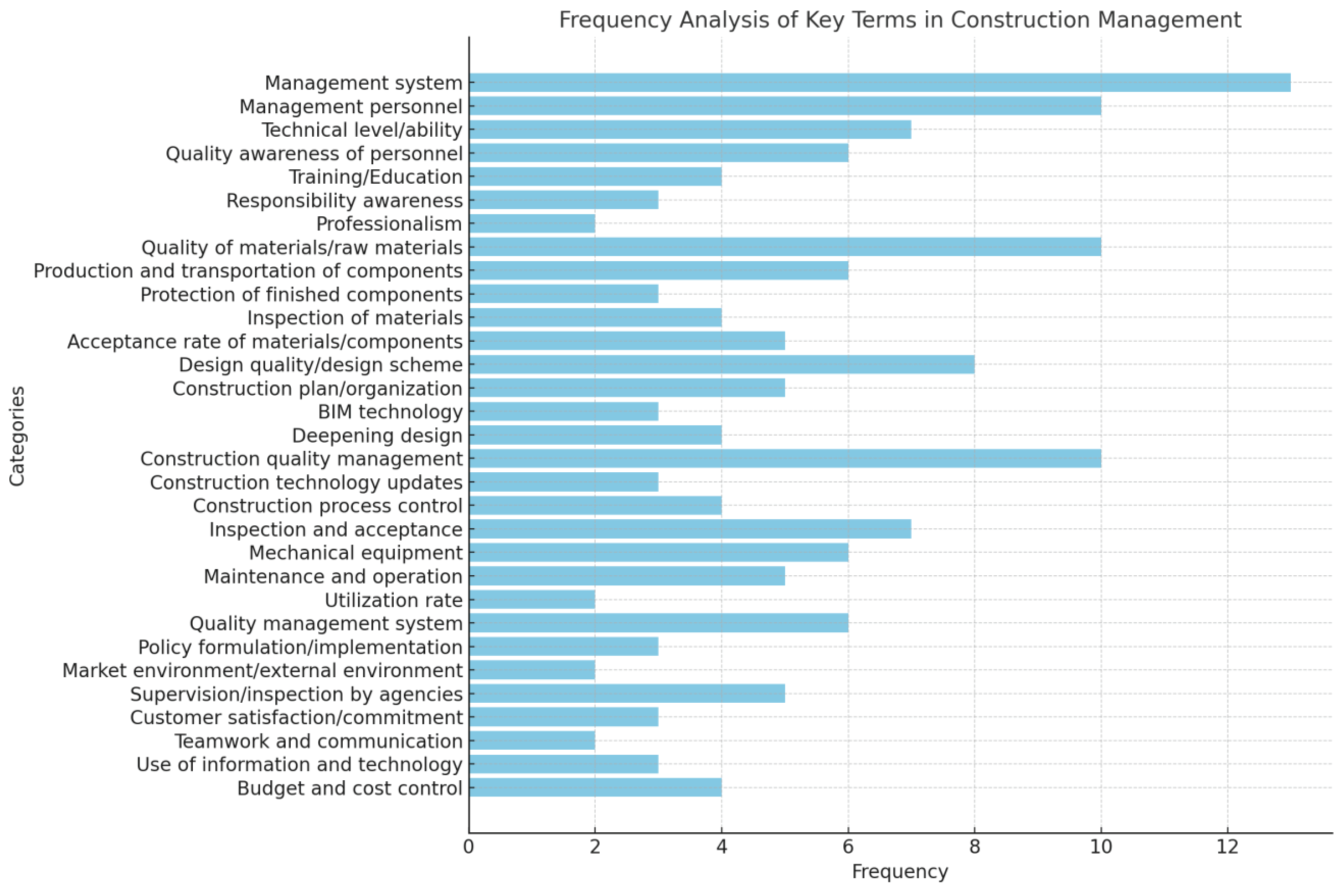


3.1 Research Methods

The main purpose of adopting the literature analysis method is to systematically sort out the basic theories of construction quality management evaluation of prefabricated residential projects, and initially identify and summarize the evaluation indicators. This method lays a theoretical foundation for the follow-up establishment of the evaluation index system and ensures the academic rigor and theoretical basis of the research indicators.

Retrieval channels include Chinese and foreign academic databases (such as CNKI, Web of Science), university libraries, and industry monographs. The retrieval keywords are "prefabricated building", "residential engineering", "construction quality management", "construction quality management evaluation", etc. According to the research theme, 23 high-relevance literatures are screened out from the retrieved documents, focusing on the research results related to construction quality management evaluation of prefabricated buildings. The evaluation indicators mentioned in the literature are sorted out, and indicators with the same or similar meanings are merged and optimized. Finally, 27 initial evaluation indicators covering six dimensions (personnel management, material management, mechanical equipment management, technical management, on-site management, and information management) are initially determined. The frequency of evaluation indicators for construction quality management of prefabricated residential project is shown in Figure2.

Figure2 Frequency Analysis of Terms in Construction Management



The expert survey method is used to further screen and confirm the initially identified evaluation indicators, determine the index weight scoring data and the section domain and grade division standards of evaluation indicators. This method combines the practical experience of industry experts to make up for the limitations of the literature analysis method and ensures the practical applicability of the evaluation index system.

A total of 10 experts are invited, including professionals from construction units, all of whom have more than 9 years of work experience in the construction industry and have professional titles or qualification certificates such as first-class constructor and registered supervision engineer. The survey is divided into two parts: indicator screening questionnaire and index weight scoring questionnaire. The questionnaires are distributed in the form of Questionnaire Star.

3.2 Data Collation and Analysis

The expert opinions are collected and sorted out. For the initial indicators, the final 27 evaluation indicators are determined according to the experts' suggestions of "adding, deleting and merging"; for the index weight scoring data, the average value of the experts' scores is taken to form the judgment matrix of AHP; for the index section domain and grade division, the final standard is determined by combining the experts' opinions and the actual engineering situation.

3.2.1 Implementation of AHP

AHP is used to calculate the weights of the evaluation indicators at all levels of the index system. This method can quantitatively handle the qualitative problems of multi-level and multi-index, and clarify the relative importance of each indicator, providing a basis for the subsequent construction of the evaluation model.

The model is divided into three levels: the target layer (construction quality management evaluation of prefabricated residential projects), the criterion layer (6 indicators including personnel management, material management, etc.), and the index layer (27 specific evaluation indicators).

Level 1 (Goal): Evaluating the quality management of prefabricated construction.

Level2 (Criteria): Key factors influencing quality, such as consistency of components, effectiveness of regulations, and reliability of supply chains.

Level3 (Sub-Criteria): Specific aspects under each criterion, such as curing methods, dimensional accuracy, and compliance monitoring.

The 1-9 scale method is used to construct the judgment matrix of the criterion layer and each index layer (see Tables 3-4 to 3-10 for the judgment matrix). The scale 1 means that the two indicators are equally important, and the scale 9 means that one indicator is absolutely more important than the other, as shown in Table 1.

Tables1 Meaning of scale 1-9

No.	Scale meaning	Ratio
1	When comparing the former element i to the latter element j, both i and j are equally important.	Aij=1
2	When comparing the former element i to the latter element j, element i is slightly more important than element j.	Aij=3
3	When comparing the former element i to the latter element j, element i is obviously more important than element j.	Aij=5
4	When comparing the former element i to the latter element j, element i is much more important than element j.	Aij=7
5	When comparing the former element i to the latter element j, element i is absolutely more important than element j.	Aij=9
6	The importance of element i and element j falls between the above judgments.	Aij=2n, (n=1,2,3,4)
7	The comparison of the importance of element j and element i results in the reciprocal of element i and element j.	Aji=1/n, (n=1,2,3,...9)

Each element Aij represents the relative importance of factor *i* compared to *j*.

3.2.2 Construct a judgment matrix

By judging each two elements in the matrix one by one according to the scale in Table 1, an n-order comparison judgment matrix table can be obtained, as shown in Table 2.

Tables2 N-order judgment matrix table

A	A_1	A_2	…	A_n
A_1	A_{11}	A_{12}	…	A_{1n}
A_2	A_{21}	A_{22}	…	A_{2n}
…	…	…	…	…
A_n	A_{n1}	A_{n2}	…	A_{nn}

The matrix A has the following properties, $A_{ij} > 0$，$A_{ij}=1/A_{ji}$（$i \neq j$），$A_{ii}=1$（i，j=1，2，…，n）。

3.2.3 Calculating Relative Weights

As can be seen from the previous text,

judgment matrix $$A = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \dots & \dots & \dots & \dots \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix}$$

(1) After normalizing each column vector in matrix A=(Aij) n × n, a new matrix B=(Bij) n × n is obtained.

$$B= \begin{bmatrix} B_{11} & B_{12} & \dots & B_{1n} \\ B_{21} & B_{22} & \dots & B_{2n} \\ \dots & \dots & \dots & \dots \\ B_{n1} & B_{n2} & \dots & B_{nn} \end{bmatrix}$$

Where:

$B_{ij} = \frac{A_{ij}}{\sum_{i=1}^{n} A_{ij}}$（i=1，2，3，…，n，j=1，2，3，…，n）

(2) Add the row vectors of the normalized matrix B to obtain a new vector T.

$$T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ \dots \\ T_n \end{bmatrix} = (T_1, T_2, \dots, T_n)^T$$

Where:

$T_i = \sum_{j=1}^{n} B_{ij}$（i=1，2，3，…，n，j=1，2，3，…，n）

(3) Normalize the vector $T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ \dots \\ T_n \end{bmatrix}$ to obtain the feature vector w.

$$W = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \dots \\ w_n \end{bmatrix}$$

Where:

$w_i = \frac{T_i}{\sum_{i=1}^{n} B_{ij}}$（i=1，2，3，…，n）.

This feature vector is the weight vector of each indicator, and w_i (i=1, 2, 3,..., n) is the weight of each corresponding indicator.

3.2.4 Consistency check of judgment matrix

A critical aspect of AHP is ensuring the consistency of stakeholder judgments through the Consistency Ratio (CR). The CR measures the reliability of pair wise comparisons and ensures that judgments are logically consistent.

1) Find the maximum characteristic value λmax.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(Aw)_i}{w_i} = \frac{1}{n}\sum_{i=1}^{n} \frac{\sum_{j=1}^{n} A_{ij}.w_j}{w_i}$$

In the above equation, (Aw)i is the i-th component of (Aw).

2) Calculating the Consistency Index (CI):

The Consistency Index (CI) is computed using:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where:

λmax: Principal eigenvalue of the matrix.

n: Number of criteria.

3) Determining the Consistency Ratio (CR):

The CR is derived by comparing the CI to a Random Index (RI), which represents the average consistency of randomly generated matrices of the same size:

$$CR = \frac{CI}{RI}$$

The RI values, as introduced by Saaty (1980), are introduced randomness index, and its value is only related to the order of the judgment matrix. The specific values are shown in Table 3.

Tables3 The Random Index (RI) values

(Source: Saaty, 1980)

n	RI
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Interpretation of CR:

The judgment matrices with $n<3$, the judgments always have complete consistency.

The judgment matrix with $n \geq 3$,

If $CR<0.10$, the judgments are considered consistent and reliable.

If $CR \geq 0.10$, the judgments are inconsistent and require revision.

Mitigating Inconsistencies:

If the CR exceeds the acceptable threshold, stakeholders are asked to revisit their pairwise comparisons. This iterative process ensures that the final judgments are both logical and defensible.

3.2.5 Significance of CR in This Study

The CR is essential to maintaining the credibility of the AHP results. Ensuring consistent judgments enhances the reliability of the derived weights, which are crucial for evaluating and prioritising quality management factors. Inconsistent judgments could compromise the framework's validity, leading to flawed conclusions and recommendations.

The calculations involved in AHP, particularly the computation of λmax and CR, can be complex. To streamline the process, software such as Microsoft Excel (with AHP templates), is employed. This tool automates matrix operations, eigenvalue calculations, and consistency checks, reducing the likelihood of errors.

4. Fuzzy Matter-element Analysis Method

The fuzzy matter-element analysis method is used to construct the construction quality management evaluation model of prefabricated residential projects. This method can handle the fuzziness and multi-index characteristics of construction quality management evaluation, and realize the quantitative evaluation of the quality management level of prefabricated residential projects.

Determine the evaluation grade (divided into 5 grades: poor, relatively poor, general, good, excellent) and the classical domain and section domain of each indicator, and establish the evaluation object's index value matter-element according to the actual data of the project. The ascending and descending semi-trapezoidal distribution functions are used as the membership degree functions to calculate the membership degree of each indicator to different evaluation grades, and the membership degree matter-element is formed. The weight matter-element of each indicator is established according to the index weight obtained by AHP. Multiply the weight matter-element and the membership degree matter-element to obtain the centralized fuzzy composite matter-element; then calculate the single fuzzy composite matter-element and the comprehensive evaluation fuzzy composite matter-element, and determine the final evaluation grade of the project according to the maximum value of the comprehensive evaluation value.

Conclusion

This study focuses on the construction quality management evaluation of prefabricated residential projects in Xi'an from the contractor's perspective, aiming to address the gaps in existing research that overlook contractors' practical challenges and regional characteristics. Through a systematic literature review, expert surveys, analytic hierarchy process (AHP), and fuzzy matter-element analysis, the research establishes a comprehensive evaluation framework and achieves three key outcomes. First, based on the 5M1E theory and characteristics of prefabricated construction, an initial set of 27 evaluation indicators across six dimensions (personnel management, material management, mechanical equipment management, technical management, on-site management, and information management) was identified and validated by industry experts, ensuring both theoretical rigor and practical applicability. Second, AHP was employed to calculate the relative weights of indicators at all levels, with consistency checks confirming the rationality of the weight distribution, which clarifies the priority of quality management focus for contractors. Third, a fuzzy matter-element evaluation model was constructed to quantify the fuzziness and multi-index nature of quality management evaluation, providing a operable tool for contractors to assess their quality management performance.

Empirically, the study highlights the unique challenges faced by Xi'an's prefabricated construction industry, such as insufficient local component production capacity, harsh winter construction conditions, and collapsible loess foundation constraints. The contractor-centric evaluation system addresses these regional specifics and contractors' roles as "full-chain coordinators," filling the gap between existing policy/owner-oriented evaluation standards and on-site practice. The research findings not only offer a scientific basis for contractors to identify quality management weaknesses and optimize strategies but also provide reference for local governments to refine prefabricated construction policies and promote the sustainable development of the industry in Xi'an and similar inland cities.

Limitations of this study include the small sample size of expert surveys and the lack of long-term tracking of case projects. Future research could expand the scope of expert consultations, incorporate more empirical data from different regions, and explore the integration of digital technologies (e.g., BIM, RFID) into the evaluation model to enhance its dynamic adaptability. Additionally, comparative studies between Xi'an and coastal cities with mature prefabricated construction industries could further enrich the understanding of regional differences in quality management.

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No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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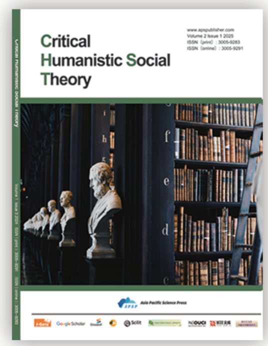

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