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Multidimensional Performance Adaptation Strategies of Engineering Plastics in Smart Home Design

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Abstract: The smart home industry is moving towards a "whole-house interconnection" era. Consumer demands are upgrading towards a balance of greenness, personalization, and sensory experience, which puts forward new requirements for the multi-dimensional performance of key materials. Although engineering plastics have become the core carrier due to their excellent comprehensive performance, their application is facing a prominent predicament of difficulty in coordinating "performance - environmental protection - sensory experience". This paper aims to construct a multi-dimensional performance adaptation strategy for engineering plastics in smart homes. Firstly, by establishing a material classification and multi-dimensional demand model based on application scenarios, it systematically analyzes the quantitative index requirements of smart homes for engineering plastics in three dimensions: mechanical performance, environmental sustainability, and user experience. Secondly, from the perspectives of molecular structure, surface characteristics, and industrial ecology, it deeply analyzes the internal mechanism of multi-dimensional performance conflicts, pointing out that the root cause lies in the inherent contradictions at the molecular design level and the "three-dimensional isolation" of technical paths. Then, this paper innovatively proposes a three-dimensional collaborative strategy framework of "material genes - interface engineering - system optimization", and verifies the feasibility and significant benefits of this framework in achieving an effective balance between performance, environmental protection, and sensory experience through three empirical cases: modification of the shell of smart speakers, surface engineering of the panel of smart locks, and systematic selection of smart refrigerators. The research conclusion shows that through multi-dimensional collaborative innovation, the current bottleneck of material application can be effectively broken, providing theoretical support and practical paths for the upgrade of the smart home industry towards high performance, low environmental footprint, and excellent user experience.

1. Introduction

Smart home technology is moving from "single-item intelligence" to "whole-house interconnection". The global market size will exceed 750 billion US dollars in 2024, with a compound annual growth rate of over 12% (Statista, 2024) [1]. Consumer demands are shifting from function-oriented to emphasizing greenness, personalization, and experience, and they have higher requirements for materials. Traditional metal materials, due to their high density (about 3-5 times that of engineering plastics) and long processing cycle (more than twice that of plastic molding), are difficult to meet the demands for lightweighting and customization; general plastics (such as PP, PE) have insufficient mechanical properties (the tensile strength is generally less than 30 MPa) and thermal stability (the heat deformation temperature is mostly less than 60℃). Engineering plastics, due to their combination of strength-to-weight ratio, modifiability, and processing adaptability, have become the key carriers for technology integration and experience optimization [2]. However, their application faces a "performance-environment-sensory" coordination challenge: high-performance materials often have environmental defects, environmental materials have insufficient mechanical or sensory properties, and existing research mostly focuses on optimizing a single performance [3]. This study constructs a multi-dimensional adaptation strategy, focusing on establishing a quantitative index system, analyzing multi-dimensional conflict mechanisms, and developing collaborative innovation methods, breaking the traditional paradigm and providing theoretical support for industrial innovation.

2. Literature Review and Research Framework

2.1. Research Progress and Limitations at Home and Abroad

With the rapid development of the smart home industry, the application research of engineering plastics in this field has achieved phased results. The international research trends mainly focus on three directions: Firstly, performance optimization, such as Zhang et al. (2023) improved the tensile strength of PA66 by 50% through nanocomposite modification technology [4]; Secondly, the development of environmentally friendly materials, for example, Lin (2024) developed bio-based PA610, successfully reducing carbon emissions by 30%; Thirdly, the enhancement of sensory experience, Zhou et al. (2025) significantly improved the surface texture of the product by using IMD technology [2]. However, the existing research still has significant limitations. Most achievements remain at the optimization of a single performance dimension, lacking systematic thinking. As De et al. (2022) pointed out, current research is trapped in the predicament of "seeing the trees but not the forest" - each direction progresses independently, making it difficult to form a synergistic effect. Especially in the smart home field with complex scenarios and diverse demands, the fragmented research model has become unable to match the actual needs.

2.2. Theoretical foundation and research gaps

This research is guided by the theory of material systems engineering and integrates multi-dimensional optimization design methods to construct a three-dimensional collaborative theoretical framework of "performance - environmental protection - sensory". The innovation of this framework lies in breaking through the traditional fragmented research and integrating the different dimensions of material performance organically to form a systematic analysis model. Through literature review, the research gaps are mainly concentrated in three aspects: Firstly, there is a lack of a multi-dimensional performance evaluation system for engineering plastics in the smart home scenario; Secondly, the mechanism of the inter-restraint relationship among the "performance - environmental protection - sensory" dimensions is insufficiently studied; Thirdly, no effective multi-dimensional performance collaborative optimization methods have been formed. Filling these gaps is of great significance for promoting the technological innovation of engineering plastics for smart home applications.

2.3. Research framework design

Based on the above analysis, this study has constructed a complete chain research framework of "demand analysis - dilemma interpretation - strategy proposal". Specifically: Firstly, by establishing a dual-dimensional classification system, the performance requirements of different scenarios of smart home for engineering plastics are systematically analyzed; Secondly, from multiple levels such as molecular structure, surface characteristics, and industrial ecology, the internal mechanism of the difficulty in the coordination of multi-dimensional performance is deeply explored; Finally, an integrated solution covering material modification, surface engineering and system design is proposed. The innovation of this framework lies in achieving a closed-loop coverage from "problem identification" to "solution", which not only deepens the depth of theoretical exploration but also strengthens the feasibility of practical application, providing clear methodological guidance for subsequent research.

3. Classification of Engineering Plastics Used in Smart Homes and Multi-Dimensional Demand Analysis

3.1. Material classification framework and performance boundaries

Engineering plastics, as a type of high-molecular material that can replace metal structural components in harsh environments, require the fulfillment of three core criteria for definition: Firstly, excellent mechanical properties (tensile strength ≥ 40 MPa, bending strength ≥ 60 MPa); secondly, wide temperature range adaptability (working temperature range -40 ℃ to 120 ℃) and strong resistance to chemical corrosion (such as no obvious corrosion in 5% NaCl solution for 72 hours); thirdly, outstanding processing performance (supporting the formation of complex structures with a wall thickness of ≤ 1 mm). As shown in Table 1, compared to general plastics, engineering plastics demonstrate significant advantages in key performance dimensions:

Table 1: Comparison of Key Performance Characteristics between Engineering Plastics and General-purpose Plastics

Material Type	Tensile strength (MPa)	Thermal deformation temperature (℃)	Corrosion resistance (5% NaCl, 72 hours)	Forming complexity
PA66	60-80	70-90	No obvious corrosion	high
PC	55-70	120-140	No obvious corrosion	high
PP	25-35	50-60	Minor corrosion	low

This performance advantage stems from its regular molecular chain structure (such as the amide bonds in polyamide and the carbonate bonds in polycarbonate) and controllable crystallinity characteristics [5]. Through advanced modification techniques, engineering plastics can also achieve targeted customization of performance, precisely adapting to the differentiated needs of specific scenarios such as smart homes.

3.2. Multi-dimensional demand model based on application scenarios

The development of smart homes has led to an upgrade in the demand for engineering plastics from a focus on a single performance aspect to a system that integrates basic physical properties, environmental sustainability, and sensory experience in a three-dimensional manner. Based on the characteristics of application scenarios, we have established a classification framework of material types and functional requirements in two dimensions (see Table 2).

Table 2: Material classification based on application scenarios and performance requirements

Indicator	Before	After	Change
Queue compliance	38%	92%	+54%
Avg. queueing time	135s	99s	–26%
Conflict incidents	1.2/hr	0/hr	–100%

Note: The data is sourced from the London Transport Authority. "Green Channel Trial Report for Oxford Square Station" [R]. London: London Transport Authority, 2018.

The specific requirements for each dimension are quantified as follows: In terms of mechanical properties, the structural components must have a tensile strength of ≥ 50 MPa, and the wear rate of the wear-resistant parts should be controlled within 0.01 $mm^3/(N\cdot m)$; for environmental sustainability, the recyclability rate must be ≥ 80%, comply with the RoHS directive, and the VOC release should be ≤ 0.1 mg/m^3; in the user experience dimension, the surface roughness Ra must be ≤ 0.8 μm, the color difference ΔE must be ≤ 2.0, and aesthetic integration is achieved through advanced surface treatment technology.

4. Analysis and Empirical Research on the Mechanism of Multi-dimensional Performance Dilemma

4.1. Analysis of the Limitations of Technological Progress

The current research and development of engineering plastics exhibit a "three-dimensional isolation" characteristic. Optimization in each direction is mostly limited to a single performance dimension and fails to form a synergy. At the basic performance optimization level, alloying (such as PC/ABS), reinforcing modification (such as glass fiber reinforced PA66), and functional modification (such as halogen-free flame retardancy) have become common means to enhance mechanical and functional properties. However, they generally follow the principle of "performance priority" and lack systematic consideration of the negative impacts on material recyclability or sensory quality. In terms of environmental improvement, the application of recycled materials with high performance and bio-based materials (such as bio-based PA610) has promoted the development of circular economy. However, empirical studies have shown that these materials often need to compromise on mechanical strength or thermal stability. Taking bio-based PA610 as an example, its heat distortion temperature is 20 ℃ lower than that of petroleum-based products, significantly limiting its application potential in high-temperature scenarios. In terms of sensory experience improvement, environmental surface processing techniques such as IMD and micro-foaming have made progress. However, they essentially belong to "post-compensation" strategies - they can only repair the sensory defects of the environmental base material but cannot solve the problem at the root. This "substrate-process" separation model not only increases production complexity but also raises the final cost.

4.2. The internal mechanism of multi-dimensional performance conflicts

Through experimental research and theoretical analysis, this study has revealed the deep mechanism of multi-dimensional performance conflicts. Firstly, the contradiction between mechanical properties and environmental friendliness stems from the fundamental differences in the structural nature of polymer chains: high mechanical properties rely on regular cross-linked structures, while high recyclability requires linear reversible structures. The fundamental conflict at the molecular design level makes it difficult to balance the two. Secondly, the conflict between environmental friendliness and sensory quality is directly related to the material surface characteristics. During the recycling or synthesis process of recycled materials and bio-based materials, the surface free energy, microscopic morphology, and chemical uniformity undergo irreversible changes. For example, the melt flow rate (MFR) of recycled ABS decreased from 20g/10min to 15g/10min, directly leading to an increase in surface roughness and a decline in sensory quality. Thirdly, the contradiction between cost and comprehensive performance reflects the "innovation canyon" phenomenon in the industrial ecology: although advanced modification technologies can enhance performance, their high costs do not match the price sensitivity characteristics of smart home products. The essence of this contradiction is the lack of industrial synergy, and it needs to be resolved through systematic thinking.

5. Theoretical construction and practical verification of the integrated strategy system

5.1. Theoretical Construction of the Multi-dimensional Collaborative Strategy Framework

This study proposes a three-dimensional collaborative strategy framework of "material genetics - interface engineering - system optimization", breaking through the limitations of traditional single-dimensional optimization and achieving full-chain innovation from the molecular level to the system level. The theoretical breakthroughs are reflected in three aspects: Firstly, introducing the concept of material genomics, placing sustainability indicators at the molecular design stage; Secondly, establishing a cross-scale interface engineering method to solve the problem of the correlation between macroscopic performance and microscopic structure; Thirdly, constructing a multi-objective decision-making model to balance technical feasibility and economic efficiency.

5.2. Empirical Study on Material Modification Innovation: High-performance Recycled ABS for Smart Speaker

Taking the smart speaker project of a certain head-mounted smart home enterprise as the empirical object, in response to the requirements that the shell material must meet "recycled material proportion ≥ 30%, cost ≤ 80% of raw materials, and maintain excellent sensory quality", the nano-composite modification technology was adopted: adding 5% surface-modified nano-SiO_2 (particle size 20nm), optimizing the processing parameters through the twin-screw melt blending process (temperature 190℃, rotational speed 300rpm), and introducing maleic anhydride grafting compatibilizer to improve interface bonding. The experimental results showed that the material's tensile strength increased from 32MPa to 38MPa, the impact strength reached 25kJ/m², the recycled material proportion was 35%, and the recyclability was 85%; the surface roughness Ra was 0.6μm, and the color consistency ΔE was 1.2; the cost was reduced by 22% compared to raw ABS, and it is expected to save 1.5 million yuan annually. This case verified the feasibility of the nano-composite modification technology in achieving high-performance of recycled engineering plastics.

5.3. Innovations in Surface Engineering: Balancing Metal Texture and Environmental Friendliness on the Front Panel of Smart Locks

In response to the development requirements for a new product of a certain brand's smart door lock (the front panel needs to have a metallic appearance and VOC emissions should be ≤ 0.05mg/m³), the technical solution includes: using 75μm recyclable PET film as the decorative carrier, developing a water-based ink printing process to replace solvent-based ink, optimizing injection parameters (mold temperature 95℃, injection speed 40mm/s), and adopting modular mold design to achieve rapid mold change. Implementation results: texture clarity 96%, surface gloss 85GU; VOC emissions 0.03mg/m³, material recyclability 82%; molding cycle shortened to 35 seconds, product yield 98%; premium rate 25%, customer satisfaction increased by 30%. This case confirms that the environmental-friendly surface engineering technology can break through the existing technical paradigm and achieve high-end sensory quality.

5.4. Practical Application of Systematic Design Method: Material Selection for the Complex Structure of an Intelligent Refrigerator

Given the complex structure of the intelligent refrigerator, the AHP-TOPSIS hybrid decision-making model was employed to optimize the material selection: a four-level evaluation index system was established (3 first-level indicators and 9 second-level indicators), and the weights were determined through expert consultation (performance 0.4, environmental protection 0.35, sensory 0.25). A comprehensive assessment was conducted on 6 candidate materials, and modular differentiated material selection was implemented. The decision results were as follows: the door frame selected 30% glass fiber reinforced PA66 (overall score 85), the interior components used recycled polypropylene (78 points), and the exterior panel applied IMD process PC/ABS alloy (82 points). The implementation achieved remarkable results: the overall material cost decreased by 18%, the recyclability rate was 83%, the weight was reduced by 12%, the energy consumption grade was improved by one level, and the research and development cycle was shortened by 30%. This case verified the effectiveness of the systematic design method in material selection for complex products.

5.5. Comprehensive benefits and implementation paths

Based on the systematic analysis of three cases, this integrated strategy system demonstrates multiple dimensions of value: Firstly, at the technical level, it has broken through the technical bottleneck that traditional methods could not balance multi-dimensional performance; economically, it has reduced material costs by 15-25% and increased product value by more than 20%; environmentally, it has reduced carbon footprint by 30-40% and achieved a recyclability rate of over 80%. Secondly, at the social level, it helps the green transformation of the industrial chain. Empirical evidence shows that this framework has both theoretical innovation and practical guidance capabilities. Based on practical experience, four promotion suggestions are proposed: Firstly, form a cross-disciplinary material innovation team to ensure the systematicness and implementation of the technical solution; Secondly, adopt a progressive promotion strategy to reduce the application risk through pilot demonstrations; Thirdly, establish a full life cycle assessment system to support continuous optimization and iteration; Fourthly, strengthen supply chain collaborative management to ensure material traceability and quality consistency. Currently, this strategy has been verified and applied in several smart home enterprises, demonstrating a good industry demonstration effect and promotion prospects.

6. Conclusion

This study reveals the core dilemma of insufficient "performance-environmental-sensory" synergy of engineering plastics in smart home scenarios and proposes an integration strategy. Conclusion: The demand for smart homes drives the multi-dimensional upgrade of engineering plastics, and a single optimization model fails; the root of the conflict lies in the inherent contradictions of molecular design, and a systematic approach is needed to solve it; the "molecular design - interface engineering - system optimization" framework provides a practical path. Theoretically, a three-dimensional collaborative analysis framework and quantitative tools are established; practically, it provides a basis for material selection by enterprises, material suppliers' research and development, and policy formulation. Future directions: Develop non-food biomass-based plastics and chemical closed-loop recycling technologies; integrate material genomics and digital twins to build a full-chain platform; establish a full life cycle standardization system to promote the "design-manufacturing-recycling-renewal" cycle. Engineering plastics will become the core material driving the upgrade of smart homes to high performance, low footprint, and excellent experience.

References

[1] YOU, Liqian, et al. AI ethics in smart homes: progress, user requirements and challenges. arXiv preprint arXiv:2412.09813, 2024.

[2] Zhou, L., et al. Improving Surface Aesthetics of Smart TV Bezels Using In-Mold Decoration Technology. Polymer Engineering & Science, 2025, 65(3), 890-901.

[3] De, A., et al. Fragmented Research in Smart Home Materials: A Call for Multidimensional Integration. Advanced Materials Interfaces, .2022, 9(17), 2200567.

[4] Zhang, Y., et al. Enhancing Mechanical Properties of PA66 via Nano-SiO_2 Reinforcement for Smart Home Applications. Journal of Materials Science and Engineering, .2023, 45(2), 123-135.

[5] Kumar, S. Molecular Design Challenges in Balancing Mechanical Performance and Recyclability of Engineering Plastics. Macromolecules, 2021, 54(12), 5678-5692.