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Requirement-Driven Engineering Design and Finite Element-Based Evaluation of a Bio-Based Enclosure for Interactive Acoustic Terminals: A Willow-Wood Case Study

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Abstract

This study presents a sustainability-oriented requirement-driven engineering design framework for an enclosure used in interactive acoustic terminals. A willow-wood enclosure is used as a case study to connect user requirement analysis, structural concept generation, and finite element-based structural and modal evaluation. Application of Kano-AHP and the subsequent structural-actionability screening retained three Must-be constraints and three One-dimensional objectives for engineering translation. TRIZ-based contradiction resolution converted these priorities into an integrated top-control layout, a faceted willow shell, and local reinforcement around the large interactive opening. Static structural and constrained modal analyses were conducted using ANSYS Workbench 2022 R1 to evaluate the structural and modal feasibility of the willow-wood shell against an ABS benchmark. Results show that the willow-wood shell reaches a first natural frequency of 216.32 Hz, close to the ABS shell (215.28 Hz), and a maximum von Mises stress of 12.63 MPa under a 100 N load. Taken together, these results indicate the potential of the proposed requirement-driven framework to support the early-stage development and preliminary structural assessment of sustainable bio-based acoustic enclosures.

Keywords: user requirements; product development; wood materials; structural analysis; Kano-AHP; TRIZ

1. Introduction

Modern acoustic devices are evolving from simple audio players into smart, interactive, and personalized acoustic terminal systems [1]. To upgrade hardware performance, traditional acoustic devices rely heavily on high-density petrochemical-based engineering plastics [2], which restricts both refined ergonomic design and the broader application of sustainable materials. Amid the global push for low-carbon manufacturing, exploring lightweight bio-based materials for product shells [3,4] has become an important direction in sustainable product design.

Existing research has made progress in substituting conventional materials with sustainable materials in smart products. To optimize design methods, Tandiono and Rau [5] integrated the Kano model with TRIZ theory to drive sustainable innovation. Rong et al. [6] combined Kano, TRIZ, and Axiomatic Design (AD), showing that integrated design-decision tools can help resolve engineering contradictions. In the realm of cross-disciplinary material innovation, Zhu et al. [7] and Malik et al. [8] explored wood-derived



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materials in flexible electronics to enhance product sustainability and natural material perception.

However, current research reveals a significant gap in the deep integration of theoretical methods with practical applications: First, existing smart interactive terminal designs primarily focus on upgrading system architectures and acoustic algorithms. For example, McLean et al. [9] explored the multidimensional variables and perceptual experiences affecting smart home voice assistant usage. Yet, few studies quantitatively translate users' interaction usability and eco-aesthetic demands into explicit engineering constraints.

Second, low-frequency acoustic waves from speakers may induce forced vibration or resonance in bio-based materials such as willow because of their relatively low elastic modulus, high porosity, and low density [10]. Currently, the application of natural wood in electronic products mostly remains at the level of surface decoration [8]. Moreover, few studies have proposed a systematic engineering solution for addressing mechanical stress concentration and acoustic distortion arising from the coupling of a low-density natural material shell, a rigid internal acoustic cavity, and a smart interactive panel [11].

To address this research gap, this study proposes a systematic design framework that integrates perceptual demand quantification, multi-criteria decision-making, and engineering-oriented structural solutions. Using a willow-based interactive acoustic terminal as a case study, the Kano model and analytic hierarchy process (AHP) are used to extract and quantify core human-factor requirements in complex interactive scenarios. Subsequently, TRIZ theory transforms the conflicts between orthotropic material properties and electronic assembly requirements into structured engineering contradictions. By applying spatial separation, condition separation, and the contradiction matrix, this approach derives topology evolution paths that help address the physical and structural conflicts among material heterogeneity, structural complexity, and interactive usability [12].

As a typical orthotropic material, wood exhibits mechanical and acoustic responses that are more complex than those of isotropic plastics. Thus, conceptual deduction alone is insufficient to address real-world physical constraints [13]. Therefore, to close the methodological loop, this study employs finite element analysis (FEA). ANSYS Workbench 2022 R1 is used to conduct static structural and constrained modal analyses of the proposed willow enclosure [14], providing computational evidence for assessing the topological strategy under static loading and low-frequency vibration conditions. The specific methodological contribution is the explicit mapping between prioritized requirements and structurally actionable contradictions. AHP weights guide requirement prioritization, but a requirement enters TRIZ analysis only when it can be linked to shell geometry, material deployment, assembly, or vibration-related behavior. The resulting structural scheme is then assessed against the ABS benchmark by FEA.

2. Methodology and Constraint Implementation

This study develops a systematic design optimization framework to address the coupling challenges between human-system performance and physical properties, including mechanical and acoustic characteristics, in bio-based acoustic terminals. As illustrated in Figure 1, the framework follows a systems engineering mapping logic: requirement quantification, contradiction resolution, and simulation-based structural assessment. The core modules proceed sequentially: employing the Kano model to define human-system boundaries, introducing AHP to quantify constraint priorities, applying TRIZ to derive topology reconstruction schemes, and utilizing FEA to evaluate the structural and modal response of the derived design under predefined numerical assumptions. This workflow establishes an engineering closed loop, transitioning from subjective interaction requirements to objective mechanical computations. In this way, the framework provides an

early-stage engineering decision-making basis while preserving the need for subsequent prototype-based structural and acoustic validation.

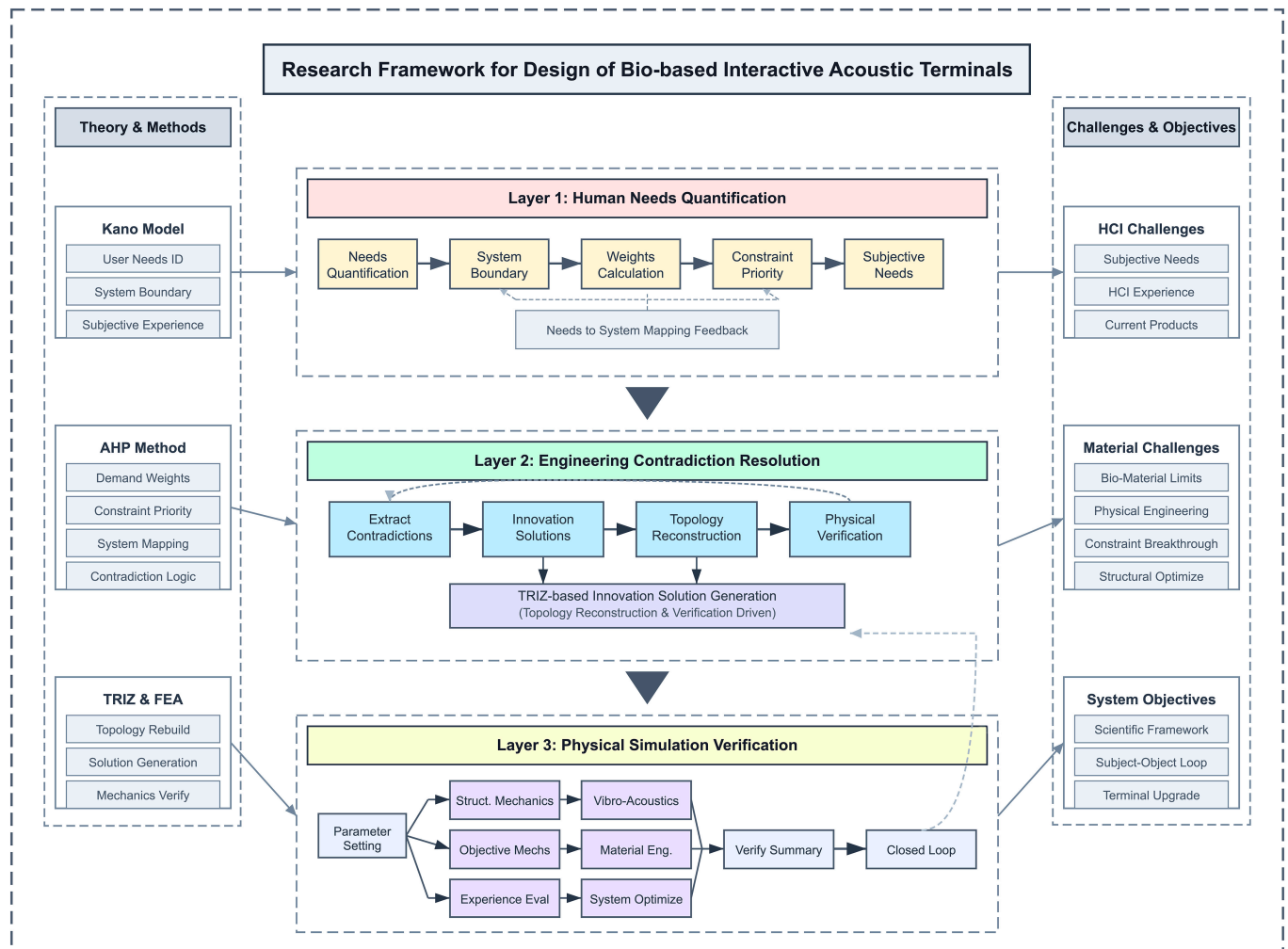


Figure 1. Research and design optimization framework for bio-based interactive acoustic terminals.

Compared with a conventional sequential design process, in which requirement analysis, concept generation, and engineering evaluation may be handled as separate activities, the proposed framework makes the links among these activities explicit. Kano–AHP establishes requirement priorities, requirements with clear engineering linkages are advanced to TRIZ-based contradiction resolution, and FEA screens the resulting configuration against the ABS benchmark. Without this mapping, the rationale connecting user priorities to structural decisions would be less traceable, and conflicts involving material anisotropy, interactive openings, assembly, and stiffness control would depend more heavily on iterative designer judgement.

2.1. Kano Model Analysis

The Kano model reveals the nonlinear impact of various attributes on overall system performance, assisting designers in identifying core elements and optimizing resource allocation [15]. For interactive acoustic terminals, this model is employed to identify users' underlying requirements related to acoustic performance, eco-material adaptation, and interaction experience. Before constructing the Kano questionnaire, exploratory semi-structured interviews [16] were conducted with approximately 20 participants, mainly individuals with industrial- or product-design backgrounds and prospective users. The

30–50 age range identified for the target use context [17] was subsequently applied as an eligibility criterion for the questionnaire. The interview guide covered typical household use scenarios, operation modes, sound-related expectations, material preferences, and visual and tactile qualities. Interview statements were consolidated by removing duplicate items, grouping semantically similar responses, and reviewing the resulting categories with design experts. Twenty candidate requirements were retained and organized into functional, emotional, and aesthetic dimensions [18], after which each requirement was converted into paired functional and dysfunctional Kano items, as presented in Tables 1 and 2.

Table 1. Breakdown of user requirements.

Dimension	ID	User Requirement
Functional	A1	Diverse operation modes
	A2	Convenient volume control
	A3	Optimal speaker layout
	A4	Device portability
	A5	Easy cleaning and maintenance
	A6	Composite material application
	A7	Modular design
	A8	Visual feedback
	A9	Sound quality stability
Emotional	B1	Warmth of home environment
	B2	Sense of security
	B3	Commemorative and collectible value
	B4	Personalized expression
	B5	Affinity to nature
	B6	Sense of environmental responsibility
Aesthetic	C1	Harmonious component proportions
	C2	Shell material aesthetics
	C3	Wood texture and tactile feel
	C4	Smooth and fluid form
	C5	Exquisite detail craftsmanship

To translate authentic user needs into quantifiable quality characteristics, this study designed a two-factor, five-point Kano-Likert scale (Table 2) to evaluate satisfaction from both functional and dysfunctional perspectives. The response options comprise “Dislike (1)”, “Tolerate (2)”, “Neutral (3)”, “Expected (4)”, and “Like (5)”. By employing bidirectional stimulus statements, the questionnaire facilitates a comprehensive evaluation of attribute satisfaction, capturing both functional expectations and the fulfillment variance of latent needs.

To reach potential users within the target use context identified through the preliminary interviews, Kano questionnaires were distributed anonymously and voluntarily via online platforms. Of the 144 distributed questionnaires, 134 valid responses were retained after excluding invalid questionnaires, yielding an effective response rate of 93.06%. Rigorous data cleaning and screening provided a reliable quantitative basis for subsequent Kano attribute classification and AHP weight calculations [12]. Prior to Kano attribute categorization and quantification, to ensure statistical robustness, the reliability and validity of the 134 valid samples were tested using SPSS 26.0.

Table 2. Kano two-factor five-point Likert questionnaire.

Functional (Provided)					User Requirement	Dysfunctional (Not Provided)				
1	2	3	4	5	A1 Diverse operation modes	1	2	3	4	5
1	2	3	4	5	A2 Convenient volume control	1	2	3	4	5
1	2	3	4	5	A3 Optimal speaker layout	1	2	3	4	5
1	2	3	4	5	A4 Device portability	1	2	3	4	5
1	2	3	4	5	A5 Easy cleaning and maintenance	1	2	3	4	5
1	2	3	4	5	A6 Composite material application	1	2	3	4	5
1	2	3	4	5	A7 Modular design	1	2	3	4	5
1	2	3	4	5	A8 Visual feedback	1	2	3	4	5
1	2	3	4	5	A9 Sound quality stability	1	2	3	4	5
1	2	3	4	5	B1 Warmth of home environment	1	2	3	4	5
1	2	3	4	5	B2 Sense of security	1	2	3	4	5
1	2	3	4	5	B3 Commemorative and collectible value	1	2	3	4	5
1	2	3	4	5	B4 Personalized expression	1	2	3	4	5
1	2	3	4	5	B5 Affinity to nature	1	2	3	4	5
1	2	3	4	5	B6 Sense of environmental responsibility	1	2	3	4	5
1	2	3	4	5	C1 Harmonious component proportions	1	2	3	4	5
1	2	3	4	5	C2 Shell material aesthetics	1	2	3	4	5
1	2	3	4	5	C3 Wood texture and tactile feel	1	2	3	4	5
1	2	3	4	5	C4 Smooth and fluid form	1	2	3	4	5
1	2	3	4	5	C5 Exquisite detail craftsmanship	1	2	3	4	5

Note: 1 = Dislike, 2 = Tolerate, 3 = Neutral, 4 = Expected, 5 = Like.

For reliability assessment, the overall Cronbach's α coefficient for the 40 measurement items, comprising functional and dysfunctional questions for 20 system requirements, was 0.960. Because this value exceeds the commonly accepted threshold of 0.80, the designed Kano two-factor scale shows excellent internal consistency and measurement stability. Further construct validity testing reveals a Kaiser-Meyer-Olkin (KMO) measure of 0.918 (>0.90). Concurrently, Bartlett's test of sphericity yields an approximate chi-square value of 3585.461, with degrees of freedom $df = 780$ and a significance level $p < 0.001$. These findings indicate significant underlying correlations among the measurement indicators, supporting the construct validity of the scale.

The 134 valid responses were considered adequate for the intended Kano classification and Better–Worse analysis, as supported by the high internal consistency (Cronbach's $\alpha = 0.960$) and sampling adequacy (KMO = 0.918) reported above. The online respondents met the study-defined age criterion of 30–50 years, supporting the relevance of the sample to the intended user group and the present requirement-prioritization analysis. Based on the Kano evaluation matrix (Table 3), the initial user quality requirements are explicitly categorized into distinct attribute types: Must-be (*M*), One-dimensional (*O*), Attractive (*A*), Indifferent (*I*), and Reverse (*R*) requirements.

Table 3. Kano evaluation criteria.

		Dysfunctional				
		Dislike (1)	Tolerate (2)	Neutral (3)	Expected (4)	Like (5)
Functional	Dislike (1)	<i>Q</i>	<i>R</i>	<i>R</i>	<i>R</i>	<i>R</i>
	Tolerate (2)	<i>M</i>	<i>I</i>	<i>I</i>	<i>I</i>	<i>R</i>
	Neutral (3)	<i>M</i>	<i>I</i>	<i>I</i>	<i>I</i>	<i>R</i>
	Expected (4)	<i>M</i>	<i>I</i>	<i>I</i>	<i>I</i>	<i>R</i>
	Like (5)	<i>O</i>	<i>A</i>	<i>A</i>	<i>A</i>	<i>Q</i>

Note: *M* = Must-be, *O* = One-dimensional, *A* = Attractive, *I* = Indifferent, *R* = Reverse, *Q* = Questionable.

Based on the evaluation matrix, the 20 initial user requirements were classified into specific attribute categories. Specifically, these comprise 3 Must-be (M), 9 Attractive (A), 3 One-dimensional (O), and 5 Indifferent (I) requirements. Although Reverse (R) responses were rare, the complex application scenarios of the willow acoustic terminal led to cognitive ambiguity or preference discrepancies among a minority of respondents regarding specific technical indicators, resulting in a small number of Questionable (Q) classifications. The proportions of each attribute were calculated using Equations (1)–(5):

$$K_M = \frac{M}{A + O + M + I + R + Q} \quad (1)$$

$$K_A = \frac{A}{A + O + M + I + R + Q} \quad (2)$$

$$K_O = \frac{O}{A + O + M + I + R + Q} \quad (3)$$

$$K_I = \frac{I}{A + O + M + I + R + Q} \quad (4)$$

$$K_R = \frac{R}{A + O + M + I + R + Q} \quad (5)$$

Based on Kano model theory, Better–Worse coefficients were further used to analyze each user requirement by calculating the satisfaction index (SI) and dissatisfaction index (DSI). In accordance with standard Kano quantitative analysis protocols, Questionable (Q) requirements lack practical engineering significance, and Reverse (R) requirements represent extreme low-frequency anomalies; thus, both are excluded from the final sensitivity calculations. Therefore, when computing SI and DSI, the formula denominators incorporate only the effectively identified core data from categories A, O, M, and I. The specific values are derived using Equations (6) and (7), respectively:

$$SI = \frac{A + O}{A + O + M + I} \quad (6)$$

$$DSI = -\frac{O + M}{A + O + M + I} \quad (7)$$

Quantitative analysis of the Better–Worse coefficients, derived from the aforementioned equations, intuitively evaluates how each functional requirement potentially impacts user satisfaction and dissatisfaction. This establishes a robust data-driven foundation for optimizing the design of the willow acoustic terminal. After excluding invalid items such as Questionable (Q) categories [6], the final attribute distribution and quantified sensitivity results for all requirements are detailed in Table 4.

Table 4. Kano classification and Better–Worse coefficient results for user requirements.

ID	M	A	O	I	R	Q	Category	SI	DSI
A1	49	40	19	19	0	7	M	0.46	−0.54
A2	14	38	4	58	1	19	I	0.37	−0.16
A3	18	58	18	29	0	11	A	0.62	−0.29
A4	44	35	24	22	1	8	M	0.47	−0.54
A5	10	33	6	65	1	19	I	0.34	−0.14
A6	48	43	5	21	0	17	M	0.41	−0.45
A7	12	17	43	55	0	7	I	0.47	−0.43
A8	11	41	13	52	2	15	I	0.46	−0.21

Table 4. Cont.

ID	M	A	O	I	R	Q	Category	SI	DSI
A9	24	30	51	26	0	3	O	0.62	−0.57
B1	22	51	24	29	0	8	A	0.60	−0.37
B2	29	41	19	34	0	11	A	0.49	−0.39
B3	5	38	2	54	7	28	I	0.40	−0.07
B4	24	52	29	21	0	8	A	0.64	−0.42
B5	24	49	26	27	1	7	A	0.60	−0.40
B6	29	36	27	33	0	9	A	0.50	−0.45
C1	30	47	23	28	0	6	A	0.55	−0.41
C2	20	24	57	31	0	2	O	0.61	−0.58
C3	18	57	22	27	0	10	A	0.64	−0.32
C4	17	55	25	32	0	5	A	0.62	−0.33
C5	17	26	51	34	0	6	O	0.60	−0.53

To determine system optimization priorities, a scatter plot was generated based on the satisfaction index (*SI*) and the absolute dissatisfaction index ($|DSI|$) of each constraint factor (Figure 2). In systematic engineering development, the screening of design variables must adhere to a strict logical hierarchy:

Scatter plot of Better-Worse coefficients

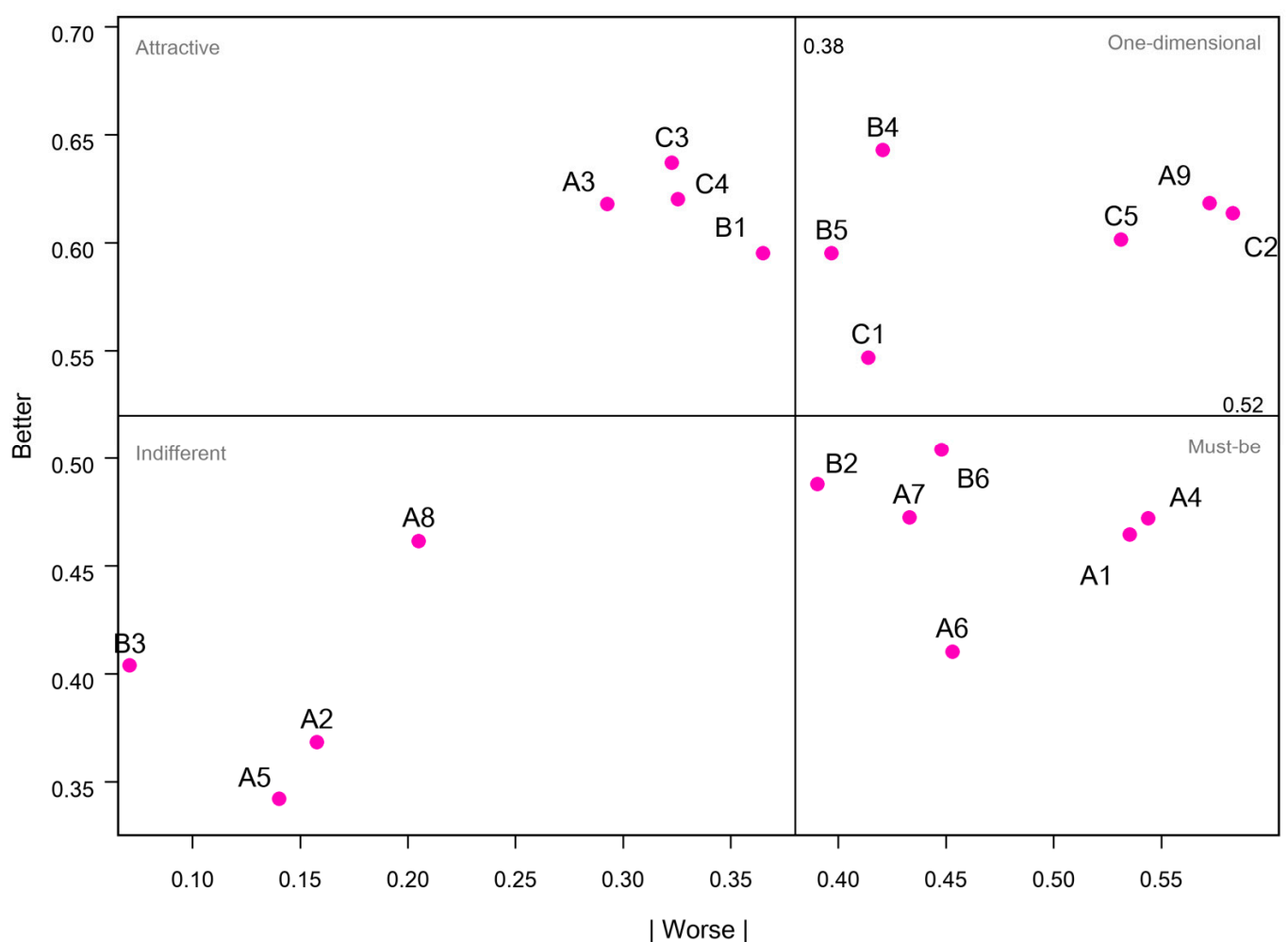


Figure 2. Four-quadrant scatter plot of Better-Worse coefficients based on *SI* and $|DSI|$.

First, for Indifferent (*I*) requirements, Kano theory suggests that their presence or absence has limited impact on system performance. A2 (Convenient volume control), A5 (Easy cleaning and maintenance), A7 (Modular design), A8 (Visual feedback), and B3 (Commemorative and collectible value) fall into this quadrant. Considering the interaction characteristics of smart acoustic terminals, these items were not advanced to subsequent engineering translation in order to optimize R&D resource allocation and avoid overdesign [19].

Second, Attractive (*A*) requirements, such as C3 (Wood texture and tactile feel) and C4 (Smooth and fluid form), mainly enhance user satisfaction and perceived system value. However, in the engineering translation of bio-based heterogeneous materials such as willow, the material's orthotropy and the processing limitations of acoustic cavities [20] mean that fully satisfying all Attractive indicators may increase structural-topology complexity and manufacturing uncertainty. Consequently, the decision-making logic established in this study is to prioritize Must-be (*M*) requirements to guarantee the fundamental physical feasibility of the system. Concurrently, efforts are concentrated on overcoming One-dimensional (*O*) requirements as the core metrics for subsequent structural harmonization, thereby achieving an optimal harmony between structural mechanical constraints and overall interactive performance.

In summary, following Kano model statistical protocols, the mean satisfaction index (*SI*) and the mean absolute dissatisfaction index ($|DSI|$) for all functional requirement indicators are calculated as 0.52 and 0.38, respectively. These mean coordinates (0.38, 0.52) serve as the baseline intersection threshold to construct the four-quadrant scatter plot. By analyzing the distribution patterns and quadrant affiliations of individual requirements relative to this new origin, functional requirements falling into the high-priority One-dimensional and Must-be zones (e.g., A1, A4, A6, and A9) are identified as core attributes for prioritization. Conversely, perceptual requirements with high satisfaction potential, such as C2 and C5, are formulated into a secondary variable matrix and input into the subsequent analytic hierarchy process (AHP) model for secondary objective weighting.

2.2. AHP Weight Analysis and Priority Ranking

2.2.1. Construction of the Hierarchical Structure Model

To further clarify the harmonization targets of the bio-based interactive acoustic terminal, AHP was introduced to rank the discrete system constraints output by the Kano model [21]. The feasible harmonization domain was defined by integrating the Kano classification matrix with structural-engineering and acoustic-manufacturing constraints.

Guided by this systems-engineering approach, this study selects three One-dimensional indicators—A9 (Sound quality stability), C2 (Shell material aesthetics), and C5 (Exquisite detail craftsmanship)—as harmonization objectives. Concurrently, three Must-be indicators—A1 (Diverse operation modes), A4 (Device portability), and A6 (Composite material application)—are established as baseline physical constraints. These six core constraint parameters constitute the core subset for design harmonization, reducing redundancy caused by high-dimensional variables [22]. Relying on this core constraint cluster, a hierarchical structural model for AHP quantitative calculation was constructed (Figure 3).

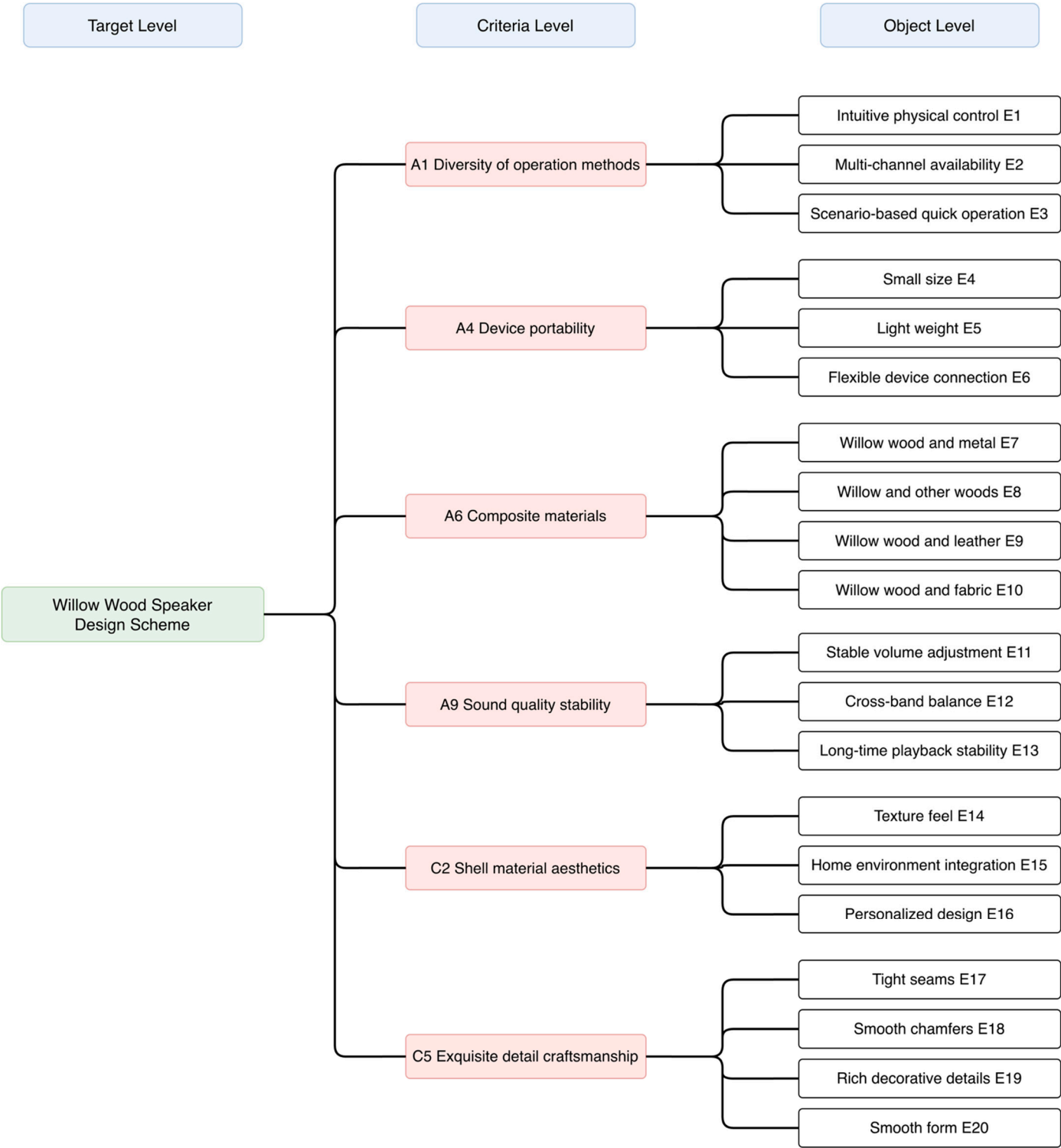


Figure 3. Hierarchical structural model for the AHP quantitative calculation.

2.2.2. Construction of the Comparison Matrix

The comparison matrix constitutes the foundational element of the AHP. During its construction, elements within the same hierarchical level are compared pairwise to determine relative weights. This study adopts Saaty’s 1–9 scale as the scoring criterion for the matrix elements [23]; the scale definitions are shown in Table 5.

Table 5. Saaty’s 1–9 fundamental scale for pairwise comparisons.

Scale	Definition
1	Elements i and j are of equal importance, i.e., $a_{ij} = 1$.
3	Element i is moderately more important than element j , i.e., $a_{ij} = 3$.
5	Element i is strongly more important than element j , i.e., $a_{ij} = 5$.
7	Element i is very strongly more important than element j , i.e., $a_{ij} = 7$.
9	Element i is absolutely more important than element j , i.e., $a_{ij} = 9$.
2, 4, 6, 8	Intermediate values between two adjacent scales.
Reciprocals	If the relative importance of element i compared to j is assigned as a_{ij} , then the relative importance of j compared to i strictly satisfies $a_{ji} = 1/a_{ij}$.

According to the 1–9 scale outlined in Table 5, pairwise comparisons are conducted among elements within the same hierarchical level to construct an $n \times n$ pairwise comparison matrix A , as expressed in Equation (8):

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (8)$$

To aggregate the expert matrices, the geometric mean method [24] is employed. The corresponding elements from the scoring matrices formulated by m experts ($k = 1, 2, \dots, m$) are multiplied and subsequently subjected to the m -th root. This process yields the elements $\bar{a}_{ij}$ of the aggregated comparison matrix $\bar{A}$, calculated as follows:

$$\bar{a}_{ij} = \left(\prod_{k=1}^m a_{ij}^{(k)} \right)^{\frac{1}{m}} \quad (9)$$

Calculation of relative weights for the comparison matrix. For the integrated matrix $\bar{A}$, the geometric mean method is utilized to compute the weights through three specific steps:

1. Multiply the elements within the same row of matrix $\bar{A}$ sequentially to yield a new column vector.
2. Calculate the n -th root for each component of this newly derived vector.
3. Normalize the resulting vector to derive the final weight vector W .

The comprehensive calculation is formulated as Equation (10):

$$W_i = \frac{\left(\prod_{j=1}^n \bar{a}_{ij} \right)^{\frac{1}{n}}}{\sum_{k=1}^n \left(\prod_{j=1}^n \bar{a}_{kj} \right)^{\frac{1}{n}}}, \quad i = 1, 2, \dots, n \quad (10)$$

Consistency check of the comparison matrix. During pairwise comparisons of indicators, logical inconsistencies may inevitably arise; therefore, a consistency check must be conducted on the established comparison matrix to ensure the rationality of the indicator weights. The consistency ratio (CR) is commonly adopted as the evaluation criterion. CR is defined as the ratio of the consistency index (CI) to the random consistency index (RI). If the calculated result satisfies $CR < 0.1$, the matrix exhibits acceptable consistency and

requires no modification; otherwise, the comparison matrix should be revised until $CR < 0.1$ is achieved. The calculation formula for CR is expressed as Equation (11):

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max} - n}{(n - 1)RI} \quad (11)$$

where $\lambda_{\max}$ is the maximum eigenvalue of the comparison matrix, calculated as shown in Equation (12):

$$\lambda_{\max} = \sum_{i=1}^n \frac{(\bar{A}W)_i}{nW_i} \quad (12)$$

In this formula, $\bar{A}$ represents the integrated comparison matrix, W denotes the corresponding weight vector, and $(\bar{A}W)_i$ indicates the i -th component of the vector $\bar{A}W$. The correspondence between the RI value and the matrix order n is presented in Table 6 [25].

Table 6. Random consistency index (RI) values.

Matrix Order (n)	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54

To quantify the global weights of the aforementioned design variables, this study assembled an expert evaluation panel comprising 16 domain experts [26]. The panel included four senior product development experts responsible for assessing the engineering translation and system feasibility of the selected indicators; four senior acoustic and structural engineers tasked with evaluating mechanical and acoustic constraints during the integration of heterogeneous materials; four researchers specializing in human factors engineering and sustainable material applications to support the methodological rigor of the evaluation system; and four lead users involved in internal system testing to represent core human-factor demands in technical decision-making.

The composition of the panel was designed to cover the principal stages of requirement-driven enclosure development. Product-development expertise informed the translation of user requirements into product attributes; acoustic and structural engineering expertise addressed enclosure-level mechanical constraints; human-factors and sustainable-materials research supported the assessment of use-context and material-related requirements; and lead-user input grounded the comparisons in anticipated interaction scenarios. This role-based composition enabled the pairwise comparisons to incorporate both user-facing expectations and engineering implementation considerations.

By collecting and consolidating the pairwise importance comparison matrices from these domain experts, the eigenvectors and weights were calculated. Addressing the data dispersion in the initial aggregated matrix caused by the diversified backgrounds of the experts, the study employed the Delphi method for multi-round feedback and revision [27]. The consistency ratios (CR) of the finally generated comparison matrices across all groups ranged from 0.04 to 0.09. This result not only strictly passed the critical mathematical validation standard of being less than 0.1, but also objectively reflected the high convergence of decision-making consensus from a multidisciplinary perspective.

2.2.3. Calculation of Evaluation Indicator Weights and Consistency Check

After establishing the hierarchical structural model, the geometric mean method is employed to aggregate the scoring matrices of the multiple experts. Subsequently, the integrated comparison matrices from the target layer to the primary criteria layer, and from each primary criterion to the sub-criteria layer, are constructed sequentially.

Based on the constructed comparison matrices, the square root method is utilized to calculate the relative weights of the evaluation indicators at each hierarchical level [28]. To ensure the logical rationality of the indicator weights, a consistency check is sequentially performed on all comparison matrices. The calculated local weights of the primary criteria, the local weights of the sub-criteria, and the consistency indicators (λ_{max} , CI , CR) of each matrix are summarized in Table 7.

Table 7. Local weights and consistency check results of hierarchical evaluation indicators.

Target Layer	Primary Criteria	Weight	Sub-Criteria	Local Weight	λ_{max}	CI	CR
Evaluation of the willow acoustic terminal design	A1	0.3528	E1	0.1151	3.0101	0.0050	0.0096
			E2	0.2997			
			E3	0.5852			
	A4	0.0972	E4	0.2036	3.0056	0.0028	0.0054
			E5	0.4922			
			E6	0.3042			
	A6	0.1813	E7	0.3234	4.0229	0.0076	0.0085
			E8	0.1298			
			E9	0.1939			
			E10	0.3529			
	A9	0.2162	E11	0.4430	3.0310	0.0155	0.0298
			E12	0.3838			
			E13	0.1733			
	C2	0.0476	E14	0.1116	3.0143	0.0071	0.0137
			E15	0.3411			
			E16	0.5473			
	C5	0.1049	E17	0.3851	4.0414	0.0138	0.0155
			E18	0.2194			
			E19	0.1303			
			E20	0.2652			

Note: The consistency check results for the comparison matrix of primary criteria with respect to the target layer are $\lambda_{max} = 6.2732$, $CI = 0.0546$, and $CR = 0.0433 < 0.1$, satisfying the consistency requirements. The definitions of E1–E20 are provided in the AHP hierarchy shown in Figure 3.

As evidenced by the computational results in Table 7, the consistency ratio (CR) values for the comparison matrix from the target layer to the primary criteria, alongside all six comparison matrices of the sub-criteria, are strictly less than 0.1. This indicates that all weight assignments meet the consistency requirement, supporting the reasonableness of the indicator weight allocation.

After obtaining the local weights at each hierarchical level, the global weights of the sub-criteria relative to the overall target layer were further calculated. The global weight is derived from the product of the local weight of the primary criterion and the local weight of its corresponding sub-criterion. The ultimately obtained global weights and their overall ranking are presented in Table 8.

Table 8. Global weights and overall ranking of the evaluation indicators.

Primary Criteria	Weight	Sub-Criteria	Local Weight	Global Weight	Ranking
A1	0.3528	E1	0.1151	0.0406	9
		E2	0.2997	0.1057	2
		E3	0.5852	0.2065	1
A4	0.0972	E4	0.2036	0.0198	17
		E5	0.4922	0.0478	7
		E6	0.3042	0.0296	13
A6	0.1813	E7	0.3234	0.0586	6
		E8	0.1298	0.0235	16
		E9	0.1939	0.0352	10
		E10	0.3529	0.0640	5
A9	0.2162	E11	0.4430	0.0958	3
		E12	0.3838	0.0830	4
		E13	0.1733	0.0375	11
C2	0.0476	E14	0.1116	0.0053	20
		E15	0.3411	0.0162	18
		E16	0.5473	0.0261	14
C5	0.1049	E17	0.3851	0.0404	8
		E18	0.2194	0.0230	15
		E19	0.1303	0.0137	19
		E20	0.2652	0.0278	12

The overall weighted ranking results show that, among the primary criteria, diverse operation modes (A1), sound-quality stability (A9), and composite material application (A6) hold the highest weights. Correspondingly, the high-weight sub-criteria mainly include scenario-based quick operation (E3), multi-channel usability (E2), stable volume adjustment (E11), and the willow–fabric composite (E10).

This weight distribution reveals the underlying user demands for the willow acoustic terminal. In terms of interaction experience, the results indicate a need for scenario-based control with low cognitive load, enabling the smart terminal to better fit complex home-use contexts. Regarding physical and aesthetic attributes, the product should address user expectations concerning acoustic performance while improving its ecological aesthetic value and adaptability to home environments through the integration of willow wood with heterogeneous materials.

2.3. TRIZ-Based Contradiction Resolution and Structural Evolution

Utilizing the core requirements identified by the Kano model and the high-weight indicators derived from the AHP, this section employs Altshuller’s contradiction matrix and the inventive principles within the TRIZ theory to translate the interdisciplinary conflicts between the characteristics of bio-based materials and interactive assembly requirements into standardized technical and physical contradictions.

2.3.1. AHP-Driven Core Contradiction Extraction and Principle Mapping

According to the weight ranking determined by the AHP analysis, this study identifies the core engineering contradictions that need to be addressed during the physical implementation of the willow acoustic terminal. This section analyzes these conflicts from both technical and physical dimensions and matches them with the corresponding TRIZ inventive principles [29].

The transition from Kano–AHP results to TRIZ-based structural development was implemented through a three-stage selection procedure. First, the AHP results in Table 8, including global ranks and relevant local weights, were used to prioritize rather than deterministically select candidate requirements. A requirement was advanced to TRIZ analysis only when it combined a relatively high priority with a clear engineering linkage to shell configuration, interactive-module integration, material deployment, or vibration-related structural behavior. Second, each retained requirement was expressed either as a technical contradiction, defined by an improvement objective and an associated deterioration parameter, or as a physical contradiction, defined by mutually exclusive states of a single engineering node. Third, the corresponding improving and worsening parameters, or the relevant separation strategy, were queried against the TRIZ contradiction matrix. Candidate inventive principles were retained only when they were compatible with the predefined geometric, material, and assembly constraints. Tables 9 and 10 provide the resulting traceability from Kano–AHP evidence to contradiction formulation, selected inventive principles, and the associated structural design schemes.

A technical contradiction focuses on the trade-off between two different parameters within the system. Addressing the issues of operational complexity and acoustic stability, the extracted technical contradictions and the mapping of the inventive principles are presented in Table 9.

Table 9. Deconstruction of technical contradictions and mapping of inventive principles.

Contradiction No.	Target Requirement	Improving vs. Worsening Parameters	AHP Data Support Chain	Corresponding TRIZ Inventive Principles
TC1	Scenario-based quick operation vs. visual complexity of the device surface.	Ease of operation (33) vs. Device complexity (36).	Sub-criterion E3 ranks first (0.5852); however, densely arranging physical buttons on the panel will disrupt the overall aesthetic appeal of C2.	Merging (No. 5), Universality (No. 6).
TC2	Enhancing the low-frequency acoustic performance of the speaker cabinet vs. controlling the overall weight of the device.	Stability of the object's composition (13) vs. Weight of stationary object (2).	Sub-criterion E5 places a high demand on lightweight design, yet low-frequency acoustic performance may require greater structural mass or stiffness to reduce resonance	Local quality (No. 3), Porous materials (No. 31).

A physical contradiction, conversely, focuses on the mutually opposing physical state requirements of a system for a single parameter. Considering the physical limits of willow wood, this study extracts physical contradictions and introduces separation strategies, such as separation in space, for structural harmonization [30], with specific mappings presented in Table 10.

Table 10. Deconstruction of physical contradictions and mapping of separation principles.

Contradiction No.	Core Engineering Node	Mutually Opposing Physical State Requirements	Kano-AHP Evidence Chain	Separation Strategy and TRIZ Inventive Principle
PC1	Anti-resonance stiffness of the cavity.	High-stiffness state: Must satisfy the acoustic demand of suppressing low-frequency resonance. vs. Low-stiffness state: Must retain the original willow material (inevitably accompanied by low-modulus attributes).	High demand for A9 acoustic quality stability (0.2162) but constrained by the low-modulus disadvantage of willow wood.	System-level separation; Spheroidality/Curvature (No. 14).
PC2	Interactive openings and shell compressive strength.	Solid and continuous: Ensuring the framework possesses sufficient compressive strength. vs. Locally hollow: Requiring accommodation for large-scale interactive control modules.	The E3 quick operation module requires assembly space, which conflicts with structural safety and the A9 sound-quality stability requirement	Separation in space; Local quality (No. 3).

2.3.2. Elaboration of Innovative Structural Engineering Design Schemes

Based on this TRIZ principle matrix, while ensuring acoustic integrity and structural safety, this study translates these principles into specific structural engineering design schemes:

Addressing the technical contradiction (TC1) regarding the integrated interactive module design: To resolve the technical conflict between operational convenience and visual minimalism, the Merging principle (No. 5) and the Universality principle (No. 6) are applied to devise a highly integrated central control hub. Abandoning the scattered button array, a versatile mechanical integration combining rotation (for volume adjustment) and pressing (for mode switching) is implemented on the top of the device. This approach reduces visual disruption to the willow panel while maintaining the natural aesthetic expression of the wood surface.

Addressing the technical contradiction (TC2) regarding the lightweight acoustic damping design: To balance the technical conflict between cabinet lightweighting and low-frequency acoustic extension, the Local Quality principle (No. 3) and the Porous Materials principle (No. 31) are applied to optimize the local arrangement of acoustic damping materials. Under the premise of not increasing the static mass of the external cabinet, the internal main cavity is locally filled with high-density porous sound-absorbing cotton. This design measure is intended to mitigate the potential risk of low-frequency standing-wave resonance within a lightweight structural concept.

Addressing the polyhedral thickened anti-resonance shell design (PC1): To address the material limitation associated with the low elastic modulus of willow, the Spheroidality–Curvature principle (No. 14) is introduced. Instead of using a traditional flat, thin-walled cabinet that may exhibit limited load-bearing and anti-resonance performance, the spatial topology of the main load-bearing willow shell is structured into a continuous faceted shell with multiple folded angles. This geometric stiffness-compensation strategy helps offset the low-stiffness limitation of the bio-based material and provides a basis for increasing the natural frequency of the system.

Addressing the topological opening and locally reinforced load-bearing design (PC2): To satisfy the user's demand for scenario-based quick operation, a large aperture is introduced at the top to accommodate the interactive control module. To resolve the ensuing degradation of structural strength, the Local quality principle (No. 3) is introduced. Building upon the framework with the reserved large through-hole at the top, local thickness compensation and topological reinforcement are executed along the load-bearing edges. This aims to smoothly dissipate the applied loads generated by high-frequency mechanical pressing, thereby reducing the risk of stress concentration. To improve the readability of the TRIZ-based design process, the structural evolution from the initial flat-panel concept to the integrated polyhedral-shell scheme is summarized schematically in Figure 4.

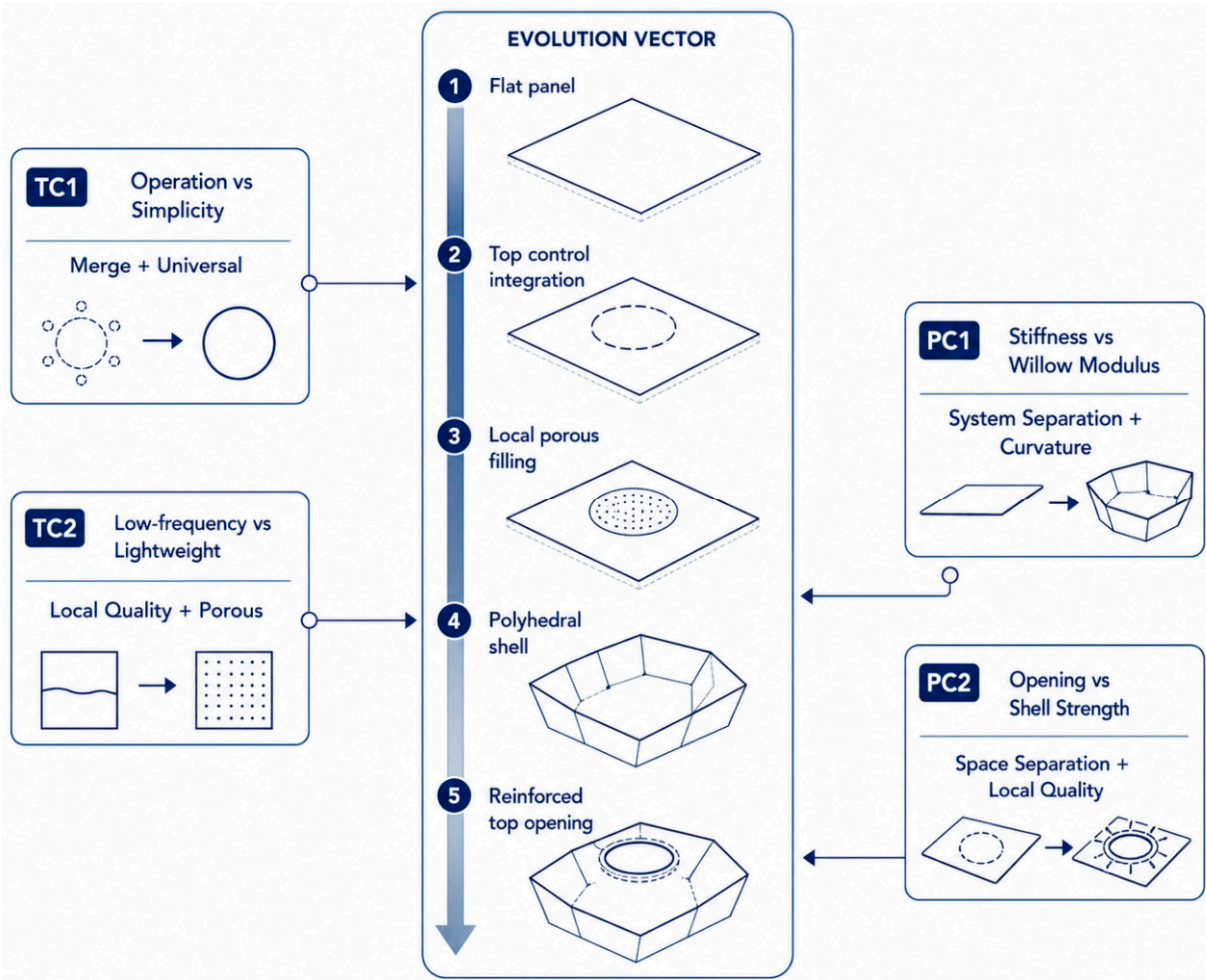


Figure 4. Schematic structural evolution from the initial flat-panel concept to the integrated polyhedral-shell scheme based on TRIZ contradiction resolution.

3. Results and Discussion

3.1. Structural and Modal Benchmark Evaluation Based on Finite Element Analysis

Constrained by the unpredictability of natural wood under complex stresses, this study employed ANSYS Workbench 2022 R1 software to conduct static structural and constrained modal simulation analyses on the harmonized polyhedral faceted thickened shell structure derived from TRIZ. To evaluate the engineering feasibility of this scheme as an alternative to traditional petrochemical materials, an isotropic ABS plastic shell with an equivalent volume was established as the benchmark model.

3.1.1. Simulation Preprocessing and Equivalent Model for Orthotropic Materials

Willow was selected as a furniture-relevant and mechanically demanding bio-based case. Its low density, pronounced orthotropy, and relatively low longitudinal modulus provide a conservative basis for assessing whether the TRIZ-derived geometric stiffness-compensation strategy can narrow the structural and modal performance gap relative to ABS.

This selection is consistent with the furniture-oriented design context of the present study, in which the visual and tactile qualities of wood form part of the user requirements. Willow has been discussed in relation to its wood properties, production, and economic context [31]. Alternative materials, including higher-stiffness solid woods and engineered wood products, remain valuable options and can offer complementary balances of mechanical uniformity, manufacturability, and end-use properties; willow-based particleboards, for example, have been investigated as sustainable materials for furniture and construction applications [32]. In related acoustic wood applications, the selection of wood species has likewise been shown to require joint consideration of mechanical and acoustic properties [33]. Accordingly, willow provides a relevant case for examining how the requirement-driven framework can inform the early-stage structural design of bio-based acoustic enclosures.

Given the complex micro-structure of natural wood, its mechanical properties exhibit substantial natural dispersion due to the influences of moisture content, growth environment, and density. Consequently, when evaluating the structural topological merits of complex acoustic cavities, the direct application of singular measured empirical data often lacks universality. To improve the engineering reliability of the simulation and reduce the influence of material variability, this study avoids the conventional isotropic simplification approach. Instead, based on classical wood mechanics theory, it constructs a representative, idealized orthotropic equivalent model.

The equivalent orthotropic model was established using representative material parameters for willow wood reported in the published literature and selected to reflect typical indoor service conditions. Accordingly, the baseline longitudinal elastic modulus E_L was set to 6.96 GPa for the equivalent orthotropic model. The remaining eight orthotropic constants, including the radial and tangential elastic moduli (E_R/E_T), the shear moduli across all directions (G), and the Poisson's ratios (ν), are derived based on the classical elastic constant proportional relationships for hardwoods proposed by Bodig and Jayne [34]. The specific input values for the parameterized equivalent model are presented in Table 11. Here, L , R , and T denote the longitudinal, radial, and tangential directions, respectively. This classical source was retained as the baseline for fundamental orthotropic proportional relationships, while recent wood-mechanics studies have likewise emphasized that finite element modeling of wood should account for its orthotropic, heterogeneous, and direction-dependent elastic behavior [35].

Table 11. Parameter settings of the equivalent constitutive models for simulation.

Material Category	Density ρ (kg/m ³)	Elastic Modulus E (GPa)	Shear Modulus G (MPa)	Poisson's Ratio ν
ABS plastic (Isotropic)	1050	$E = 2.00$	$G = 717.3$	$\nu = 0.394$
Willow wood (Orthotropic)	417	$E_L = 6.96$ $E_R = 0.56$ $E_T = 0.42$	$G_{LR} = 600$ $G_{LT} = 700$ $G_{RT} = 100$	$\nu_{LR} = 0.45$ $\nu_{LT} = 0.50$ $\nu_{RT} = 0.70$

The establishment of this equivalent model aims to provide a consistent orthotropic mechanical basis for the harmonized polyhedral faceted structure derived from TRIZ. By comparing it with the isotropic ABS plastic of equivalent volume, the objective is to compare the structural and modal responses of the topological harmonization scheme with those of the ABS benchmark under the adopted numerical-model assumptions, rather than pursuing an absolute quantitative prediction of the material's fracture limit. During mesh discretization, ten-node tetrahedral SOLID187 elements were used for all models [36]. The paired ABS and willow static models employed the same 8 mm global element size, yielding 201,276 nodes and 107,176 solid elements. The paired modal models were discretized separately, with each model comprising 47,487 nodes and 24,041 solid elements. Within each analysis type, the ABS and willow models retained the same geometry and matched nodal discretization, providing a controlled basis for material comparison. Because the archived calculations did not include a progressive mesh-refinement sequence, the reported values are interpreted at the adopted discretization levels rather than as mesh-independent estimates.

3.1.2. Static Structural Analysis of the Overall Framework Under Compressive Loading

To assess the load-bearing response of the overall willow framework under compressive loading after reserving a large through-hole at the top (the TRIZ-PC2 solution), boundary conditions were defined for the static structural analysis, as illustrated in Figure 5. The bottom contact plane of the shell was defined as a completely fixed support constraint, essentially restricting the translational degrees of freedom to $U_x = U_y = U_z = 0$, thereby accurately simulating the real physical state of the acoustic terminal resting statically on a desktop. Simultaneously, a vertically downward uniformly distributed load of 100 N (approximately 10 kg) was applied to the red-marked area on the top load-bearing surface. This setup represents a conservative loading condition corresponding to a user pressing the interactive panel during daily operation.

A: ABS:Static Structural

Static Structural

Time: 1 s

2026/4/17 12:06

- A Fixed Support
- B Force: 100. N

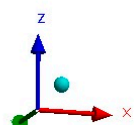
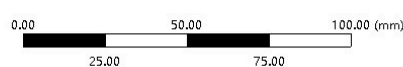
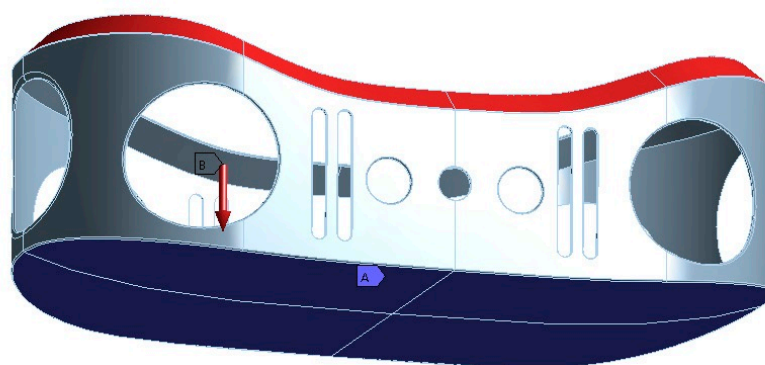


Figure 5. Boundary condition settings for the static structural simulation of the willow acoustic shell. (A) Completely fixed support constraint on the bottom surface of the shell; (B) 100 N vertically downward uniformly distributed load applied to the top load-bearing surface around the aperture.

The stress and deformation contours obtained under these boundary conditions are presented in Figure 6. Simulation results indicate that under the 100 N uniformly distributed heavy load, the maximum deformation of the ABS shell is 0.302 mm, and the maximum equivalent stress is 4.1 MPa. Constrained by the extremely low radial and tangential moduli, the maximum deformation of the willow shell reaches 1.21 mm, which, as indicated by the red and orange highlighted regions in Figure 6c, is primarily concentrated in the center of the loaded top surface; meanwhile, the maximum equivalent stress is concentrated in the edge transition zone of the curved aperture, with a peak value of 12.63 MPa. Although the deformation of the willow shell is larger than that of the ABS shell, this is consistent with the physical characteristics of orthotropic bio-based materials, and the 1.21 mm deformation remains within the allowable range considered for the acoustic structural design.

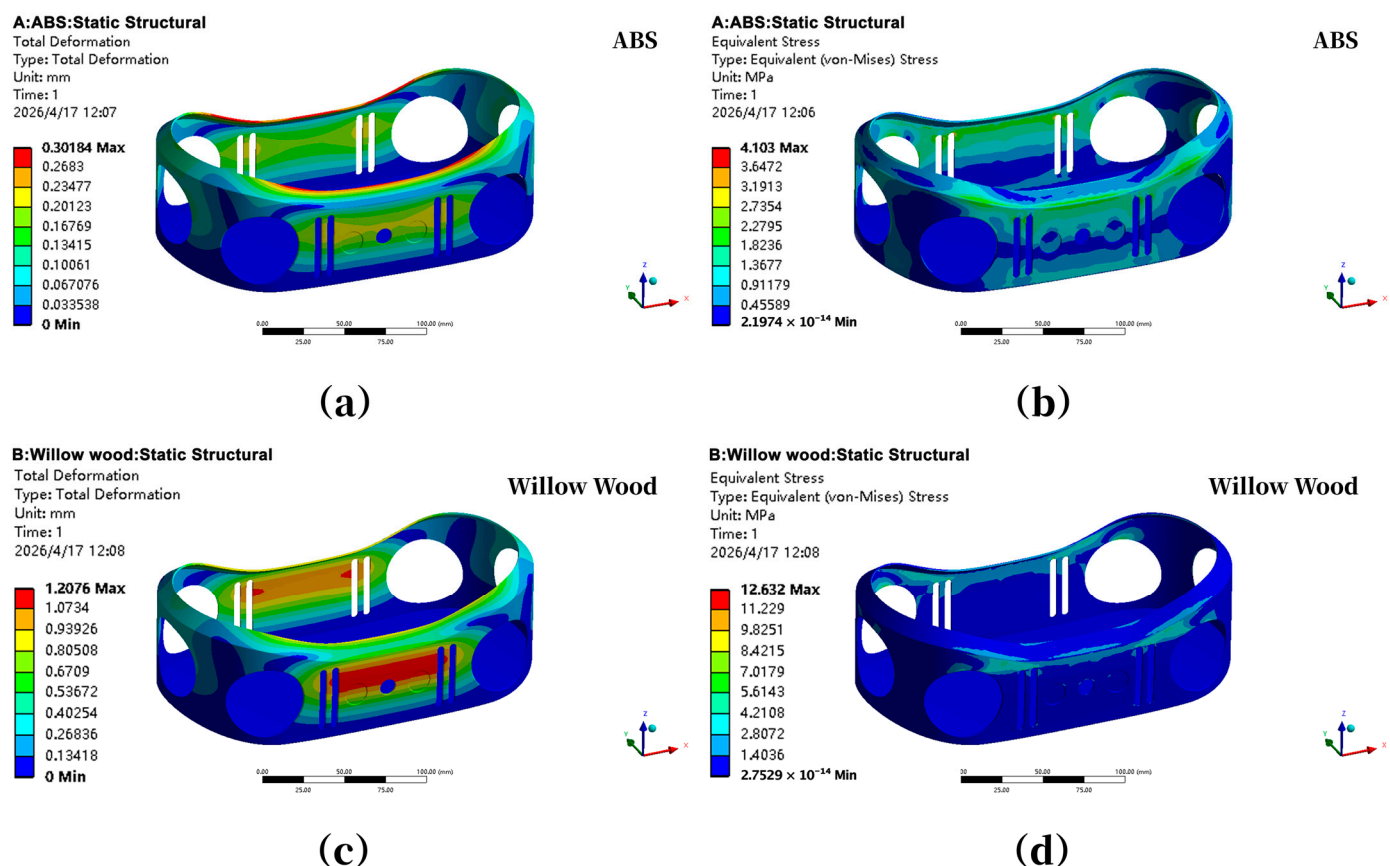


Figure 6. Comparison of total deformation and equivalent stress contours between the ABS and willow shells under a 100 N static load. (a) Total deformation contour of the ABS plastic shell (Maximum: 0.302 mm); (b) Equivalent stress contour of the ABS plastic shell (Maximum: 4.10 MPa); (c) Total deformation contour of the willow shell (Maximum: 1.21 mm); (d) Equivalent stress contour of the willow shell (Maximum: 12.63 MPa).

However, by observing the color gradient distribution of the equivalent stress contour in Figure 6d, it is clearly evident that, benefiting from the previously derived topological reinforcement strategy for the aperture edge based on TRIZ, the extreme stress peak of 12.63 MPa—represented by the scattered red extreme points in the figure—does not form a destructive localized point concentration at the vulnerable edge of the interactive aperture; instead, the high-stress region exhibits a band-like distribution characteristic, smoothly transitioning from yellow-green to the deep blue base. This continuous stress gradient is consistent with a more distributed load-transfer path through the reinforced transition zone, which may reduce the risk of localized stress concentration under the adopted numerical

conditions. This value is far below the longitudinal and transverse compressive yield limits of willow wood (>25 MPa). From a mechanical perspective, these results support the preliminary structural feasibility of the design scheme under the adopted numerical conditions, with the predicted stress remaining below the cited compressive-strength values while accommodating the interactive control module.

3.1.3. Constrained Modal Analysis and Vibration-Related Structural Assessment

To evaluate the suppression capability of the faceted shell structure against the low-frequency mechanical vibration of the loudspeaker, a constrained modal analysis was conducted while retaining the completely fixed support constraint at the bottom. The first six natural frequencies and their corresponding mode shapes were extracted, as detailed in Table 12 and illustrated in Figures 7 and 8.

Table 12. Comparison of the first six constrained modal frequencies between the ABS and harmonized willow shells.

Mode	ABS Shell Frequency (Hz)	Harmonized Willow Shell Frequency (Hz)	Mode-Shape Characteristics
1	215.28	216.32	Lateral bending and torsion at the top opening
2	239.56	256.46	Overall longitudinal bending of the side walls
3	356.43	370.66	Local wave-like vibration of the top cover
4	461.69	419.58	Lateral symmetric torsional vibration
5	487.89	455.06	Compound vibration of the bottom support surface
6	574.01	492.56	Global high-order standing wave mode

In acoustic engineering, the primary excitation range of a low-frequency loudspeaker unit generally falls within 40–200 Hz. If the first natural frequency of an acoustic enclosure falls within this range, forced resonance may occur, leading to sound coloration and degraded acoustic performance. As shown in Table 12, the first natural frequency of the ABS benchmark shell is 215.28 Hz, slightly above the main low-frequency excitation range. Similarly, the optimized orthotropic willow shell reaches a first natural frequency of 216.32 Hz. This close modal response suggests that the geometric stiffness-enhancement strategy, combining polyhedral faceting and local thickness compensation derived through TRIZ, may help compensate for the relatively low elastic modulus of low-density bio-based willow wood at the structural level. Within the scope of the present numerical study, the first-order natural frequency of the optimized willow shell remains above the principal low-frequency excitation range and close to that of the ABS benchmark, thereby providing a structurally meaningful indicator of resonance-related design risk.

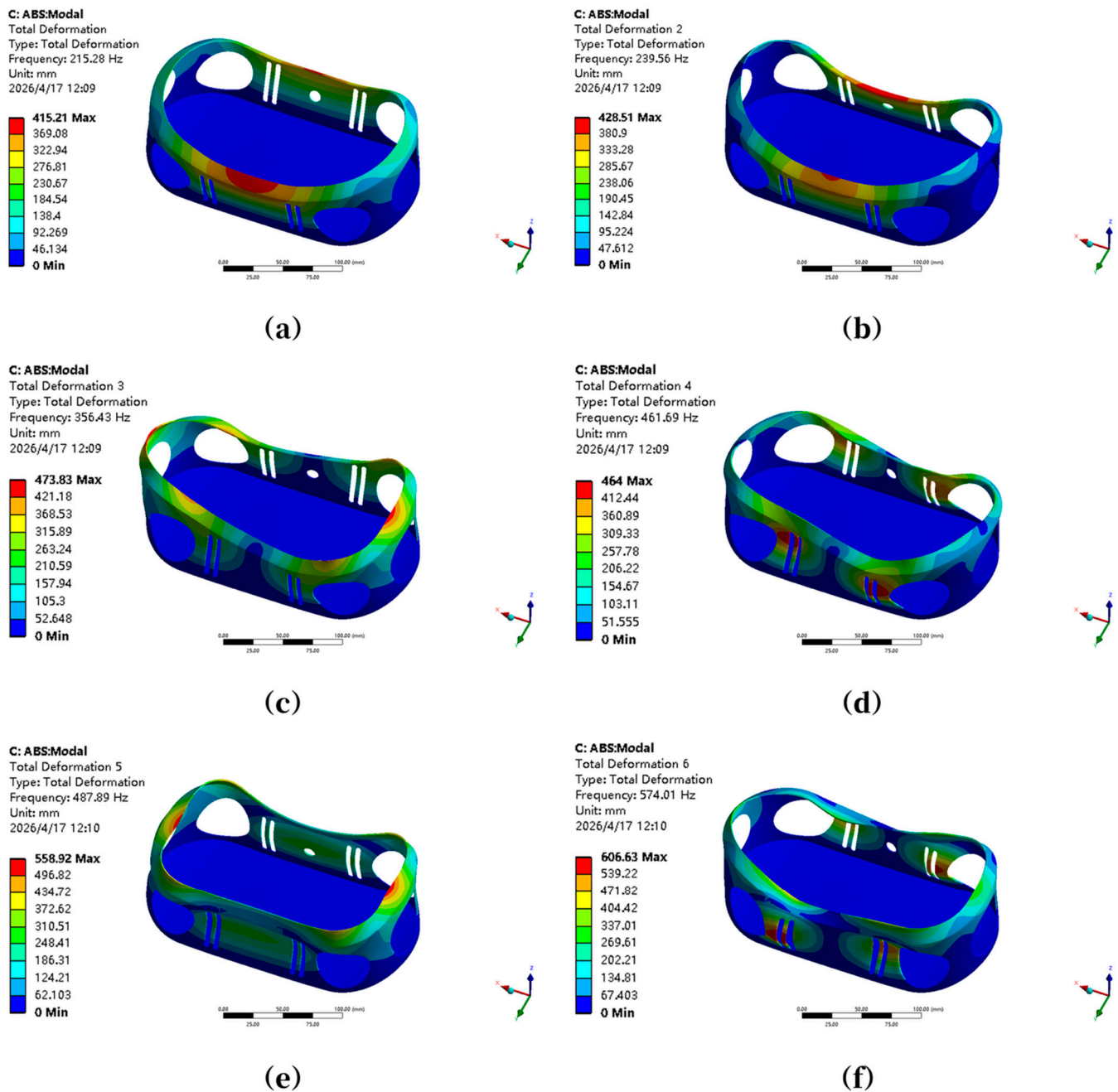


Figure 7. Distribution of the first six constrained mode shapes for the ABS plastic shell. (a) 1st mode shape; (b) 2nd mode shape; (c) 3rd mode shape; (d) 4th mode shape; (e) 5th mode shape; (f) 6th mode shape.

Further combining the mode shape comparisons in Figures 7 and 8, it is evident that the vibration evolution morphology of the willow shell at various orders—such as the 1st-order lateral bending and torsion, and the 3rd-order local wave-like vibration of the top cover—shows modal deformation characteristics broadly similar to those of the ABS shell. This result indicates that the geometric stiffness-compensation strategy based on TRIZ inventive principles helps offset the lower elastic modulus of bio-based materials.

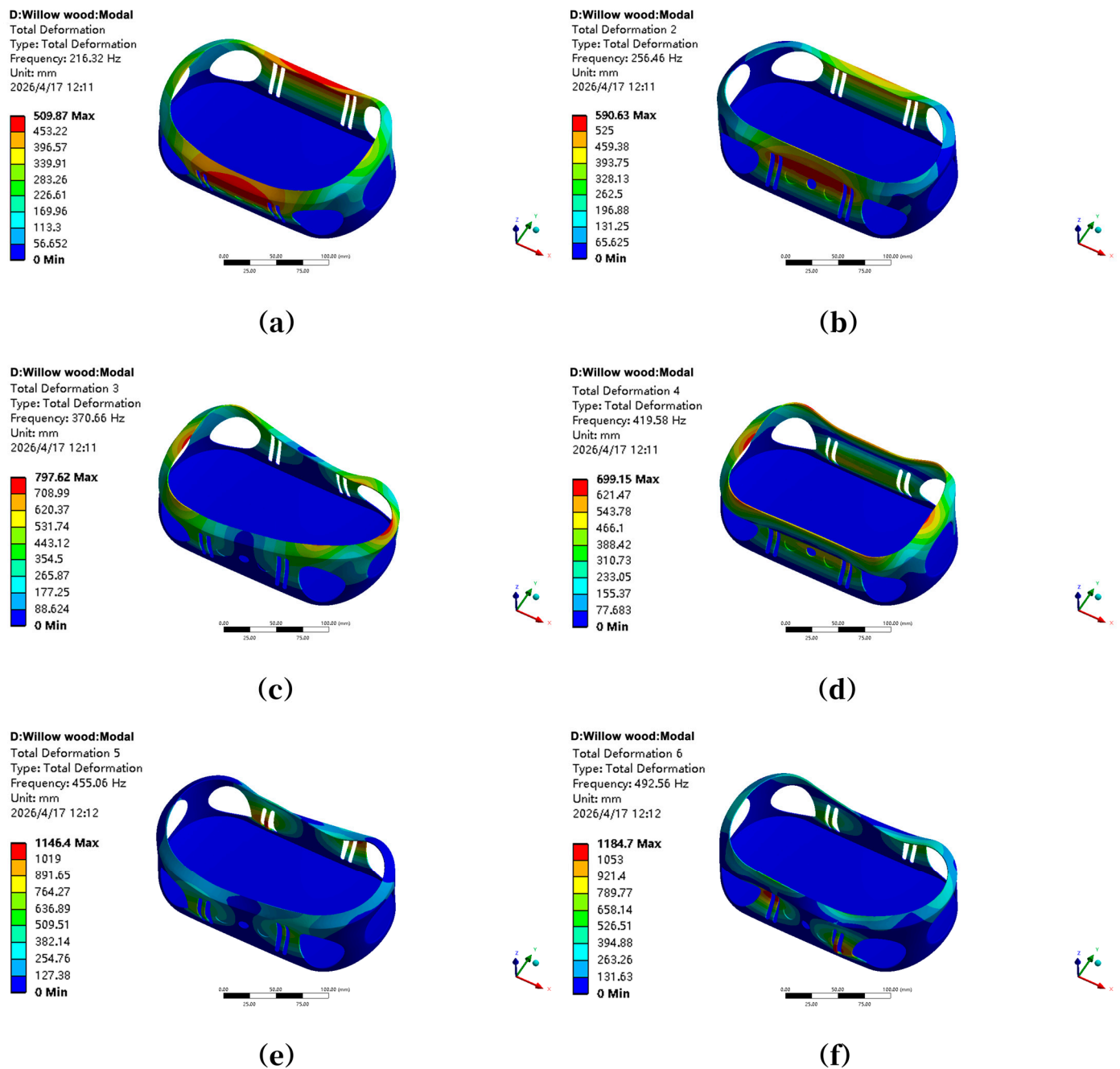


Figure 8. Distribution of the first six constrained mode shapes for the harmonized orthotropic willow shell. (a) 1st mode shape; (b) 2nd mode shape; (c) 3rd mode shape; (d) 4th mode shape; (e) 5th mode shape; (f) 6th mode shape.

3.2. Structural and Modal Assessment of the Final Design Scheme

The preliminary quantitative Kano analysis indicates that the target audience possesses a pronounced sense of green environmental responsibility. In conventional enclosure design, high-density engineering plastics such as ABS are commonly used to provide structural rigidity and mass. This design context motivates the exploration of bio-based material-substitution pathways in sustainable product development.

Under the premise of introducing no additional anti-resonance counterweights, this study substitutes traditional ABS plastic with the orthotropic bio-based willow wood. Finite element model data reveal that the density of ABS plastic is 1050 kg/m^3 , whereas

the density of willow wood is 417 kg/m^3 . This signifies that, given an equivalent cavity volume, the willow scheme realizes an approximate 60.3% reduction in baseline static mass.

Despite this substantial weight reduction, the numerical results indicate that the proposed scheme may accommodate the required interactive layout while maintaining a first-order modal response outside the principal low-frequency excitation range under the adopted simulation assumptions. On the one hand, the static structural results indicate that even after creating a large-sized physical through-hole at the top to accommodate the interactive module, following topological reconstruction and local mass compensation, the extreme stress in the vulnerable aperture region remains strictly controlled at 12.63 MPa. This is far below the longitudinal yield limit of the material, thereby helping to balance structural strength with interactive integrity; on the other hand, the first-order natural frequency of the harmonized willow shell reaches 216.32 Hz, showing a first-order modal response close to that of the ABS benchmark shell (215.28 Hz).

From an engineering perspective, the aperture transition should therefore be treated as a priority region for prototype detailing and structural verification.

These findings are consistent with previous studies showing that resonance behavior in wooden loudspeaker enclosures depends on enclosure geometry and internal filling [10], while wave propagation in wood is direction dependent because of material anisotropy [20]. Related studies have further emphasized the joint consideration of mechanical and acoustic properties in acoustic wood selection [33] and the influence of geometric representation on resonance-based numerical assessment [36]. In this context, the present study applies these material and geometric considerations within a requirement-driven enclosure design process that connects requirement prioritization, TRIZ-derived structural development, and finite element assessment.

The finite element results indicate that the proposed topological evolution and stiffness-compensation strategies can partially offset the low stiffness of bio-based materials. This design framework may help address vibration-related structural challenges inherent in the combination of heterogeneous materials at the physical level, providing a preliminary engineering reference for the early-stage structural design of low-carbon interactive acoustic terminals. The final rendered result of the willow acoustic model, derived based on the aforementioned multi-dimensional constraints, is illustrated in Figure 9.



Figure 9. Final rendered scheme of the harmonized willow acoustic terminal.

3.3. Limitations and Future Validation

The present study focuses on the early-stage design and numerical assessment of a bio-based acoustic enclosure and should be interpreted within this scope. Within this scope, the use of willow wood is intended to explore a bio-based material-substitution pathway relevant to sustainable product development. Because a comparative life-cycle assessment or carbon-footprint analysis was not conducted, the environmental implications

of willow substitution relative to ABS remain to be established. The proposed willow-wood enclosure was evaluated through finite element-based static structural and constrained modal analyses, while prototype fabrication and direct experimental measurements were outside the scope of the present study. The modal results provide an initial indication of vibration-related structural behavior, but they do not represent a complete acoustic performance evaluation. Further prototype-oriented work involving structural testing, frequency-response measurement, sound-pressure-level measurement, harmonic-distortion analysis, and listening-based evaluation would help characterize practical performance and refine the proposed framework for subsequent engineering applications. In addition, the willow material was represented using an idealized orthotropic equivalent model based on literature values; variations in moisture content, density, growth conditions, and fiber orientation can influence the response of physical prototypes. Future work should examine the sensitivity of the structural and modal responses to documented material-parameter ranges and progressive mesh refinement, together with specimen-specific characterization and prototype testing.

Beyond these case-specific validation needs, the framework is intended to be configured for each design application rather than used with a universal set of requirement weights and requirement-to-TRIZ mappings. The present willow-enclosure case demonstrates how requirement prioritization, TRIZ-based contradiction resolution, and finite element assessment can be connected within one design context. For application to other products or bio-based materials, the requirements, AHP comparisons, contradiction definitions, and material inputs should be established for the corresponding context. Future studies may examine this procedure in additional bio-based enclosure cases.

4. Conclusions

To address the application limitations of bio-based materials in interactive acoustic enclosures, this study developed a requirement-driven engineering design framework integrating Kano–AHP, TRIZ, and FEA. Using a willow-wood interactive acoustic enclosure as an engineering case study, the following conclusions are drawn:

1. A synergistic decision-making mechanism was established to bridge user requirements and physical engineering boundaries. To reduce the methodological gap between perceptual interaction demands and engineering translation in intelligent hardware development, Kano–AHP was used to extract and quantify key objectives such as interaction usability and acoustic stability. By introducing TRIZ theory, these user-oriented objectives were transformed into structured technical and physical contradictions, providing a mapping route from requirement-driven inputs to topological structural solutions in bio-based hardware design.
2. The finite element results support the structural feasibility of bio-based material substitution through geometric stiffness compensation under the assumptions of the numerical model. Under a 100 N static load, the maximum equivalent stress of the harmonized willow shell was 12.63 MPa, remaining below the reported compressive strength limit of the material. Meanwhile, its first natural frequency reached 216.32 Hz, close to that of the ABS benchmark shell at 215.28 Hz. These results indicate that the proposed strategy can partially offset the low stiffness of bio-based materials while maintaining structural feasibility.
3. The study provides an explicit decision path from requirement prioritization to contradiction formulation, structural development, and finite element assessment for a willow enclosure. In this case, the decision path led to a faceted shell and a locally reinforced opening intended to address stress concentration and vibration-related structural risk under the adopted numerical assumptions. The framework provides an

engineering decision-making reference for applying bio-based materials in interactive acoustic terminals. Further proto-type-oriented structural and acoustic characterization would help evaluate the practical performance of the proposed enclosure.

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Institutional Review Board Statement: Ethical review and approval were not required for this study because the questionnaire collected only anonymous and voluntary opinions on product design requirements and did not involve identifiable personal information, sensitive personal data, clinical intervention, or biological samples.

Informed Consent Statement: Informed consent was obtained from all participants before the anonymous questionnaire survey.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABS	Acrylonitrile butadiene styrene
Kano	Kano model of customer satisfaction
AHP	Analytic Hierarchy Process
TRIZ	Theory of Inventive Problem Solving
FEA	Finite element analysis
CI	Consistency index
CR	Consistency ratio
RI	Random index
$\lambda_{\max}$	Maximum eigenvalue
SI	Satisfaction index
DSI	Dissatisfaction index

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