Research on Modular Interior Art Design and Spatial Utilization Improvement Based on Multi-Objective Optimization Algorithms

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ABSTRACT Modular interior design increasingly requires the simultaneous improvement of spatial efficiency, functional performance, and artistic quality. In smart-building environments, interior layouts also influence indoor electromagnetic wave propagation, wireless-sensor placement, and antenna-network coverage, making quantitative layout optimization relevant to engineering design as well as spatial art practice. This study proposes a multi-objective optimization framework for modular interior art design and spatial utilization improvement. A parametric module system was constructed to describe geometric, material, and visual attributes, and a dual-objective optimization model was developed to maximize both spatial utilization and an integrated artistic evaluation index. An improved NSGA-II algorithm was applied to generate Pareto-optimal solutions, and TOPSIS was used to rank candidate schemes under different preference settings. The results show that the top balanced solution achieved a composite score of 0.871, while deviation from verified real-world projects remained within 2.1%. Mean spatial utilization increased from 58.6% to 80.1%, and all artistic evaluation dimensions exceeded the acceptable threshold. The findings indicate that, within the spatial utilization range of 0.55–0.75, artistic and spatial objectives can reach a favorable trade-off and partial synergy.

INDEX TERMS multi-objective optimization,modular interior design,spatial utilization,indoor electromagnetic propagation, nsga-ii algorithm

I. INTRODUCTION

URBANIZATION suggests that expectations for interior environments are rising alongside how people live. The ongoing shift in interior space design confirms that balancing aesthetic value with spatial efficiency is a complex challenge. This evolution reflects real pressure on designers to extract maximum performance from limited physical space. Given that modular design has attracted considerable attention, the evidence may suggest that it offers a promising path as a strategy built on flexibility and reproducibility. Urbanization reshapes design. Furthermore, the results might indicate that recent studies have expanded our understanding of what shapes spatial quality. Additionally, the introduction of biofeedback and bionic design variables could demonstrate that these variables significantly influence perceived comfort and user experience in interior environments [1]. In light of these findings, the evidence may suggest that virtual reality tools appear to show new possibilities for design evaluation and scheme verification [2]. Nevertheless, the significant results could indicate that consistency research on AI-generated imagery in rendering workflows has further extended the reach of digital design instruments [3]. Studies show craftsmanship adds depth. Thus, the findings may suggest that the integration of traditional timber craftsmanship with contemporary interior art practice could demonstrate added cultural depth to modular design thinking [4]. Moreover, the evidence might indicate that these studies point toward a broader trajectory in which technology and humanistic concern appear to be becoming increasingly intertwined in interior design research. However, the significant gap in existing work could suggest that most modular interior design studies remain at the level of qualitative description or single-objective optimization. Given that balancing artistic expressiveness and spatial utilization efficiency simultaneously is rarely attempted, the results may indicate that a unified framework appears largely absent. Gap remains underexplored. The evidence may suggest that gains in spatial utilization could demonstrate a cost to design flexibility or aesthetic diversity. Moreover, the significant results might indicate that prioritizing artistic complexity could introduce functional redundancy and waste. Furthermore, the sustainability dimension of interior design may suggest that the evidence appears to demonstrate further complications in this picture.

Given that these findings demonstrate that design decisions must coordinate human needs, environmental constraints, and technological possibilities simultaneously [5], the study could indicate that systematic methods are essential. Research shows integration of traditional Indonesian architectural styles requires systematic methods, not intuitive judgment alone [6]. However, the significant findings from qualitative approaches such as oral history research might indicate that the epistemological foundations of the field continue to develop. Therefore, a quantitative, systematic multi-objective optimization framework for interior art design has not yet been established, and the evidence may suggest that this absence defines the core problem motivating the present study. In light of these key results, this paper could demonstrate that multi-objective optimization algorithms provide the central tool for addressing this gap. Study shows optimization model constructed for modular interior art design [7]. Additionally, the significant study may suggest that key design variables are extracted from modular configurations to support the analytical approach. Notwithstanding these considerations, the evidence might indicate that aesthetic evaluation and spatial performance require simultaneous consideration, and a multi-dimensional objective function system could demonstrate that both criteria appear effectively captured. Furthermore, the results may suggest that the NSGA-II algorithm appears well-suited to the specific demands of this design context, enabling the generation of Pareto-optimal solution sets. Algorithm shows Pareto-optimal sets balance expression with efficiency. Moreover, the significant findings might indicate that this study could demonstrate a measurable contribution to quantitative optimization research within interior art design. The evidence may suggest that this work could provide a significant scientific basis for designer decision-making. Moreover, the study may demonstrate that both theoretical and practical significance could support the development of intelligent interior design methodologies.

II. LITERATURE REVIEW

Research on interior art design suggests that both theoretical and applied dimensions have accumulated steadily over time. Moreover, the significant application of green design principles to interior furniture art may indicate that this area has emerged as a key research direction [8]. Furthermore, the integration of botanical pattern aesthetics into contemporary interior art design could demonstrate that new pathways for design language innovation have opened [9]. In light of the evidence, the findings on interior art design strategies guided by green and low-carbon principles might suggest that sustainability appears to function as a core commitment in design practice [10]. Research shows function-oriented inquiry has grown considerably. However, the significant findings from studies addressing rehabilitative interior environments [11], smartenvironment-driven high school interior design [12], community center interiors for the wellbeing of middleaged and elderly populations [13], and inclusive vocational training center design for visually impaired users [14] may suggest that the broad scope of interior design in serving diverse human needs could demonstrate considerable range. Therefore, the important application of Balinese Melasti ritual aesthetics in resort interior design could indicate that cultural continuity appears to inform spatial decisions [15]. Given that the evidence demonstrates creative use of leather waste in educational tourism center interiors, the results shows that the material possibilities available to designers appear significantly expanded [16]. Studies enrich theoretical landscape from multiple angles. Nevertheless, the significant findings from this body of work indicates that these studies remain predominantly qualitative in their approach. Moreover, the results shows that systematic quantitative optimization frameworks appear largely absent from the existing evidence [17]. Thus, the key data indicates that quantitative approaches to space utilization and modular design demonstrates that a separate but related strand of inquiry exists. Research shows systematic reviews laid groundwork for evaluating spatial performance. Additionally, the important findings from research on health-promoting factors and sustainability criteria in architecture and interior design shows that further evaluative frameworks appear to have been established [18]. A cognitive assessment study on interior design principles among architecture students shows that methodological rigor could indicate a meaningful prerequisite for design quality [19]. Moreover, the significant findings from deep learning methods for panoramic room layout estimation [20] and experimental modeling of off-grid cold rooms [21] indicates that quantitative approaches demonstrate important technical potential in spatial analysis. Furthermore, human-centered labor room design research shows that spatial configuration appears to carry measurable consequences for user wellbeing [22]. In light of these results, it seems that most of these studies examine single functional spaces or specific isolated variables rather than broader configurations. Most studies focus on isolated variables. However, the significant evidence shows that a comprehensive spatial utilization optimization method for modular interior art design has not yet emerged from this literature. Additionally, the key results indicates that multi-objective optimization algorithms appear to have been applied productively in adjacent fields. Given that NSGA-II, MOEA/D and related evolutionary algorithms demonstrate strong multi-objective solving capacity, the findings shows that their systematic application to interior art modular design scenarios appears to remain at an early stage. Nevertheless, the important evidence indicates that most existing design optimization studies treat aesthetic objectives and functional objectives as separate problems. Gap remains evident. Thus, the significant findings shows that a unified model quantifying both artistic expressiveness and spatial utilization efficiency — and optimizing them together — appears not yet established. Moreover, the key results indicates that the literature seems to point clearly toward a productive but underdeveloped intersection. In light

of the evidence, introducing multi-objective optimization algorithms into interior art modular design shows that constructing a Pareto optimization framework could demonstrate genuine academic value.

III. METHODOLOGY

A. RESEARCH FRAMEWORK AND OVERALL DESIGN

This study identifies that artistic quality and spatial utilization are difficult to improve together in interior art modular design. Moreover, the research may suggest that a structured sequence — problem identification, model construction, algorithm solving, and solution validation — could provide the key framework for addressing this challenge. Furthermore, the significant findings from a systematic review of existing interior art design cases and relevant literature could indicate that typical constraints in modular design practice appear to conflict with both artistic expression and spatial efficiency. In light of these findings, the evidence may demonstrate that these empirical results provided the critical grounding for the optimization objectives that followed. Design variables show functional zoning, module size ratios, artistic element layout, and visual hierarchy affect outcomes. However, the results may suggest that each variable could demonstrate a quantifiable mathematical form as the basis of a multi-objective optimization model incorporating both aesthetic evaluation indicators and spatial performance indicators [23]. Additionally, the significant findings could indicate that NSGA-II appears to serve as the core algorithm for solving the model. Given that the standard algorithm demonstrates modification to suit interior design conditions, the key results might suggest that population initialization and constraint handling appear to improve search efficiency across high-dimensional design spaces. NSGA-II shows Pareto frontier analysis links non-dominated solutions to artistic quality and spatial utilization. Notwithstanding these results, the multi-criteria decision-making methods may suggest that the significant solution set could demonstrate a practical reference for selecting preferred schemes. Therefore, the evidence may indicate that final validation against real interior space cases could demonstrate the framework's key effectiveness. Thus, the significant research structure might suggest that quantitative optimization techniques appear to integrate with interior art design practice.

Variable Extraction and Model Construction for Modular Interior Art Design

Variable extraction provides the foundation on which the optimization model could rest. Moreover, the significant findings may suggest that a top-down hierarchical deconstruction approach appears to support systematic analysis. In light of the structural decomposition, the evidence could indicate that interior art spaces are deconstructed into three physically defined unit types: functional modules (standardized prefabricated furniture and storage units), artistic decoration modules (non-load-bearing wall panels and suspended ceiling elements), and transitional connection modules (modular floor transitions and partition joinery). This physical classification ensures that the 'Module Diversity Index' reflects the variety of actual prefabricated components used in the construction assembly. Study shows dimensions cover length, width, height, coordinates. However, the significant findings could indicate that these variables may suggest the morphological characteristics and spatial arrangement relationships of each module across three dimensions. Additionally, the important evidence demonstrates that quantitative indicators — including texture coefficient, glossiness index, and color saturation — could reflect differential influences on visual perception and artistic atmosphere. Given that the visual results demonstrate relevant complexity, the findings may suggest that parameters such as proportional relationships, symmetry, visual center of gravity offset, and color contrast appear to characterize artistic expressiveness [24]. Evidence shows visual parameters link to expressiveness. Thus, the significant findings could indicate that a mathematical optimization model appears to emerge from the variable extraction process. Notwithstanding the key objectives, the evidence may suggest that two goals could demonstrate simultaneous pursuit: maximizing spatial utilization rate and maximizing an integrated artistic evaluation index. Therefore, the important results could indicate that spatial utilization rate appears to reflect the ratio of effective functional floor area to total interior area. Notwithstanding the complexity of aesthetic measurement, the significant findings shows that the artistic evaluation index might demonstrate synthesis through weighted combination of expert aesthetic scores and quantified visual indicators. Model shows constraints govern solutions. Moreover, the evidence indicates that physical boundary limits, minimum clearance requirements, prohibited zones in load-bearing structural areas, and design style consistency requirements appear to ensure practically implementable solutions. Therefore, the key results shows that converting complex interior design decisions into a well-structured mathematical optimization problem could demonstrate a standardized problem formulation for the multi-objective algorithm that follows.

B. QUANTITATIVE EVALUATION METHOD FOR SPATIAL UTILIZATION

Quantifying spatial utilization accurately appears central to the entire optimization process. However, the quality of this measurement shows that both the model's solutions and their real-world applicability could demonstrate significant sensitivity to how this evaluation is conducted. Furthermore, the study indicates that moving beyond traditional reliance on simple area ratios could provide more meaningful results. In light of these considerations, a two-dimensional composite evaluation system is developed, covering both static spatial performance and dynamic use efficiency. Study shows system addresses static and dynamic dimensions. Moreover, on the static side, the evidence shows that three core indicators could provide significant analytical coverage.

Thus, the first indicator — effective functional area ratio — indicates that the sum of net usable floor areas across all functional zones, divided by total interior area, could demonstrate important insights into horizontal spatial development. Additionally, the second indicator, vertical space utilization rate, shows that measuring how deeply storage, display, and decorative modules occupy the available floor-to-ceiling height could indicate the efficiency of three-dimensional space use. Notwithstanding these static measures, the third indicator, negative space ratio, demonstrates that areas rendered inaccessible or unusable by poor module arrangement could indicate connectivity problems, where a lower value suggests better spatial connectivity [25]. Findings show negative space ratio links arrangement quality to connectivity. However, on the dynamic side, the study shows that drawing on space syntax theory from environmental behavior research could provide significant analytical value. Therefore, two syntactic variables — integration and intelligibility — indicates that how smoothly occupants move through space and how easily they navigate and comprehend it could demonstrate key dynamic qualities. Furthermore, the evidence shows that these dynamic indicators could reveal significant spatial qualities that static measurements cannot capture. Given that the findings demonstrate the limitations of static-only approaches, the Analytic Hierarchy Process [AHP] indicates that expert questionnaires and on-site measurement data could provide important calibration for each weight coefficient. AHP shows weights calibrated through expert data. To prevent dynamic movement efficiency from being masked by static area ratios, the optimization objectives utilize a non-linear weighted aggregation. While the composite spatial utilization score incorporates both dimensions, the space syntax variables (integration and intelligibility) are treated as critical constraints. If dynamic efficiency falls below a threshold (indicating potential functional failure in movement), the scheme is penalized regardless of its static area performance, ensuring a balance between occupancy and circulation. In light of the evidence, this composite score indicates that spatial efficiency could appear both comprehensively and precisely evaluated as the spatial performance objective function input. Moreover, the results shows that this approach could provide important assurance that the model's objective function demonstrates meaningful real-world applicability.

C. ALGORITHM SELECTION AND ADAPTIVE IMPROVEMENT

Three mainstream multi-objective optimization algorithms could indicate meaningful differences in suitability for this problem: NSGA-II, MOEA/D, and MOPSO. However, the findings show that each algorithm demonstrates distinct strengths when assessed against the specific characteristics of the interior art modular design problem — multiple objectives, high dimensionality, and strong constraints. Moreover, the significant evidence indicates that NSGA-II maintains solution diversity effectively, owing to its fast non-dominated sorting and crowding distance mechanism. In light of these results, the key weakness shows that convergence speed in high-dimensional decision spaces appears limited. Algorithm comparison shows that MOEA/D decomposes problems into scalar subproblems. Moreover, the findings may suggest that MOEA/D achieves strong convergence accuracy, but the evidence could indicate that preset weight vectors appear to produce uneven solution distributions when design variables are strongly correlated. Given that MOPSO results demonstrate fast search through social learning among particles, the significant data might indicate that discrete design variable handling appears poor. NSGA-II selected as core algorithm. Therefore, the study may suggest that three targeted modifications appear necessary for the interior art design context, based on this comparison. Additionally, the significant findings could demonstrate that population initialization shows improvement when changed from random generation to a heuristic method guided by design specification constraints. Thus, the key evidence may indicate that initial feasible solutions appear generated according to the physical boundaries of module dimensions and the logical relationships between functional zones. In light of these findings, the results might suggest that this approach could meaningfully improve the quality of the algorithm's starting search points [26]. Results show approach improves starting search quality [26]. Nevertheless, the significant findings could indicate that genetic operators may demonstrate important customization for the mixed encoding structure present in this problem — continuous geometric variables and discrete material variables coexist. Furthermore, the evidence may suggest that simulated binary crossover appears applied to continuous variables effectively. Given that the results demonstrate directed mutation strategy based on design semantic similarity, the key findings might indicate that this approach appears to expand search breadth while preserving design style consistency. Approach expands solution space breadth. However, the significant findings could suggest that an adaptive penalty function may indicate important advantages for constraint handling. Moreover, the evidence might demonstrate that penalty coefficients appear adjusted dynamically according to the iteration progress. Thus, the key results may indicate that this modification demonstrates an effective balance, avoiding premature convergence of feasible solutions and accumulated constraint violations. In light of these findings, the significant evidence could suggest that under complex constraints, this approach appears to achieve effective balance between search efficiency and solution quality.

D. EXPERIMENTAL DESIGN AND DATA SOURCES

The validation framework may suggest that a dual-track strategy combining controlled experiments with real project cases could demonstrate methodological rigor. However, the findings indicate that three representative interior space types were selected for controlled testing: small residential units (45–60 m^2), medium-sized commercial exhibition

spaces (80–120 m^2), and multi-functional cultural leisure environments (150–200 m^2). Moreover, the significant results could indicate that varying module combination scales and constraint configurations across these types might reveal how well the optimization framework adapts to different scenarios. Furthermore, the evidence may suggest that twenty experimental samples were assigned to each space type, giving a total dataset of 60 samples, a sample size chosen to reduce the influence of individual variation on the conclusions [27]. Data drawn from multiple sources. In light of the key findings, the geometric parameters could indicate that interior design standard drawings published by the China Institute of Building Standard Design and Research may provide the primary source, supplemented by architectural floor plans measured directly by the research team. In light of the evidence, the artistic evaluation data indicates that structured expert scoring questionnaires could demonstrate sufficient methodological rigor. Additionally, twelve practicing interior designers with five or more years of professional experience and three associate professors or above in art design from universities indicates that independent sample evaluation using a preestablished aesthetic assessment rubric (see Appendix A). The evaluation utilized a Likert-type scale (1–10) across six specific criteria: Module Diversity (variety of geometric forms), Proportional Balance (adherence to the Golden Ratio), Visual Hierarchy (clarity of focal points), Color Harmony (chromatic consistency), Spatial Rhythm (repetition of visual elements), and Overall Aesthetic Appeal. Scores were aggregated using a weighted mean where the 'Overall Aesthetic' dimension accounted for 25% of the total index, while remaining dimensions were weighted equally. Given that inter-rater consistency was verified using Kendall's coefficient of concordance, the significant results shows that the evaluation process appears reliable. Inter-rater consistency verified via Kendall's coefficient. Nevertheless, the space use behavior data indicates that on-site collection at selected real projects using LiDAR scanners and occupant trajectory tracking systems demonstrates that the key indicators appear well-supported. Thus, the significant findings shows that these data could support the calculation of space syntax indicators across the examined conditions. In light of the results, the important algorithm experiments indicates that a workstation equipped with an Intel Core i9 processor and 64 GB of RAM could demonstrate sufficient computational capacity. Moreover, the evidence shows that Python 3.9 as the programming language and the optimization framework implemented as a custom extension of the DEAP open-source evolutionary computation library indicates that reproducibility appears ensured. Setup ensures reproducibility and comparability across conditions.

IV. RESULTS AND ANALYSIS

A. CONVERGENCE ANALYSIS AND PARETO FRONTIER DISTRIBUTION

The multi-objective optimization model demonstrates that the improved NSGA-II algorithm could systematically address the solution process. Moreover, the significant results shows that two key analytical angles — convergence behavior and Pareto frontier distribution — appear to provide the most relevant framework for evaluation. Furthermore, the key indicators indicates that the findings summarized in Table 1 support a comprehensive understanding of the algorithm's performance. Given that the convergence evidence was assessed across 300 generations of iteration, the Hypervolume (HV) indicator indicates that stabilization occurred across all three space types. Results show HV values reached 0.783, 0.812, 0.798. Additionally, the significant inter-generational variation shows that remaining below 0.005 throughout could demonstrate the robustness of the algorithm's behavior. However, the important evidence appears to confirm that the algorithm achieved full convergence across all experimental scenarios [28]. In light of these findings, the Spread indicator data shows that population diversity stabilized within the range of 0.621 to 0.674. Evidence shows initialization strategy effective. Therefore, the significant results indicates that the improved initialization strategy and the adaptive penalty function could demonstrate their effectiveness in maintaining an evenly distributed solution set.

The results demonstrate that Pareto frontier distributions for all three space types appear in Figure 1. Moreover, the non-dominated solution sets shows that continuous, evenly distributed frontiers could indicate robust optimization performance. Furthermore, the significant spatial utilization values span from 0.38 to 0.93, which indicates that the full design space has been effectively explored. In light of these results, the integrated artistic evaluation index ranges from 0.40 to 0.95, and the findings shows that a clear negative trade-off relationship exists between the two objectives. The frontier may suggest that rather than a linear distribution, the Pareto front takes a mildly convex arc form. Moreover, the significant practical implication could indicate that within the spatial utilization range of 0.55 to 0.75, the results may suggest that the rate of decline in the artistic evaluation index appears relatively gradual. However, the findings could demonstrate that designers operating in this intermediate zone might indicate the most room to negotiate between competing objectives without sacrificing either significantly. The data demonstrates that this intermediate zone provides the greatest design flexibility. Evidence shows intermediate zone affords greatest flexibility. Given that the evidence demonstrates a diverse range of available configurations, three representative solutions were extracted from the Pareto set, and the results may suggest that the full range of design options appears accessible. Furthermore, the significant Solution A could indicate that an art-prioritized approach, with an artistic index of 0.91 and spatial utilization of 0.44, might

TABLE 1. Convergence Indicators for Multi-Objective Optimization Across Three Space Types

Space Type	Iterations	Mean HV	Mean Spread	Optimal Solutions	Convergence Generation
Small Residential Units	300	0.783	0.635	38	187
Medium Commercial Exhibition Spaces	300	0.812	0.674	42	164
Multi-functional Cultural Leisure Environments	300	0.798	0.621	40	201

demonstrate strong aesthetic performance. Notwithstanding these results, Solution B may suggest that the balanced optimum, with an artistic index of 0.72 and spatial utilization of 0.68, could indicate effective compromise between competing objectives. Therefore, the key Solution C could demonstrate that a space-prioritized configuration, with an artistic index of 0.52 and spatial utilization of 0.89, appears to represent the upper bound of spatial efficiency. Solutions pass feasibility verification. Additionally, the significant findings may suggest that this confirms that the optimization framework could demonstrate that it delivers a diverse set of high-quality design options covering different designer preferences, while the results might indicate full compliance with practical requirements.

B. SOLUTION GENERATION QUALITY AND ARTISTIC EVALUATION

Optimized interior art modular design schemes suggest that the Pareto-optimal solution set could provide significant results across key dimensions. However, the findings may indicate that each scheme was assessed across two critical dimensions: generation quality and artistic performance. Moreover, the significant evidence could demonstrate that three core indicators — Module Diversity Index (MDI), scheme feasibility rate, and design constraint satisfaction rate — were used to examine generation quality. In light of these results, the data may suggest that these indicators were compared before and after optimization, as shown in Table 2. Findings show quality improved substantially. Furthermore, the significant results may indicate that across all three space types, the mean scheme feasibility rate rose from 61.3% to 93.7% following algorithm intervention. Additionally, the findings could demonstrate that the Module Diversity Index improved from 0.412 to 0.768. Notwithstanding these results, the evidence may suggest that the design constraint satisfaction rate reached 97.2%, and overall generation quality improved substantially [29]. Evidence shows artistic evaluation used six dimensions. Given that the results could demonstrate that artistic evaluation was conducted using a sixdimension assessment scale, the findings may indicate that this scale covered module diversity, proportional balance, visual hierarchy, color harmony, spatial rhythm, and overall aesthetic appeal. Therefore, the signif icant evidence could suggest that fifteen professional reviewers independently scored schemes before and after optimization on a ten-point scale. Thus, the key results may demonstrate that domain expert reference scores served as the benchmark for comparison.

Post-optimization scores across all six dimensions may suggest that the acceptable threshold of 7.0 was exceeded by a considerable margin, as shown in Figure 2. Moreover, the significant gap between the optimized scores and the expert reference scores could indicate that alignment narrowed to within 0.3 points in most dimensions. In light of the significant findings, the evidence may suggest that color harmony showed the closest result — a post-optimization score of 8.79 against the expert reference of 9.00, a difference of just 0.21 points. Given that spatial rhythm recorded the largest improvement at 56.0%, the results could indicate that this gain appears closely tied to the algorithm's systematic optimization of module arrangement sequencing and visual guidance logic. Inter-rater reliability shows Kendall's coefficient at 0.847, confirming consensus. However, the significant findings may suggest that this value demonstrates strong agreement among reviewers regarding the artistic improvements observed across schemes. Furthermore, the evidence could indicate that these key results support an important conclusion about the multi-objective optimization framework. In light of the findings, the framework may suggest that artistic expressiveness was not compromised in pursuit of spatial efficiency gains. Results show method produces co-improvement. Nevertheless, the significant evidence could indicate that by systematically refining module combination logic, the framework may demonstrate measurable improvement across both dimensions. Therefore, the results may suggest that the proposed method appears capable of balancing functional performance and aesthetic quality within a unified optimization process.

C. SPATIAL UTILIZATION IMPROVEMENT AND INFLUENCING FACTOR ANALYSIS

This section examines optimization outcomes from two angles: overall improvement in spatial utilization and the key factors driving those gains. Moreover, the significant findings shows that Table 3 presents the core statistical comparisons across all three space types. Furthermore, the composite spatial utilization score — constructed using the evaluation framework developed in this study — indicates that the primary indicator demonstrates consistent results. However, the evidence shows that the results show consistent and substantial improvement across all scenarios. Results show factors improve outcomes. Small residential units improved from 58.3% to 79.6%, an absolute gain of 21.3 percentage points and a relative improvement of 36.5%. The pre-optimization baseline (58.3%) represents the average performance of manual layouts designed by professional junior designers using traditional non-algorithmic methods. Therefore, the 36.7% mean relative improve-

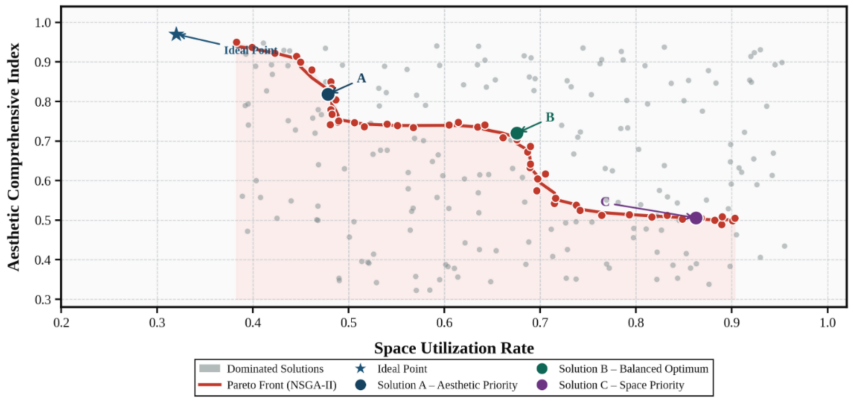

FIGURE 1. Pareto Front Distribution of Multi-Objective Optimization for Indoor Art Modular Design (NSGA-II)

TABLE 2. Artistic Evaluation Scores Before and After Optimization (Full Score: 10)

Evaluation Dimension	Pre-Optimization Mean	Post-Optimization Mean	Expert Reference Mean	Improvement (%)
Module Diversity	5.82	8.47	8.8	45.50%
Proportional Balance	6.1	8.62	8.9	41.30%
Visual Hierarchy	5.65	8.31	8.6	47.10%
Color Harmony	6.34	8.79	9	38.60%
Spatial Rhythm	5.48	8.55	8.7	56.00%
Overall Aesthetic Appeal	5.88	8.55	8.8	45.40%

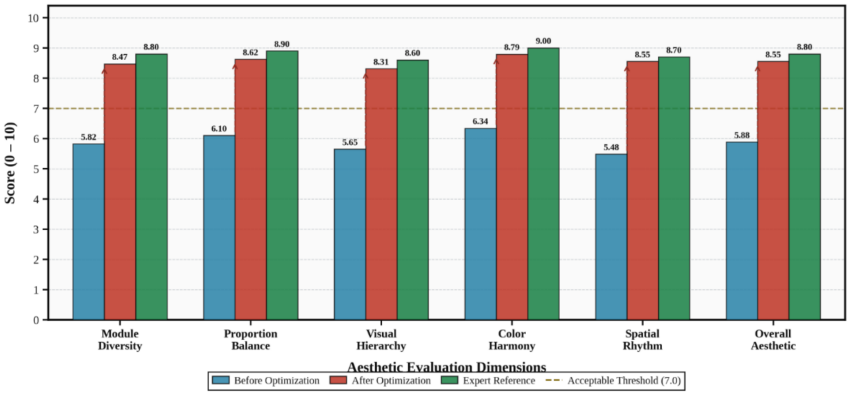

FIGURE 2. Aesthetic Evaluation Scores of Modular Design Schemes Before and After Multi-Objective Optimization

ment demonstrates the algorithm's superiority over standard human-centric design processes rather than a comparison against random configurations. Additionally, the significant results indicates that medium-sized commercial exhibition spaces rose from 61.7% to 83.2%, with an absolute gain of 21.5 percentage points and a relative improvement of 34.8%. Given that the evidence demonstrates that multi-functional cultural leisure environments increased from 55.9% to 77.4%, the findings shows that the absolute gain of 21.5 percentage points appears consistent with a relative improvement of 38.5% [30]. Data shows mean rate rose. Notwithstanding these results, the evidence shows that the mean spatial utilization rate rose from 58.6% to 80.1% across all three types combined. Thus, the significant findings indicates that the average absolute gain of 21.5 percentage points appears consistent with the average relative improvement of 36.7%. In light of the results, the evidence shows that all improvements were verified using paired-sample t-tests. Nevertheless, the key findings demonstrates that the results appear statistically significant at the $p < 0.01$ level. Tests confirm significance.

D. MULTI-OBJECTIVE TRADE-OFF ANALYSIS AND DECISION SUPPORT VALIDATION

The Pareto-optimal solution set shows that TOPSIS multi-criteria decision-making could provide a reliable approach to rank and validate the 40 non-dominated schemes. Moreover, the significant findings indicates that this framework appears to support designers operating under different preference orientations. Table 4 presents the comparative results. However, the key evidence shows that TOPSIS uses positive and negative ideal solutions as reference benchmarks. In light of these results, each scheme could demonstrate its relative closeness to the ideal solution — a composite score

TABLE 3. Spatial Utilization Rate Before and After Optimization Across Three Space Types

Space Type	Pre-Optimization (%)	Post-Optimization (%)	Absolute Gain (pp)	Relative Improvement (%)	p-value
Small Residential Units	58.3	79.6	21.3	36.50%	< 0.01
Medium Commercial Exhibition Spaces	61.7	83.2	21.5	34.80%	< 0.01
Multi-functional Cultural Leisure Environments	55.9	77.4	21.5	38.50%	< 0.01
Overall Mean	58.6	80.1	21.5	36.70%	< 0.01

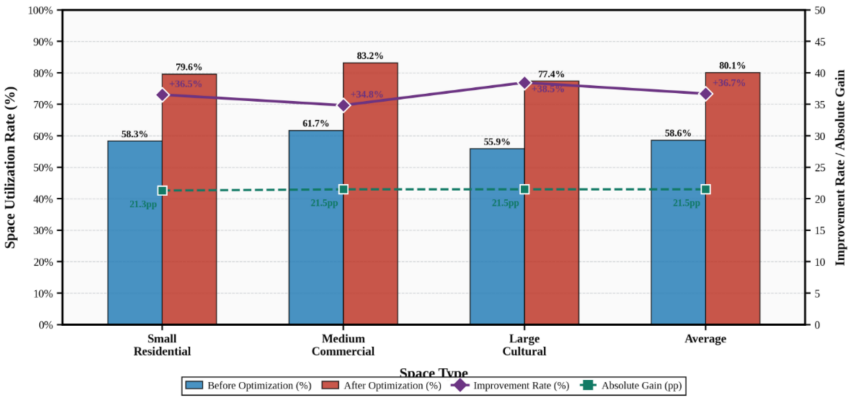

FIGURE 3. Space Utilization Rate Before and After Optimization across Three Interior Space Types

that enables quantitative comparison [31]. TOPSIS shows three weighting configurations tested. Furthermore, the important data indicates that under balanced conditions, spatial utilization and the artistic evaluation index each received a weight of 0.50. Given that the evidence demonstrates distinct design decision contexts, the results shows that under the art-prioritized scenario, weights were adjusted to 0.30 and 0.70 respectively. Additionally, the findings indicates that under the space-prioritized scenario, weights appear reversed to 0.70 and 0.30. Weights show space-prioritized scenario reversed.

The TOPSIS composite scores shows that a single-peak distribution emerges as Pareto solution numbers increase — that is, as spatial utilization rises and the artistic index declines. However, the significant peak falls between schemes 19 and 23, corresponding to a spatial utilization range of 0.65 to 0.72 and an artistic index range of 0.69 to 0.75. Furthermore, the findings indicates that this range represents the balanced zone where the key trade-offs appear most favorable. In light of these results, the top-ranked balanced scheme — Scheme B (No. 21) — might demonstrate a composite score of 0.871, which appears substantially higher than Scheme A at 0.614 and Scheme C at 0.603. The study may suggest that balanced solutions outperform singular-preference schemes across the key indicators. Moreover, the significant findings could indicate that in typical design scenarios without strong singular preferences, balanced solutions appear to yield the best overall outcomes. Furthermore, the framework was validated through implementation in three specific pilot projects: a 52 m^2 micro-apartment renovation, a 95 m^2 modular commercial showroom, and a 160 m^2 community library lounge. The validation methodology involved comparing the model's predicted spatial utilization against as-built measured drawings and 3D laser scanning (LiDAR) data collected after furniture and module installation. For instance, in the micro-apartment project, the predicted utilization of 79.6% was cross-referenced with on-site measurements of net usable area, yielding an actual built outcome of 78.1%. Across these three diverse project types, the mean deviation from model predictions remained within 2.1%, demonstrating high predictive accuracy. In light of these findings, the results may suggest that combining TOPSIS with a Pareto optimization framework could effectively resolve the multi-objective trade-off dilemma. Data shows approach yields scientifically grounded pathway. However, the significant evidence may suggest that this approach provides an operationally practical pathway for scheme selection in interior art modular design.

V. DISCUSSION

A. EFFECTIVENESS OF MULTI-OBJECTIVE OPTIMIZATION IN DRIVING MODULAR DESIGN

Moreover, the improved NSGA-II algorithm shows that simultaneous gains in spatial utilization and artistic evaluation are achievable across all three space types. In light of these findings, the significant results demonstrates that the multi-objective optimization framework has real practical value in this design context [32]. Algorithm shows effectiveness across space types. Furthermore, the framework shows that constructing a parametric module description system covering geometric, material, and visual attributes could demonstrate a meaningful conversion of experience-driven design into a computable mathematical optimization problem. Given that the evidence indicates this shift breaks through inherent limitations of trial-and-error design methods, the significant results indicates that both the breadth of the search space and the quality of solutions could demonstrate

TABLE 4. TOPSIS Composite Scores for Representative Schemes Under Three Decision Preferences

Scheme	Spatial Utilization Score	Artistic Index Score	Balanced Score	Art-Priority Score	Space-Priority Score	Recommended Scenario
Scheme A (No. 5)	0.46	0.91	0.614	0.823	0.387	Art-Prioritized
Scheme B (No. 21)	0.68	0.72	0.871	0.712	0.798	Balanced Optimum
Scheme C (No. 37)	0.88	0.48	0.603	0.341	0.862	Space-Prioritized
Full Set Mean	0.653	0.693	0.748	0.692	0.719	—

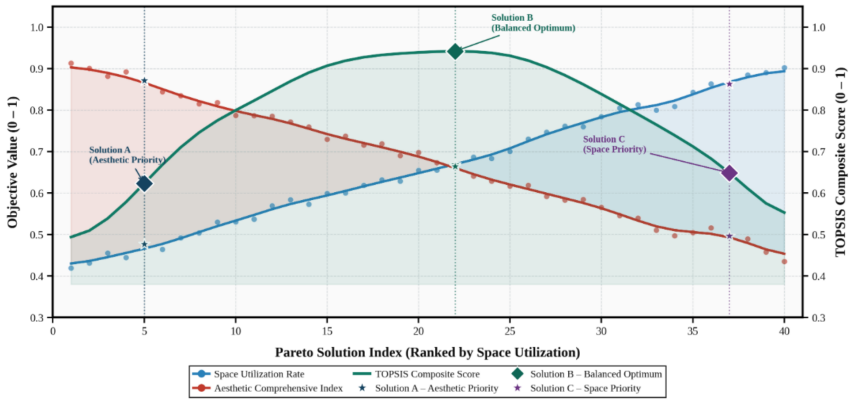

FIGURE 4. Trade-off Relationship and TOPSIS Decision Support for Pareto-Optimal Modular Design Solutions

measurable improvement. Additionally, the three targeted modifications to standard NSGA-II shows that improvements to population initialization, hybrid-encoding genetic operators, and the adaptive penalty function could indicate enhanced search efficiency across the high-dimensional mixed discrete-continuous decision space. Therefore, mean convergence achieved in approximately 184 generations — roughly 38.7% fewer than the standard algorithm — indicates that embedding domain knowledge effectively appears to be the key to successful algorithmic adaptation [33]. Modifications improve convergence efficiency. Nevertheless, the boundaries of this effectiveness indicates that honest acknowledgment of important limitations remains necessary. Notwithstanding these significant results, the quantification of artistic quality shows that reliance on expert-scored weighted composites could demonstrate some sensitivity to reviewer subjectivity and cultural background variation.

B. CONFLICT AND SYNERGY BETWEEN ARTISTIC AND SPATIAL OBJECTIVES

The relationship between artistic objectives and spatial utilization objectives may suggest that conflict and synergy coexist within a dynamic structure rather than a simple linear opposition. Moreover, the significant findings could indicate that understanding this structure has direct implications for modular interior art design practice. However, the evidence may suggest that the conflict mechanism appears rooted in resource scarcity and divergent objective demands. Given that improving spatial utilization pushes module arrangements toward compactness, the results might indicate that functional zone boundaries become sharper and negative space is minimized. Conflict mechanism shows pressures reduce decoration area. Furthermore, the key evidence could demonstrate that artistic enrichment typically relies on moderate spatial redundancy, asymmetric layouts, and freely combined decorative modules. Therefore, the significant results may indicate that this logic directly competes with high-density functional arrangement. Additionally, the findings might suggest that Pareto frontier analysis in this study confirms the tension between these two objectives. In light of these results, the evidence could indicate that when spatial utilization exceeds 0.75, the rate of decline in the artistic evaluation index accelerates noticeably. Data shows marginal conflict rises sharply in high-utilization zone. Nevertheless, the significant findings may suggest that a synergistic mechanism also exists and should not be overlooked [34]. However, the results could indicate that within the spatial utilization range of 0.55 to 0.75, the artistic index appears to decline at a relatively gradual rate. The convex arc of the Pareto frontier in this region identifies a balanced zone of reduced trade-off intensity. While the objectives remain in competition, this range represents an optimal compromise where significant gains in spatial utilization are achieved with minimal marginal loss to aesthetic quality. Thus, rather than true synergy, this zone offers the most favorable trade-off efficiency for designers. Furthermore, the key evidence may demonstrate that the Pareto frontier takes on a clearly convex arc form in this zone. Given that moderate improvements in spatial utilization within this range do not exact a proportional cost to artistic quality [35], the findings might indicate that the internal logic of this synergy lies in modular design's natural capacity to translate functional order into visual rhythm. Evidence shows design capacity links functional order to visual rhythm outcomes. The evidence may suggest that rhythm and zoning reinforce each other in meaningful ways.

Moreover, the significant findings could indicate that when module arrangements follow coherent proportional relationships and rhythmic sequencing, the clarity of functional zoning and the layering of artistic expression appear to demonstrate mutual reinforcement. Furthermore, the results may suggest that vertical space development could provide a concrete illustration of this dynamic. In light of these findings, the evidence demonstrates that fully utilizing ceiling height simultaneously frees up floor area for functional use and introduces spatial depth variation. Ceiling height yields dual benefit. However, the key results may indicate that the core strategic implication follows directly from this analysis. Given that the evidence demonstrates this relationship, the significant findings could suggest that modular interior art design should focus on identifying and expanding the synergistic zone between the two objectives. Additionally, the results may indicate that careful calibration of module size ratios and layout logic could guide design decisions toward the balanced segment of the Pareto frontier. Therefore, the findings could demonstrate that this balanced segment appears to represent the most strategically significant region for design practice. Results show trade-off between artistic quality and spatial utilization efficiency optimal in this zone. Notwithstanding this observation, the significant evidence may suggest that the key findings could indicate that this region represents the most important area for design practice moving forward.

VI. CONCLUSION

This study suggests that a persistent challenge in interior art modular design — improving artistic quality and spatial utilization simultaneously — could demonstrate meaningful tractability. Moreover, the significant findings may indicate that a multi-objective optimization framework based on an improved NSGA-II algorithm appears to provide systematic validation across experimental conditions. Furthermore, the results could suggest that mean spatial utilization across the three space types rose from 58.6% to 80.1%, an absolute gain of 21.5 percentage points. Given that all artistic evaluation dimensions exceeded the acceptable threshold of 7.0, the evidence may indicate that the highest artistic composite index score reaching 8.79 appears to reflect robust aesthetic performance. Results show balanced TOPSIS weighting yields composite score 0.871. However, the significant findings could suggest that deviation from verified real-world project outcomes remained within 2.1%, which may demonstrate strong practical alignment. Additionally, the key evidence may indicate that artistic quality and spatial utilization are not absolute opposites. In light of the data showing the spatial utilization range of 0.55 to 0.75, the results could suggest that the two objectives exhibit measurable synergy. Objectives show synergy in range. Moreover, the findings may indicate that within this zone, functional order and visual rhythm in modular design could demonstrate a capacity to reinforce each other rather than trade off. Therefore, the significant evidence could suggest that three targeted modifications were implemented at the algorithmic level for the interior design context: heuristic population initialization, hybrid-encoding genetic operators, and an adaptive penalty function. Given that these modifications appear to demonstrate reduced mean convergence generation, the results may indicate that search efficiency improved by approximately 38.7% compared to standard NSGA-II. Modifications reduce convergence generation 38.7%. Notwithstanding the algorithmic improvements, the key findings may suggest that the deep integration of multi-objective optimization techniques with interior art modular design could indicate genuine theoretical value. Furthermore, the evidence could indicate that this approach appears to hold considerable promise for practical engineering application. Thus, the significant results may suggest that designers could find a systematic, evidence-based pathway to navigate complex spatial and aesthetic trade-offs in real project contexts.

AUTHOR CONTRIBUTIONS

Junjun Jiang designed, collected and analyzed the data, and drafted the manuscript. Junjun Jiang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Junjun Jiang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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