



# A Participatory Design Method Integrating Structured Representation and Design Scheme Clustering

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**Abstract.** Children's expressions in Participatory Design with Children (PDC) are often unstructured and difficult to quantify, which limits systematic comparison and decision making across diverse design outcomes. This study focuses on an integrated children's study desk and proposes a PDC approach that integrates structured representation, design scheme clustering, and multi-criteria evaluation. A unified design parameter system is established using the Analytic Hierarchy Process (AHP) and Axiomatic Design (AD). It is then translated into a participatory design toolkit that supports children's expression under explicit parameter constraints. Children's design schemes are quantitatively encoded and clustered to identify similarities and differences. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is applied to support multi-criteria decision making. The results indicate that the proposed method enables quantitative analysis and comparison of children's design outcomes while preserving their creative expression.

**Keywords:** Participatory Design with Children; Axiomatic Design; Structured Representation; Generative toolkit

## 1 Introduction

As the home learning environment becomes increasingly important in children's development, integrated study desks have emerged as a flexible form of learning furniture. While they can improve convenience and autonomy, their structural and functional complexity increases design demands. However, most existing study desks are still developed based on adult-centered assumptions. This makes it difficult to capture children's diverse usage behaviors and preferences, often resulting in limited adaptability to their actual needs.

PDC involves children as active contributors, allowing them to articulate their needs and lived usage experiences and helping to address the limitations of adult-centered design[1]. Previous studies have utilized various tools and workshops to support children's participation, yielding positive outcomes in public space and environmental design[2]. However, when applied to structurally complex and highly integrated products such as integrated study desks, conventional approaches show clear limitations. Chil-

dren's expressions are often unstructured and difficult to analyze, and the resulting design schemes are challenging to compare and evaluate due to the lack of unified quantitative and decision-making frameworks[3].

The challenge is to quantify children's needs without constraining creativity and to compare diverse design schemes under a unified set of requirements. This study proposes a PDC approach that integrates structured representation, design-scheme clustering, and multi-criteria evaluation.

## 2 Methods

The overall research framework is shown in Figure 1.

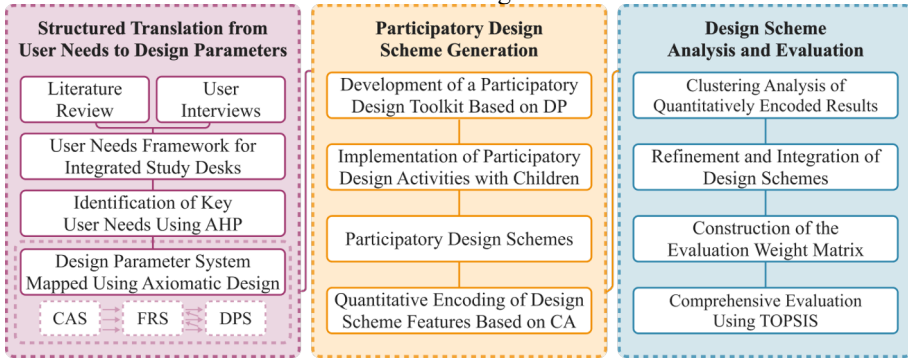


Fig. 1. Research framework.

This study uses AHP to model and weight key needs for integrated study desks. It then uses AD to map these needs to functional requirements (FRs) and design parameters (DPs), forming a unified system for toolkit development and multi-scheme analysis.

Participatory design emphasizes users' active involvement in the design process to better understand their latent needs[4]. However, because children differ from adults in cognitive and expressive abilities, their ideas often do not translate into decisions or tangible outcomes. Williams et al. note that children may be invited to contribute yet see little visible change, suggesting that their influence must be intentionally planned and safeguarded[5]. Meanwhile, structured approaches for complex product evaluation are typically expert led and are difficult to apply directly in PDC[6]. Building on the Generative Toolkit, this study introduces a unified design parameter framework that translates abstract parameters into operable modules. This framework enables children's expression under explicit constraints while maintaining a consistent basis for structured representation across design schemes.

After the participatory design activities, this study quantitatively encodes each child-generated design scheme across CA-based evaluation dimensions. The encoded schemes are then clustered to summarize diverse alternatives into groups with similar strategies, and representative schemes are selected from each cluster. Under a unified design-parameter and weighting system, TOPSIS is applied to conduct a multi-criteria

evaluation of the representative schemes, supporting subsequent scheme selection and optimization[7].

**Table 1.** Weights of first-level criteria based on AHP.

Criterion Layer	Weight
Adjustability B <sub>1</sub>	0.29199
Mobility B <sub>2</sub>	0.12679
Reconfigurability B <sub>3</sub>	0.15380
Storability B <sub>4</sub>	0.32527
InteractivityB <sub>5</sub>	0.10215

**Table 2.** Weights of second-level criteria based on AHP.

Sub- Criterion Layer	Weight	Comprehensive Weight	Rank
Adequate Desktop Space A <sub>1</sub>	0.16648	0.04860	8
Adjustable Desktop Angle A <sub>2</sub>	0.07790	0.02275	18
Adjustable Desk and Chair Height A <sub>3</sub>	0.21259	0.06207	5
Ergonomic Comfort A <sub>4</sub>	0.41509	0.12120	1
Dedicated Learning Space A <sub>5</sub>	0.12793	0.03735	11
Easy Mobility A <sub>6</sub>	0.16910	0.02144	19
Safety Design A <sub>7</sub>	0.21272	0.02697	16
Structural Stability A <sub>8</sub>	0.61818	0.07838	4
Expandable Functional Modules A <sub>9</sub>	0.28837	0.04435	10
Detachable Desk and Chair A <sub>10</sub>	0.24252	0.03730	12
Visual Consistency A <sub>11</sub>	0.32087	0.04935	6
Intelligent Assistive Functions A <sub>12</sub>	0.14825	0.02280	17
Foldable Desktop Design A <sub>13</sub>	0.09700	0.03155	15
Sufficient Under-Desk Space A <sub>14</sub>	0.33430	0.10874	2
Built-in Fixed Storage A <sub>15</sub>	0.14746	0.04797	9
Classified Storage A <sub>16</sub>	0.15074	0.04903	7
Adjustable Storage Space A <sub>17</sub>	0.27049	0.08798	3
Close-Range Accompaniment and Guidance A <sub>18</sub>	0.17963	0.01835	20
Remote Visual Supervision A <sub>19</sub>	0.14921	0.01524	21
Accompanied/Independent Switch A <sub>20</sub>	0.35496	0.03626	13
User-Friendly Operation A <sub>21</sub>	0.31620	0.03230	14

### 3 Design Practice

#### 3.1 User Needs Analysis and Key Needs Identification

Based on the literature review, existing product analysis, and user interviews[8], this study synthesizes user needs for integrated study desks into five dimensions with 21

items and constructs an AHP hierarchy. Twelve experts provided pairwise comparisons for the matrices, and weights were aggregated using the geometric mean method. All matrices passed the consistency test, and the results are reported in Tables 1 and 2.

Based on the AHP weights, storability, adjustability, and reconfigurability constitute the highest-ranked first-level criteria, followed by interactivity and mobility. For subsequent design development, the two highest ranked second-level user needs within each dimension are selected as priority needs. In addition, classified storage and adequate desktop space are treated as priorities because they are ranked the top ten.

### 3.2 Design Parameter Mapping

The prioritized needs are used as inputs for AD mapping to construct the DP system and inform the participatory design toolkit, with the mappings reported in Table 3. The constructed FR<sub>S</sub>–DP<sub>S</sub> design matrix exhibits a non-coupled diagonal structure, satisfying the Independence Axiom of AD and indicating consistency between FR<sub>S</sub> and DP<sub>S</sub>.

**Table 3.** CA–FR–DP Mapping for Integrated Study Desks.

Customer Attributes(CA <sub>S</sub> )	Functional Requirements(FR <sub>S</sub> )	Design Parameters(DP <sub>S</sub> )
Ergonomic Comfort CA <sub>1</sub>	Support child-friendly sitting posture FR <sub>1</sub>	Ergonomic desk–chair structural design DP <sub>1</sub>
Adjustable Desk and Chair Height CA <sub>2</sub>	Accommodate children’s growth through height adjustment FR <sub>2</sub>	Adjustable lifting and lowering mechanism DP <sub>2</sub>
Adequate Desktop Space CA <sub>3</sub>	Provide sufficient desktop area for multiple usage scenarios FR <sub>3</sub>	Sufficient main desktop surface DP <sub>3</sub>
Structural Stability CA <sub>4</sub>	Ensure overall structural stability of the desk and chair FR <sub>4</sub>	Stable support frame configuration DP <sub>4</sub>
Safety Design CA <sub>5</sub>	Ensure safety during movement and use FR <sub>5</sub>	Mobile locking devices and protective components DP <sub>5</sub>
Visual Consistency CA <sub>6</sub>	Maintain visual consistency in overall appearance FR <sub>6</sub>	Unified dimensional standards and color schemes DP <sub>6</sub>
Expandable Functional Modules CA <sub>7</sub>	Support modular add/replace FR <sub>7</sub>	Modular functional accessories DP <sub>7</sub>
Sufficient Under-Desk Space CA <sub>8</sub>	Provide adequate clearance for leg movement FR <sub>8</sub>	Under-desk clearance ≥ 520 mm DP <sub>8</sub>
Adjustable Storage Space CA <sub>9</sub>	Allow flexible adjustment of storage space FR <sub>9</sub>	Drawer combinations and modular storage units DP <sub>9</sub>
Classified Storage CA <sub>10</sub>	Support organized storage for long and temporary items FR <sub>10</sub>	Categorized storage guidance and zoning design DP <sub>10</sub>
Accompanied/Independent Switch CA <sub>11</sub>	Enable flexible switching between accompanied and independent learning FR <sub>11</sub>	Auxiliary modules for parent–child interaction and independent use DP <sub>11</sub>
User-Friendly Operation CA <sub>12</sub>	Provide clear and intuitive operation methods FR <sub>12</sub>	Operation guidance and simplified structural design DP <sub>12</sub>

### 3.3 Generative Toolkit Development

Based on the identified DPs, this study develops a generative toolkit for PDC. To fit children's cognitive and operational characteristics, the toolkit is organized into basic, functional, and decorative modules according to their roles in the construction process, facilitating comprehension of product structure and use while reducing cognitive load.

The generative toolkit comprises basic, functional, and decorative modules. Basic modules represent the core structure of the integrated study desk and support children's understanding of overall structure and spatial relationships, primarily corresponding to DPs related to ergonomics and structural stability. Functional modules support children's expression of functional configuration and usage and reflect the expandability and diversity of use scenarios, corresponding to DPs related to functional expansion and storage. Decorative modules support the expression of usage context, operation, and appearance and assist in scenario construction, corresponding to DPs related to visual consistency, classified guidance, and operation. To support children's engagement with the design task, scenario materials related to the study desk were provided with brief explanations, and drawing materials were offered as optional tools for supplementary expression.

Figure 2 shows two modules for each type: (a) basic, (b) functional, (c) decorative.

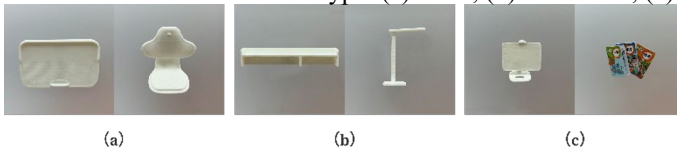


Fig. 2. Illustrative Examples of Basic, Functional, and Decorative Modules.

### 3.4 Participatory Design with Children

Thirty-six children aged 6-12 years participated in activity. The activity lasted approximately 30-60 minutes per child. Following a consistent activity flow, children used the modular participatory toolkit to construct integrated study desk concepts and briefly explained their design intentions. The resulting schemes were documented through photographs of the assembled configurations and field notes capturing key verbal and behavioral expressions.

## 4 Results

A total of 36 complete integrated study desk design schemes were independently generated by children through the participatory activities. Rather than focusing on a single function, the schemes reflected attention to multiple needs in real use contexts, including organizing and classifying learning materials and avoiding desktop clutter and distractions. Children also explicitly considered seating comfort and structural stability, suggesting that, with support from the proposed toolkit, their design expressions were grounded in real needs and experiences, rather than abstract functional imagination.

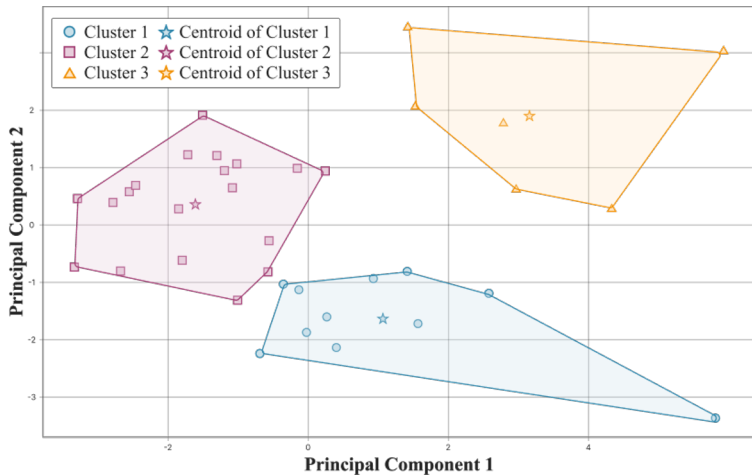
#### 4.1 Fitting and Analysis

To identify similarities and differences among child generated design schemes, this study systematically coded and quantitatively represented each scheme using a predefined 1–5 scoring rubric (Table 4). Modules from the generative toolkit were treated as the smallest coding units. The evaluation dimensions were derived from the key user needs defined as CA1–CA12 in AD. When a CA was influenced by multiple modules, the CA score was computed as the mean of the relevant module scores to reduce bias caused by differences in module quantity. Children’s verbal and behavioral data were not included as independent features but were used as interpretive references to verify consistency between the quantitative results and design intentions. Each design scheme was represented as a 12-dimensional CA feature vector.

**Table 4.** Scoring rubric.

CA Dimension	Relevant Modules	Design Parameters(DP <sub>s</sub> )
Ergonomic Comfort CA <sub>1</sub>	Basic	Scored based on the ergonomic comfort reflected by the selected structural modules
Adjustable Desk and Chair Height CA <sub>2</sub>	Basic	Scored according to the flexibility of height adjustment mechanisms.
Adequate Desktop Space CA <sub>3</sub>	Basic, Functional	Scored based on desktop space occupation and layout.
Structural Stability CA <sub>4</sub>	Basic	Scored according to the overall structural stability of the scheme
Safety Design CA <sub>5</sub>	Basic, Functional, Decorative	Scored based on the number and types of safety design features included in the scheme.
Visual Consistency CA <sub>6</sub>	Basic, Functional, Decorative	Scored according to children’s expression of visual preferences
Expandable Functional Modules CA <sub>7</sub>	Functional	Scored based on the number of expandable functional modules
Sufficient Under-Desk Space CA <sub>8</sub>	Basic, Functional	Scored based on whether under-desk space is free from obstruction
Adjustable Storage Space CA <sub>9</sub>	Functional	Scored according to the adjustability of storage modules
Classified Storage CA <sub>10</sub>	Basic, Functional, Decorative	Scored based on the presence of clear storage classification
Accompanied/Independent Switch CA <sub>11</sub>	Functional	Scored according to support for mode switching
User-Friendly Operation CA <sub>12</sub>	Functional, Decorative	Scored based on ease of operation and interaction

Clustering was performed on the 36 scheme feature vectors, revealing differences in design strategies and responses to user needs. Using K-means, the cluster number was set to  $k=3$  based on the Elbow Method. Clusters were visualized using PCA (Fig. 3).

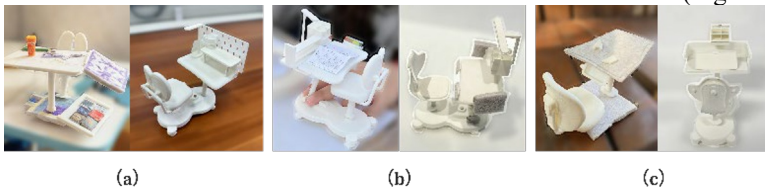


**Fig. 3.** PCA visualization of K-means clustering results for the 36 design schemes.

Cluster 1 is characterized by a high level of functional integration, with children emphasizing desktop space and storage through the combination of multiple functional modules. This cluster scored relatively high on CA<sub>3</sub>, CA<sub>7</sub>, CA<sub>9</sub>, and CA<sub>10</sub>, while maintaining medium to high levels in CA<sub>1</sub> and CA<sub>4</sub>, indicating that comfort and stability served as prerequisites for further functional configuration (Figure 4(a)).

Cluster 2 primarily focused on stability and comfort during use, with children repeatedly adjusting the desk and chair relationships and support structures. High scores were observed in CA<sub>1</sub>, CA<sub>2</sub>, and CA<sub>4</sub>, while functional expansion and storage remained moderate, as children tended to limit further module additions once basic needs were met (Figure 4(b)).

Cluster 3 emphasized flexibility and freedom of use rather than fixed functional layouts, showing relatively high performance in CA<sub>11</sub> and more variable, moderate to low scores in CA<sub>7</sub>, CA<sub>9</sub>, and CA<sub>10</sub>. Although some children proposed multi context usage scenarios, these ideas largely remained at the level of intended use and were not translated into stable structural features because of module constraints (Figure 4(c)).



**Fig. 4.** Participatory Design Schemes with Children.

## 4.2 Design Scheme

Due to limitations in children's cognition, expression, and the generative toolkit, the original schemes were refined within each cluster to produce representative schemes for TOPSIS evaluation. Use Gemini to generate product concept renderings. Scheme 1

emphasizes classified and adjustable storage through a perforated desktop enclosure, reducing desktop occupation while improving organization. Linear zoning on the desktop provides usage guidance without additional structural complexity, supported by a stable base and appropriate desk and chair proportions (Figure 5(a)).

Scheme 2 focuses on stability and seating comfort by widening the base structure and guiding foot placement to support proper posture. A saddle-style seat and a widened desktop enclosure enhance sitting adaptability, while magnetic attachments enable flexible accessory arrangement (Figure 5(b)).

Scheme 3 supports flexible, multi-task use via a switchable desktop and modular side extensions for task transitions and temporary expansion, and it adopts an open desktop without an enclosure to reduce constraints (Figure 5(c)).



Fig. 5. Design Scheme.

### 4.3 Scheme Evaluation

To evaluate the overall performance of the proposed schemes and their relative advantages over existing products, TOPSIS was applied using CA1–CA12 as evaluation criteria weighted by AHP results. Thirty raters, including users and domain experts, assessed three proposed schemes and a market benchmark on a 5-point Likert scale. Cronbach’s alpha indicated acceptable reliability (Table 5).

Table 5. Distances to the Ideal Solutions and Relative Closeness.

Scheme	Distance to the Positive Ideal Solution (D <sup>+</sup> )	Distance to the Negative Ideal Solution (D <sup>-</sup> )	Relative Closeness (C)	Rank
S1	0.0024	0.0133	0.8495	1
S2	0.0028	0.0125	0.8162	2
S3	0.004	0.0112	0.7342	3
Market Sample	0.0144	0	0	4

S1 shows the shortest distance to the positive ideal solution and the highest relative closeness value, ranking first among all evaluated schemes and indicating the best overall fit under the given criteria and weights. S2 and 3 exhibit slightly lower relative closeness values, while the market reference product shows a clear gap from the ideal solution; therefore, S1 is selected as the optimal scheme for further refinement.

## 5 Conclusion

This study proposes a PDC approach that integrates structured representation, design scheme clustering, and multi-criteria evaluation to support decision making for children's integrated study desks. By combining AHP and AD, the approach translates key user needs into a unified DP system and implements it as the proposed toolkit, enabling children to express design intentions within feasible structural constraints. Quantitative encoding and clustering make child generated schemes comparable by revealing distinct patterns in design strategies and responses to user needs, and TOPSIS evaluation is used to select the preferred representative scheme. The results demonstrate that the proposed approach preserves children's creative expression while enabling systematic analysis and comparison across diverse schemes, thereby addressing unstructured expressions that are difficult to quantify and the lack of a unified basis for comparison and decision making in PDC for complex product design.

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