Design Science

Design ideation through large language model-driven design operation: a case study of architectural design using pattern language

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Abstract

This research proposes a systematic method for design ideation with large language models (LLMs), grounded in the design operation model inspired by Christopher Alexander's pattern language (PL). Design operation refers here to a tree of thought for the step-by-step definition of the design context behind a design problem, the functional requirements, the physical attributes of alternative solutions and the generation of design alternatives that synthesize those attributes. To examine how the design operation improves LLM performance for design ideation, we implemented an architectural design ideation case study and compared four prompt methods for generating design alternatives. The four prompt methods are designed with and without the design operation and the PL. Respective prompts generated 100 design alternatives which were evaluated both by human experts and through computational diversity metrics. The results showed that prompts using the PL tend to generate design alternatives whose creativity is highly rated by humans, but are strongly influenced by the given knowledge and lack diversity, whereas prompts incorporating the design operation have the potential to enhance validity and feasibility and attribute diversity.

Keywords: Creativity supported, Design approaches, Methods and tools, Large language model, Pattern language, Design operation, Ideation

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1. Introduction

Design ideation in this study is defined as a process of understanding and redefining problems at the upstream, establishing the design space and direction and generating creative design alternatives, which contribute to downstream creativity. In design engineering, various theories and methodologies have been developed to understand this process. Although these theories differ in scope and perspective, they commonly provide human designers with iterative operations of design representations – such as concepts and knowledge – to systematically decompose and define the right problems with the aim of generating creative alternative solutions. In this context, knowledge refers to what humans have learned and abstracted from past or present designs, which can be utilized in future designs. Knowledge is often systematically aggregated for reuse, and studies on knowledge-based design typically employ representative knowledge bases. In

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this study, we refer to a series of actions that transform design representations to generate design alternatives that solve current design problems as a *design operation* (Nomaguchi & Fujita 2013).

Advancements in LLMs such as generative pre-trained transformer (GPT) (Radford *et al.* 2018) have significantly expanded the scope of study on their application in the field of conceptual design (Kocaballi 2023; Ma *et al.* 2023, 2025; Wang, B. *et al.* 2023; Chen, Jing *et al.* 2024; Chen, Xia *et al.* 2025). While these studies demonstrate the preliminary effectiveness of LLMs for design ideation using various prompt strategies, many focus on relatively simple design problems or generate design concepts directly without explicitly incorporating the design operation. Others rely heavily on human intervention, which limits the generalizability of their methods. Recent studies have also suggested that integrating external technical knowledge sources such as patents, literature and scientific publications with retrieval-based techniques can enhance the trustworthiness and usefulness of LLM-assisted design processes (Siddharth, Blessing & Luo 2022; Siddharth & Luo 2025). Such approaches highlight the importance of grounding LLM-driven ideation in structured and curated knowledge.

This study implements design ideation using LLMs with minimal human–designer interaction in the context of architectural design. Architectural design is particularly relevant because it involves ill-defined and evolving problems, making it an appropriate test case for examining whether design operations can support creativity in LLM-driven design ideation. The proposed method employs the pattern language (Alexander, Ishikawa & Silverstein 1977) as a knowledge base and models the design operation through a prompt strategy. A case study involving three design ideations compared four prompt strategies that differ in their use of PL and the design operation. The outputs are evaluated from two perspectives: the diversity of explored attributes and the creativity of the resulting design alternatives. This two-stage evaluation allows us to analyze whether LLMs, like human designers, can generate creative alternatives by exploring diverse solutions and then synthesizing them. We expect that it will also identify which specific elements contribute to creativity for each prompt.

Based on the above, this study addresses the following research questions. RQ1: How do prompting strategies that incorporate design operations enhance the creativity of LLM-generated concepts compared with conventional prompting strategies? And RQ2: To what extent does providing PL as external knowledge enhance creativity in knowledge-based LLM-driven design ideation? Through examining these questions, this study demonstrates that design operations grounded in design engineering theory can be effectively applied across different domains and offers preliminary insights for various fields related to ideation with LLMs.

For the implementation, we confirmed with the legal affairs section at The University of Osaka that the use of copyrighted materials in this research does not violate Japanese copyright law.

2. Theoretical background and our approach

2.1. Design ideation theories and design operation

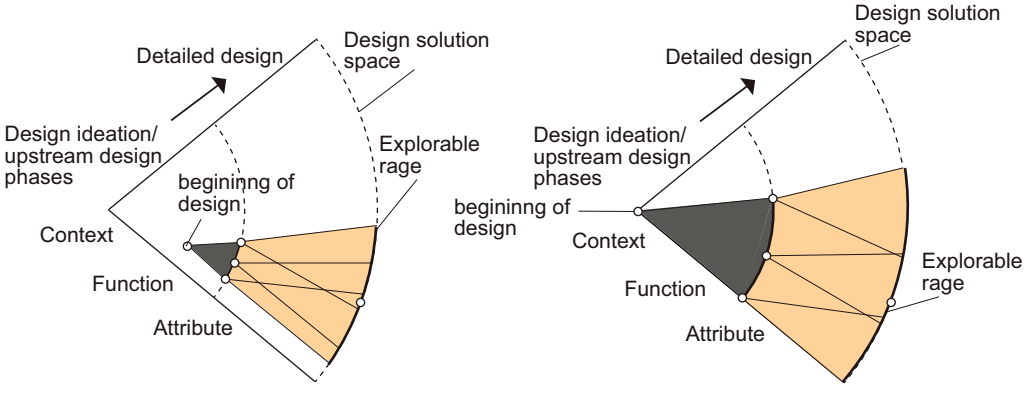
Researchers in design engineering have developed theories and methodologies to understand the design ideation process. The systematic approach introduced in the

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1970s by Pahl *et al.* (2007), its pioneering one, decomposed conceptual design into structured steps, including defining required functions, decomposing the functions into sub-functions, finding design principles corresponding to the sub-functions and synthesizing design principles. Subsequent theories further formalized this view of design. The function–behavior–structure (FBS) model (Gero 1990) translates abstract requirements into concrete solutions by decomposing design tasks into a hierarchical framework of function, behavior and structure of a design object. The general design theory (GDT) (Yoshikawa 1981) models the design as a set operational process connecting function and attribute spaces, aiming to describe design processes in a mathematically rigorous and domain-independent manner. The C-K theory (Hatchuel & Weil 2009) models design ideation as the dynamic interaction between a space of concepts and a space of knowledge, emphasizing the expansion of both through validation.

While each of these theories focuses on different points, they share the view that the design process can be understood as a design operation. Design operation refers to operations applied to a design representation used in the design process, through which abstract descriptions such as context and function are generated, transformed and organized into more concrete descriptions such as structure and materials, thereby advancing the state of design stepwise. Such operations include transformations between representations at different levels of abstraction, decomposition and integration, combinations of multiple elements, as well as examination and revision based on existing knowledge.

In this study, particular importance is placed on upstream operations based on abstract design representations such as context and function. Fujita (2023) diagrammatically explains this shared idea of design operation by presenting design ideation as a conceptual exploration process, as shown in Figure 1. Conceptualizing the design space as a fan-shaped area intuitively demonstrates the importance of considering context and function at the upstream stage. It is assumed that initiating design operations from such upstream representations expands the design space



(a) Exploration of the Design Solution Space from Attributes

(b) Exploration of the Design Solution Space from Contexts or Functions

Figure 1. Differences in exportability of the design solution space depending on the starting point of design operation.

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(Figure 1b) more than those from attributes, enables exploration of diverse concrete representations and consequently leads to the attainment of highly creative design solutions.

The above considerations serve as general guidelines for human designers. In practice, designers perform upstream design operations to varying degrees depending on their expertise and experience, yet such operations are commonly observed in human design processes. Will the same phenomenon occur in AI-based design ideation? That is, if LLMs start their reasoning from the context corresponding to design problems, can they explore diverse attribute concepts? This question constitutes the fundamental motivation of this study.

2.2. LLMs' application to design ideation

Design ideation is far from being automated. Early attempts using expert systems in the 1980s and 1990s sought to automate or semi-automate conceptual design (Gullichsen & Chang 1985; Akagi & Fujita 1990), its success is limited due to fundamental issues in scalability, flexibility and generality of design operation. For this reason, much of the prior research on computer-aided design ideation has remained limited to providing humans with design stimuli, i.e., some insight that stimulates humans' creativity, rather than automating it (Luo, Sarica & Wood 2021).

Large language models (LLMs) are overcoming the above limitations. Unlike expert systems, LLMs are trained on large-scale text corpora and implicitly encode diverse design-relevant knowledge, enabling them to flexibly recombine and transform knowledge through natural language reasoning. The larger models in the GPT series have shown capabilities in tasks previously thought to require human creativity (Beaulieu-Jones *et al.* 2024; Kumar 2024). Researchers in design engineering have developed design methods using various prompt-engineering strategies. These strategies draw on techniques such as few-shot (Brown *et al.* 2020), zero-shot (Kojima *et al.* 2022), chain-of-thought (CoT) (Wei *et al.* 2022), tree-of-thought (ToT) prompting (Yao *et al.* 2023), among others, to obtain desired outputs in highly creative design processes.

However, conceptual design remains an open field (Regenwetter, Nobari & Ahmed 2022; Zhu & Luo 2023), particularly regarding creativity. Kocaballi (2023) used ChatGPT to generate personas, simulate interviews, create design ideas, simulate usage scenarios and conversations and evaluate user experience. Although ChatGPT could effectively perform these tasks and provide appropriate responses, it still exhibited a notable limitation: a lack of output diversity. Ma *et al.* (2023, 2025) compared the design solution generated by GPT using various prompt strategies with one generated by humans. Their results indicate that although LLMs using few-shot prompting can generate solutions comparable to human designs in terms of feasibility and usefulness, they tend to produce less novel and less diverse solutions. These studies explored fundamental ways to utilize LLMs in design ideation, focusing on relatively simple design problems and employing prompts that do not involve design operations or external design knowledge.

Other studies have emerged proposing prompting methods that incorporate design operations. Wang, B. *et al.* (2023) proposed a task-decomposed AI-aided approach based on Gero's FBS model, utilizing GPT-3, in which design requirements are decomposed into function, behavior and structure and addressed

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through stage-specific prompts. Chen, Xia *et al.* (2025) extended the C–K theory by modeling the design operators (C → K, K → K, K → C, C → C) as prompts for GPT-4, enabling LLMs to acquire and apply knowledge across domains relevant to the design task. These studies demonstrate that design operations can be effectively embedded in prompts and, through case studies, that such approaches tend to enhance the creativity of generated concepts. However, these methods are premised on human–AI co-design and often rely on human expert intervention to achieve the desired results, thereby limiting their validation.

In addition to prompt-based reasoning that relies on LLMs' internal knowledge, some research has focused on integrating external knowledge sources such as patents and scientific documents into LLM-driven design processes. Chen, Cai *et al.* (2025) proposed AskNatureGPT, a concept generation method for bio-inspired design that integrates AskNature knowledge with LLMs. Their approach enables LLMs to effectively utilize bio-inspired knowledge and reasoning. Jiang *et al.* (2025) proposed AutoTRIZ, which automates the systematic ideation process of the theory of inventive problem solving (TRIZ) (Al′tshuller, Shulyak & Rodman 1999) using LLMs. Starting with a user-provided problem statement, AutoTRIZ executes a four-step reasoning process grounded in TRIZ core logic and automatically generates a structured solution report. By embedding a TRIZ knowledge base and combining it with LLM reasoning, AutoTRIZ enables processes that previously relied on human knowledge and expertise to be performed in a controllable and interpretable manner.

This research focuses on design ideation using LLMs, adopting a similar direction to the aforementioned studies while differentiating itself in the following ways. First, rather than using simple design problems, it employs architectural design problems that are more complex and require human inner creativity to solve effectively, depending on the situation (Casakin & Kreitler 2010). Second, this research investigates how LLMs' inherent creativity can be enhanced through a design operation method that operates independently of human expert intuition or experience. Third, it utilizes PL as external knowledge – a knowledge collection renowned in architecture, long considered promising for application to knowledge-based design, yet one whose substance has not been deeply explored (Dawes & Ostwald 2017).

2.3. Christopher Alexander's pattern language in the LLM era

Pattern language (PL) is a collection of design knowledge involving design problems to be solved and the core of a solution in architectural design. Alexander, the author, defined a *pattern* as an element that appears repeatedly in a given context and fulfills a specific function. He organized 253 patterns related to towns, buildings and construction into a unified format with the aim of creating more livable and lively buildings and cities by allowing residents and architects to combine independent patterns like a common language (Alexander *et al.* 1977). Designers are expected to generate design concepts by referring to the background of the problems, requirements, structures and examples described in each pattern, and by combining multiple patterns according to the design problem at hand. Many architectural practices have been carried out, and their evaluations vary (Dawes & Ostwald 2017).

Figure 2 shows the *Activity Pocket* as an example pattern of public squares in towns. It says that the life of a public square forms naturally around its edge. Therefore, surrounding public gathering places with pockets of activity, which are

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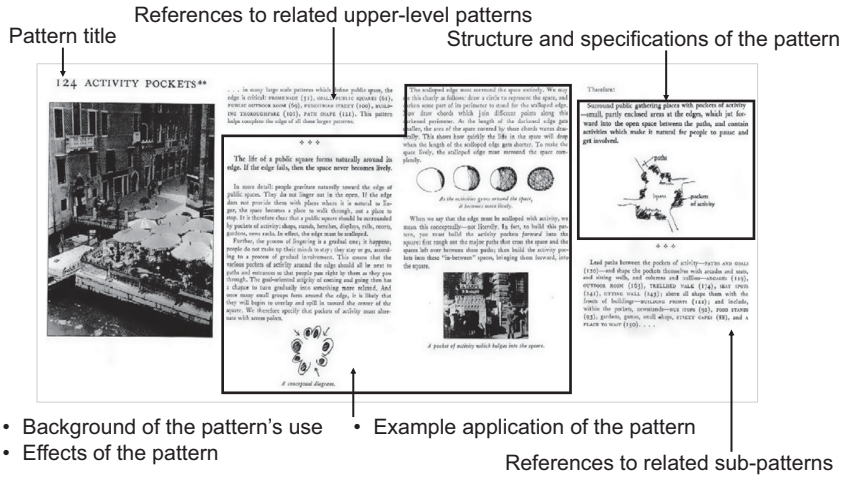


Figure 2. Example of a pattern in *A Pattern Language*: *Activity Pockets*.

small, partly enclosed areas at the edges, would make it natural for people to pause and get involved.

PL has been applied in architectural research since early studies, which suggested its effectiveness for knowledge-based design (Gullichsen & Chang 1985). With the advent of LLMs, the applicability of PL to knowledge-based LLM-driven design is beginning to be explored. Postle and Salingaros (2025) propose a collaborative design method that integrates PL with LLMs to support human-centered architectural design. In their proof-of-concept study, human experts curate project-specific patterns and structured briefs, enabling LLMs to generate spatial experience narratives and corresponding visual representations that translate PL into coherent design proposals grounded in human perception and experience. Before this work, Salingaros (2025) explored the use of LLMs grounded in Alexander's concept of "living geometry" (Alexander 2020) to support creative architectural studio design. He proposed a method that leverages this framework to prompt LLMs to "propose a studio environment that maximizes creative learning," enabling them to generate concrete renovation strategies informed by human cognition and emotion. Their findings demonstrate a new approach that combines LLMs with theoretical design knowledge to construct creative and supportive learning environments. In the LLM era, PLs are attracting renewed attention, and their applications are being explored.

Furthermore, the PL approach has influenced diverse fields such as software design (Gamma *et al.* 1994) and education (Goodyear 2005). Therefore, if successful case studies of methods that use PL through design operations can be demonstrated, it is expected that the proposed method in this study will be expanded and explored not only in architecture but also across various fields.

3. Method

3.1. Design operation model

This section reinterprets architectural design based on PL from a design engineering standpoint and describes how the design operation model in this context was defined.

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Alexander argues that although the ultimate goal of design is form, equal emphasis should be placed on *context*, namely, the surrounding situation related to the problem to be solved. He states that context poses requirements for a desirable form, and that design is the effort to adapt form to those requirements. Accordingly, in each pattern, he first describes the context, then explains the system of forces that gives rise to the problem and finally presents a solution that the space should embody to reconcile those forces.

Alexander recommends the following process for design ideation using PL: First, from a table of contents that lists all pattern titles, the designer selects the pattern that best represents the overall picture of the design problem. The designer reads the text, examines relationships with other patterns and selects likely useful patterns to solve the design problem. The designer combines the selected patterns to generate a concept for an architectural space. In this process, Alexander argues that the number of languages created by designers is potentially infinite and that design solutions themselves are likewise unbounded. He regarded PL as an ever-evolving body of knowledge rather than a fixed system. Designers are encouraged to revise and extend the language by adding, modifying and developing their own patterns. From this perspective, PL offers a non-deterministic knowledge base and supports a design process.

This process can be reconsidered from the perspective of design operation as follows. Designers start the design process with a set of concepts for artifacts intended to solve the design problem, and reinterpret it as an abstracted context, grasp the system of forces that constitutes that context, explore the structural and spatial relationships required to realize it, and finally integrate these elements to generate a design concept. The context refers to a generalized and abstract representation of the design problem. In this respect, design using PL resonates with the systematic approach, as it initiates design from such an abstract description. It differs, however, in that its knowledge structure does not rely on the modularity and determinism found in a systematic approach. The other two types of design representation in PL – namely, the system of forces and the structural and spatial relationships of architecture – can be described as function and attribute, respectively, whose terminology we borrow mainly from GDT. However, this study does not adopt GDT as a design theory, nor does it rely on its axiomatic system or theoretical knowledge space based on set theory. These abstract terms are used merely as descriptive labels to organize the types of information contained in the design process using PL and to clarify the design operation involved.

Based on this interpretation, the design operation using PL can be represented as shown in Figure 3. The three concepts are defined as follows:

- **A "context"** represents the background of the design, current issues and customer needs for a design object. Contexts should be expressed in full sentences.
- **A "function"** is defined as an interpretation of an artifact's behavior in relation to a specific intent held by an observer. Functions should be expressed in meaningful verb–object phrases.
- **An "attribute"** is defined as a geometric, physical, chemical or mechanical property of an artifact. Attributes should be expressed as noun phrases with concrete meanings, rather than as single words.

The design ideation process can be systematically organized into the stages of (1) a set of candidate contexts corresponding to the design problem, (2) a set of

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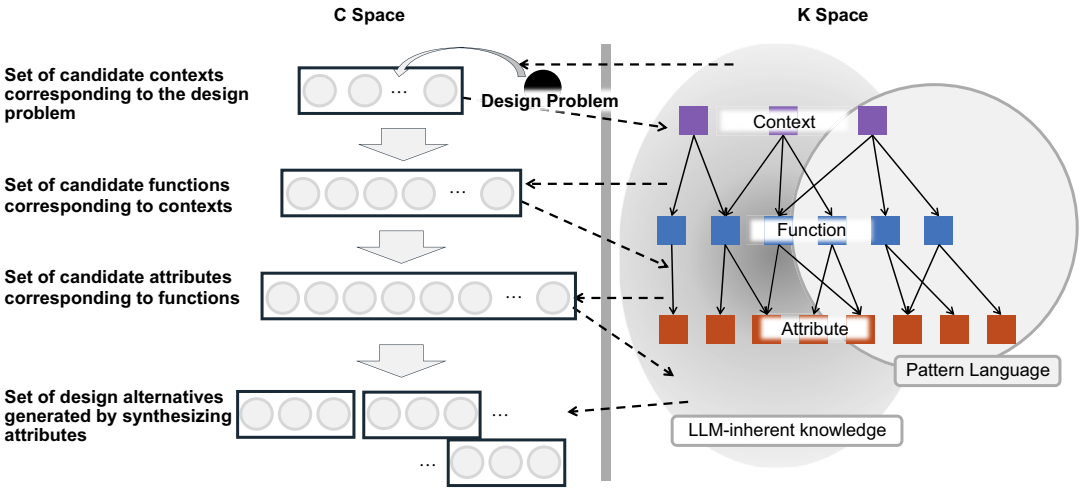


Figure 3. Design operation model using the pattern language with large language models. Various combinations and syntheses of the explored attributes are expected to generate diverse alternatives.

candidate functions corresponding to the contexts, (3) a set of candidate attributes corresponding to the functions and (4) a set of design alternatives generated by synthesizing the attributes. Those are conducted through the interplay of C space exploration and K space exploration. Since the descriptions in PL can be regarded as a collection of externalized design knowledge, designers who use PL corresponding to the concepts can be considered to be exploring the knowledge space (C → K, K → K). By applying the explored knowledge, a design concept is generated (K → C, C → C). The generated concept is adapted from the K space to fit the design problem. In this study, contexts, functions and attributes are explored as tentative representations in the C space. In contrast, the PL and the LLM's internal knowledge are treated as elements of the K space that inform and constrain this exploration. For example, applying the "activity pockets" pattern to campus facility design may lead to kiosks and research project displays that foster interaction among students and faculty. The knowledge space encompasses both PL and the LLMs' inherent knowledge.

This study does not aim to propose a new design theory. Rather, by reinterpreting PL-based design from the perspective of design operations rooted in design theory, we found that design representations can be more clearly organized using GDT terminology and that the approach can also be described in terms of the systematic approach and C–K theory. Furthermore, this reinterpretation exhibits a high degree of similarity to the C–K-theoretical analysis of the systematic approach by Le Masson & Weil (2013). Although this study does not directly apply these theories, its significance lies in offering a perspective on whether the discussion by Le Masson et al. remains applicable in the era of LLM-driven design.

3.2. Prompt strategy based on design operation model

Based on the above definitions, we developed a prompt strategy: Prompt D. To supply PL as external knowledge to LLMs, all 253 patterns were organized into a text dataset, each consisting of a pattern number and title, and a body text, and

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separated by a line of hyphens ("----"). The prompt explicitly explains this structural format so that the LLM can effectively refer to and utilize the knowledge.

This approach can be regarded as a form of retrieval-augmented generation (RAG) (Lewis *et al.* 2020; Siddharth & Luo 2024). A similar idea has been applied in the AutoTRIZ system (Jiang *et al.* 2025). Although certain knowledge may be included in the pretraining data for GPT, explicitly providing such knowledge as external input plays a crucial role in reflecting our intentions in the LLM reasoning, and in that sense, we regard it as a form of prompt strategy.

In the design operation model, an LLM is encouraged to draw on both the knowledge provided by PL and its own internal knowledge. The overview of the prompt for the design operation model is shown in Figure 4. Full prompt text and sample outputs are provided in Appendices A-3 and A-4. The LLM initiates the design process from a concept of an object that addresses the given design problem. Then, the LLM explores three contexts for a given design problem (context exploration), derives three corresponding functions for each context (function exploration) and generates three associated attributes for each function (attribute exploration), resulting in 27 attributes. These attributes are then evaluated for relevance to the design problem, and the 10 most important ones are selected and synthesized to generate design alternatives (concept generation). The output text is automatically saved to separate repositories at each step.

This step-by-step procedure – comprising branching, expansion, evaluation and integration – can be positioned within the framework of ToT prompting (Yao *et al.* 2023), which enables the exploration and comparison of multiple reasoning paths rather than reliance on a single one, thereby suggesting the potential to support more diverse and creative design ideation.

In this study, the number of design representations explored and selected at each stage was fixed (three for exploration and 10 for selection) as a heuristic to balance the breadth of exploration with the overall tractability of the reasoning process. In addition, since one of the objectives of this study is to minimize designer intervention, the assessment of attribute importance was delegated to the LLM. These settings are not fixed and can be adjusted in future applications depending on the design context, allowing the proposed method to remain flexible and extensible.

The definitions of context, function and attributes are stated in the prompt. LLM reasoning is fundamentally a black box, and determining whether the knowledge it explores aligns with its definitions remains debatable. This challenge similarly applies to other studies proposing prompt strategies modeled after FBS or C–K theory (Chen, Xia *et al.* 2025; Wang B. *et al.* 2023). At least in the author's investigation, no instances were identified where the output text bore no relation whatsoever to the concept definitions.

3.3. Prompt strategies for comparative evaluation

To verify the effectiveness of the proposed prompt strategy, this study compares the generation results of the following four alternative prompts (prompts A–D), which differ in their use of the design operation model and PL. An overview of them is shown in Figure 5. Their full text is provided in Appendices A-1 to A-4. Through any of the prompts, the LLM initiates the design process from a concept

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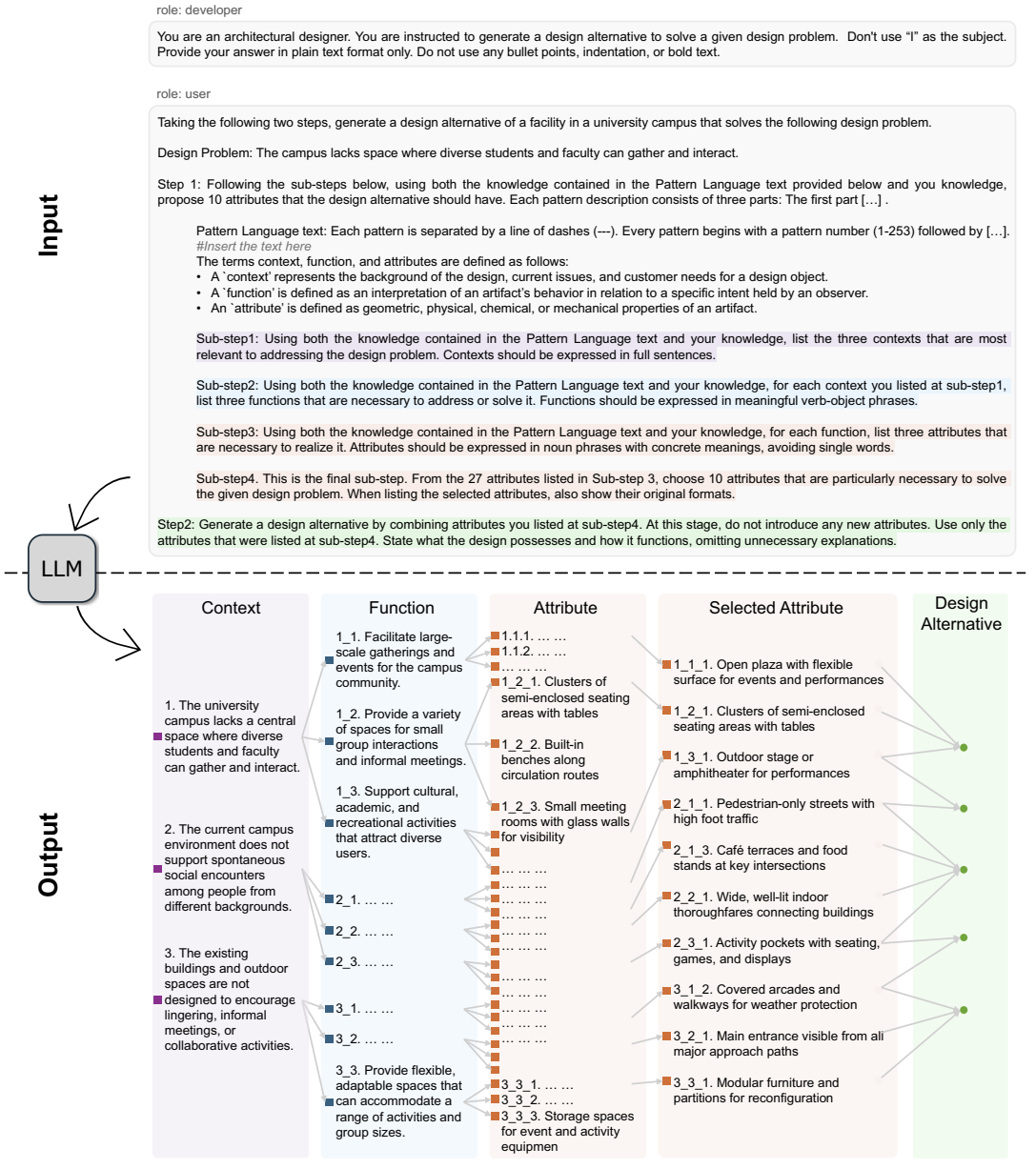


Figure 4. The outlines of the input text and output of our proposed prompt strategy, Prompt D. This applies when designing university campus facilities, as described in the Case Study section. The LLM develops a tree-structured thought process to solve the given design problem. The output format is instructed to assign identification numbers to context, function and attribute. For example, when representing the second possible context for a design problem, the first function to solve that context, and the third attribute to realize that function, the user can observe the tree-structured exploration process as "2. CONTEXT," "2_1. FUNCTION," and "2_1_3. ATTRIBUTE."

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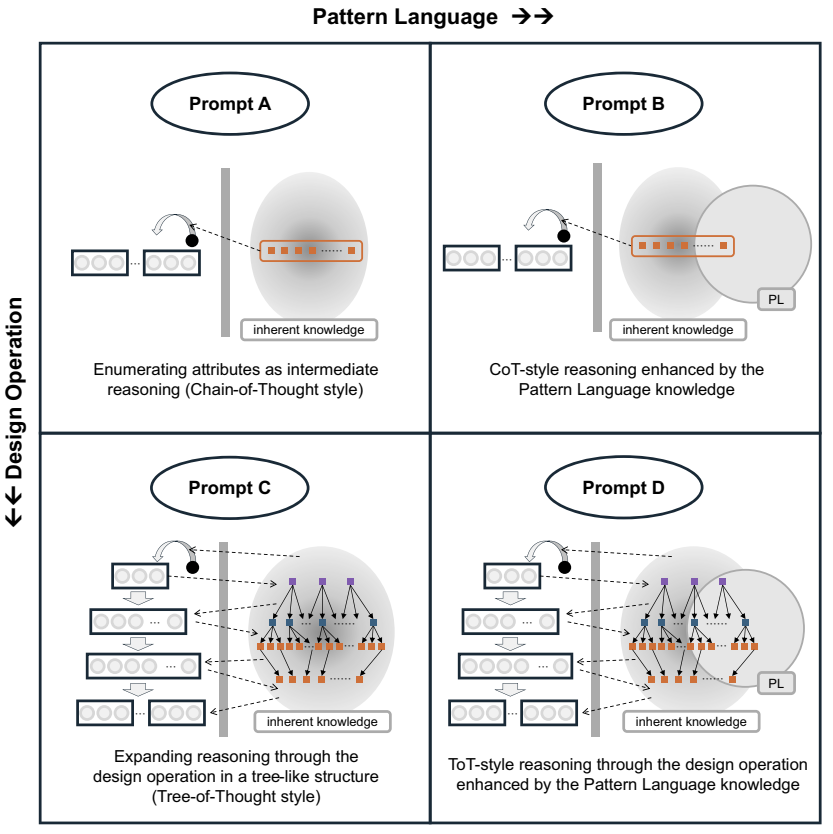


Figure 5. An overview of four prompt strategies for comparative evaluation. Prompts A and B involve a chain of thought that enumerates attributes for generating design alternatives. Prompts C and D involve a tree-structured thought process through the design operation. Prompts A and C use only the LLM's internal knowledge for reasoning, while Prompts B and D can also leverage the Pattern Language knowledge.

of an object that addresses the given design problem and generates design alternatives.

- **Prompt A**: This prompt instructs the LLM to first enumerate 10 attributes necessary to solve the given design problem, then generate a design alternative by combining those attributes. Since the LLM does not produce the design alternative directly but instead goes through an intermediate reasoning process, this approach functions as a form of CoT (Wei *et al.* 2022). CoT prompting is a technique that guides LLMs to perform stepwise reasoning to accomplish complex tasks.
- **Prompt B**: This prompt provides the LLM with PL as external knowledge and instructs it to enumerate 10 attributes by leveraging both the knowledge contained in PL and the LLM's own internal knowledge. This is a CoT prompt utilizing external knowledge.
- **Prompt C**: This prompt performs a ToT reasoning process driven by the design operation model without using PL. The LLM uses only its internal knowledge to enumerate contexts, derive the functions for each context and list the attributes

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of each function. From the resulting 27 attributes, the LLM selects the 10 most important and synthesizes them into a design alternative.

- **Prompt D**: This prompt performs a ToT reasoning driven by the design operation model using both PL and LLM's own knowledge.

All prompts were executed using gpt-4.1 via the OpenAI API within a Python script. To ensure reproducibility and consistency across prompt comparisons, the temperature parameter was set to 0, reducing output randomness and increasing response stability. However, slight variations may still occur due to nondeterministic factors in the generation process. Therefore, each prompt strategy was executed multiple times to ensure robustness (see Section 3.4). All reasoning steps for each design alternative were executed within a single prompt, thereby avoiding the cumulative loss of reliability and reproducibility that can occur when reasoning steps are executed separately. The design alternatives obtained in this manner are evaluated for creativity by humans.

As an applied effort, we used visualized images of them as visual aids for evaluation. This approach was adopted because spatial relationships and atmospheres are difficult to fully grasp from text alone, and the images were intended to facilitate the judges' understanding. Specifically, each text-based design alternative was provided to an image-generation model with the following prompt: "Generate a front porch design based on the description in {text_design_alternative}." In this field, the use of image generation AI in design and its evaluation has been actively discussed in recent years (Koehler 2023; Wang, J. *et al.* 2023; Horvath & Pouliou 2024; Li *et al.* 2025; Lim, Bentley & Ishikawa 2024; Paananen, Oppenlaender & Visuri 2024). Against this background, this study positions AI-based image generation as a supplementary means for supporting evaluation. It aims to provide initial insights that may contribute to the future development of design research using multimodal AI.

We used the GPT-Image-1 model for image generation. Since GPT-Image-1 does not have diverse control parameters such as temperature, it produces noticeably different images even when the same prompt is used. This issue will be further discussed in the Discussion section.

3.4. Evaluation framework

According to Shah, Smith & Vargas-Hernandez (2003), evaluations of ideation methods can be classified into *process-based* and *outcome-based approaches*. While the process-based approach focuses on the cognitive processes underlying creative thinking, these processes are difficult to observe, and their applicability to complex engineering design problems remains unclear. Consequently, outcome-based evaluation, which assesses ideation methods through the design ideas generated during ideation, has become more common in creativity research. Following this outcome-based perspective, this study assesses the creativity of outputs generated by each prompt strategy using specific evaluative dimensions.

The dimensions are the diversity of attributes explored, and the validity, novelty and feasibility of the design alternatives generated by combining those attributes. These are evaluated by computers and humans, respectively. As emphasized in Figure 1, this study assumes that greater diversity among the enumerated attributes leads to greater novelty in the resulting design alternatives. In addition, because the

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design operation model traces back to the context of the design problem, it is expected to yield solutions that are more valid for the problem. Furthermore, by considering the relationships among multiple functions, the design operation is also expected to enhance the physical feasibility of the generated design alternatives.

Although a single prompt input can, in principle, produce multiple attribute sets or design alternatives, this study treats the attribute set or design alternative with the highest likelihood of being generated – obtained by setting the temperature parameter to 0 – as representative of the output characteristics of each prompt strategy. This setting was adopted to focus on the structural effects of prompt strategies rather than stochastic variation in LLM outputs, while ensuring reproducibility.

Even with the temperature fixed at 0, slight variations in the outputs can still occur due to nondeterministic factors in the generation process. To ensure robustness, each prompt strategy was executed 100 times for each design problem, yielding 4,000 attributes and 400 design alternatives.

3.4.1. Computational evaluation of attribute diversity

Prior studies often evaluate creativity using diversity metrics but typically focus on final design outcomes rather than the diversity of attributes themselves (Brown & Mueller 2019; Ma *et al.* 2025). Because all prompt strategies require explicit enumeration of attributes, the resulting attribute sets can be directly compared across prompts.

This study employs the following four metrics to examine diversity from multiple perspectives, extending those introduced by Regenwetter *et al.* (2023). Specifically, the metrics capture global dispersion, local separation, spatial extent of the attribute space and redundancy-aware semantic diversity, respectively.

- **Mean pairwise distance (MPD)** captures the global dispersion of attributes in the semantic space, representing global diversity. This metric calculates the distances between all attributes within an attribute set generated by a given prompt and summarizes their distribution using the mean.
- **Minimum pairwise distance (MinPD)** captures the degree of local separation among attributes, representing local diversity. This metric computes the distance to the nearest neighbor for each attribute within an attribute set generated by a given prompt, then summarizes the distribution of these distances using their mean.
- **Convex hull volume** captures the spatial extent of the attribute space that a prompt explores. This metric defines diversity as the hypervolume of the convex hull that encloses all generated attributes.
- **Determinantal point processes (DPP) diversity score** captures redundancy-aware semantic diversity by penalizing overlapping or semantically similar attributes. This score is computed based on the eigenvalues of a matrix constructed from all of the semantic distances among attributes within an attribute set. An attribute set containing many semantically similar attributes yields lower scores, whereas those containing more dissimilar attributes yield higher scores.

As a related study, Ma *et al.* (2025) investigated how parameter tuning and prompt engineering techniques influence the diversity of generated ideas by employing four different diversity metrics. The originality of our study lies in two aspects:

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(1) incorporating the design operation to generate ideas and (2) evaluating not the final ideas themselves but the attributes that form their basis.

For the implementation, all attribute texts were encoded into 384-dimensional vectors using *all-MiniLM-L6-v2* (Reimers & Gurevych 2019). The convex hull volume was calculated after reducing the embeddings to three-dimensional space using PCA to aid in understanding the inherently difficult-to-comprehend high-dimensional attribute space.

3.4.2. Human evaluation of design alternatives: validity, novelty and feasibility

Creativity of design alternatives was evaluated through expert judgement using the consensual assessment technique (Cseh & Jeffries 2019). The evaluation was conducted using a five-point Likert scale for the following three dimensions.

- **Validity**: The artifact correctly addresses the design problem and is useful for solving it.
- **Novelty**: The artifact is novel and unique.
- **Feasibility**: The artifact is physically feasible.

Eight experts participated as judges, including four specialists in architecture and design education and four in mechanical and information engineering. All judges held academic positions at universities and had experience in design education or research. Each judge independently rated each design alternative, which was presented in random order to mitigate ordering bias. They were not informed about the prompts or the research objectives in advance. As the images are intended as visual aids, we encouraged the judges to primarily base their judgements on the text-based description. After the evaluation, we interviewed all experts to understand the reasons behind their judgments and to confirm their reliability.

Inter-rater reliability was assessed using the intraclass correlation coefficient (ICC). Considering that the judges formed a fixed group of experts in this study, ICC(3,k) (two-way mixed-effects model, consistency type) was employed, with $k = 8$ corresponding to the number of expert judges. Ratings were based on a five-point Likert scale and averaged across judges for each design alternative.

Evaluating 400 design alternatives for a single design problem through relative judgment was considered to impose excessive cognitive load. Therefore, two design alternatives were randomly selected from the 100 generated by each prompt strategy, yielding a total of eight. This number was chosen because eight falls within the range of items that can be simultaneously maintained in human short-term memory, as suggested by findings in cognitive psychology (Miller 1956).

4. Case study and evaluation results

The four prompt strategies are applied to three architectural design problems of varying difficulty. The design subjects and their respective design problems are shown in Table 1.

These subjects were selected to represent design problems with progressively increasing complexity – from a relatively well-established spatial typology (the front porch), through a multifunctional space with intensified human interaction (the living room), to a large-scale, open-ended facility involving diverse and unspecified stakeholders (the university campus facility). While all cases are

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Table 1. Design subjects and corresponding design problems

Design subject	Design problem
Front porch	The entrance is somewhat dark and gloomy.
Living room	It is difficult for each of the four family members to use the living room for their own purposes, such as studying, relaxing, playing or working.
Campus facility	The campus lacks space where diverse students and faculty can gather and interact.

architectural, they are intended to exemplify general characteristics of design problem difficulty, such as functional complexity, interaction density and openness of the design space, rather than to represent architectural design as a whole comprehensively.

This comparative setup also clarifies the research questions addressed in this study. This is because this approach verifies whether the proposed method is effective across a broad range of subjects, independent of any specific design subject.

Moreover, employing multiple design subjects helps mitigate potential fixation effects (Agogué *et al.* 2014) in generative AI (Wadinambiarachchi *et al.* 2024; Song *et al.* 2025). Although fixation effects are not explicitly measured in this study, evaluating the proposed method across multiple design subjects reduces the risk of bias from subject-specific characteristics and constraints.

4.1. Observed characteristics of prompt-specific attributes and design alternatives

A summary of the unique attributes that appeared only in respective prompts is compiled in Table 2. The characteristics of the design alternatives proposed for each prompt are shown below. The full text and images of the design alternatives are included in Appendices A1 to A5.

- **Front porch**: Prompt A tended to propose bright, airy entrances through the use of light and materials. Prompt B tended to propose porches as outdoor living spaces where people could stay. Prompt C tended to propose refined brightness through reflection and optical properties. Prompt D formed symbolic entrance spaces through steps and composition.
- **Living room**: Prompt A adopted a functional integration approach, providing a space oriented toward intellectual activities. Prompt B employed an architectural composition approach, emphasizing light and a sense of spatial enclosure. Prompt C focused on creating manipulable living spaces, showing a tendency to frequently utilize movable modules. Prompt D featured a human-centered design approach, tending to prioritize psychological inclusiveness.
- **Campus facility**: Prompt A designed flexible and integrated indoor spaces. Prompt B emphasized continuity with the town, proposing socially open spaces. Prompt C proposed indoor shared spaces, prioritizing support for human diversity and creative activities. Prompt D tended to propose hub spaces supporting events and social activities.

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Table 2. Summary of generated attributes

Prompt	Front porch	Living room	Campus facility
A	• light-colored wooden decking • skylight strip above entry door • textured white stucco wall finish • reflective stainless-steel handrails	• Fold-out workstations • large central coffee table (has lift-top sections) • multi-level ambient and task lighting system • semi-private reading nook	• integrated tiered seating • communal kitchen and café area • movable modular furniture systems • digital display walls
B	• gallery with open arcades and columns • trellises and climbing plants • canvas awnings • built-in window seats and benches	• thin wings radiating • darker corners offering restful retreats • a sequence of graded sitting spaces • positive outdoor space, partly enclosed by building wings	• marketplace of many small, individually owned shops and food stands • network of paths and green streets connecting to surrounding neighborhoods • many entrances and open stairs • graded sitting spaces from public to private
C	• light-reflective ceramic tile • coated in semi-gloss warm white • translucent glass sidelights • angled roof	• mobile storage carts • area rugs • acoustic ceiling tiles • lightweight, movable furniture on casters	• rotating art displays • semi-enclosed pods • flexible stage and display zones • barrier-free circulation and gender-neutral accessible restrooms
D	• a raised terrace slightly above street level • a trellis archway • boldly shaped and highly visible from the street • the spatial enclosure gradually increases	• central sitting circle with a loose arrangement of chairs • sequence of sitting spaces transitioning from public to private • storage and work surfaces • dimmable wall sconces and floor lamps	• large open plaza with a flexible surface for events and performances • outdoor stage or amphitheater anchors one side of the plaza • circulation realms with named zones • marketplace-style food and retail stalls operated by diverse campus groups

4.2 Results of computational evaluation

The evaluation results of attribute diversity are shown in Table 3. Bold and underlined scores indicate the highest value among all prompts for a given dimension, while bold scores indicate the second-highest value.

According to these results, a pattern of variation in diversity metric scores was observed across prompts. For MPD, Prompt A tended to yield the highest values, while Prompt B consistently showed the smallest values. For MinPD, Prompts C and D consistently showed high tendencies, while Prompts A and B sometimes

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Table 3. Calculation results for four diversity metrics

Design subject	Metrics	Prompt A	Prompt B	Prompt C	Prompt D
Front porch	**MPD**	**0.73836**	0.58805	**0.69840**	0.63318
	MinPD	0.00620	0.00791	**0.07363**	**0.03894**
	Convex hull	0.22778	0.20976	**0.37529**	**0.28052**
	DPP	83.11185	68.75627	**122.33431**	**96.40518**
Living room	**MPD**	**0.72840**	0.59510	0.69589	**0.69980**
	MinPD	0.01023	0.00900	**0.05884**	**0.06735**
	Convex hull	0.16669	0.16597	**0.27680**	**0.30068**
	DPP	89.49558	82.74341	**121.98884**	**123.11088**
Campus facility	**MPD**	**0.73325**	0.60353	**0.74715**	0.68471
	MinPD	0.00536	0.01421	**0.06156**	**0.07865**
	Convex hull	0.24656	0.14262	**0.29785**	**0.31631**
	DPP	85.12644	76.35330	**128.45557**	**120.54734**

yielded values less than one-tenth of those for Prompts C and D. Furthermore, both the convex hull volume and DPP diversity score showed a tendency for Prompts C or D to be the highest.

4.3. Results of human evaluation

The results are shown in Table 4 and Figure 6. Bold and underlined scores indicate the highest value among all prompts for a given dimension, while bold scores indicate the second-highest value. Scores were calculated by averaging the evaluations of the design alternatives generated by each prompt strategy. For example, the two design alternatives generated by Prompt A (A_1 and A_2) were evaluated separately, and the judge used their average as the final score for Prompt A.

Inter-rater reliability for each dimension, measured by ICC(3,k), is shown below the dimension name, with values closer to 1 indicating greater agreement among judges.

These results indicate that the prompts generating design alternatives judged to be highly creative varied across design problems, and no consistent pattern of creativity attributable to prompt differences was observed. Furthermore, inter-rater reliability was often low, which limited the consistency of the evaluation results. For example, the ICC for the validity of the front porch was negative, suggesting a lack of shared evaluation criteria among the judges on this dimension. In contrast, the feasibility of the front porch showed relatively high agreement. The validity and novelty of the living room were moderately to highly agreed upon. The campus facility generally showed low-to-moderate agreement. Overall, the proposed method, Prompt D, rarely received the highest evaluations. By comparison, Prompts A and B tended to obtain higher scores in cases where inter-rater reliability was relatively high.

In this way, comparisons based on average scores did not yield consistent results under reliable conditions. To address this limitation and capture differences in the distributions that the mean score cannot reveal, we analyzed the relative

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Table 4. Results of human evaluation based on mean creativity scores

Design object	Dimensions	Prompt A	Prompt B	Prompt C	Prompt D
Front porch	**Validity** ICC = –0.522	**3.31** (SD = 0.79)	3.19 (SD = 0.91)	**3.44** (SD = 0.89)	2.94 (SD = 1.00)
	Novelty ICC = 0.01	**3.19** (SD = 1.11)	3.00 (SD = 0.97)	**3.38** (SD = 0.81)	2.75 (SD = 0.93)
	Feasibility ICC = 0.72	3.38 (SD = 1.02)	**4.06** (SD = 0.57)	**3.88** (SD = 0.89)	3.63 (SD = 0.96)
Living room	**Validity** ICC = 0.70	**3.19** (SD = 0.75)	**3.56** (SD = 0.51)	2.88 (SD = 0.72)	3.06 (SD = 0.77)
	Novelty ICC = 0.57	**3.19** (SD = 0.75)	**3.19** (SD = 0.75)	2.44 (SD = 1.03)	2.94 (SD = 0.68)
	Feasibility ICC = 0.14	3.63 (SD = 0.81)	**3.81** (SD = 0.75)	3.63 (SD = 0.89)	**3.88** (SD = 0.81)
Campus facility	**Validity** ICC = 0.56	**3.38** (SD = 0.62)	2.63 (SD = 0.96)	**3.44** (SD = 0.73)	3.19 (SD = 0.91)
	Novelty ICC = 0.45	**3.06** (SD = 0.85)	**3.25** (SD = 0.93)	2.56 (SD = 0.81)	2.81 (SD = 0.66)
	Feasibility ICC = 0.32	**3.56** (SD = 0.89)	3.31 (SD = 1.14)	**3.81** (SD = 0.75)	**3.56** (SD = 0.89)

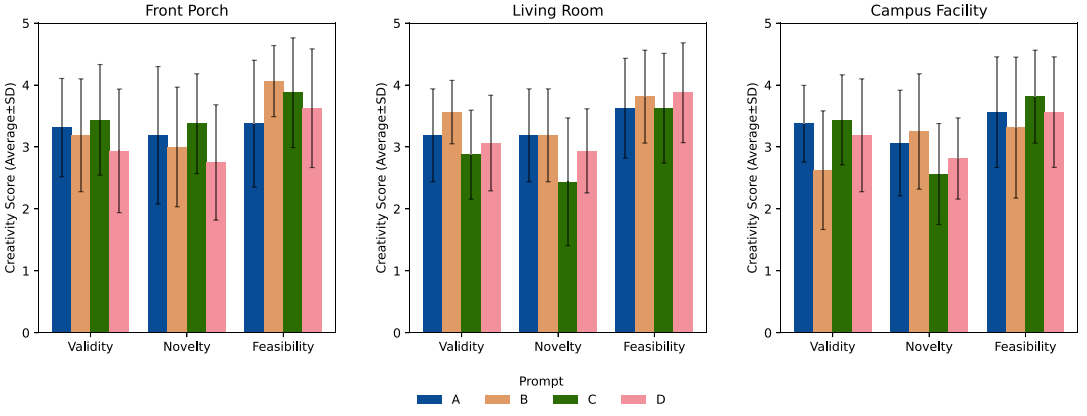


Figure 6. Results of human evaluation based on mean creativity scores.

rankings assigned by each judge. Specifically, we aggregated the number of times each design alternative was ranked first. When multiple design alternatives were tied for first place, the vote was divided equally among them (e.g., a tie between two alternatives resulted in 0.5 votes each). This tie-handling approach has a theoretical and practical background in ranking models and recommender systems. It is supported, for example, by an extension of the Bradley–Terry model (Baker & Scarf 2021), research on ranking aggregation methods that handle ties (Brancotte *et al.* 2015), and studies of methods to correct for rank correlation (Amerise & Tarsitano 2015).

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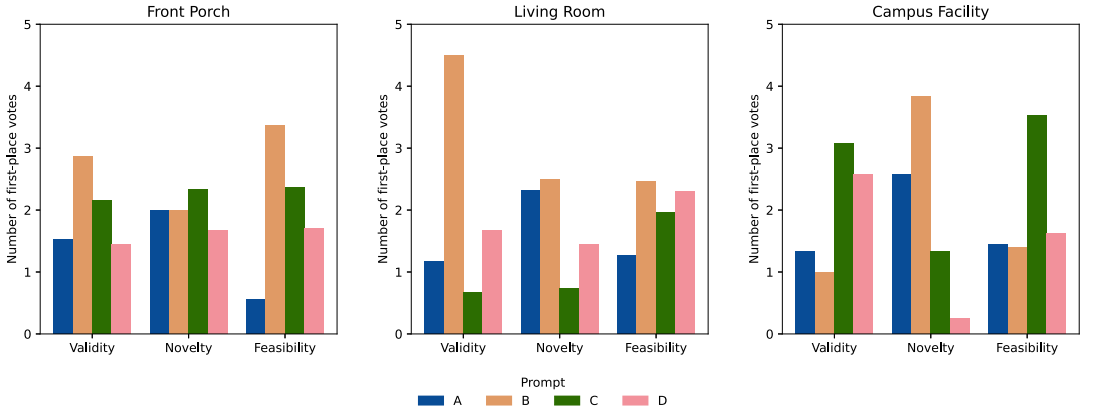


Figure 7. Results of human evaluation based on relative ranking (number of first-place selections).

Figure 7 shows the number of first-place votes for respective prompt methods across three evaluation dimensions. Compared to Figure 6, the difference is visible: in general, the votes for A are lower, while those for C and D are slightly higher. Prompt B received the most first-place votes for the validity and feasibility of front porch design, all indices of living room design and the novelty of campus facility design. Prompt C received the most first-place votes for the novelty of front porch design and for the validity and feasibility of campus facility design.

In this way, Prompts B and C received more first-place votes than Prompts A and D. This tendency reflects differences in the distribution of evaluations: Prompt A tended to receive moderate ratings, with relatively few first-place or low-ranking votes, whereas Prompts B and C were more frequently rated either highly or poorly by different judges.

5. Discussion

In this section, we present answers to the research questions and discuss future directions for LLM-driven design.

5.1. Contribution of design operation to attribute diversity

As shown in Table 3, Prompt A exhibits the highest MPD and the smallest MinPD. This indicates that large distances between attribute clusters but low local diversity within clusters. Although the distance between attribute clusters is large, the relatively small 3D convex hull volume compared with Prompts C and D suggests limited exploration across diverse semantic directions. This tendency may be related to the deterministic nature of LLM outputs when the temperature parameter is set to 0.

Prompt B shows trends similar to those of Prompt A in MPD and MinPD, suggesting a comparable structure of the attribute space. However, its smaller MPD relative to Prompt A indicates that the distance between clusters also becomes smaller, implying that providing PL may cause the search space to specialize in specific domains, potentially leading to a lack of diversity even globally.

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On the other hand, Prompts C and D show moderate to high values for both MPD and MinPD. This indicates that attribute distances are large both within and between clusters. This suggests that Prompts C and D can explore diverse attributes both locally and globally. Furthermore, the large convex hull volumes imply the ability to explore diverse semantic directions, while the high DPP scores indicate fewer attributes with the same meaning, resulting in less spatial overlap. Notably, this tendency was observed despite the temperature parameter being set to 0. This result can be explained by the inference step of ToT included in the design operation. Compared to simple inference, this step considers a broader set of candidate attributes with similar or competing probabilities of occurrence. Consequently, different attributes tend to be selected across executions.

To facilitate comparison of exploration spaces across prompt strategies, the generated attribute sets were visualized in a two-dimensional space (Figures 8–10). Although quantitative evaluations were based on high-dimensional metrics, these visualizations help illustrate overall trends in attribute dispersion and search-space specialization associated with the use of the PL. Observing the figures, Prompts C and D exhibit more dispersed attribute points than Prompts A and B, consistent with the higher DPP score mentioned above. Examination of distances between the

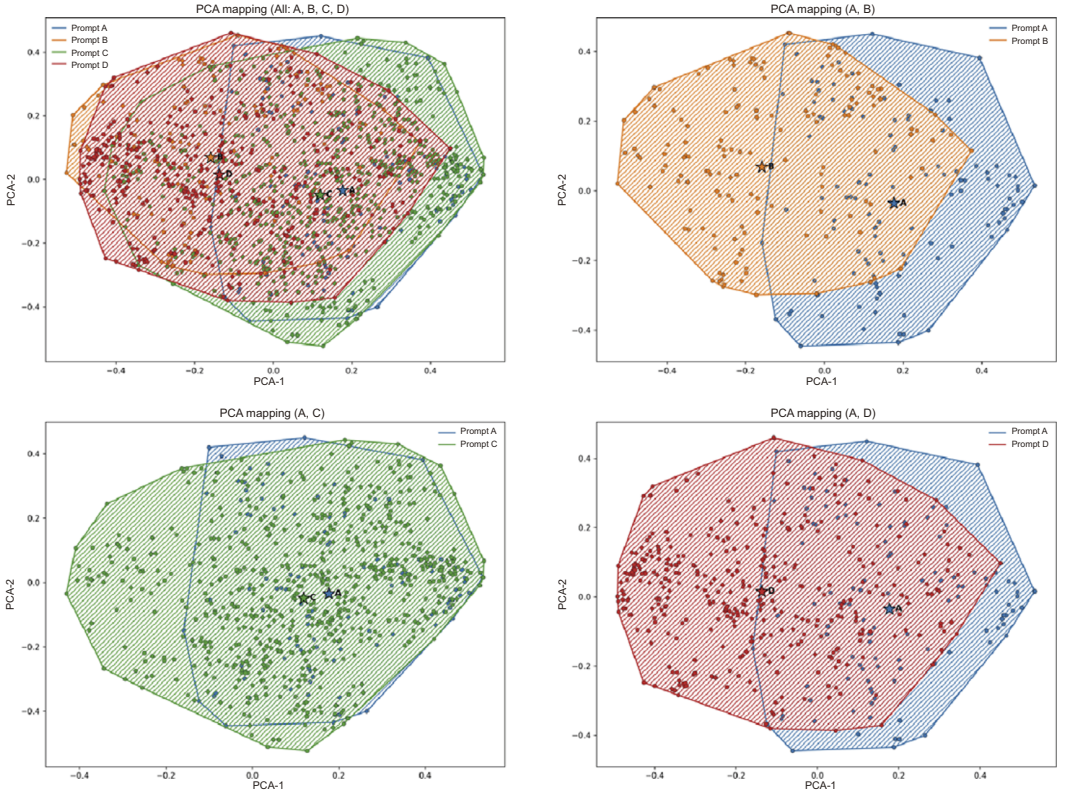


Figure 8. Two-dimensional visualization of generated attribute space differences between prompt strategies for the front porch case. The distances from the centroid of Prompt A to those of Prompts B, C and D are 0.3514, 0.0592 and 0.3177, respectively, calculated using the Euclidean distance in the two-dimensional PCA space.

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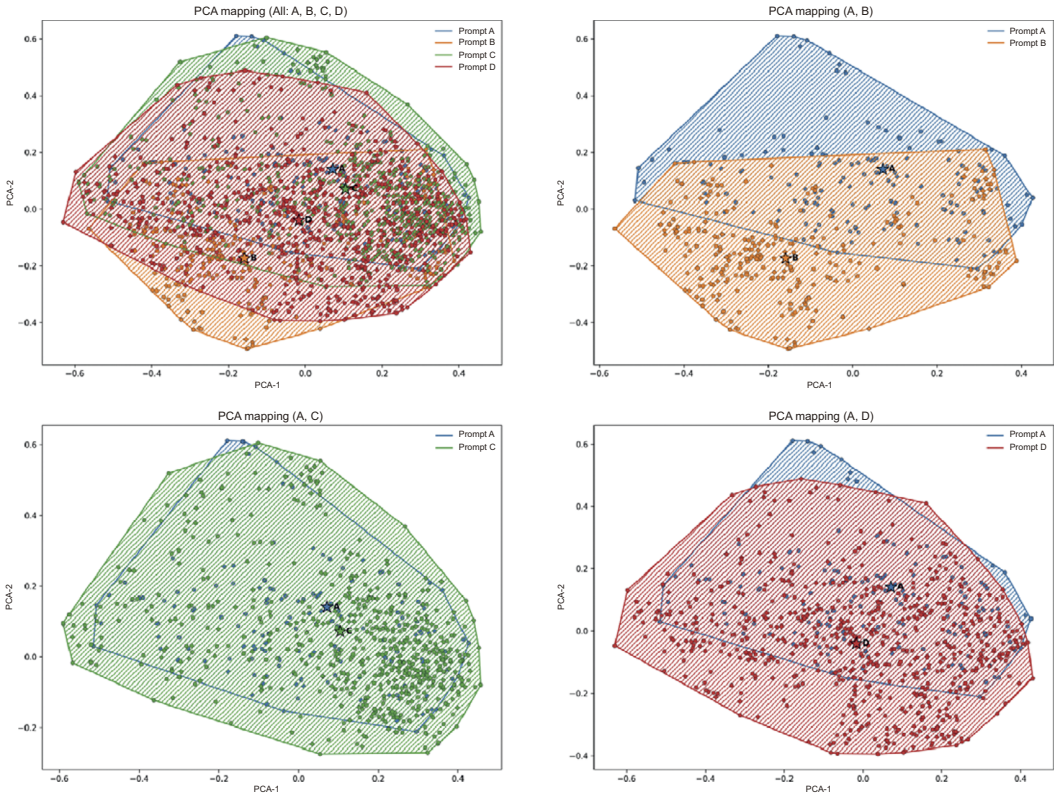


Figure 9. Two-dimensional visualization of generated attribute space differences between prompt strategies for the living room case. The distances from the centroid of Prompt A to those of Prompts B, C and D are 0.3892, 0.0770 and 0.2007, respectively, calculated using the Euclidean distance in the two-dimensional PCA space.

centroids of each set, indicated by stars, reveals systematic differences between prompts with and without the PL: across all design problems, the centroid of Prompt B is farthest from that of Prompt A, indicating that the PL shifts the LLM's attribute exploration toward a specific region. While Prompts C and D explore broadly similar regions, the centroid locations suggest that Prompt D generates a greater proportion of attributes influenced by PL.

Taken together, these results indicate that design operation contributes to diversity by expanding the search space and increasing attribute variability. This suggests that theoretical explanations developed for human designers (Fujita 2023) – namely, that tracing back to the fundamental context of a design problem enables exploration of diverse solutions – may also be applicable to LLMs. In contrast, although providing PL did not expand attribute diversity, observations suggest it may have restructured the LLM's internal knowledge space.

5.2. Attributes diversity and creativity of LLM

We analyze the human evaluation results to determine whether attribute diversity is related to the creativity of the resulting design alternatives.

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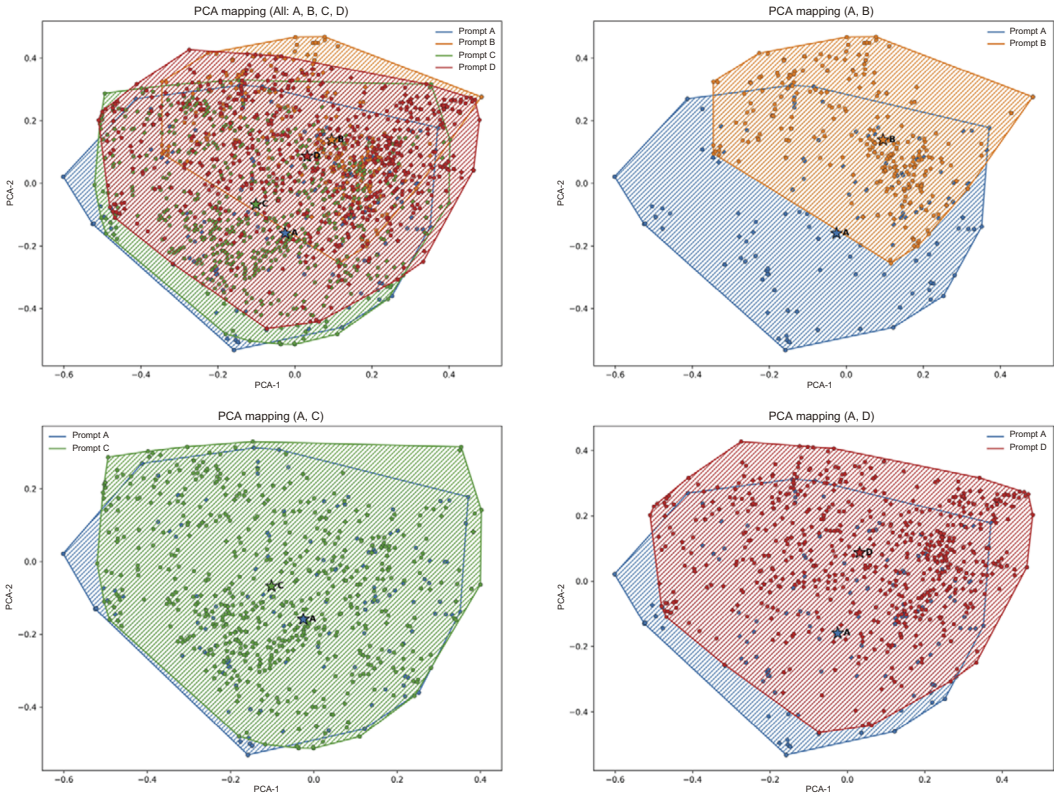


Figure 10. Two-dimensional visualization of generated attribute space differences between prompt strategies for the campus facility case. The distances from the centroid of Prompt A to those of Prompts B, C and D are 0.3218, 0.1190 and 0.2528, respectively, calculated using the Euclidean distance in the two-dimensional PCA space.

Prompt C received a higher rating than Prompt A, making it the second-highest rating after Prompt B. This suggests that even without PL, incorporating appropriate design operations can enhance LLMs' creativity.

Prompt B, while yielding results with low attribute diversity, consistently received the most first-place votes across design problems and evaluation dimensions. In the post-evaluation interview, some judges pointed out that the design alternatives appeared calm and well-balanced, giving a sense of human familiarity, or that they embodied complex ideas. Some of them were aware of PL's existence but did not recognize that it had been incorporated into the prompt. Taken together with the observations on centroid shifts, this result suggests that providing a PL function as a form of knowledge stimulus that dynamically reorganizes the LLM's reasoning structure, potentially inducing branching toward directions of reasoning that would not be reached in its absence. As a result, more creative design ideas can be interpreted as having been generated. Moreover, it is important to note that PL itself constitutes a knowledge structure characterized by non-determinism and non-modularity. Introducing new contextual relations and semantic overlaps into an existing knowledge system can induce non-deterministic and non-modular exploration within the reasoning process, exhibiting behavior that approaches the

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splitting condition (Le Masson et al. 2016) – a theoretical requirement associated with enabling high creativity.

Although Prompt D integrates both design operation and PL and was therefore expected to perform better, the results did not support this expectation. Nevertheless, it received a higher rating than Prompt B in campus design validity and outperformed Prompt C across all dimensions in living room design.

Taken together, these results indicate that design operation enables LLMs to explore diverse attributes and, depending on the design problem, may improve the validity and feasibility of the generated design alternatives (RQ1).

By contrast, although attribute diversity is constrained, appropriately integrating PL into the design problem can relatively enhance LLMs' creativity. This indicates that PL is a valuable external knowledge source worth considering for application in LLM-driven design (RQ2). However, the integration between PL and the design operation model defined in this study remains open to discussion. While Prompt B, which incorporated PL, received a high number of first-place votes, suggesting its effectiveness for certain design subjects, this trend diminished when combined with design operation. One possible interpretation is that, although the design operations in this study include processes similar to those of the systematic approach, such operations rely on deterministic knowledge structures rooted in engineering design, which inhibit the splitting condition and lead to lower creativity evaluations, as noted by Le Masson et al. (2016). On the other hand, the comparison between Prompts A and C shows that Prompt C achieved higher human-evaluation scores, which appears to contradict this interpretation. This result remains to be clarified in future work.

5.3. Consideration of validity of proposed prompt strategy and future direction

Based on the examination of the research questions, we identify two possible explanations for the issues discussed above and outline directions for future research.

First, with respect to RQ1, the fact that our assumption was only partially supported by the results may reflect limitations of current LLMs in the convergence phase of the ideation process. As seen in most research on LLM-driven conceptual design (Chen *et al.* 2024, 2025), while acknowledging that LLMs possess capabilities surpassing humans in the idea divergence phase, these studies assume that human capability is still necessary for the synthesis phase. In other words, LLMs possess the ability to diverge ideas but are not sufficiently capable of synthesizing multiple ideas into new concepts. By deliberately excluding human intervention, this study makes this limitation explicit.

From this perspective, future design support frameworks are expected to emphasize human–GenAI collaboration (Fang *et al.* 2025) that complementarily combine LLM-driven divergent exploration with human-led convergent integration. Additionally, a promising research direction lies in exploring how LLMs can be applied specifically during the synthesis phase. Prompt engineering will continue to expand into more advanced forms. This includes leveraging domain-specific, fine-tuned LLMs for each reasoning step, as well as deploying multiple LLMs as design agents to broaden the scope of exploration (Mushtaq *et al.* 2025). In this context, comparing design alternatives created with and without human

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intervention can clarify the roles of humans and GenAI in co-creative design processes, potentially enabling the generation of innovative ideas.

Second, methodological issues emerged from the human evaluation in this study. Presenting design alternatives as sets of text and images made judgments more susceptible to personal preferences. Although judges were instructed to treat images only as supplementary reference material, post-evaluation interviews revealed that many stated they "primarily judged based on the images." As a result, visual impressions may have had a stronger influence on the judges than the textual design description. Therefore, it cannot be ruled out that what was actually evaluated was not the LLM output itself, but rather the descriptive capabilities and output characteristics of the image-generating AI. This mismatch may explain why the human evaluation did not yield the expected insights when compared with the quantitative results on attribute diversity, which directly target LLM-generated outputs. Moreover, this issue can be considered a factor underlying the inconsistency observed in RQ2.

In future human–GenAI collaborative design frameworks, multimodal representations are expected to become increasingly common. As a result, the number of generative components will increase, leading to greater complexity within the internal system and a larger set of elements that constitute design methods proposed in future research. Under such conditions, evaluating creativity solely on final outcomes risks overlooking factors within the design process that may contribute to it, such as the expansion of attribute diversity through design operations and the potential role of external knowledge in enabling splitting conditions, as examined in this study. Therefore, a process-based evaluation approach (Shah *et al.* 2003), which focuses on the internal processes of ideation, is expected to become increasingly important for understanding and improving creativity in human–GenAI collaborative design systems. From this perspective, the evaluation framework proposed in this study should be interpreted not as an assessment of LLMs' creativity in isolation, but as an evaluation of creativity within a multimodal generative AI pipeline encompassing both text and image generation. In this respect, this framework highlights key challenges and provides directions for future research.

5.4. Limitations of the used model

This study conducted case studies using only GPT-4.1 as the LLM and GPT-Image-1 as the image generation AI. Therefore, it did not examine how using other LLMs or fine-tuned models might affect the results. Nevertheless, the proposed method, which integrates design theory and ToT prompting into a widely used general-purpose GPT framework, is both original and extensible, offering valuable insights for future research in conceptual design.

6. Conclusion

This study proposed a systematic approach to design ideation through LLM-driven design operation with PL. By comparing four prompt strategies across three architectural design tasks, the research demonstrated the contributions of external knowledge and structured reasoning to LLM-driven creativity. The results suggest two key findings. (1) Prompts with design operations increase the diversity of

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generated attributes, potentially expanding the design solution space. (2) Prompts incorporating PL tend to generate more human-like ideas by integrating complex concepts and are thus highly rated by human judges but are strongly influenced by knowledge of PL and lack diversity. This study investigates the usefulness of the design operation and PL in LLM-driven design ideation and provides initial insights that contribute to the accumulation of knowledge in this field.

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Appendix

A1. Sample of Prompt A

- **Prompt for GPT-4.1**

Table A1

Taking the following two steps, generate a design alternative of
Front Porch: a front porch for an entrance that solves the following design problem.
Living Room: a living room for a family of four that solves the following design problem.
Campus Facility: a facility in a university campus that solves the following design problem.
Design Problem:
Front Porch: The entrance is somewhat dark and gloomy.
Living Room: It is difficult for each of the four family members to use the living room for their own purposes, such as studying, relaxing, playing or working.
Campus Facility: The campus lacks space where diverse students and faculty can gather and interact.

Step 1: Using your knowledge, propose 10 attributes that the design alternative should have. An `attribute' is defined as geometric, physical, chemical or mechanical properties of an artifact. Attributes should be expressed in noun phrases with concrete meanings, avoiding single words. You must propose between 5 and 10 tokens.

Step 2: Generate a design alternative by combining attributes you listed at step 1. At this stage, do not introduce any new attributes. Use only the attributes that were listed at step 1. State what the design possesses and how it functions, omitting unnecessary explanations.
Follow the output format below.
|||Attributes |||
1.
2.
…
10.
||| Concept |||
[Provide the design alternative here. It must be within 200 tokens.]

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- **Prompt for GPT-Image-1**

Table A2

Generate a new university facility and its surroundings based on the description in {*Insert the content in |||Concept||| here*}.
Front Porch: The image must show eye-level view of the front porch viewed from outside, facing the entrance directly from the front, with sunny weather in the background. Do not include any text or people. Under cool daylight (6500 K).
Living Room: The image must show wide-angle view and corner-to-corner perspective of the entire living room with the room's interior visible. The living room shall have a large area and deep depth. The image must not include any people.
Campus Facility: The image must show a photorealistic vertical top-down view and must not include any text or people. The roof of the building is removed so the interior rooms and spaces are visible, in a realistic cutaway style like a dollhouse. The facility area shall be 32 meters x 18 meters.

A2. Sample of Prompt B

- **Prompt for gpt-4.1**

Table A3

Taking the following two steps, generate a design alternative of
Front Porch: a front porch for an entrance that solves the following design problem.
Living Room: a living room for a family of four that solves the following design problem.
Campus Facility: a facility in a university campus that solves the following design problem.
Design Problem:
Front Porch: The entrance is somewhat dark and gloomy.
Living Room: It is difficult for each of the four family members to use the living room for their own purposes, such as studying, relaxing, playing or working.
Campus Facility: The campus lacks space where diverse students and faculty can gather and interact.

Step 1: Using both the knowledge contained in the pattern language text provided below and your knowledge, propose 10 attributes that the design alternative should have. Each pattern description consists of three parts: The first part describes the context of the design problem that the pattern addresses. The middle part describes the function of the pattern. The last part describes the attributes of the pattern. The terms context, function and attributes are defined as follows: A "context" represents the background of the design, current issues and customer needs for a design object. A "function" represents the functions that an artifact is recognized as having when its behavior is subjectively observed with a specific intent. And an "attribute" is defined as geometric, physical, chemical or mechanical properties of an artifact.

Continued

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Table A3 Continued

Pattern Language text: Each pattern is separated by a line of dashes (---). Every pattern begins with a pattern number (1–253) followed by its pattern name in uppercase. For example: 1 INDEPENDENT REGIONS." {*Insert the Pattern Language text data here*}
When listing attributes from the pattern language text, include the corresponding pattern number in parentheses, e.g., [an attribute] |Pattern 124|,| and when the attribute comes from your own knowledge, write |own knowledge|.|| Each line must end with |Pattern N| (N = 1–253) or |own knowledge|. Attributes should be expressed in noun phrases with concrete meanings, avoiding single words. You must propose between 5 and 10 tokens.

Step2: Generate a design alternative by combining attributes you listed at step 1. At this stage, do not introduce any new attributes. Use only the attributes that were listed at step 1. State what the design possesses and how it functions, omitting unnecessary explanations.
Follow the output format below.
Same as A–1.

- **Prompt for GPT-Image-1**

  Same as A-1.

A3. Sample of Prompt C

- **Prompt for gpt-4.1**

Table A4

Taking the following two steps, generate a design alternative of
 # Front Porch: a front porch for an entrance that solves the following design problem.
 # Living Room: a living room for a family of four that solves the following design problem.
 # Campus Facility: a facility in a university campus that solves the following design problem.
Design Problem:
 # Front Porch: The entrance is somewhat dark and gloomy.
 # Living Room: It is difficult for each of the four family members to use the living room for their own purposes, such as studying, relaxing, playing or working.
 # Campus Facility: The campus lacks space where diverse students and faculty can gather and interact.

Step 1: Following the sub-steps below, propose attributes that the design alternative should have.
Sub-step1: Using your knowledge, list the three contexts that are most relevant to addressing the design problem. A "context" represents the background of the design, current issues and customer needs for a design object. Contexts should be expressed in full sentences.

Continued

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Table A4 Continued

Sub-step2: Using your knowledge, for each context you listed at sub-step1, list three functions that are necessary to address or solve it. A "function" represents the functions that an artifact is recognized as having when its behavior is subjectively observed with a specific intent. Functions should be expressed in meaningful verb-object phrases.
Sub-step3: Using your knowledge, for each function, list three attributes that are necessary to realize it. An `attribute' is defined as geometric, physical, chemical or mechanical properties of an artifact. Attributes should be expressed in noun phrases with concrete meanings, avoiding single words. You must propose between 5 and 10 tokens.
Sub-step4. This is the final sub-step. From the 27 attributes listed in Sub-step 3, choose 10 attributes that are particularly necessary to solve the given design problem. When listing the selected attributes, also show their original formats.

Step2: Generate a new design alternative by combining attributes you listed at sub-step 4. At this stage, do not introduce any new attributes. Use only the attributes that were listed at sub-step 4. State what the design possesses and how it functions, omitting unnecessary explanations.

Follow the output format below.
||| Contexts |||
1.
2.
3.
||| Functions |||
1_1.
1_2.
1_3.
2_1.
2_2.
2_3.
…
3_3.
||| Attributes |||
1_1_1.
1_1_2.
1_1_3.
1_2_1.
1_2_2.
1_2_3.
1_3_1.
1_3_2.
1_3_3.
2_1_1.
2_1_2.
…
3_3_3.
||| Important Attributes |||
[Identification Number].
[Identification Number].

Continued

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Table A4 Continued

…
[Identification Number].
||| Concept |||
[Provide the design alternative here. It must be within 200 tokens.]

In this notation, 1–2–3 denotes the third attribute, which realizes the second function; that function solves the first context.

- **Prompt for GPT-Image-1**

  Same as A-1.

- **Sample concepts explored through the design operation**
  - Front Porch

Table A5. Outputs of the design operations for the front porch.

Context	1. The entrance receives limited natural light due to its orientation and surrounding structures. 2. The current porch design does not encourage a welcoming atmosphere for visitors. 3. The materials and finishes of the existing porch absorb rather than reflect available light.
Function	1_1. Increase the amount of natural light reaching the entrance. 1_2. Reduce visual obstructions that block sunlight. 1_3. Direct available daylight toward the entry door. 2_1. Create a visually inviting threshold for guests. 2_2. Enhance the sense of openness at the entrance. 2_3. Provide cues that guide visitors toward the entry. 3_1. Use materials that reflect rather than absorb light. 3_2. Incorporate finishes that brighten the porch area. 3_3. Select colors that visually lift the space.
Attribute	1_1_1. Overhead glazing panels in the porch roof structure 1_1_2. Translucent side screens adjacent to the entry path 1_1_3. Clerestory windows above the entry door 1_2_1. Slim-profile porch columns with minimal cross-section 1_2_2. Open railing design with horizontal metal bars 1_2_3. Elevated porch floor with open riser steps 1_3_1. Angled soffit surfaces to bounce light toward the door 1_3_2. Light-colored ceiling paint with high reflectance 1_3_3. Integrated light shelves above the door 2_1_1. Wide entry platform with generous proportions 2_1_2. Flared entry steps leading up to the porch 2_1_3. Decorative planters with bright foliage at the threshold 2_2_1. Frameless glass side panels at the porch perimeter 2_2_2. Extended roof overhang with thin edge profile 2_2_3. Recessed LED strip lighting along the ceiling edge

Continued

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Table A5. Continued

	2_3_1. Contrasting entry door color for visual focus 2_3_2. Pathway lighting embedded in the porch floor 2_3_3. Vertical signage with illuminated lettering 3_1_1. High-gloss white composite decking for the porch floor 3_1_2. Polished stainless steel handrails 3_1_3. Reflective glass inserts in the porch balustrade 3_2_1. Satin-finish light stone cladding on porch walls 3_2_2. Semi-gloss exterior paint in warm white for trim 3_2_3. Frosted glass wall sconces with LED bulbs 3_3_1. Soft pastel color palette for porch furnishings 3_3_2. Light-reflective ceramic tile at the entry landing 3_3_3. Pale yellow accent wall adjacent to the door
Selected Attribute	1_1_1. Overhead glazing panels in the porch roof structure 1_1_3. Clerestory windows above the entry door 1_3_2. Light-colored ceiling paint with high reflectance 2_1_1. Wide entry platform with generous proportions 2_2_1. Frameless glass side panels at the porch perimeter 2_2_3. Recessed LED strip lighting along the ceiling edge 3_1_1. High-gloss white composite decking for the porch floor 3_1_3. Reflective glass inserts in the porch balustrade 3_2_2. Semi-gloss exterior paint in warm white for trim 3_3_2. Light-reflective ceramic tile at the entry landing

○ Living Room

Table A6. Outputs of the design operations for the living room.

Context	1. Each family member has different activities and needs that must be accommodated simultaneously in the living room. 2. The living room currently lacks defined zones, leading to conflicts and distractions among users. 3. The space does not provide adequate storage or organization for diverse activities and belongings.
Function	1_1. Enable simultaneous multi-activity use. 1_2. Support individual privacy within a shared space. 1_3. Facilitate easy transition between activities. 2_1. Create distinct zones for different activities. 2_2. Reduce noise and visual distractions. 2_3. Allow flexible reconfiguration of space. 3_1. Provide accessible storage for study, work, play and relaxation items. 3_2. Organize personal belongings for each family member. 3_3. Integrate storage solutions without reducing usable space.
Attribute	1_1_1. Modular furniture with movable components. 1_1_2. Adjustable lighting for task and ambient needs. 1_1_3. Multi-purpose surfaces for work, play and relaxation. 1_2_1. Sliding partition panels with sound-absorbing material.

Continued

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Table A6. Continued

	1_2_2. Built-in alcoves or nooks for semi-private use. 1_2_3. High-backed seating to create visual separation. 1_3_1. Foldable desks integrated into wall units. 1_3_2. Mobile storage carts for activity-specific items. 1_3_3. Quick-release connectors for rearranging furniture. 2_1_1. Area rugs to define activity zones. 2_1_2. Open shelving units as space dividers. 2_1_3. Color-coded décor elements for each zone. 2_2_1. Acoustic ceiling panels to dampen sound. 2_2_2. Curtains or screens for temporary separation. 2_2_3. Bookshelves with staggered heights to block sightlines. 2_3_1. Lightweight, stackable chairs and tables. 2_3_2. Track-mounted sliding walls. 2_3_3. Collapsible play equipment. 3_1_1. Under-sofa storage drawers. 3_1_2. Wall-mounted cubbies for books and devices. 3_1_3. Hidden compartments in coffee tables. 3_2_1. Personalized storage bins for each family member. 3_2_2. Labelled hooks and shelves for organization. 3_2_3. Color-coded storage baskets. 3_3_1. Built-in cabinetry along unused wall space. 3_3_2. Storage ottomans with lift-up lids. 3_3_3. Vertical storage towers to maximize floor area.
Selected Attribute	1_1_1. Modular furniture with movable components. 1_1_2. Adjustable lighting for task and ambient needs. 1_2_1. Sliding partition panels with sound-absorbing material. 1_2_2. Built-in alcoves or nooks for semi-private use. 1_3_2. Mobile storage carts for activity-specific items. 2_1_1. Area rugs to define activity zones. 2_1_2. Open shelving units as space dividers. 2_2_1. Acoustic ceiling panels to dampen sound. 3_1_2. Wall-mounted cubbies for books and devices. 3_2_1. Personalized storage bins for each family member.

○ Campus facility

Table A7. Outputs of the design operations for the campus facility.

Context	1. The campus lacks inclusive spaces that encourage interaction among students and faculty from diverse backgrounds. 2. Existing facilities do not support flexible, multipurpose use for both formal and informal gatherings. 3. There is a need for environments that foster spontaneous collaboration and cultural exchange.
Function	1_1. Facilitate face-to-face communication among diverse users. 1_2. Support group activities and collaborative work.

Continued

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Table A7. Continued

	1_3. Encourage informal socialization and relaxation. 2_1. Accommodate various event types and group sizes. 2_2. Enable easy reconfiguration of space for different uses. 2_3. Provide accessible amenities for all users. 3_1. Promote visibility and openness to invite participation. 3_2. Integrate cultural elements to celebrate diversity. 3_3. Offer comfortable micro-environments for small group interactions.
Attribute	1_1_1. Open-plan seating arrangements with movable furniture. 1_1_2. Transparent glass partitions for visual connectivity. 1_1_3. Central gathering zones with circular layouts. 1_2_1. Large writable wall surfaces for brainstorming. 1_2_2. Modular tables with integrated power outlets. 1_2_3. Flexible lighting systems for different activity modes. 1_3_1. Lounge areas with soft seating and greenery. 1_3_2. Café-style nooks with acoustic treatments. 1_3_3. Outdoor terraces connected to indoor spaces. 2_1_1. Retractable walls for space expansion or division. 2_1_2. Stackable chairs and foldable tables for storage. 2_1_3. Multi-level platforms for tiered seating. 2_2_1. Sliding partitions for rapid reconfiguration. 2_2_2. Mobile presentation screens and AV equipment. 2_2_3. Universal design features for barrier-free access. 2_3_1. Gender-neutral restrooms near main areas. 2_3_2. Water bottle refill stations and snack kiosks. 2_3_3. Digital wayfinding displays for easy navigation. 3_1_1. Floor-to-ceiling windows for natural light and views. 3_1_2. Double-height atrium for spatial openness. 3_1_3. Transparent entryways with welcoming signage. 3_2_1. Rotating art displays from students and faculty artists. 3_2_2. Multilingual signage and information boards. 3_2_3. Display niches for cultural artifacts and exhibits. 3_3_1. Semi-enclosed pods for private conversations. 3_3_2. Adjustable climate control zones for comfort. 3_3_3. Sound-absorbing ceiling panels for noise reduction.
Selected Attribute	1_1_1. Open-plan seating arrangements with movable furniture. 1_1_2. Transparent glass partitions for visual connectivity. 1_3_1. Lounge areas with soft seating and greenery. 2_1_1. Retractable walls for space expansion or division. 2_2_3. Universal design features for barrier-free access. 2_3_1. Gender-neutral restrooms near main areas. 3_1_1. Floor-to-ceiling windows for natural light and views. 3_2_1. Rotating art displays from students and faculty artists. 3_2_2. Multilingual signage and information boards. 3_3_1. Semi-enclosed pods for private conversations.

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A4. Sample of Prompt D

- **Prompt for gpt-4.1**

Table A8.

Taking the following two steps, generate a design alternative of
 # Front Porch: a front porch for an entrance that solves the following design problem.
 # Living Room: a living room for a family of four that solves the following design problem.
 # Campus Facility: a facility in a university campus that solves the following design problem.
Design Problem:
 # Front Porch: The entrance is somewhat dark and gloomy.
 # Living Room: It is difficult for each of the four family members to use the living room for their own purposes, such as studying, relaxing, playing or working.
 # Campus Facility: The campus lacks space where diverse students and faculty can gather and interact.

Step 1: Following the sub-steps below, using both the knowledge contained in the pattern language text provided below and your knowledge, propose 10 attributes that the design alternative should have. Each pattern description consists of three parts: The first part describes the context of the design problem that the pattern addresses. The middle part describes the function of the pattern. The last part describes the attributes of the pattern. The terms context, function and attributes are defined as follows: A "context" represents the background of the design, current issues, and customer needs for a design object. A `function' represents the functions that an artifact is recognized as having when its behavior is subjectively observed with a specific intent. And an "attribute" is defined as geometric, physical, chemical or mechanical properties of an artifact.
Pattern Language text: Each pattern is separated by a line of dashes (—---). Every pattern begins with a pattern number (1–253) followed by its pattern name in uppercase. For example: 1 INDEPENDENT REGIONS." *{# Insert the Pattern Language text data here}*
When listing contexts, functions, and attributes from the Pattern Language text, include the corresponding pattern number in parentheses, e.g., [a context/function/attribute] |Pattern 124|,| and when the those comes from your own knowledge, write [a context/function/attribute] |own knowledge|.|| Each line must end with |Pattern N| (N = 1–253) or |own knowledge|.
Sub-step1: Using both the knowledge contained in the Pattern Language text and your knowledge, list the three contexts that are most relevant to addressing the design problem. Contexts should be expressed in full sentences.
Sub-step2: Using both the knowledge contained in the Pattern Language text and your knowledge, for each context you listed at sub-step1, list three functions that are necessary to address or solve it. Functions should be expressed in meaningful verb-object phrases.
Sub-step3: Using both the knowledge contained in the Pattern Language text and your knowledge, Using your knowledge, for each function, list three attributes that are necessary to realize it. Attributes should be expressed in noun phrases

Continued

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Table A8. Continued

with concrete meanings, avoiding single words. You must propose between 5 and 10 tokens.
Sub-step4. This is the final sub-step. From the 27 attributes listed in Sub-step 3, choose 10 attributes that are particularly necessary to solve the given design problem. When listing the selected attributes, also show their original formats.

Step2: Generate a design alternative by combining attributes you listed at sub-step4. At this stage, do not introduce any new attributes. Use only the attributes that were listed at sub-step4. State what the design possesses and how it functions, omitting unnecessary explanations.

Follow the output format below.
Same as A–3.

- **Prompt for GPT-Image-1**

  Same as A-1.

- **Sample concepts explored through the design operation**

○ Front Proch

Table A9. Outputs of the design operations for the front porch.

Context	1. The entrance is somewhat dark and gloomy, making it unwelcoming and uncomfortable for users. |own knowledge| 2. The front porch lacks features that encourage lingering and social interaction, reducing its liveliness. |Pattern 160| 3. The transition between the outdoors and indoors is abrupt, failing to create a sense of arrival and comfort. |Pattern 112|
Function	1_1. Increase the amount of natural light at the entrance. |Pattern 128| 1_2. Create visual interest and a sense of warmth at the front porch. |Pattern 135| 1_3. Make the entrance more visible and inviting from the street. |Pattern 110| 2_1. Provide comfortable places for people to sit and linger. |Pattern 160| 2_2. Encourage social interaction and casual gathering at the porch. |Pattern 124| 2_3. Offer protection from weather while maintaining openness to the outdoors. |Pattern 119| 3_1. Establish a gradual transition from the street to the entrance. |Pattern 112| 3_2. Mark the threshold with changes in light, material and level. |Pattern 112| 3_3. Frame the entrance with elements that signal arrival and welcome. |Pattern 130|

Continued

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Table A9. Continued

Attribute	1_1_1. South-facing orientation for maximum sunlight exposure. | Pattern 105| 1_1_2. Large windows or glazed doors at the entrance area. | Pattern 128| 1_1_3. Light-colored surfaces and reflective materials on porch and entry walls. |own knowledge| 1_2_1. Alternating areas of light and shadow created by trellises or overhangs. |Pattern 135| 1_2_2. Warm-toned wood or brick finishes for porch surfaces. | Pattern 250| 1_2_3. Decorative elements such as potted plants and climbing vines. |Pattern 246| 1_3_1. Projecting entrance volume with a covered porch roof. | Pattern 130| 1_3_2. Bold, visible entrance shape that stands out from the building line. |Pattern 110| 1_3_3. Contrasting color or material at the entry to highlight the threshold. |own knowledge| 2_1_1. Built-in benches or seating walls along the porch edge. | Pattern 160| 2_1_2. Deep porch (at least six feet) to allow for group seating. | Pattern 167| 2_1_3. Movable chairs and small tables for flexible use. |own knowledge| 2_2_1. Pockets of activity such as a small table for coffee or games. |Pattern 124| 2_2_2. Scalloped or indented porch edge to create semi-private nooks. |Pattern 124| 2_2_3. Visual connection to the street for people-watching. | Pattern 140| 2_3_1. Overhead cover or arcade for shelter from rain and sun. | Pattern 119| 2_3_2. Open sides or low walls to maintain connection with outdoors. |Pattern 160| 2_3_3. Columns or trellis to support climbing plants and define space. |Pattern 246| 3_1_1. Pathway with changes in paving texture leading from street to porch. |Pattern 112| 3_1_2. Sequence of steps or level changes between sidewalk and entry. |Pattern 112| 3_1_3. Landscaping or low walls to guide movement toward the entrance. |Pattern 173| 3_2_1. Gradual increase in light intensity as one approaches the door. |Pattern 135| 3_2_2. Use of different materials (stone, wood, tile) to mark zones. |Pattern 112| 3_2_3. Subtle changes in elevation or steps at the threshold. | Pattern 112| 3_3_1. Entrance room or vestibule with windows on two or three sides. |Pattern 130|

Continued

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Table A9. Continued

	3_3_2. Covered outdoor area that straddles inside and outside. | Pattern 130| 3_3_3. Built-in shelf or bench for packages and waiting. |Pattern 130|
Selected Attribute	1_1_2. Large windows or glazed doors at the entrance area. | Pattern 128| 1_2_1. Alternating areas of light and shadow created by trellises or overhangs. |Pattern 135| 1_2_2. Warm-toned wood or brick finishes for porch surfaces. | Pattern 250| 1_3_2. Bold, visible entrance shape that stands out from the building line. |Pattern 110| 2_1_1. Built-in benches or seating walls along the porch edge. | Pattern 160| 2_1_2. Deep porch (at least six feet) to allow for group seating. | Pattern 167| 2_3_1. Overhead cover or arcade for shelter from rain and sun. | Pattern 119| 3_1_1. Pathway with changes in paving texture leading from street to porch. |Pattern 112| 3_2_1. Gradual increase in light intensity as one approaches the door. |Pattern 135| 3_3_2. Covered outdoor area that straddles inside and outside. | Pattern 130|

○ Living room

Table A10. Outputs of the design operations for the living room.

Context	1. Each family member has different needs for using the living room, such as studying, relaxing, playing or working. |own knowledge| 2. The living room must support both communal activities and individual privacy to prevent conflicts and overcrowding. | Pattern 109| 3. The living room should be organized to allow easy transitions between shared and private uses throughout the day. |Pattern 127|
Function	1_1. Provide distinct zones for different activities within the living room. |own knowledge| 1_2. Allow simultaneous use of the living room by multiple family members without interference. |own knowledge| 1_3. Support flexible reconfiguration of spaces for changing needs. |Pattern 146| 2_1. Create semi-private alcoves or nooks for focused activities. | Pattern 179|

Continued

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Table A10. Continued

	2_2. Encourage informal gathering in a central common area. | Pattern 129| 2_3. Reduce noise and visual distractions between zones. |own knowledge| 3_1. Enable smooth movement between private and communal areas. |Pattern 131| 3_2. Offer a sequence of sitting spaces with varying degrees of enclosure. |Pattern 142| 3_3. Integrate storage and work surfaces to support multiple functions. |Pattern 197|
Attribute	1_1_1. Long, thin room shape with separated activity zones | Pattern 109| 1_1_2. Built-in shelves and desks at the perimeter for study or work |Pattern 197| 1_1_3. Movable partitions or sliding panels between zones |own knowledge| 1_2_1. Sound-absorbing wall finishes and soft floor materials | own knowledge| 1_2_2. Visual screens or half-height walls between activity areas | Pattern 193| 1_2_3. Separate lighting controls for each zone |own knowledge| 1_3_1. Freestanding furniture that can be rearranged easily |own knowledge| 1_3_2. Modular storage units on casters |own knowledge| 1_3_3. Flexible seating arrangements with different chair types | Pattern 251| 2_1_1. Alcoves with lower ceilings and partial enclosure |Pattern 179| 2_1_2. Window seats or bay windows for individual retreat | Pattern 180| 2_1_3. Desk nooks with task lighting and shelves |Pattern 183| 2_2_1. Central sitting circle with loose arrangement of chairs | Pattern 185| 2_2_2. Large table for shared activities and meals |Pattern 139| 2_2_3. Fireplace or focal point for gathering |Pattern 181| 2_3_1. Area rugs and curtains to dampen sound |own knowledge| 2_3_2. Bookshelves or storage walls as spatial dividers |Pattern 197| 2_3_3. Plant screens or trellises for visual separation |own knowledge| 3_1_1. Wide, unobstructed circulation paths around zones | Pattern 131| 3_1_2. Corner doors to minimize traffic through activity areas | Pattern 196| 3_1_3. Short passages with natural light and views |Pattern 132| 3_2_1. Sequence of sitting spaces from public to private |Pattern 142| 3_2_2. Built-in benches and window seats at different locations | Pattern 202|

Continued

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Table A10. Continued

	3_2_3. Partial walls or columns to define sitting areas |Pattern 193| 3_3_1. Deep wall niches for books, games and supplies |Pattern 197| 3_3_2. Integrated work counters with open shelves above |Pattern 200| 3_3_3. Concealed storage for toys and electronics |own knowledge|
Selected Attribute	1_1_1. Long, thin room shape with separated activity zones | Pattern 109| 1_1_3. Movable partitions or sliding panels between zones |own knowledge| 1_2_2. Visual screens or half-height walls between activity areas | Pattern 193| 2_1_1. Alcoves with lower ceilings and partial enclosure |Pattern 179| 2_1_2. Window seats or bay windows for individual retreat | Pattern 180| 2_2_1. Central sitting circle with loose arrangement of chairs | Pattern 185| 3_1_1. Wide, unobstructed circulation paths around zones | Pattern 131| 3_2_1. Sequence of sitting spaces from public to private |Pattern 142| 3_3_1. Deep wall niches for books, games and supplies |Pattern 197| 3_3_2. Integrated work counters with open shelves above |Pattern 200|

○ Campus facility

Table A11. Outputs of the design operations for the campus facility.

Context	1. The campus lacks a central space where diverse students and faculty can gather and interact. |own knowledge| 2. The existing campus environment does not support spontaneous or informal social encounters among different groups. |own knowledge| 3. The current campus layout does not provide a variety of settings that accommodate both large and small group activities for a diverse population. |own knowledge|
Function	1_1. Facilitate inclusive gathering for students and faculty from different backgrounds. |own knowledge| 1_2. Support a sense of belonging and identity for various campus subcultures. |Pattern 8| 1_3. Encourage cross-disciplinary and cross-cultural exchange. |own knowledge|

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Table A11. Continued

	2_1. Enable spontaneous social interaction in public spaces. | Pattern 100| 2_2. Provide comfortable places for lingering and informal conversation. |Pattern 124| 2_3. Connect indoor and outdoor circulation to maximize chance encounters. |Pattern 101| 3_1. Offer flexible spaces for both large events and small group meetings. |Pattern 146| 3_2. Integrate a range of seating and activity pockets to suit different group sizes and needs. |Pattern 124| 3_3. Ensure accessibility and visibility of gathering spaces from main campus paths. |Pattern 110|
Attribute	1_1_1. Large, open central plaza with pedestrian-only access | Pattern 100| 1_1_2. Multiple entrances visible from all main campus approaches |Pattern 110| 1_1_3. Flexible, reconfigurable furniture and movable partitions |Pattern 146| 1_2_1. Distinct zones or alcoves for different student groups, visually connected |Pattern 8| 1_2_2. Display areas for cultural and academic expression |own knowledge| 1_2_3. Architectural elements reflecting diverse identities |own knowledge| 1_3_1. Shared activity pockets along circulation routes |Pattern 124| 1_3_2. Open gallery or arcade connecting different departments |Pattern 119| 1_3_3. Central event space with adaptable lighting and sound | own knowledge| 2_1_1. Outdoor pedestrian street lined with entrances and open stairs |Pattern 100| 2_1_2. Frequent nodes with benches, trees and shade structures |Pattern 124| 2_1_3. Transparent facades for visual connection between inside and outside |Pattern 165| 2_2_1. Scalloped edges with built-in seating and small gardens | Pattern 124| 2_2_2. Covered arcades for weather protection and informal gathering |Pattern 119| 2_2_3. Varied ceiling heights to create intimate and open areas | Pattern 190| 2_3_1. Wide, light-filled indoor thoroughfares with activity along the edge |Pattern 101| 2_3_2. Shortcut paths that slice through the building and connect to outdoor spaces |Pattern 101|

Continued

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Table A11. Continued

	2_3_3. Multiple wide gateways aligned with campus pedestrian network |Pattern 110| 3_1_1. Modular rooms with operable walls for event flexibility | Pattern 146| 3_1_2. Central hall with adjacent breakout spaces |Pattern 146| 3_1_3. Outdoor amphitheater integrated with main plaza |own knowledge| 3_2_1. Activity pockets alternating with access points around the plaza |Pattern 124| 3_2_2. Sequence of sitting spaces with different degrees of enclosure |Pattern 142| 3_2_3. Movable tables and chairs for group customization | Pattern 146| 3_3_1. Main entrance as a bold, visible shape facing campus arteries |Pattern 110| 3_3_2. Transparent signage and wayfinding integrated into architecture |own knowledge| 3_3_3. Open sightlines from main paths to gathering areas | Pattern 110|
Selected Attribute	1_1_1. Large, open central plaza with pedestrian-only access | Pattern 100| 1_1_2. Multiple entrances visible from all main campus approaches |Pattern 110| 1_3_1. Shared activity pockets along circulation routes |Pattern 124| 2_1_1. Outdoor pedestrian street lined with entrances and open stairs |Pattern 100| 2_1_2. Frequent nodes with benches, trees and shade structures |Pattern 124| 2_2_2. Covered arcades for weather protection and informal gathering |Pattern 119| 2_3_1. Wide, light-filled indoor thoroughfares with activity along the edge |Pattern 101| 3_1_1. Modular rooms with operable walls for event flexibility | Pattern 146| 3_2_2. Sequence of sitting spaces with different degrees of enclosure |Pattern 142| 3_3_3. Open sightlines from main paths to gathering areas | Pattern 110|

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A5 Evaluated design alternatives by human expert

In practice, the text was translated into Japanese and evaluated.

- Front porch

Table A12. Full text of the design alternatives for the front porch.

	Design alternative
A_1	The design features a wide overhanging glass canopy that shelters the entrance while allowing natural light to penetrate. The porch floor is finished with light-colored wooden decking, and open riser steps with light stone treads lead up to the entry. A vertical slatted screen with open spacing flanks one side, providing partial enclosure without blocking daylight. Integrated linear LED uplighting is concealed along the canopy and steps, ensuring the area remains bright after sunset. Frosted glass side panels and a frameless glass balustrade maintain openness and maximize light diffusion. A reflective white ceiling finish amplifies both natural and artificial light. Planter boxes with low-maintenance greenery soften the space, while a skylight strip above the entry door further brightens the threshold.
A_2	The design features a wide overhanging glass canopy with skylight cutouts, allowing natural light to filter through while providing shelter. The porch floor is finished with light-colored wooden decking, enhancing brightness underfoot. Open riser steps lead to the entrance, minimizing visual heaviness and allowing light to pass through. Vertical slatted screens with spacing flank the porch, creating partial enclosure without blocking daylight. Frosted glass side panels diffuse sunlight and maintain privacy. Integrated linear LED uplighting is concealed along the decking and under the canopy, ensuring the entrance remains well-lit after dark. Reflective stainless steel handrails further amplify available light. Planter boxes with light-toned foliage soften the space, while a textured white stucco wall finish maximizes reflectivity and visual warmth.
B_1	The design alternative is a south-facing, long, thin front porch that projects from the entrance, forming a six-foot deep covered gallery with open arcades and columns. The porch features alternating pools of sunlight and shade, created by a tapestry of filtered light from trellises and climbing plants, and is finished in warm colors and natural materials. Built-in seating and raised flower beds line the porch edge, with low, wide window sills and glazed doors connecting the porch to the interior. The gallery surround provides a gradual transition from outside to inside, while the porch's depth and orientation ensure it is filled with natural light, making the entrance bright, lively, and inviting.
B_2	The design alternative features a long, thin, south-facing front porch that projects from the entrance, forming a positive outdoor space partially enclosed by low sitting walls, trellises and hedges. The porch is at least six feet deep, with a gallery surround or arcade along its edge, providing a sheltered transition between inside and outside. Alternating areas of light and dark are created by a tapestry of filtered sunlight, achieved

Continued

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Table A12. Continued

	Design alternative
	through climbing plants on trellises and canvas awnings. Built-in window seats and benches are oriented toward the sun and street, encouraging lingering and social interaction. The entrance room, straddling the threshold, is filled with light from multiple sides, enhancing the sense of arrival. Raised flower beds and sitting walls soften the porch edge, adding color and inviting touch, while the overall arrangement maximizes sunlight, reduces gloom, and creates a welcoming, lively entrance.
C_1	The design features a wide entry platform surfaced with high-gloss white composite decking and light-reflective ceramic tile at the landing. Overhead glazing panels in the porch roof and clerestory windows above the entry door maximize daylight penetration. Frameless glass side panels and reflective glass inserts in the balustrade maintain openness and bounce light. The ceiling is finished with high-reflectance light-colored paint, while trim is coated in semi-gloss warm white. Recessed LED strip lighting along the ceiling edge ensures brightness after dark. The overall effect is a luminous, welcoming entrance that feels open and inviting.
C_2	The front porch features overhead glazing panels integrated into the roof structure, allowing abundant natural light to filter through. Translucent glass sidelights flank the entrance, further brightening the entryway. Slim-profile structural columns and frameless glass guardrails minimize visual obstructions, while angled roof eaves direct sunlight toward the door. Reflective wall panels adjacent to the entry amplify available light. Wide, welcoming front steps with light stone treads lead to the porch, which is finished with high-reflectance white paint on the ceiling and semi-gloss exterior paint on trim and moldings. The flooring consists of pale, neutral-colored pavers, creating a luminous and inviting threshold.
D_1	The design features a south-facing front porch with an overhead canopy and integrated skylights, ensuring abundant natural light throughout the day. Large glazed doors connect the porch to the interior, while a raised terrace slightly above street level provides privacy and a clear view outward. The porch is wide enough for a small group to gather and includes a built-in bench along its edge. Alternating areas of light and shadow, created by the canopy and a trellis archway at the entry, guide visitors toward the entrance and mark the transition from outside to inside. Light-colored surfaces and warm-toned wood finishes reflect and amplify daylight, creating a welcoming, cheerful atmosphere.
D_2	The design alternative features a deep, covered front porch with open sides, oriented to the south or southwest and slightly raised above street level to form a wide terrace. Large windows and glazed doors connect the porch to a light-filled entrance room that straddles indoors and outdoors, amplifying daylight with light-colored, reflective surfaces. The porch edge is softened with climbing plants and raised flower beds, while a sunny, sheltered sitting area invites lingering. The entrance is boldly shaped and highly visible from the street. The approach to the porch

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Table A12. Continued

	Design alternative
	offers a sequence of light and shadow, and the spatial enclosure gradually increases from open terrace to semi-enclosed porch to the entrance room, creating a welcoming, luminous and psychologically comfortable transition from public to private space.



Figure A1. Images of the design alternatives for the front porch.

- Living room

Table A13. Full text of the design alternatives for the living room.

	Design alternative
A_1	The living room features movable partition walls with sound insulation, allowing the space to be divided into separate zones for studying, relaxing, playing or working. Built-in adjustable lighting zones cater to different activities, while modular seating with integrated storage can be rearranged as needed. Fold-out workstations with charging ports are concealed within the walls for easy access. A low-profile play area with soft flooring is positioned near the windows, and wall-mounted bookshelves with sliding panels provide flexible storage. The large central coffee table has lift-top sections for work or play. Floor-to-ceiling windows with blackout curtains offer natural light control, complemented by overhead ceiling fans and acoustic ceiling panels for comfort and noise reduction.

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Table A13. Continued

	Design alternative
A_2	The living room features movable partition walls that allow the space to be divided into separate zones as needed. Built-in wall-mounted foldable desks provide dedicated work or study areas for family members. A large sectional modular sofa with adjustable segments offers flexible seating arrangements for relaxation or group activities. Integrated sound-absorbing ceiling panels reduce noise transfer between zones. Floor-to-ceiling shelving with concealed storage keeps the room organized and clutter-free. A multi-level ambient and task lighting system ensures each area is well-lit for its intended use. Sliding glass doors open to a semi-private reading nook, while a low-profile play area with soft, removable mats accommodates children's activities. Durable, easy-to-clean flooring and a central charging station with multiple outlets support daily family needs.
B_1	The living room is organized as a series of long, thin wings radiating from a central common area, each wing defined by abundant daylight from windows on two sides. Along the edges, alcoves and minor rooms provide semi-private spaces for studying, working or playing, each with built-in shelves for personal items. The central area features a large table and soft chairs, forming the heart of family life and connecting directly to a partially enclosed terrace for outdoor relaxation. Entrances to each zone are clearly marked and visible, supporting easy movement and orientation. Pools of light highlight sitting circles and alcoves, while darker corners offer restful retreats. Flexible furniture allows each family member to adapt the space for their own purpose, ensuring the living room supports simultaneous, diverse activities without conflict.
B_2	The living room is organized as a long, thin space with a central common area at its heart, tangent to the main circulation path and accessible from a family of clearly visible entrances. Along the edges, a sequence of graded sitting spaces and small alcoves provide semi-enclosed nooks for studying, working or quiet play, each with built-in open shelves and waist-high surfaces for personal materials. The room is shaped to allow light on two sides, with a tapestry of light and dark creating distinct pools of light for reading, relaxing or group activities. The living room opens directly onto a positive outdoor space, partly enclosed by building wings, and features a sunny place sheltered from wind for outdoor relaxation or play. This arrangement allows each family member to find a comfortable, well-lit, and acoustically separated spot for their own purpose, while maintaining visual and social connection to the common area.
C_1	The living room features modular furniture with movable components, allowing flexible arrangement for different activities. Adjustable lighting supports both focused tasks and ambient relaxation. Sliding partition panels with sound-absorbing material and built-in alcoves provide semi-private spaces for study or work. Mobile storage carts hold activity-specific items and can be moved as needed. Area rugs and open shelving units define distinct zones for play, relaxation and work. Acoustic ceiling panels reduce noise, while wall-mounted cubbies and

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Table A13. Continued

	Design alternative
	personalized storage bins keep belongings organized and accessible for each family member.
C_2	The living room is organized into four flexible zones using sliding partition panels with sound-absorbing surfaces and modular shelving units as spatial dividers. Acoustic ceiling tiles are installed above study and work areas to minimize noise. Adjustable folding screens provide additional privacy as needed. Lightweight, movable furniture on casters and a sectional sofa with movable components allow easy reconfiguration for group or individual activities. Dimmable LED ceiling lights offer adaptable illumination for reading, working or relaxing. Each family member has an individual cubby storage unit, while built-in cabinetry with sliding doors and pull-out trays in the coffee table keep the space organized and clutter-free.
D_1	The living room is organized as a long, thin space with clearly separated activity zones. Movable partitions or sliding panels allow flexible division between areas, while visual screens or half-height walls provide further separation. Along the perimeter, deep wall niches and integrated work counters with open shelves support study, work, and storage. Alcoves with lower ceilings and partial enclosure, as well as window seats or bay windows, offer private retreats for individuals. A central sitting circle with a loose arrangement of chairs forms the heart of the room for shared activities. Circulation paths are wide and unobstructed, enabling easy movement between zones. The sequence of sitting spaces transitions from public to private, supporting both group and individual use. This arrangement allows all four family members to use the living room simultaneously for different purposes, with minimal interference and maximum adaptability.
D_2	The living room is organized with movable partitions and shelving units that define distinct activity zones, such as study, play, relaxation and work. Sliding doors or curtains provide flexible privacy between these zones. Modular furniture, including a variety of chairs, sofas and floor cushions, can be rearranged to suit individual or group needs. Alcoves or nooks with partial enclosure offer semi-private spaces for focused activities. Bookshelves and cabinets serve as acoustic buffers between zones, while open shelves and drop-down desks provide accessible storage and work surfaces for books, games and supplies. Wide, unobstructed circulation paths connect all areas, ensuring easy movement. Dimmable wall sconces and floor lamps allow each zone to be lit according to its function. This arrangement enables all four family members to use the living room simultaneously for their own purposes, with options for both interaction and retreat.

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Figure A2. Images of the design alternatives for the living room.

- Campus facility

Table A14. Full text of the design alternatives for the campus facility.

	Design alternative
A_1	The design features a flexible open-plan interior layout with movable acoustic partitions, allowing the space to be easily reconfigured for events, study or social interaction. Large operable glass walls connect the interior to a covered outdoor plaza, providing seamless indoor-outdoor flow and weather protection. A central skylight brings abundant natural daylighting into the core, while integrated tiered seating encourages informal gatherings. Multi-lingual digital information displays foster inclusivity, and accessible entrances and circulation routes ensure universal access. The communal kitchen and café area support shared meals and casual conversation. A green roof with native plantings offers a tranquil retreat and environmental benefits.
A_2	The design alternative is a campus gathering pavilion featuring a flexible open-plan interior layout with large operable glass walls that seamlessly connect to a covered outdoor gathering terrace. A central skylight provides abundant natural daylighting, while integrated acoustic ceiling panels ensure a comfortable sound environment. Movable modular furniture systems and multi-level seating platforms allow for diverse group arrangements and activities. Accessible entryways and circulation paths ensure inclusivity for all users. Built-in digital display walls support collaborative presentations and events. Indoor green planting zones enhance the atmosphere and promote well-being, creating a vibrant, adaptable space for students and faculty to gather and interact.
B_1	The design alternative is a university campus gathering facility organized around a central pedestrian street lined with a family of entrances and open stairs, allowing direct outdoor movement between levels. The

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Table A14. Continued

	Design alternative
	facility is composed of a series of small, interconnected buildings forming a building complex, with a prominent main building at the heart, marked by a higher roof and central position. Outdoor rooms and positive outdoor spaces, partially enclosed by building wings, trees and trellises, create comfortable gathering areas. Activity pockets and sitting walls are distributed along the edges for informal interaction. Common areas with communal eating and a kitchen are located at the heart, tangent to main circulation paths. Roof gardens and gallery surrounds at various stories are directly accessible from lived-in spaces, providing additional gathering and relaxation areas. A marketplace of many small, individually owned shops and food stands opens to the street, supporting diverse social and cultural exchange. The entire facility is connected to surrounding neighborhoods by a network of paths and green streets, ensuring accessibility and integration with the broader campus.
B_2	The design alternative is a university campus gathering facility composed of a cluster of small, interconnected buildings arranged along a central pedestrian street. The street is lined with many entrances and open stairs from upper stories, creating a vibrant, accessible public realm. At the heart of the complex stands a main building with a prominent roof, housing a large common area for communal eating and informal gatherings. Outdoor rooms and positive outdoor spaces, shaped by building wings, trees, and trellised walks, provide sunny, partly enclosed places for relaxation and interaction. Activity pockets, sitting walls and alcoves are distributed along the edges, offering graded sitting spaces from public to private. A marketplace of small, individually owned shops and food stands opens directly to the street, encouraging spontaneous encounters. Roof gardens and gallery surrounds at various levels are accessible from lived-in spaces, supporting both quiet reflection and group activities. All entrances form a visible family, with bold shapes and clear transitions, making navigation intuitive and welcoming for diverse students and faculty.
C_1	The design features an open-plan facility with movable furniture and transparent glass partitions, creating flexible zones for interaction. Lounge areas with soft seating and greenery foster relaxation, while retractable walls allow for space expansion or division. Universal design ensures barrier-free access, complemented by gender-neutral restrooms. Floor-to-ceiling windows provide abundant natural light. Rotating art displays and multilingual signage celebrate campus diversity. Semi-enclosed pods offer privacy for small groups, supporting both collaboration and informal socialization.
C_2	The design features a central gathering facility with open-plan seating arrangements and movable furniture, allowing for spontaneous interaction and flexible groupings. A visually connected central area serves as the heart of the space, surrounded by informal lounge zones with writable surfaces for discussion and collaboration. Modular partitions enable easy subdivision for events or study, while a flexible

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Table A14. Continued

	Design alternative
	stage and display zones support multicultural activities. Multilingual signage and wayfinding ensure inclusivity. The facility provides barrier-free circulation and gender-neutral, accessible restrooms. Abundant natural daylighting and a warm, inviting color palette create a welcoming atmosphere for all users.
D_1	The design alternative is a campus community hub that features a large open plaza with a flexible surface for events and performances, surrounded by clusters of semi-enclosed seating areas with tables for informal meetings. An outdoor stage or amphitheater anchors one side of the plaza, supporting cultural and academic performances. Pedestrian-only streets with high foot traffic connect the hub to the rest of campus, lined with café terraces and food stands at key intersections to encourage lingering and socializing. Wide, well-lit indoor thoroughfares link adjacent buildings, providing weather-protected circulation and integrating activity pockets with seating, games and displays. Covered arcades and walkways offer shelter and year-round comfort, while the main entrance to the facility is visible from all major approach paths, ensuring accessibility and orientation. Modular furniture and partitions throughout the hub allow spaces to be reconfigured for a range of group sizes and activities, supporting both planned and spontaneous gatherings for the diverse campus community.
D_2	The design alternative is a campus gathering facility located at a central crossroads, with direct sightlines from major campus approaches. The building features an open-plan layout with movable furniture, allowing for adaptable groupings and flexible use. Multiple entrances, each with clear signage and visual connections to campus paths, welcome users from all directions. Inside, comfortable seating clusters – comprising a mix of chairs, benches and built-in seats – are arranged in a sequence of spaces from public to semi-private, supporting both informal and formal interactions. Warm lighting and abundant natural daylight from windows on two sides create a welcoming atmosphere. Circulation realms are clearly defined, with named zones and visible gateways aiding navigation. A south-facing outdoor terrace, positively enclosed by landscaping and low walls, extends the social space outdoors. User-controlled display areas for art, announcements and cultural exhibits foster a sense of ownership and belonging. Marketplace-style food and retail stalls, operated by diverse campus groups, activate the space and encourage cultural exchange. This facility functions as a vibrant, inclusive hub for gathering, collaboration and community on campus.

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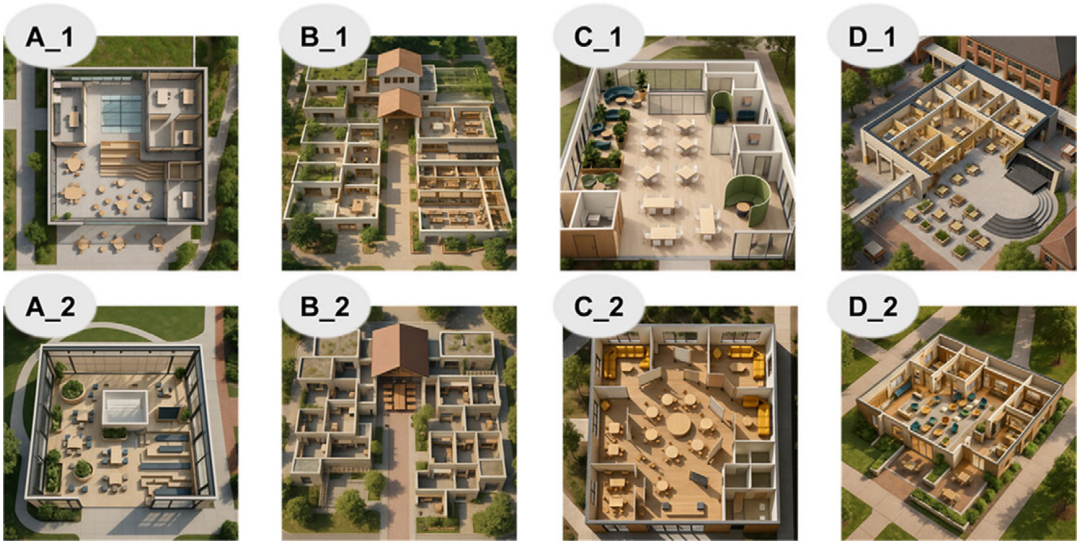


Figure A3. Images of the design alternatives for the campus facility.

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