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Enhancing efficiency and user-centricity in architectural remodeling: A comprehensive system design for structural renovation

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Abstract. The home renovation industry has witnessed remarkable growth, driven by shifts in lifestyle necessitating adjustments in living spaces. This paper addresses critical gaps in the domain of architectural remodeling, with a particular focus on improving efficiency, referenceability, and user-centricity in structural remodeling. This research introduces a system design tailored for structural remodeling within house renovation, catering to both comprehensive and partial projects to facilitate the creation of structurally viable renovation options and optimizing them to align precisely with user requirements. The proposed system's accessibility and consideration of architectural factors set it apart. While offering substantial benefits, the system has limitations, such as the exclusion of interior furnishing styles in output solutions. In conclusion, contributes to the improvement of remodeling projects and offers a promising approach, particularly in the early stages of these endeavors.

Keywords: Deep Learning, Structural Renovation, Architecture Remodeling, House Renovation.

1. Introduction

The home renovation market has experienced significant growth, driven by shifts in lifestyle due to the pandemic. As a result, homeowners have found it necessary to reconfigure or remodel their living spaces to optimize functionality and adapt to new demands, underscoring the continued relevance and importance of the home renovation industry [1]. According to data from the Joint Center for Housing Studies (JCHS) at Harvard University, expenditures on home improvement projects have surged from $328 billion in 2019 to an estimated $472 billion in 2022, with projected expenses reaching $485 billion in 2023 [2]. Homeowners embark on home renovation projects for a multitude of reasons, including enhancing aesthetics, comfort, and functionality. Notably, remodeling projects can significantly increase the return on investment (ROI) [2].

In the context of residential renovation, space allocation, often interchangeable with nomenclatures such as space planning and space layout design, is emblematic of the intricate methodology employed to distribute spaces in accordance with stringent topological and geometric parameters. This component assumes a paramount position within the complex domain of architectural layout design for residences, constituting the foundational underpinning upon which the functionality and seamless integration of living spaces are fastidiously wrought. Its ramifications reverberate throughout various aspects including spatial functionality, the establishment of logical transitions between rooms, the delineation of zones, and the facilitation of adaptability, among others [3]. Its effective execution ensures that each area within a residence is thoughtfully tailored to serve its intended purpose while facilitating effortless mobility and fostering an ambiance of spaciousness. This discerning allocation of space, far from being static, holds the potential to optimize the present living experience while also affording homeowners the adaptability to accommodate evolving circumstances, personal preferences, and changing requirements. In essence, the meticulous consideration of space allocation within architectural layout design sets the stage for the dynamic evolution of a home. Given the intricate interplay of space layout parameters and the amalgamation of both continuous and discontinuous exploration spaces, architectural space layout is rightly recognized as a multifaceted problem [4,5].

In the evolution of architectural design, graph theory's incorporation since the groundbreaking suggestion in 1966 has become pivotal.[6] Scholars have not only deepened their exploration of graph theories in architecture but have also developed graph-based design approaches that can autonomously generate floor plans while adhering to user-specified constraints. [4, 7] Additionally, the introduction of Generative Adversarial Networks (GANs) [8] marked a notable shift, where researchers applied various types of GANs to architectural design, creating synthetic architectural data. These advancements encompass a range of applications propelled by pioneering methodologies that amalgamate deep learning techniques with graph algorithms. [4, 9, 10]

In contemporary times, several notable methodologies have emerged for the automation of spatial layout design. Noteworthy among these methodologies are Conditional Generative Adversarial Networks (cGAN), Agent-Based Modeling (ABM), and U-Net, each distinguished by their specific areas of focus. For instance, the utilization of a GAN-based system, Pix2pixHD, has been employed for architectural drawing recognition and generation [10], while conditional GANs have found application in space allocation probabilities [11]. The use of a multi-agent system by Z. Guo [12] has contributed to the improvement of 3-D architectural topology. Additionally, M. Rahbar [4] has emphasized the automation of space layout creation and integrating factors through an innovative hybrid ABM approach. Furthermore, L. Wang et al. [9] have integrated U-Net with spatial attention mechanisms and graph algorithms for automation of building layout generation. Their focus centers on the segmentation of spaces within building boundaries and spatial arrangements optimization.

While significant research endeavors are directed toward automating these structural alterations, it is worth emphasizing that the practical implementation of these advancements is primarily tailored to industry professionals as opposed to the broader public. Though there are AI applications targeting the general public, their primary focus lies in aspects such as furniture arrangement and room décor style generation, rather than addressing renovation problems. Notably, certain home renovation projects with substantial financial implications involve structural alterations, such as room expansions or extensions [13]. This pronounced gap emphasizes the imperative for continued research and development efforts aimed at bridging this divide.

This research introduces a system design tailored for structural remodeling applications within the field of house renovation. The system's applicability extends to two primary scenarios, covering both comprehensive and partial house renovation projects. Its operation involves the submission of a graphical representation of the floor plan alongside specific remodeling criteria. During the training phase, the system undergoes an extensive assimilation process of diverse data variables, encompassing considerations such as lighting, wall material selections, and accessibility aspects. This comprehensive approach facilitates the generation of design proposals, each meticulously optimized within their respective categories to align precisely with the user's articulated requirements.

The primary aim of the proposed system is to provide holistic and user-centric solutions that address both the structural and functional aspects of architectural remodeling. By furnishing users with a wide array of remodeling options, this research seeks to enhance efficiency and effectiveness in the initial phases of remodeling projects.

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2. Background

In the specific domain of structure remodeling that focuses on modifications to the existing spatial layout, encompassing tasks that involve the alteration, removal, or addition of load-bearing elements. Concurrently, as researchers in the field of space layout design continued to explore methods for optimizing and automating spatial arrangements within complete floor plans, a parallel exploration emerged within the subset of architectural space layout design, namely structural remodeling. One recent example of this exploration is found in the work of Y. Sun, who delves into the design and optimization of interior space layouts within commercial housing decoration. This study employs advanced techniques such as spatial convolutional neural networks and fuzzy convolutional neural networks, culminating in the development of a sophisticated deep learning countermeasure neural network algorithm. This algorithm effectively automates and intelligently addresses design tasks, including structural wall modifications, repositioning of doors and windows, floor space division, and layout planning [14].

The previous research endeavors have underscored significant potential in automating structural modifications and layout generation. However, it is crucial to recognize that the current practical application of these advancements places a significant emphasis on specific input formats, adhering to professional standards, notably exemplified by the use of formats like AutoCAD. Nonetheless, specific applications already exist with the general public as their primary users. For instance, these applications can autonomously generate 2D and 3D diagrams for interior furnishing designs, including furniture placement, based on floorplans in picture format. Nevertheless, such applications are typically limited to providing a singular furniture arrangement solution, with little to no flexibility for users to input more intricate requirements beyond basic floor plans. Furthermore, architectural designs inherently encompass a multitude of potential solutions. However, prevailing applications commonly provide singular output choices, constraining users in their exploration of diverse design possibilities. Certain companies offer customers a range of design plans accompanied by 3D virtual tours for office spaces within relatively compressed timeframes. It is worth mentioning, though, that these services are primarily tailored to office spaces. In contrast, the layout design of residential spaces presents a unique set of challenges, particularly due to the often compact nature of residential layouts, which inherently imposes more stringent constraints, rendering them more intricate to address. Moreover, communicating between homeowners and architectural designers often consumes a substantial amount of time. Typically, homeowners engage in a series of meetings with architects to deliberate design concepts and ideas, a process that may extend over several months before they can witness the final conceptual design [15]. Consequently, this process is renowned for its time-intensive nature.

This research aims to address industry challenges and limitations by placing emphasis on critical factors including non-load-bearing walls, individual preferences, and the willingness to modify non-load-bearing walls (non-structural walls) within the output design solutions space. A notable feature of this system is its accessibility, characterized by minimal prerequisites in terms of prior technological expertise, thereby accommodating a broad user base. Consequently, the system generates a range of structurally feasible renovation options, varying in size, location, and spatial division, while considering potential features like niches and sliding doors. Additionally, the research explores integrating essential architectural considerations, such as lighting and waterproofing, into the design recommendations.

3. System Design

The proposed system encompasses two distinct applications:

- Full-House Renovation: In this scenario, users input specific parameters such as desired bedroom count, the necessity for a study, and their openness to the removal or reconstruction of non-structural walls. Additionally, users furnish floor plans annotated with the precise locations of these non-load-bearing walls. Subsequently, the system generates a spectrum of structurally viable renovation options.
- Partial Renovation: Targeting localized transformations, users provide floorplans featuring existing room designations and their envisioned renovations, which might involve, for instance, merging an

excess utility room into the living area through the modification of non-structural walls, thereby creating a study space. The system then produces multiple potential renovation outcomes, varying in size and spatial division.

The following section elucidates the system's architectural design, delineates the functionalities of its components, and provides the rationale behind pivotal design choices.

3.1. System Architecture

Figure 1 is a graphical representation that elucidates the core constituents constituting the proposed system. It serves as a graphic manifestation delineating the interrelations and interactions between the system components. The directional arrows, featured within the graph, denote the transfer of solutions emanating from the output component, subsequently serving as inputs to the ensuing stages of the process.

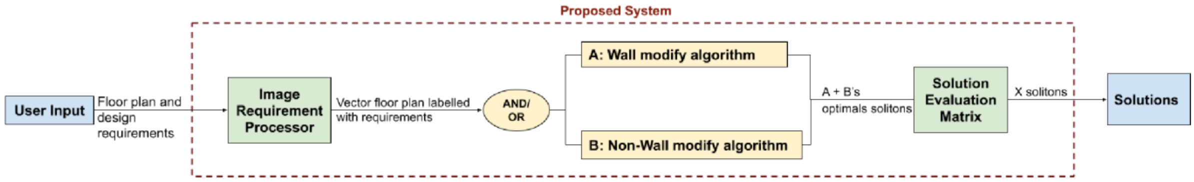

Figure 1. Proposed System Architecture Diagram.

- User input: Users are required to provide a detailed floor plan inclusive of labeled wall functionalities, denoting the location of non-structural walls, room functionalities where applicable, and specific modification requirements. This meticulously labeled input serves as the foundational data source for the subsequent stages of the system
- Image-Requirement Processor: This process ensures scalability, consistency, and precision for subsequent modifications. The vectorized representation is further enriched with specific user requirement notations, facilitating a more refined and efficient progression through subsequent phases of the system.
- AND/OR Decision Point: This decision point is predicated on the user's expressed willingness to modify non-structural walls. In response to the user input, the system engages Method A (wall modification) and Method B (no wall modification). Notably, for users who do not explicitly specify their preferences, the system undertakes both Method A and Method B concurrently, thereby providing a comprehensive solution encompassing all potential scenarios.
- Algorithm A (Wall Modification) and B (No Wall Modification): Within Algorithm A and B, the system deploys a myriad of modification strategies. As an illustrative example, within Algorithm A, these modifications include:
  1. The addition of sliding doors with a total area is denoted as 'a1.'
  2. The incorporation of rooms with doors, featuring a total area marked as 'a2.'

  …(Additional modifications as necessitated by user requirements)

  Each type of modification executed within Algorithms A and B adheres rigorously to mandatory constraints. The output consists of locally optimal solutions, each corresponding to a specific modification type. Upon completion, all locally optimal solutions are compiled into the solution evaluation matrix for further analysis.
- Evaluation metrics: This matrix is to assess the suite of locally optimal solutions generated during the prior phases. For all local optimal solutions, the matrix evaluates based on non-mandatory requirements (desirable requirements) encompassing factors such as lightning, ventilation, and disability accessibility. The matrix's objective is to identify a maximum of 'X' globally optimal solutions.
- Up to 'X' solutions: The precise value of 'X' remains dynamic and subject to an iterative approach. In its initial phase, a conservative value of 'X' is established during the experimental stage. Subsequently,

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this value undergoes adjustments based on user feedback and evolving project requirements. This adaptive approach ensures the system remains responsive to user input and optimally aligned with project objectives.

3.2. System Design Justification

In this section, the design rationale and the key considerations that underpin the architecture of the proposed system will be justified. functional requirements, constraints, and design considerations are all being considered thoroughly before the decision-making process throughout the system's development.

The system is driven by the main functional requirement intrinsic to its mission. The primary objective of the system is to generate a diverse range of optimal structural remodel solutions that cater to various user requirements. These solutions encompass different combinations and functionality options, offering users a comprehensive array of choices to address their specific needs and preferences.

In order to find the ‘x’ optimal solutions among all the possible design ways, it is essential to clarify the assessment criteria, separate them into mandatory constraints and desirable constraints, and coordinate accordingly within the proposed system. While both categories impose restrictions on the system's behavior, they serve distinct purposes. For example: A mandatory constraint might entail the necessity of meeting safety standards including adequate egress routes. A desirable constraint, on the other hand, could involve adequate natural light and good ventilation. The solutions generated must satisfy a series of mandatory constraints, among all the solutions that satisfy the mandatory constraints in each type of modification strategy, output ‘x’ optimal solutions satisfy most of the desirable constraints.

To best address the requirement stated above, the following major design decisions were made during the development process.

3.2.1. Vectorization of Graphs:

The vectorization of floor plans as an initial step in the solution generation process is imperative. This choice is underpinned by a comprehensive rationale that underscores its necessity. Precision accuracy, a cornerstone of architectural and design endeavors, is facilitated by the use of vectorized graphs, which offer scalability while maintaining consistent precision throughout the process. Furthermore, the vectorized representation grants the advantage of ease of editing and modification, a crucial aspect during the design and revision stages, enabling architects and designers to effect changes without compromising quality. Compatibility with a myriad of design and drafting software, coupled with seamless integration into existing automation algorithms, bolsters the utility of vector graphs. The benefits derived from this choice are manifold, ranging from heightened quality to enhanced ease of editing and adaptability to diverse output formats.

3.2.2. Separation of Wall and No-Wall algorithm

The decision to employ two distinct AI algorithms for Algorithm A and Algorithm B presents both benefits and trade-offs. On the positive side, this approach offers specialization, allowing each algorithm to finely address the specific complexities of its respective task, wall modification or no-wall modification, resulting in more efficient and tailored solutions. Performance optimization becomes feasible, as the algorithms can be individually fine-tuned to excel in their designated domains, avoiding the pitfalls of a one-size-fits-all solution. Furthermore, scalability is facilitated, permitting the independent expansion or modification of one algorithm without impacting the other, thus adapting to future requirements. However, there are trade-offs to consider, including heightened resource usage due to the concurrent operation of two algorithms, potentially necessitating increased computational resources and incurring higher operational costs. Development complexity also escalates, as it demands additional resources and time compared to building a unified solution. However, it is crucial to underscore that the advantages of the segregated algorithm approach strongly align with the core objectives of the proposed system and significantly surpass the associated trade-offs. Therefore, the deliberate choice has been made to retain two discrete algorithms, thereby ensuring the system's capability to adeptly cater to the multifaceted demands of structural remodeling.

3.2.3. Evaluation after local optimal solutions

The evaluation of globally optimal solutions following the generation of locally optimal solutions constitutes a pivotal procedural step. This approach is underscored by the imperative of ensuring strict adherence to mandatory constraints and the systematic fulfillment of specific strategy constraints before embarking on the evaluation of desirable constraints. Adopting this approach yields notable advantages, including the augmentation of solution quality and alignment with user needs. It is important to note that, as the granularity of user requirements increases, the likelihood of the generated global optimal solution aligning with the desirable solution amplifies.

3.2.4. Maximum solution limit

The implementation of a maximum solution limit represents a pivotal design decision within the system. This constraint is introduced subsequent to the accumulation of locally optimal solutions, encapsulating several underlying considerations. The rationale for this decision is rooted in the need to strike a balance between exploration and exploitation. By limiting the number of presented solutions, the system aims to harmonize the quest for diverse solutions (exploration) with the refinement of the best solution found (exploitation). This equilibrium is congruent with scalability considerations, as inundating users with an excessive number of outputs can potentially overwhelm them, rendering decision-making challenging. Setting a maximum limit on solutions yields a more user-friendly experience, permitting users to concentrate on a manageable set of options. Additionally, this constraint enables the algorithm to prioritize and proffer the most pertinent and actionable solutions, enhancing the overall usability of the system. The resultant benefit lies in the provision of a manageable number of solutions for users, thereby preserving system adaptability. Nonetheless, it is imperative to acknowledge that this decision does entail trade-offs, as it may present limitations for users with unspecified or vague requirements, rendering the precise generation of the "'x' most suitable" solutions a more intricate endeavor.

4. Data Requirements

This section discusses the essential data prerequisites for training the AI models. The training set comprises two primary categories of information:

4.1. Layout Information

Layout information encompasses data pertaining to the structural layout and architectural features of the space. It serves as the foundation for understanding the spatial arrangement of the environment.

- Wall type: collect different types of wall modification possibilities. Examples of the types of walls are sliding doors, archways, niches, pass-through windows, and glass blocks. accompanying these possibilities, Ensure that the respective constraints governing each modification type are incorporated into the training data to facilitate the model's understanding of these constraints.
- Floor Plan Data: Curate a comprehensive dataset that includes a diverse set of floor plans featuring varying layouts, sizes, and configurations. This dataset should encompass residential, commercial, and institutional spaces. Additionally, define rooms within the floor plans, specifying their functions (e.g., bedroom, kitchen, bathroom). For each floor plan, provide details about the location, dimensions, and properties of non-structural walls. This should encompass information about wall types (e.g., drywall, partitions), thickness, height, and any other relevant attributes.
- Furniture Data: Construct a dataset comprising information about various types of furniture items. For each item, include comprehensive details such as dimensions (length, width, height), style, color, and other relevant attributes. High-quality images of each piece of furniture from multiple angles would enhance the dataset's utility.
- Room Layout Data: Compile information about various room layouts, including their size, shape, and the positions of doors and windows. Account for any architectural features that may influence

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furniture placement. Given that room layouts can vary significantly based on specific functionality, it is essential to include a diverse set of room configurations.

- Contextual Data: Providing information about the context in which the furniture arrangement is needed can be beneficial. This might include the purpose of the room (e.g., bedroom, living room, office), the number of occupants, and the room's intended use (e.g., dining, entertainment, workspace).

4.2. Functional Attributes

Functional attributes refer to data pertaining to the space's functional aspects and environmental attributes. These attributes play a crucial role in determining the usability and comfort of the environment.

- Lighting Information: Collect data on lighting fixtures, specifications, and the presence of windows or natural light sources
- Ventilation data: Gather data on ventilation assessments for architectural layouts. This could include measurements of airflow rates, air quality parameters, or any relevant ventilation metrics. Consider using computational fluid dynamics (CFD) simulations or real-world measurements.
- Space Accessibility: Identify spaces or features that are accessible to individuals with disabilities such as accessibility dimensions (e.g., door width, ramp slope). Note the presence of ramps, wider doorways, accessible bathrooms, and any other accommodations that enhance accessibility.
- Regulations and Standards: Incorporate data on building codes, regulations, and standards related to lighting, ventilation, HVAC, and accessibility. Ensure compliance with applicable laws.
- Constraints and Guidelines: Incorporate data on constraints and guidelines that need to be followed during furniture arrangement. These could include safety regulations, accessibility requirements, and any architectural constraints (e.g., load-bearing walls). Incorporate data on building codes, regulations, and constraints that apply to structural modifications. This includes information on fire safety regulations and any other legal or safety-related constraints.

The above comprehensive datasets form the basis for training the AI model and facilitate the generation of optimal and compliant solutions for various spatial design challenges.

5. Practical Analysis

5.1. Practical Application Scenario

To illustrate the practical application of the proposed system for structural remodeling in partial home renovation, consider the following scenario assuming a maximum of five solutions are outputted after solution evaluation.

Scenario: The house owner wishes to locate a study space in the existing floor plan and is open to operation on non-structural walls.

Input Example: The house owner inputs the hand-drawn floor plan into the system, which includes measurements, location on non-structural walls labeled in red, and room designations with furniture. The house owner also specifies in the text the remodeling criteria and locates a study space in the existing home space allocation. The owner emphasizes her preference for maximizing natural light in the new study space. Figure 2 is an example of input floor plans with non-structural walls highlighted in red and user requirements.

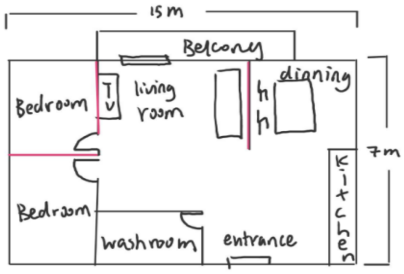

Figure 2. Example hand-draw Input floor plan.

Output Examples: The proposed system outputted four solution designs. Figure 3 presented two no-wall modification solutions and Figure 4 presented two wall modification solutions. Four solutions are the ones that best utilize natural light in the designed new study space among all other solutions generated.

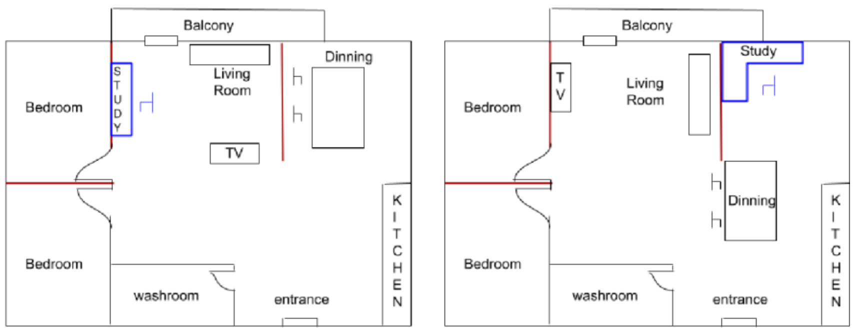

Figure 3. Design solutions outputted by no-wall modification algorithm.

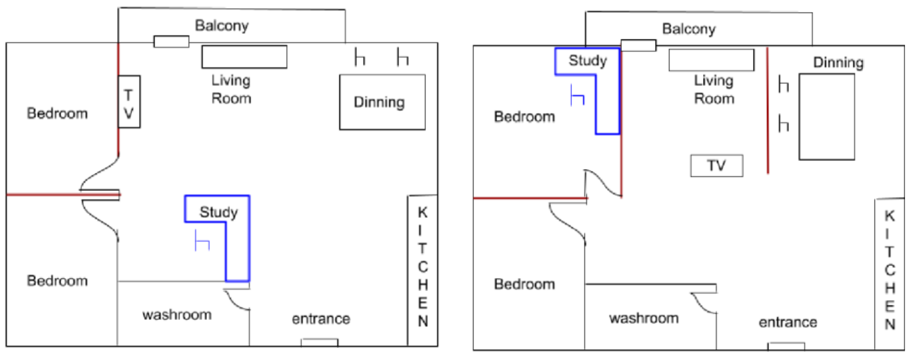

Figure 4. Design solutions outputted by wall modification algorithm.

An example of one of the eliminated solutions is shown in Figure 5 which does not satisfy the user's desired requirements of utilizing natural lights.

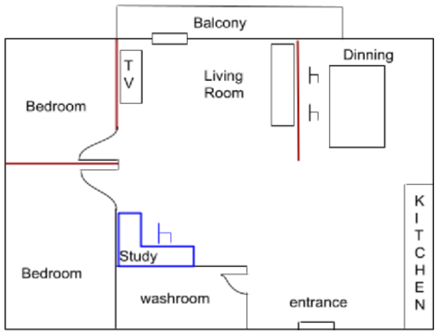

Figure 5. Eliminated design solution.

5.2. Integration and Deployment

The proposed system can be integrated into the initial stages of an architectural remodeling workflow, offering valuable insights and solutions to both architects and house owners. Prior to the initial consultation and assessment phase, architects engage in preliminary discussions with house owners to ascertain their specific needs, objectives, and budget constraints. For prospective house renovators, the system serves as a preliminary resource to explore potential renovation designs, enabling them to assess the feasibility of their remodeling endeavors. Similarly, for those committed to a renovation project, the proposed system facilitates the generation of solutions, which can be employed as reference points during consultations with renovation companies.

During the Concept Development stage, architects collaborate closely with clients to conceptualize the project, considering architectural styles, spatial layouts, and design elements that align with the house owner's preferences. At this juncture, the proposed system assumes a pivotal role in streamlining the consulting process. Specialists can swiftly provide house owners with a selection of possible solutions, thus expediting decision-making and design development. Furthermore, homeowners can iteratively engage with the system based on insights gained during consultations with architects. Adjustments to requirements and preferences can be incorporated into the proposed system, allowing for the generation of updated remodel plans. This iterative process empowers homeowners to explore diverse remodeling possibilities and fine-tune their vision.

6. Conclusion

In conclusion, this research addresses critical gaps within the architectural remodeling domain, with a central focus on enhancing efficiency, referenceability, and user-centricity in the context of structural remodeling. The proposed system seeks to overcome the accessibility barrier faced by homeowners lacking professional knowledge and, in parallel, streamline architectural consultations, thereby expediting the consultation process. The paper presents the system design, encompassing comprehensive and partial renovation projects while justifying design decisions and acknowledging trade-offs. It underscores the importance of potential datasets for model training and offers homeowners the ability to explore structurally viable renovation options tailored to their requirements. The system addresses multiple solution outputs and explores innovative room partitioning, spatial optimization, and integration of architectural considerations, enhancing remodeling solutions. While the system offers notable advantages, limitations exist, such as the absence of options to specify interior furnishing styles, including wallpaper and decorations in the output solutions. Overall, this research showcases the potential to improve early-stage remodeling projects through data-driven, user-centric design, albeit with room for further refinement.

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