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Eco-Centric Generative Design Workflow: Extending Sustainability in Architecture

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Abstract. The advancement of technology will bring about industry transformation, and in the context of the widespread application of digital design, the introduction of artificial intelligence (AI) into architectural design is an inevitable necessity. This article explores the advantages and necessity of applying generative design technology to the entire process of sustainable architectural design. It introduces how generative design and AI techniques are being used throughout the design workflow, from generative model training, alternative design proposal production, design optimization, to visualization export. Conclusively, the introduction of generative design not only enhances design efficiency but also significantly improves the ecological attributes of architectural design, offering a fresh perspective for the sustainable development of the architecture field.

Keywords. Generative design, digital design, ecological eesign, sustainable architecture, design optimization

1. Introduction

In the contemporary context, sustainability has risen as an urgent concern, prompting a thorough reevaluation of how practitioners approach design and innovation. Sustainable architecture surpasses mere technical obstacles; it necessitates the integration of diverse disciplines and interdisciplinary collaboration. Yet, traditional design process often faces constraints when grappling with these intricate challenges. Therefore, introducing AI technologies such as generative design into the traditional design process can significantly enhance the sustainability of architecture.

Generative design is an intelligent computer-based design process where during the design process the designer does not interact with the materials and products in a direct way[1]. Instead, they employ iterative algorithmic frameworks to automatically propose a large number of initial designs which are handled by a topology optimization method for making sure that user definitions and constraints are satisfied accordingly[2]; these design proposals can be generated by the computer itself, thus support human designers and (or) automate parts of the design process[3-4]. With the breakthrough of AI technology, generative design is ushering in unprecedented prospects.

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For now, research on generative design in architecture is still in its relatively early stages. There are case studies about generated interior design models based on BIM technology[5], addressing the challenge of generating BIM models using natural language; there are case studies of generating design proposal with specified styles by extracting design features[6], addressing the challenge of stylization challenges during the design phase; and there are case studies of generating layout solutions with the goal of improving architectural cost efficiency through intelligent planning systems[7], address the challenge of parameterized design challenges under specified conditions. However, in the context of achieving the objective of creating sustainable architecture, there have been relatively fewer studies that have comprehensively integrated generative design into the entire design process with the specific goal of enhancing sustainable performance.

This paper aims to explore the utilization of generative design technology to attain sustainable architectural design, underlined by ecological considerations in the era of artificial intelligence. By conducting a comprehensive investigation, this study explores the application of AI technologies, particularly represented by generative design techniques, throughout the entire design workflow—from generative model training to visualization export. It reveals their significant impact on optimizing workflows and enhancing the sustainability of architectural designs. This research seeks to provide fresh insights that contribute to the ongoing evolution of the architectural realm towards sustainability.

2. Integration of Generative Design in the Design Workflow

2.1. Self-Supervised Learning Models

In the comprehensive exploration of the application of generative design within the workflow, the establishment of an efficient generative model through self-supervised learning based on an exemplary design case repository is crucial. This approach aims to enable the generative model to learn autonomously by utilizing a vast collection of exceptional design cases.

The essence of self-supervised learning lies in formulating supervisory conditions to guide the learning trajectory of the generative model. This involves establishing effective supervisory conditions that encompass both qualitative parameters, such as layout combinations, building orientations, and room topological relationships, and quantitative parameters, such as area, room dimensions, door/window openings, and window-to-wall ratios. This enables the generative model to gradually assimilate environmental concepts and seamlessly integrate them into design solutions.

During this process, qualitative parameters provide guidance on the overall architectural characteristics and environmental principles. By learning from these parameters, the generative model comprehends the effects of different layouts, orientations, and room configurations on energy efficiency, ventilation, and other aspects. Quantitative parameters, on the other hand, offer specific numerical information, such as area and dimensions. Learning the relationships between these parameters allows the generative model to optimize design details like room layouts and window sizes to maximize energy efficiency and minimize environmental impact.

By combining qualitative and quantitative parameters, the generative model continuously refines design solutions throughout the learning process, aligning them with principles of environmental sustainability. This self-supervised learning approach not only reduces the need for manually labeled data but also enhances the intelligence and innovation of the design process, ushering in new possibilities for the field of sustainable architecture.

2.2. Generating Alternatives

The generation of alternative solutions consists of two primary phases: information input and solution creation. During the information input phase, it is essential to provide details regarding condition information and objective settings, which encompass both design objectives and performance targets. By leveraging Natural Language Processing (NLP) and Knowledge Graphs, the system identifies key entities and attributes from the input. These are then mapped to existing knowledge graphs for analysis, achieving the structured transformation and conversion of information, culminating in a parametric encoding of design requirements. Using pre-trained models, preliminary solutions are generated in alignment with these requirements. Afterward, by introducing a set of predefined criteria from a condition library, these solutions undergo filtering and ranking, leaving the designer with a refined set of alternative design solutions to choose from.

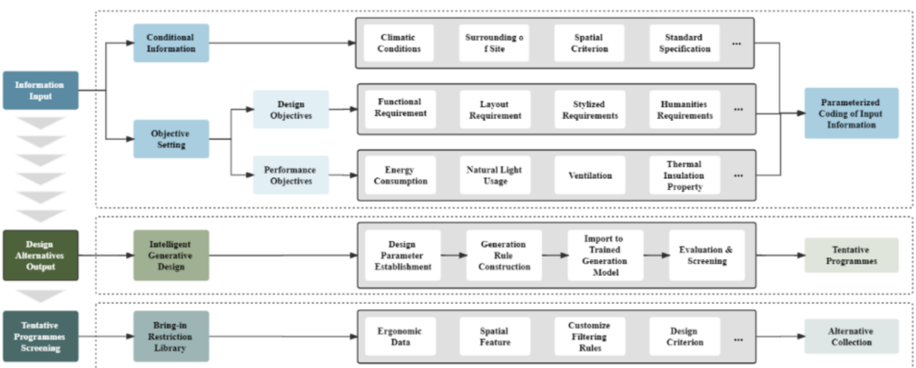

Figure 1. Technology roadmap for alternative generation.

Through the parametrization of the design process, a rapid response mechanism is established between the proposals and the design parameters, enhancing the feedback rate for modifications to the proposal. This feedback mechanism allows designers to swiftly observe changes in the proposal when adjusting design parameters, thereby enabling quick adjustments and optimizations throughout iterative cycles. This not only boosts the feedback rate for modifications but also elevates the overall efficiency and coordination of the design process. By harnessing swift parametrization and automated generation, certain limitations in traditional design methods are addressed. This empowers designers to delve deeper into the design space, seeking optimal solutions for environmental objectives, thus shaping more sustainable design proposals.

2.3. Identification and Optimization of the Variable Parameters

The solution chosen by the designer will proceed to an optimization process. The optimization process consists of two distinct stages: the recognition phase of optimizable parameters and the specific optimization phase.

In the recognition phase of optimizable parameters, a focused analysis is carried out on both spatial structure and exterior design aspects. By deconstructing the spatial form and structure parameters presented in the design drafts and in conjunction with constraints and optimization preferences specified by the user in advance, it becomes feasible to definitively identify the variable parameters within the proposed design. These parameters encompass both the interior layout and the envelope structure of the building. Subsequently, guided by these recognized variable parameters, the designer can choose which parameters are to be optimized. Additionally, automated performance-driven parametric design optimization can be employed, involving algorithmic direct optimization based on environmental performance metrics.

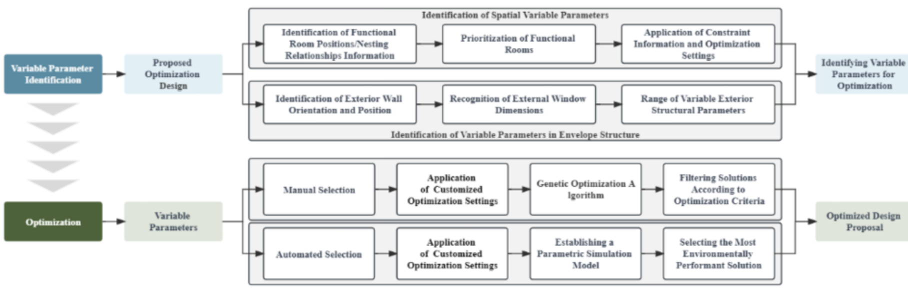

Figure 2. Technology roadmap for design optimization.

In the specific optimization phase, these recognized variable parameters undergo optimization utilizing a Genetic Algorithm (GA). The GA takes inspiration from biological evolution principles and simulates processes such as gene inheritance, crossover, and mutation. It progressively refines and iterates through the design by searching within the space of optional parameters. The objective is to achieve predefined optimization goals, which can range from maximizing energy efficiency to fulfilling aesthetic and functional requirements, or any user-defined objectives.

By implementing the GA, designers are enabled to discover more optimal parameter combinations within the design proposal, thus achieving heightened optimization. This process harnesses the power of artificial intelligence technology to efficiently navigate the design space in an intelligent and expedited manner. As a result, it satisfies multifaceted requirements such as environmental sustainability, aesthetics, and performance, across various dimensions.

2.4. Visualization Export of Design Proposals

Visualization of design proposals encompasses both the visual representation of the design itself and the presentation of relevant data. Through this approach, a direct and intuitive connection is established between design choices and variations in performance. When modifications are made to the design proposal, the corresponding performance parameters are visually displayed, enabling designers to directly observe the impact of design changes on performance. Additionally, as adjustments are made to the relevant performance parameters, algorithms dynamically synchronize and adjust the visualization model and associated information in real-time to maintain consistency.

The visualization modules orchestrate the transformation of abstract design parameters, variables, and attributes into visually coherent presentations. Through interactive visualizations, designers can scrutinize the spatial arrangements, material selections, energy performance, and environmental implications of each selected solution. This immersive engagement empowers designers to critically evaluate the design outcomes, aligning them with the overarching environmental aspirations and functional demands.

3. Algorithm-Based Generative Design Case Study

With the evolving landscape of computer-aided design, an increasing number of designers have turned to generative design as a foundational element for architectural projects, such as the Autodesk MaRS Office.

Situated in Toronto, Canada, this project entails the construction of a new 3-story office building spanning approximately 5600 square meters. During the interior layout design phase, the design team diligently collected the often-overlooked usage requirements of over 250 office occupants. Six target parameters were formulated to guide algorithmic generation and evaluation of office space[8].

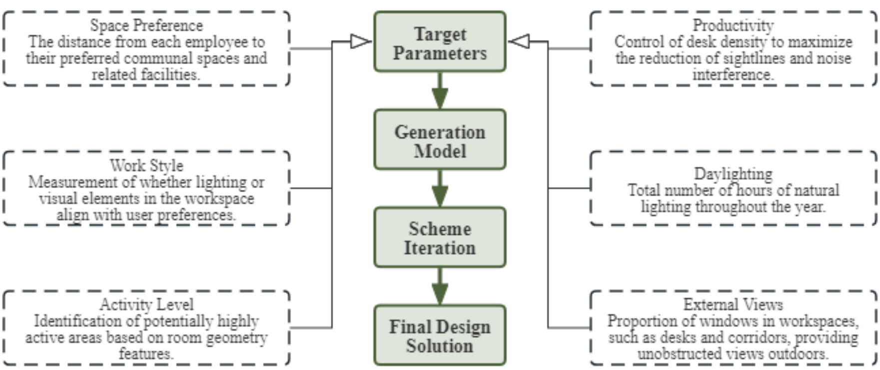

Figure 3. Target parameters for Autodesk MaRS Office design process.

3.1. Generation Model

The generation model in the design process involves the predefinition of the logic based on the nature of office space. This includes establishing plan outlines and standard column grids from the design floor plan to delineate areas requiring optimization. Subsequently, axis lines, boundaries, and capture points are set for different work team areas. Changes in capture points can automatically trigger boundary adjustments. Meeting room units are then automatically generated on one boundary of each area, while employee workstations are automatically arranged in other areas. This structured approach results in various design options through different combinations of capture points and boundaries for designers to choose from.

3.2. Iterative Process

Following the establishment of the basic generation model system, the design team employs a Multi-Objective Genetic Algorithm (MOGA) to compute evaluations of the six target parameters for different design options. This initiates a process of iterative design where evaluations guide adjustments and refinements in the generated solutions. Post-iteration, data analysis and filtering are performed on the performance of various design options. Through MOGA, a Pareto-optimal solution set is obtained, narrowing down the design range. Finally, based on parameter scores, the design team selects a solution from the Pareto-optimal set with balanced parameter scores as the final design.

3.3. Design Solution Finalize

The final design solution is chosen from the Pareto-optimal set, considering the balanced parameter scores obtained through the Multi-Objective Genetic Algorithm. This solution reflects a synthesis of the generated possibilities, meeting predefined criteria and providing an optimal balance across the identified design objectives. The final design solution encapsulates the outcome of the generative design process, incorporating both computational insights and human design considerations.

3.4. Comparative Advantages

The comprehensive design process of this project highlights several advantages of algorithm-based generative design:

- It genuinely achieves "human-computer collaboration" in the design process.
- Compared to traditional design methods, it allows the evolution of solutions by establishing goals, constraints, and geometric systems, rather than directly designing a final form.
- It explores thousands of choices, ultimately obtaining optimal solutions for different predefined target parameters.
- It enables data exchange, creating possibilities for more innovative designs.
- The algorithmic and evolutionary processes can be cyclically utilized, providing reference and inspiration for future project planning and design solutions.

4. Advantages and Limitations of Generative Design Workflow

4.1. Advantages of Generative Design workflow

Sustainable architectural design often entails tackling complex challenges that span multiple disciplines and domains, posing unprecedented difficulties for conventional design approaches. Given the multitude of interrelated factors, utilizing traditional methods necessitates designers to grapple with vast and intricate information, thereby testing their personal capacities and introducing an element of uncertainty. Furthermore, due to delayed performance feedback, the design process frequently requires iterative adjustments to arrive at optimal design iterations. In contrast, employing generative design in sustainable architectural design undoubtedly offers significant advantages.

By considering its characteristics, the process of sustainable architectural design can be conceptualized as a Non-Deterministic Polynomial. For propositions characterized by unknown, ambiguous, or uncertain outcomes, introducing algorithms into the design workflow can effectively address this challenge. Algorithms possess the ability to deduce new knowledge and extend its potential limitations[9], enabling them to be employed for deduction, induction, abstraction, generalization, and structured logic. This capability facilitates the systematic generation of logically grounded principles and, subsequently, the development of comprehensive design solutions. Within this design workflow, designers do not directly engage in the design of individual solutions; instead, they exert control over the process by establishing generative rules and limiting conditions, thus governing the automatic generation of design solutions. This design approach allows for a holistic integration of quantitative and non-quantitative, subjective and objective factors in the design and decision-making process, mitigating the biases in design outcomes resulting from conventional "experience-based" design processes.

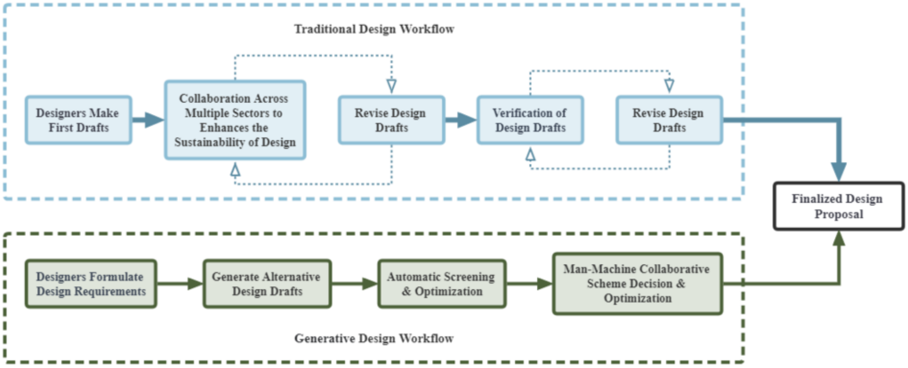

Figure 4. Traditional Design Workflow vs Generative Design Workflow.

Introducing generative design into the design process holds significance beyond the enhancement of workflow efficiency; it also bears considerable importance for elevating the sustainability of architectural projects. During the planning phase, the utilization of urban design grammar codes enables the automatic generation of city layouts[10], aiding in the selection of environmentally favorable building locations or the revival of abandoned sites through redevelopment. In the early stages of design, the rapid generation of a multitude of design possibilities, followed by screening and optimization based on performance simulation data, expeditiously yields viable alternatives with superior performance. Generative design facilitates the integration of sustainability concepts from the very inception of the design process, revealing enhanced performance through subsequent iterative cycles. During the optimization phase, genetic algorithms can be employed to optimize building energy efficiency, water usage strategies, and indoor environmental quality. In the final decision-making stage, data visualization techniques can generate intuitive representations of performance simulation parameters, aiding in quantifying environmental indicators and favoring designs with heightened sustainability.

In summary, the necessity of introducing generative design throughout the entire process of sustainable architectural design lies in its capacity to not only enhance the efficiency of designers and architects but also substantially enhance the ecological attributes of design solutions.

4.2. Limitations of Generative Design Workflow

The generative design process, based on the principles of logic and computation, has the potential to significantly enhance the efficiency of the architectural design process and the environmental sustainability of buildings. However, it is not without limitations, which can be classified into quantifiable and non-quantifiable aspects.

The quantifiable limitations within the generative design process primarily manifest in the quality of data and inputs. The effectiveness of generative design is highly dependent on the quality of input data and parameters. Inaccurate input data or inappropriate parameter settings may lead to generated design solutions that do not meet practical requirements or are impractical to implement. To overcome this challenge, designers should pay meticulous attention to ensuring the accuracy of data and carefully adjusting parameter settings.

On the other hand, the non-quantifiable limitations within the generative design process pose a more challenging aspect for researchers at the current stage. Generative design may face difficulties in addressing complex human factors inherent in architectural design, involving subjective elements such as emotions, culture, and societal habits. To overcome this challenge, researchers may explore the incorporation of humanistic factors or consider approaches like human-machine collaborative design to enhance the generative design's understanding and responsiveness to these nuanced aspects.

Simultaneously, due to the inherent presence of unique creative and artistic elements in architectural design, the iterative nature of generative design may struggle to completely replace the subjective judgment and creative thinking of designers. Consequently, the outcomes of generative design may lean towards producing variations based on existing designs rather than entirely novel creative solutions. From this perspective, overreliance on generative design could potentially limit the long-term development of the field of architectural design. Therefore, when utilizing generative design, there should be a balance between automation and the subjective judgment of designers to foster more creatively rich designs.

Despite these limitations, generative design remains a powerful tool in the architectural design process, particularly during the early stages of conceptual exploration and design optimization. To achieve superior design outcomes, it is crucial to emphasize the collaborative synergy between generative design and human designers, making it an effective means to enhance design efficiency and innovation. Through this organic integration, the full potential of generative design can be more effectively harnessed, contributing positively to the ongoing development of the field of architectural design.

5. Conclusion

This study focuses on the application of generative design technology in sustainable architectural design, aiming to explore how to leverage the comprehensive integration of artificial intelligence technology into the design workflow. The goal is to achieve more environmentally conscious design solutions and optimize the workflow.

The introduction of self-supervised learning generative models provides an enriched foundation and inspiration for the generative models. During the phase of generating alternative design proposals, the integration of algorithms allows designers to swiftly modify and optimize designs, better aligning with ecological objectives. Within the phase of identifying and optimizing variable parameters, the application of Genetic Algorithms enables designers to explore optimal parameter combinations in the design space, realizing a multifaceted optimization of designs. Furthermore, through the visualization export of design proposals, designers can intuitively perceive the influence of design modifications on performance, enabling superior design adjustments. These visualization modules not only facilitate the alignment of designers with ecological objectives but also offer powerful tools for communicating and articulating design proposals.

In summary, the application of generative design technology in sustainable architectural design not only elevates design efficiency but also enhances the ecological attributes of design solutions. By integrating artificial intelligence technology, we can make a valuable contribution to the sustainable development of the architectural industry, paving the way for a future characterized by more environmentally-friendly, efficient, and aesthetically pleasing architectural designs.

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