

Article

Reinforcement Learning-Based Design Approach for Kinetic Facades in ICU Rooms: Enhancing Patient Comfort and Visual Conditions

Sida Dai ^{1,*}, Yuqing Zhou ², Michael Carlos Barrios Kleiss ³, Mostafa Alani ⁴ , Yiming Jiao ¹ 
and Seyedehaysan Mokhtarimousavi ⁵

¹ School of Architecture, Virginia Tech, Blacksburg, VA 24061, USA; yimingjiao@vt.edu

² NBBJ Architecture and Design, Seattle, WA 98109, USA

³ School of Architecture, Planning & Preservation, College Park, University of Maryland, Baltimore, MD 20742, USA

⁴ School of Architecture and Construction Science, Tuskegee University, Tuskegee, AL 36088, USA; malani@tuskegee.edu

⁵ School of Architecture, Clemson University, Clemson, SC 29634, USA

* Correspondence: sidad@vt.edu

Abstract

The intensive care unit (ICU) plays a crucial role in modern hospitals. ICU patients endure severe physical and mental conditions, making it essential to create a healing environment that reduces stress and promotes recovery. Among common environmental parameters, lighting conditions are particularly critical, as patients often face challenges with mobility and body positioning. Kinetic facades with adjustable external shading elements have gained attention for their ability to regulate sunlight effectively. However, their complexity poses challenges for design and implementation. This study proposes a reinforcement learning-based method, using Q-learning to handle discrete facade configurations and adaptive control under varying solar conditions for optimizing facade configurations in ICU rooms. The method aims to: (1) reduce direct sunlight glare and heat; and (2) maximize landscape views. A case study at Providence Alaska Medical Center demonstrates the method's effectiveness, showing reduced glare and heat gain and improved landscape view availability through simulation. The results highlight the potential of reinforcement learning to address ICU-specific environmental challenges.

Keywords: reinforcement learning; kinetic facade; ICU design; health care; patient-centered design



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1. Introduction

The Intensive Care Unit (ICU) is an integral component of the modern hospital system, offering intensive and specialized medical and nursing care for critically ill patients who require prolonged hospital stays [1]. Unlike outpatient care, ICU patients often endure severe physical and mental conditions, making it essential to create a healing environment that soothes and stabilizes their emotional state [2,3]. Common environmental stressors in the ICU include noise, ambient lights, limited mobility, and social isolation [4]. ICU patients often face challenges with mobility and body positioning during their stay, making it even more critical to provide a comfortable, adaptable lighting environment [5–7].

The design of the ICU environment requires higher standards to promote recovery and well-being due to the critical nature of ICU patients. One key aspect is the management of direct sunlight exposure, which can notably impact the healing process [8,9]. Certain medications necessitate avoiding sunlight exposure [10]. Direct sunlight can also lead to localized temperature increases, causing discomfort and interfering with thermal stability [11]. Additionally, glare from sunlight can result in visual discomfort, further contributing to the stress experienced by patients [12]. Conversely, a landscape view can help reduce patient stress and accelerate recovery [13]. Addressing these environmental factors is essential to create a supportive and effective healing environment. Existing ICU lighting and facade strategies face limitations in balancing sunlight control and view preservation, especially under varying conditions.

Kinetic facades have gained increasing attention in recent years for their ability to dynamically adjust indoor lighting conditions [14]. However, their design and optimization present significant challenges due to the higher number and complexity of parameters compared to static shading systems [15], particularly in medical buildings where facade control must respond to varying solar conditions, patient body positions, and strict comfort requirements. As a result, existing kinetic facade applications often rely on predefined rules or static configurations, which struggle to balance glare reduction and view preservation simultaneously in ICU settings. Moreover, achieving such multi-objective performance often requires complex control and actuation systems, leading to increased system cost and maintenance difficulty, which limits the practical adoption of kinetic facades in healthcare environments. To address this challenge, reinforcement learning (RL) provides a promising solution, offering strong adaptability and the capability to optimize multi-parameter systems. Accordingly, this study proposes an RL-based design method for kinetic facades in ICU rooms, with the objectives of: (1) mitigating the effects of direct sunlight glare and localized heating, and (2) minimizing obstructions to patients' views of the exterior landscape.

The paper is organized as follows: First, a review of related work explores existing studies on ICU design and the use of RL in architecture. Next, the design system is presented in detail, outlining its framework and the design process. This is followed by a case study at Providence Alaska Medical Center, showcasing the practical application of the proposed method and evaluating its effectiveness through experiments. Finally, the paper concludes by discussing the contributions and limitations of the approach, along with potential directions for future research.

2. Literature Review

Previous studies on ICU design emphasize the critical role of environmental factors, particularly window design, daylight, and views, in improving patient outcomes. Rashid's study identified strengths like private rooms, freestanding beds, and natural light but noted challenges such as inconsistent layouts and restricted family access [16]. The importance of daylight and window views is emphasized in studies by Chiu et al. and Jafarifiroozabadi et al., showing reduced lengths of stay for patients in rooms with natural light and views, particularly for those with anxiety and dementia [4,7]. Lighting design is crucial for circadian rhythm regulation. Luetz et al. found that LED light ceilings with high circadian-effective irradiance improve patient recovery without causing glare [17]. Similarly, neonatal ICUs have evolved from staff-centric lighting to patient-focused designs that support development and circadian rhythms [18].

Although contemporary ICU design increasingly incorporates larger windows and daylight-oriented layouts, recent studies suggest that existing lighting conditions remain insufficient for supporting patient circadian health. Empirical investigations of ICU lighting

environments have shown that patient rooms are often too dim during daytime and excessively bright at night, contributing to disrupted sleep–wake cycles and circadian misalignment. One observational study of medical ICU rooms found average daytime illuminance levels of approximately 208 lux and nighttime levels of 76 lux, conditions considered inadequate for effective circadian entrainment [19]. Similarly, recent ICU lighting research has highlighted that even modern ICU environments with access to natural daylight frequently fail to provide consistent circadian-supportive illumination at the patient level [20]. These findings suggest that static daylighting strategies and conventional lighting configurations alone may not sufficiently respond to changing environmental conditions and patient needs.

To address these limitations, several studies have explored dynamic and circadian-oriented lighting interventions in ICU environments. Engwall et al. introduced a cycled lighting system that simulated natural daylight rhythms through automatically controlled lighting scenes, reporting improved patient perceptions of sleep quality, circadian orientation, and psychological comfort [21]. Recent review studies further suggest that dynamic lighting interventions may support sleep quality and circadian regulation in ICU patients, while also highlighting persistent limitations in current ICU lighting research [20]. Existing studies remain largely focused on interior electric lighting systems rather than adaptive architectural systems capable of modulating natural daylight conditions. In addition, many investigations rely on multi-component environmental interventions, making it difficult to isolate the independent effects of lighting adaptation on patient outcomes [20]. Methodological inconsistencies, limited standardization of lighting measurements, and the absence of adaptive control frameworks further restrict comparative evaluation across studies [20]. These limitations indicate the need for more responsive and continuously adaptive environmental control strategies in ICU design.

As summarized in Table 1, previous studies have separately explored ICU lighting design, dynamic lighting interventions, and RL-based architectural optimization. However, limited research has investigated the integration of adaptive kinetic facade systems and RL methodologies within ICU environments, particularly for balancing glare reduction and preservation of exterior landscape views under changing environmental conditions.

In parallel, RL has shown significant potential in addressing complex, multi-objective challenges in architectural design and environmental control. It has been applied to optimize indoor environmental quality (IEQ), as Ribino and Bonomolo demonstrated by improving thermal, acoustic, and visual comfort in home-working spaces [22]. Similarly, Ali et al. integrated RL into energy optimization frameworks, enhancing thermal performance in tropical buildings while reducing computational costs [23]. In spatial configuration, Veloso and Krishnamurti employed RL to generate adaptable layouts using multi-agent systems [24]. RL has also been explored in hotel facade design by Dai et al., optimizing shading panels to reduce glare and improve energy efficiency [25]. Additionally, RL has advanced construction workflows, as Elmaraghy et al. developed a framework combining design and construction through RL-trained agents for real-time simulations [26]. In sustainable design, Apellániz et al. introduced the “Pug” Grasshopper plugin to optimize material reuse and cradle-to-cradle principles [27]. These examples highlight RL’s growing role in improving environmental quality, generative design, and sustainable architectural practices.

Despite notable advancements in ICU design, certain critical gaps remain unaddressed. First, while kinetic facades have been extensively studied as dynamic systems for regulating indoor lighting and thermal conditions, their application in ICU settings has been limited. Most studies on lighting in medical spaces focus on static window design, artificial lighting strategies, or circadian-oriented illumination, with limited emphasis on adaptive

facade control under changing solar conditions. The unique needs of ICU patients require specialized design considerations that have not been fully explored in the context of kinetic facades. Second, the integration of RL-based design methodologies into ICU design represents an untapped opportunity. While RL has demonstrated its potential for optimizing complex systems in other fields, its application in architectural design—particularly for healthcare environments—remains underexplored. Leveraging RL could enable more adaptive and efficient solutions by addressing the inherent complexities of kinetic facades in ICU settings, such as balancing multiple conflicting objectives (e.g., reducing glare while preserving views).

Table 1. Summary of Previous Studies Related to ICU Lighting, Dynamic Lighting Systems, and Adaptive Facade Optimization.

Ref.	Research Focus	Method/Approach	Key Findings	Limitations
Rashid [16]	ICU environmental design	Review of ICU design strategies	Natural light and private-room layouts improve patient environments	Focused on static architectural design
Luetz et al. [17]	Circadian lighting in ICU	LED lighting intervention	Circadian-effective lighting improved patient recovery conditions	Focused on interior electric lighting
White [18]	Neonatal ICU lighting	Lighting design review	Patient-centered lighting supports circadian development	Did not address adaptive facade systems
Intihar et al. [19]	ICU lighting conditions	Observational lighting study	ICU rooms showed insufficient daytime lighting and excessive nighttime illumination	No adaptive environmental control strategy
Linders et al. [20]	ICU light interventions	Review of dynamic lighting studies	Dynamic lighting may improve circadian regulation and sleep quality	Methodological inconsistency across studies
Engwall et al. [21]	Cycled ICU lighting	Dynamic lighting intervention	Improved patient perception of sleep and circadian orientation	Relied on programmed interior lighting systems
Ribino and Bonomolo [22]	RL for IEQ optimization	RL-based environmental optimization	Improved thermal, acoustic, and visual comfort	Not applied to healthcare environments
Veloso and Krishnamurti [24]	RL spatial configuration	Multi-agent RL system	Generated adaptable spatial layouts	Did not address facade or daylight control
Dai et al. [25]	RL-based kinetic facade optimization	RL-controlled adaptive facade	Reduced glare and improved energy efficiency	Not developed for ICU environments

3. Methodology

3.1. Case Study Context: ICU Room at Providence Alaska Medical Center

As shown in Figure 1, the selected case for analysis is the Providence Alaska Medical Center, located in Anchorage, Alaska. As a high-latitude region, Anchorage experiences unique solar conditions that exacerbate sunlight-related challenges. The low solar altitude angle and the phenomenon of polar day significantly increase the intensity and duration of

direct sunlight, leading to heightened issues with glare and localized heating. The existing ICU rooms at Providence Alaska Medical Center have been particularly affected by these conditions. To mitigate the problem of glare, the current practice involves rotating patient beds to face away from the windows. Although this reduces direct sunlight exposure, it comes at the cost of completely obstructing patients' view to the exterior landscape, which is an essential component of a healing environment. These existing operational challenges motivated the exploration of adaptive facade strategies for balancing glare reduction and view preservation.

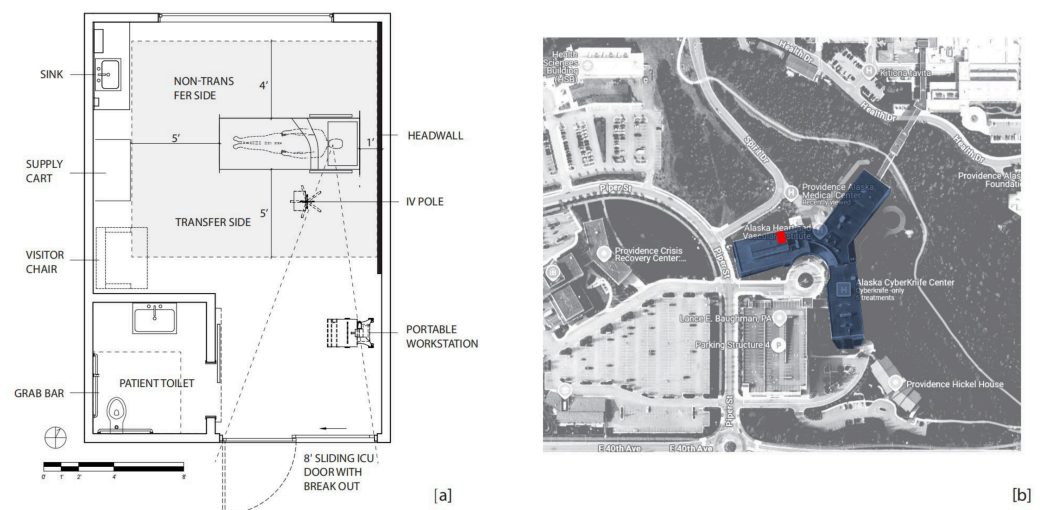


Figure 1. (a) Floor plan of the ICU room with dimensions and solar orientation; (b) Site plan of Providence Alaska Medical Center (Anchorage, AK, United States), where the red rectangle indicates the location of the ICU rooms used in the case study.

The case study included two ICU room layouts with mirrored spatial configurations, reflecting the left-handed and right-handed arrangements commonly used in ICU design to accommodate different clinical workflows. Since the primary focus of this research was the adaptive shading behavior of the kinetic facade system, the glazing system was simplified as fully transparent to isolate the environmental effects of the facade operation. Similarly, interior blinds were excluded from the simulation environment to avoid introducing additional shading variables into the evaluation process.

In this study, three distinct design objectives were established: (1) prioritizing the reduction in obstructions to the exterior landscape view; (2) prioritizing the reduction in direct sunlight exposure on the patient's bed area; and (3) balancing both objectives to simultaneously minimize view obstructions and direct sunlight exposure. These preferences guided the optimization process and informed the design solutions.

3.2. Kinetic Facade Design Variables and Operation Mode

As shown in Figure 2, the design incorporated 100% coverage of the window area to address the challenges posed by the high-latitude region. To balance cost and practicality, the study utilized a common kinetic facade configuration with square folding panels, each measuring 400 mm × 400 mm. These panels were arranged in a regular square grid pattern. The folding direction of each shading panel significantly impacts both the direct sunlight exposure area and the patient's view of the exterior landscape. Since each square panel can fold in four distinct directions, the total number of possible configurations for the kinetic facade is 424. This vast design space underscores the necessity of using RL to efficiently explore and optimize the design. Furthermore, the case study adopted a fixed operational model, as illustrated in Figure 3. This mode was chosen for its suitability in high-latitude

environments and its ability to operate with a simple cyclic mechanical structure, reducing both the cost and operational complexity of the kinetic facade. The selected facade operation modes were based on commonly adopted horizontal and vertical folding typologies in practical adaptive facade systems, ensuring that the evaluated configurations remained compatible with realistic architectural and mechanical applications.

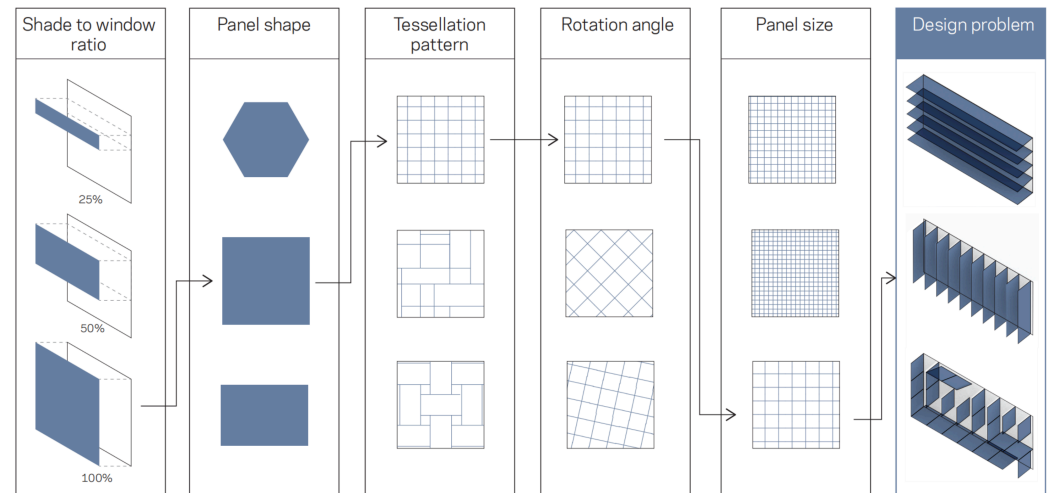


Figure 2. Design Process of the Kinetic Façade.

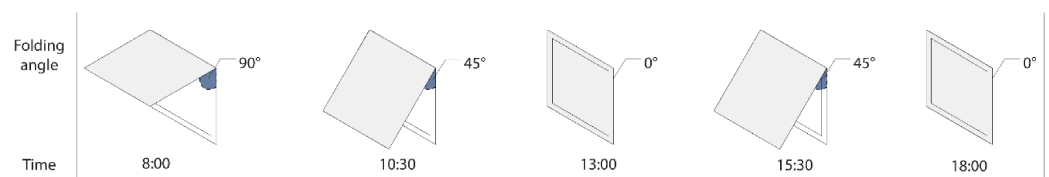


Figure 3. Operation Mode of the Kinetic Façade.

3.3. RL-Based Design Framework

The framework of an RL system, as illustrated in Figure 4, consists of two key components: the agent and the environment. The agent observes the environment and performs actions that cause changes in the environment's state. In response, the environment provides feedback to the agent. Through continuous interaction, the agent gradually learns to maximize rewards. The learning process itself is guided by a specific algorithm, which defines how the agent interprets and learns from these interactions.



Figure 4. Framework of the RL System.

Q-learning was adopted as the RL algorithm, which is a widely used model-free approach based on the Markov Decision Process (MDP) framework. Model-free MDP algorithms generally include methods like Monte Carlo Learning and Temporal-Difference Learning, with Q-learning being among the most efficient. The core concept of Q-learning lies in the use of a Q-table, which evaluates the quality of different actions in a given state.

The learning process in Q-learning involves iteratively updating the Q-table values. The Q-table update process is governed by the Bellman equation, expressed as:

$$\text{New } Q(s, a) = (1 - \alpha)Q(s, a) + \alpha \left[R(s, a) + \gamma \max_{a'} Q(s', a') \right] \quad (1)$$

Here, $Q(s, a)$ and $\text{New } Q(s, a)$ represent the current and updated Q-values, respectively. The parameter α denotes the learning rate, where a lower value reduces the influence of previous learning. $R(s, a)$ is the reward for taking action a in state s , while γ is the discount factor, controlling the importance of future rewards relative to immediate ones. Lastly, $\max_{a'} Q(s', a')$ refers to the highest expected Q-value for the next state. The learning rate α was set to 0.1, while the discount factor γ was set to 0.9 to balance immediate and long-term environmental rewards during training.

In this study, the state space represents all possible kinetic facade configurations generated by the folding orientations of the facade panels. Since each panel can adopt four possible folding directions, the total number of possible states is defined as 4^n , where n represents the number of panels within the facade system. The action space consists of four directional folding operations corresponding to upward, downward, leftward, and rightward panel transformations.

The reward function is formulated as a weighted combination of two penalty terms: direct sunlight exposure on the patient bed and obstruction of exterior landscape views. The agent aims to maximize the reward by minimizing both penalties. The reward function is expressed as:

$$R(s, a) = -(w_{\text{sun}} \sum_{i=1}^n w_i A_i + w_{\text{view}} \frac{A_{\text{blocked}}}{A_{\text{view}}}) \quad (2)$$

where A_i represents the sunlight projection area on different regions of the patient bed, w_i denotes the weighting coefficient assigned to each region, A_{blocked} represents the obstructed landscape view area, and A_{view} represents the total available view area. w_{sun} and w_{view} control the relative importance between sunlight reduction and view preservation objectives.

Following the Agent–Environment framework of RL, this research developed a modular design system, as illustrated in Figure 5. The system is divided into two key modules: Learning and Evaluation. The Learning module forms the core of the system and governs the RL process. Since Q-learning is the algorithm used in this research, the Learning module is responsible for constructing and updating the Q-table based on the design problem. It selects the agent's actions and provides corresponding feedback to refine the agent's behavior. Subsequently, the module adjusts the environment in response to the agent's actions.

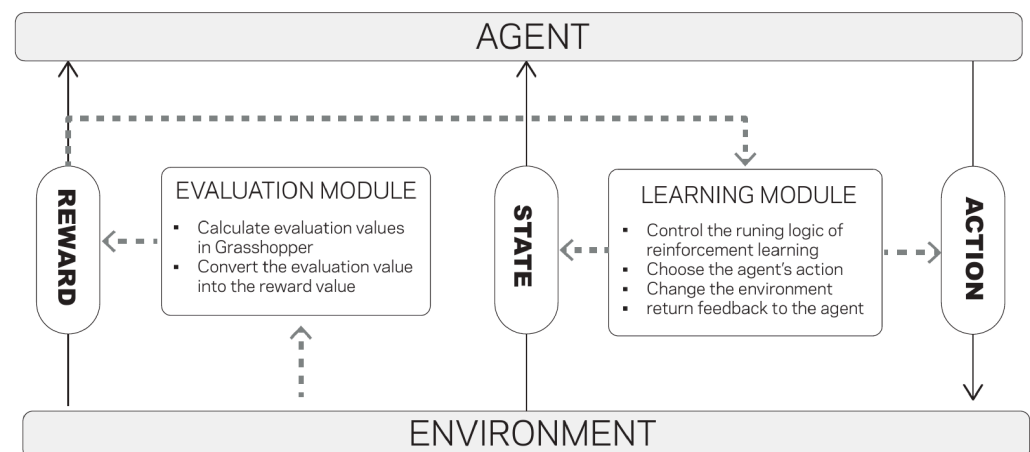


Figure 5. Design System Based on RL Framework.

The Evaluation module processes environmental information generated from a custom simulation environment developed using Python 3 and Grasshopper-based scripts. Instead of relying on high-fidelity daylight simulation engines such as Radiance or EnergyPlus, this research adopted a lightweight geometric simulation workflow. While physically based simulation tools provide highly accurate environmental analysis, their computational costs are prohibitively high for RL workflows requiring thousands of iterative training episodes. Previous studies have similarly noted that conventional daylight simulation methods are computationally intensive and difficult to integrate into continuous real-time optimization and control processes [28,29].

To maintain computational efficiency while preserving meaningful environmental evaluation, this study employed projection-based geometric analysis methods. Landscape view performance was quantified by calculating the proportion of exterior view area obstructed by the kinetic facade panels from the patient's viewpoint. Similarly, direct sunlight exposure was evaluated by calculating the projected sunlight area on the patient bed under specific solar conditions. Comparable visibility-based and projection-based evaluation approaches have been widely adopted in facade optimization and daylighting studies because of their computational efficiency and compatibility with iterative optimization workflows. Previous facade studies have evaluated daylight and view performance through geometric visibility metrics, projected obstruction areas, view-access analysis, and facade-based daylight mapping methods during early-stage optimization processes [29–32]. Therefore, the simplified simulation method used in this study was considered appropriate for RL-based environmental optimization requiring continuous real-time feedback.

3.4. RL-Based Design Process

As shown in Figure 6, the design process begins with gathering information about the project and its environmental context. This step ensures a comprehensive understanding of the specific conditions and constraints that will influence the design of the kinetic facade. The next step involves discussions with the client to establish design objectives. In this study, the primary goals are to optimize the view of the exterior landscape, minimize direct sunlight exposure, or balance both objectives. These discussions help define the priorities that guide the RL optimization process. The design problem is defined after the design objectives are finalized, specifying the parameters that the RL system will optimize. Given the complexity of kinetic facade design, allowing RL to optimize all parameters simultaneously can lead to excessively long training times. To maintain computational feasibility and preserve architectural design intent, the optimization scope of the RL system was intentionally constrained. Parameters related to overall facade geometry, panel dimensions, material selection, and aesthetic composition were manually determined by designers based on conventional architectural design practices and project-specific requirements. The RL system was responsible solely for optimizing panel folding directions in response to environmental performance objectives. This division establishes a clear boundary between designer-driven architectural decisions and algorithm-driven environmental optimization.

As shown in Figure 7, the evaluation method for landscape view calculates the projected area of the shading panels from the patient's viewpoint. Similarly, the evaluation method for direct sunlight exposure calculates the area of sunlight projected onto the patient's bed. To further enhance patient comfort, weighting coefficients were introduced to reflect commonly recognized comfort priorities in healthcare environments, particularly the sensitivity of patient head regions to glare exposure (Area 1 in Figure 7b). The coefficients were implemented as adjustable design parameters intended to support exploratory environmental optimization rather than represent clinically validated medical standards. Future studies may further calibrate these coefficients through clinical evidence or user-

based evaluation methods. Finally, the RL model is trained, and design solutions that meet the objectives are selected. If no satisfactory solutions are found, the process loops back to refine the reward function and retrain the model.

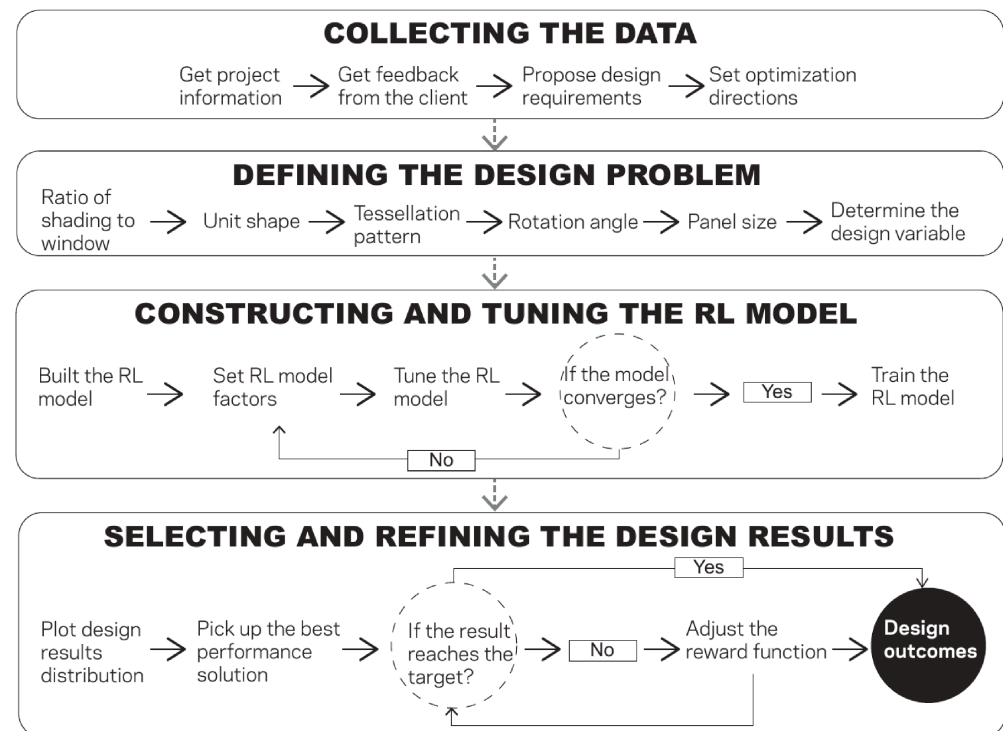


Figure 6. Design process of the RL-based design method.

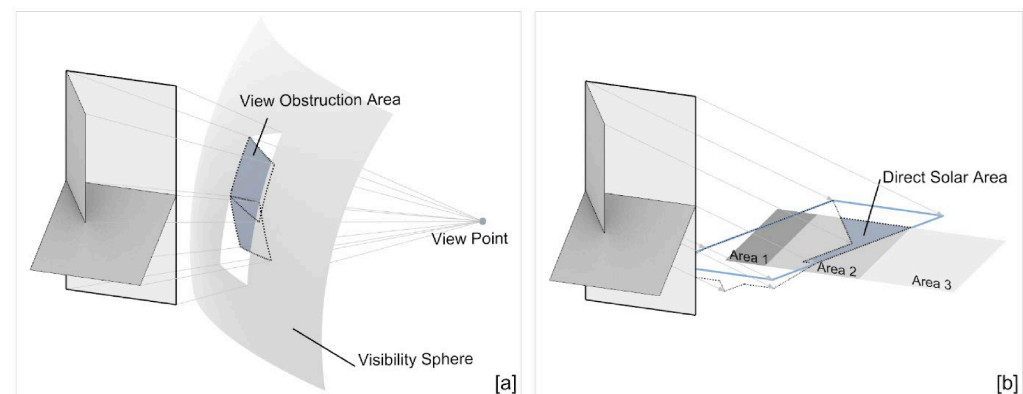


Figure 7. (a) Evaluation method for view obstruction; (b) Evaluation method for direct sunlight exposure.

3.5. Simulation Setup and Performance Evaluation

To further evaluate the effectiveness of the proposed RL-based design method, a simulation-based performance evaluation was conducted using a larger sampling dataset and higher sampling density. The simulation utilized real weather data from Anchorage, Alaska. The independent variable was the kinetic facade design, while the dependent variables were cumulative direct sunlight exposure and view obstruction.

The simulation compared the performance of several kinetic facade configurations, including a pure horizontal facade, a pure vertical facade, an RL-generated facade, and a randomly generated facade. The horizontal and vertical configurations were selected as baseline conditions because they represent two commonly adopted operational typologies in adaptive facade systems. These baseline configurations provide practical references for evaluating the performance of the RL-generated design. A randomly generated facade was

also included as an additional benchmark to assess whether the proposed optimization approach could outperform non-optimized design solutions.

For the direct sunlight exposure assessment, all facade configurations were simulated over a 91-day period from 7 May to 5 August, with the summer solstice located near the midpoint of the evaluation period. This timeframe was selected because Anchorage experiences substantial seasonal variations in daylight conditions due to its high-latitude location. The summer period represents the condition with the greatest direct sunlight exposure and, consequently, the highest operational demand for adaptive shading systems.

For the view obstruction assessment, simulations were performed using a 10 min sampling interval between 8:00 and 18:00. Direct sunlight exposure and view obstruction were calculated using geometric computation functions implemented in Grasshopper. The resulting performance metrics were subsequently used to compare the effectiveness of different facade configurations. The simulation results are presented and discussed in Section 4.

4. Results

4.1. Generated Facade Designs Under Different Objectives

The training process began by setting the critical parameters of the RL model, including the learning rate, discount factor, and reward function coefficients. These parameters were fine-tuned through several iterations to ensure the model's performance aligned with the desired design objectives. After multiple rounds of tuning, the RL model was trained to generate optimal design solutions based on the defined objectives. As shown in Figure 8, the training process illustrates a clear improvement in the agent's performance over successive training rounds. The agent becomes increasingly stable and demonstrates a higher likelihood of achieving design results with lower evaluation values for both direct sunlight exposure and view obstruction. This reflects better overall performance in reducing direct sunlight on the patient bed while minimizing obstructions to the exterior landscape view.

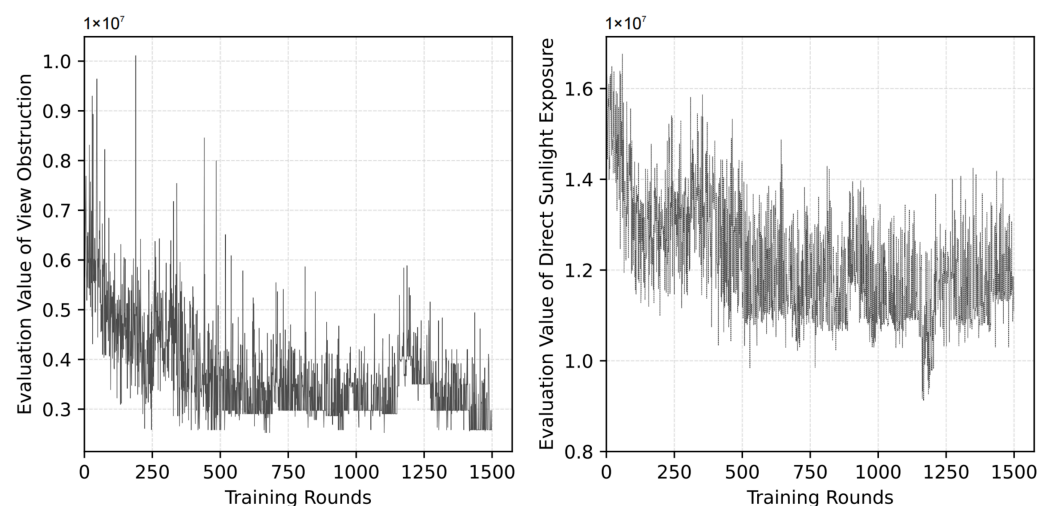


Figure 8. Training Process of the RL Model.

Figure 9 presents the best results generated by the RL model for the three distinct design objectives. Notably, in conventional kinetic facade designs, upward-folding panels are rarely used due to their limited effectiveness in blocking sunlight. However, in ICU settings, where the patient's viewpoint is lower, upward-folding panels are more effective in reducing view obstruction. The RL model ensures that upward-folding panels do not result in extra direct sunlight exposure, making them more viable in the design. These results

highlight the effectiveness of the RL model in adapting to different design preferences and optimizing the kinetic facade to meet specific performance goals.

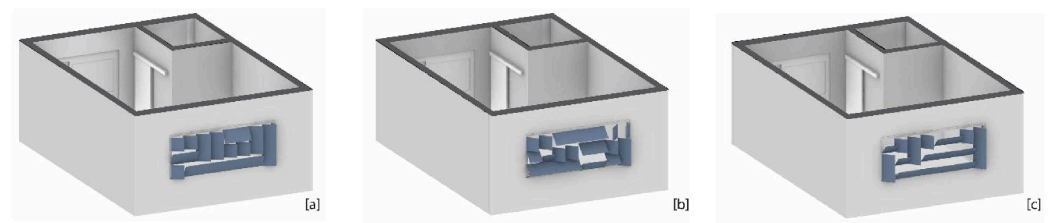


Figure 9. (a) Design result for reducing both view obstruction and direct sunlight exposure; (b) Design result for reducing direct sunlight exposure; (c) Design result for reducing view obstruction.

In ICU design, the handedness of clinical staff and the care team is an important consideration, as some ICU rooms are designed with a mirrored layout to accommodate left-handed personnel. As shown in Figure 10a, the mirrored arrangement changes the relative positioning of the patient and the window, which in turn impacts the configuration of the kinetic facade. To address this scenario, the study incorporated the mirrored layout into the RL model training. For this case, the design objective remained focused on balancing the reduction in direct sunlight exposure and view obstruction. Figure 10b presents the final design solution generated for the left-handed ICU layout. Compared to the right-handed layout, a notable difference in the left-handed layout is the orientation of the vertically folded shading panels. These panels are adjusted to fold in the opposite direction, further reducing their obstruction of the patient's landscape view. This demonstrates the flexibility of the RL-based design method in adapting to varying spatial layouts, ensuring optimized performance for different ICU configurations.

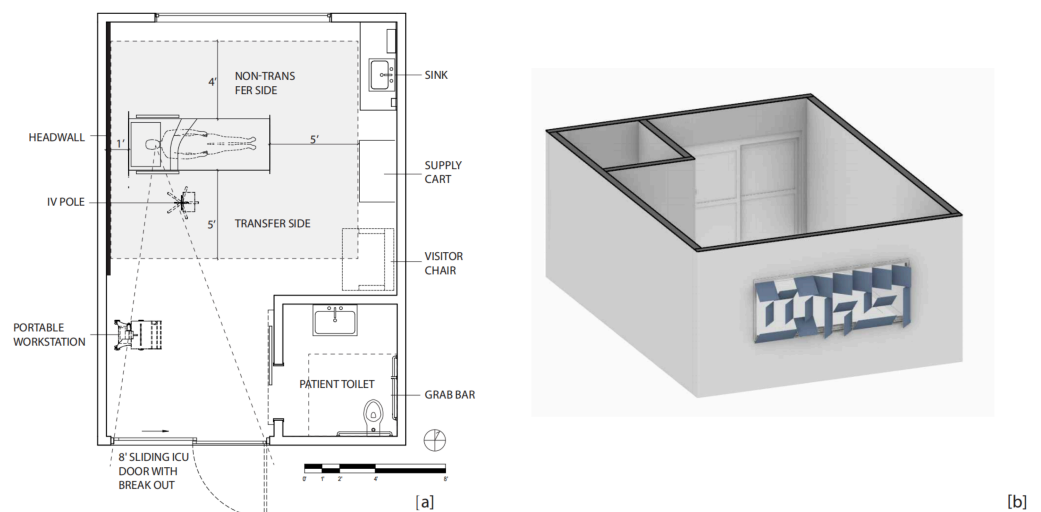


Figure 10. (a) Floor plan of the mirrored ICU; (b) Design result for the mirrored ICU.

4.2. Performance Comparison of Facade Configurations

The simulation results are summarized in Figures 11 and 12. Figure 11 presents the view obstruction results, while Figure 12 shows the direct sunlight exposure results for the evaluated facade configurations. Overall, the RL-generated facade outperformed the other three facade designs in both minimizing view obstruction and reducing direct sunlight exposure.

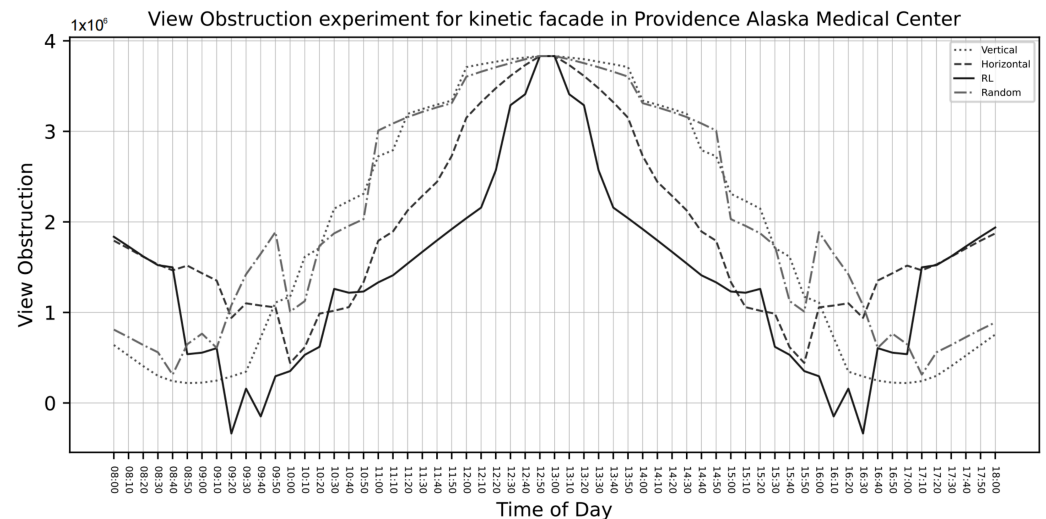


Figure 11. Result of View Obstruction Experiment.

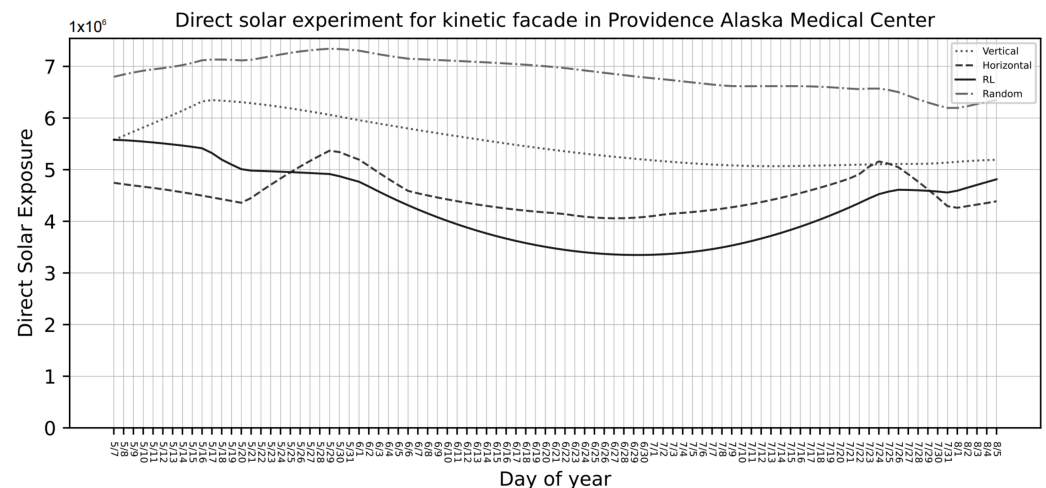


Figure 12. Result of Direct Sunlight Exposure Experiment.

Notably, the RL-generated facade demonstrated its greatest advantage during periods close to the summer solstice. This can be attributed to the training process, which used the summer solstice as the primary sampling condition for optimization. As a result, the RL model was able to identify facade configurations that were particularly effective under peak solar exposure conditions. In contrast, during periods farther from the summer solstice, the performance differences between facade configurations became smaller, and some baseline designs occasionally achieved better results. Nevertheless, the RL-generated facade maintained superior overall performance across the evaluation period, demonstrating its effectiveness in balancing solar control and view preservation.

5. Conclusions and Limitations

This study contributes to ICU design research and computational architectural design in three primary aspects.

First, at the methodological level, the study proposes an RL-based design framework for kinetic facade optimization in ICU environments. Unlike conventional rule-based or static facade design approaches, the proposed framework integrates adaptive environmental evaluation with iterative RL, enabling the system to balance multiple competing objectives, including direct sunlight reduction and preservation of exterior landscape views.

Second, at the architectural application level, the study demonstrates how RL-based optimization can be adapted to healthcare environments with specialized environmental requirements. Through the Providence Alaska Medical Center case study, the research illustrates the potential of kinetic facade systems to address glare-related challenges in high-latitude ICU environments while maintaining patient access to daylight and exterior views.

Third, at the practical design level, the research presents a computationally efficient workflow combining Python-based RL with Grasshopper-based geometric environmental evaluation. By adopting lightweight projection-based simulation methods, the framework remains compatible with iterative optimization processes requiring continuous environmental feedback, providing a practical approach for early-stage adaptive facade exploration.

Despite these contributions, the research has certain limitations that present opportunities for future work:

- The RL optimization in this study is limited to a set of critical design parameters. Future research could expand the scope by incorporating additional parameters, potentially improving the adaptability and performance of the design system.
- The evaluation method for landscape views does not account for the quality of the exterior scenery. In subsequent studies, the landscape within the view range could be segmented based on its visual quality, assigning different coefficients to further refine the evaluation method. This enhancement could better reflect the importance of specific areas within the landscape.
- The current study relies solely on computer simulations to validate the proposed approach. Future research should incorporate physical testing to verify the simulation results and evaluate the kinetic facade's real-world performance.
- This study focuses on a high-latitude case study, where unique solar conditions such as low solar angles and polar day phenomena are significant. To generalize the findings, future research should extend the application of the proposed method to different geographical locations and climatic conditions, exploring its adaptability and performance in diverse environmental contexts.

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