RESEARCH ARTICLE

AI-Based Hospital Design Process through Neuro-Symbolic Strategies

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Abstract

Objectives: Hospitals represent one of the most complex subjects in architectural design. Over time, many hospitals undergo changes in their initial spatial layouts to accommodate evolving needs. This process often presents various challenges and problems, and the absence of an optimal design process for hospitals is a primary contributor to these issues. Artificial intelligence (AI), with its advanced capabilities, can offer highly accurate and rapid solutions. This research aims to present an integrated approach that combines architecture and AI for AI-based hospital design through neuro-symbolic strategies.

Methods: This research employs a theoretical-applied framework, and utilizes a descriptive-analytical method to investigate the role of artificial intelligence in the design process, particularly within hospitals. The data collection methods include a literature review and an examination of texts and studies related to architectural design and AI. Furthermore, by analyzing the data through content analysis, integrated neuro-symbolic strategies were introduced as a comprehensive approach to AI. The final model of the hospital design process, based on this approach, was subsequently presented.

Results: Unified and hybrid techniques are two methods for integrating symbolic and sub-symbolic algorithms within the integrated neuro-symbolic approach. This innovative methodology leverages the strengths of both categories of algorithms while mitigating their respective weaknesses. Among the six methods presented in this paper, the hybrid strategy—method number three (neuro-symbolic) — emerges as the most effective means of achieving an integrated process that merges AI and architecture in hospital design.

Conclusion: In this process, the designer's interventions are minimized, allowing AI to produce the most optimal architectural design for a hospital by leveraging its capabilities.

Level of evidence: V

Keywords: AI generative design process, Artificial intelligence (AI), Hospital design, Hybrid technique, Neuro-symbolic, Unified technique

Introduction

Designing a healthcare facility, such as a hospital, is a highly complex endeavor. These facilities are constructed and operated to treat patients and improve the health of the community. They are visited by diverse groups of users, each with unique needs. Given that most of these individuals are either patients themselves or are patient associates, they often experience high levels of stress and anxiety. This stress is exacerbated in an environment that is considered weak in terms of architectural integrity, as well as psychological and environmental factors.[1] Numerous studies have been conducted on the impact of healthcare facility architecture on patient recovery,[2] highlighting its role in reducing tension and stress for both the patients and their companions, improving the efficiency

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of medical staff, ensuring safety, and many other issues. Everyone acknowledges that the architectural design of healthcare centers and the resolution of spatial relationships within them are of great importance.[3]

In a large medical center, such as a hospital, data is generated from the moment a patient arrives. This includes the entire journey the patient undertakes, the activities performed for various diagnostic and therapeutic tasks, the individuals involved in this process, and all the work conducted for the patient's discharge. All of this information considered data and must be carefully examined and analyzed during the architectural design process.

Therefore, it can be inferred that architects are confronted with a significant amount of data that must be identified and analyzed to address hospital design challanges.[4] AI technology, due to its speed, accuracy, multi-dimensional problem-solving capabilities, and ability to provide powerful solutions, can significantly enhance the architectural design process, from data analysis to the presentation of the final design.[5] Utilizing this technology can alleviate many concerns for architects, including the complexity of computations, elucidating relationships between variables, predicting probabilities, and selecting optimal solutions.[3] Addressing these challenges through conventional human methods often requires considerable time and can be exceedingly difficult, if not impossible. However, AI can facilitate optimal decision-making by its functionality, leveraging amounts of data and information employing various methods and techniques.[6]

A key point is that achieving an architectural design process that incorporates AI requires a thorough review and redefinition of the conventional architectural design process to make it AI-based. Accordingly, this research aims to develop a unified design process that integrates AI effectively. It is important to note that AI technology encompasses a wide range of algorithms and techniques for integration. Therefore, selecting an appropriate strategy for addressing each specific problem is essential. Neuro-symbolic strategies represent comprehensive methods for combining algorithms to achieve an AI-based generative design process. However, determining which strategies are suitable for the hospital architectural design process is a central focus of this study.

In previous studies, a design process model specifically for hospitals has not been presented. Furthermore, few practical studies in this field have utilized algorithms solely for designing specific components of medical centers, such as layout or facade design.[7-9] From this perspective, the innovation of this research lies in the introduction of integrated neuro-symbolic strategies, which aim to present a comprehensive AI-based design process model for hospitals.

Materials and Methods

This study presents both theoretical and applied research aimed at investigating the role of AI in the hospital design process. The aim of the research is to develop a comprehensive model that illustrates the collaborative relationship between architects and AI in the architectural hospital design. To achieve this, the study employs a descriptive-analytical approach, utilizing data collected from a review of library resources, relevant texts, and previous studies in the field. In the first phase, the common hospital design process is analyzed from the researchers' perspective, identifying the key components that influence hospital design. Subsequently, studies that investigate the role of AI in the architectural design of hospitals are reviewed. This examination reveals existing research gaps in the integration of AI within the hospital design process. In the following phase, a content analysis method is used to evaluate previous approaches to AI, ultimately proposing integrated neuro-symbolic strategies as a novel approach to AI in the design process. The final model presents the hospital design process based on this innovative methodology.

Results

Review of Research on the Hospital Design Process and Artificial Intelligence

The design process of healthcare centers and hospitals is one of the most complex topics in architectural design, attracting considerable attention from researchers. According to Hicks et al.,[10] the design of hospitals and healthcare facilities is a challenging endeavor that not only emphasizes spatial layout and the design of physical spaces but also seeks to facilitate dynamic interactions among patients, staff, visitors, equipment, and information. Halawa et al.[2] also discuss the design of hospitals and medical centers within the context of multifaceted architecture by presenting a common design process [Figure 1]. Some researchers have identified spatial layout,[11] circulation,[12] and wayfinding[13] as the most critical factors in the hospital design process, which significantly influence the concepts of form and plan. Other aspects of the research have examined aesthetic components in the interior design of spaces and their role in reducing stress and improving patients' well-being. These components include factors such as light, sound, and color,[14,15] noise pollution,[16] visual landscape,[17] energy considerations,[18] safety,[19] as well as issues related to environmental psychology and neuroscience.[20]

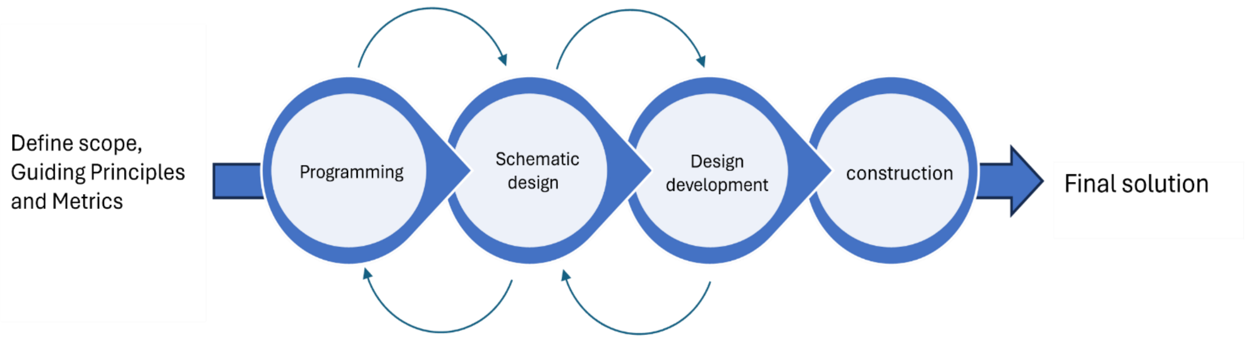

Figure 1. The process of hospital design[2]

The body of research indicates that the architectural characteristics of a hospital significantly affect patients, their treatment processes, and the alleviation of stress and tension within the environment, while simultaneously increasing the productivity of medical staff.[21] Frandsen[22] posits that, under normal circumstances, if an individual feels physically uncomfortable in their environment, they can choose to leave; however, a sick person is often compelled to spend their illness in a hospital setting. Some symptoms reported by patients in studies include emotional experiences such as stress and anxiety, as well as physical manifestations such as dry skin, headaches, and lethargy, which may not be necessarily related to their illness but can be exacerbated by the hospital environment.[23] Ulrich[24], one of the most influential researchers in hospital design, also acknowledges that designing a healing environment that simultaneously respects both the desirable parameters of architectural form and the conceptual aspects of architecture, has remarkable results on recovery and well-being of both patients and staff. Figure 2 shows the various design process factors that researchers have studied for their impact on patients and staff [Figure 2].

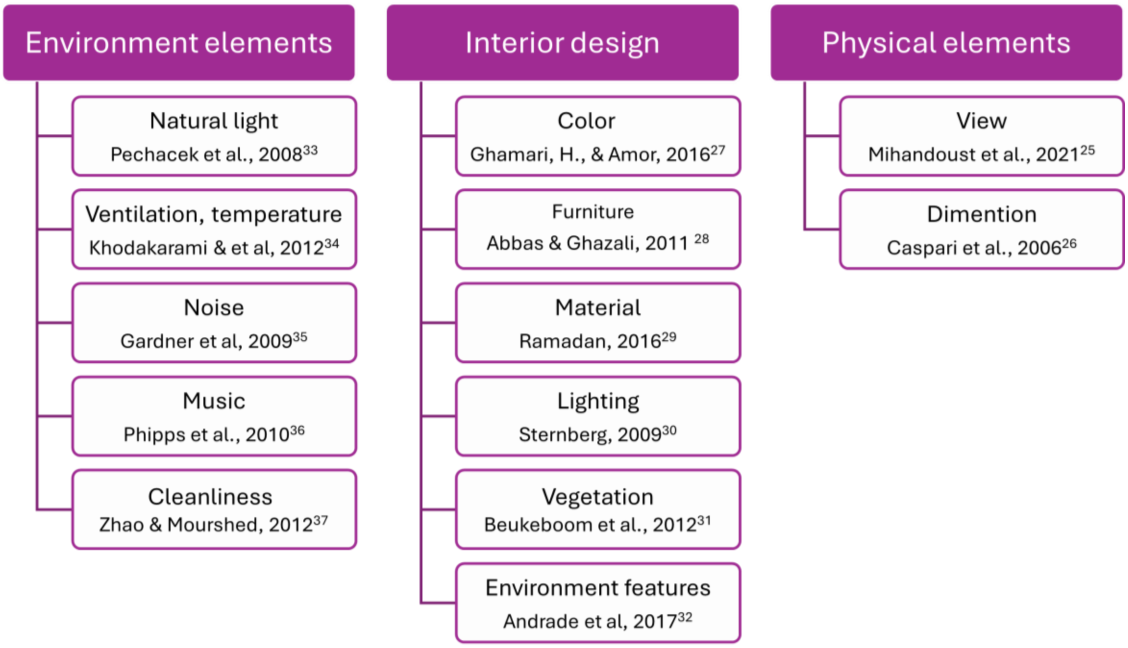

Figure 2. Factors of hospitals and medical centers design process [10,11]

In recent decades, the growth of AI in the design process has led to numerous studies evaluating its application in architecture. Notably, researchers have predominately used algorithms to achieve the goals of the hybrid process that integrates architecture and AI, which include high speed, accuracy, and the provision of multiple optimal options. Additionally, many studies have focused on combinations of algorithms within the same category. Pena *et al.*[38] in their review study, acknowledge that 85% of the articles published over the last three decades used evolutionary algorithms, particularly genetic algorithms, which provide acceptable results in optimizing design options. [39-42] Conversely, the advancement of deep learning algorithms has expanded their use in architectural research, resulting in desirable outcomes across various stages of the design process.[43-45] In some studies, researchers have used mathematical models and their logic to generate and evaluate options presented by machines. In this way, they were able to measure the degree of compliance of these options with the goals envisaged in the architectural design process.[46-48] It should be noted that the process presented in [Figure 1] is designed for humans as an architect, and there is no role for AI as a collaborator with the architect which is seen merely as a tool in the architect's hands. However, few studies have addressed theoretical issues or presented theoretical models for the generative design process of healthcare centers, and mostly, due to the functional nature of AI, have specifically measured the role of this technology in the design process practically and experimentally. Among the studies that used AI in the field of designing medical centers and hospitals, Yeh & Ford [49] used a convolutional neural network to optimize the spatial layout of a hospital.

Cheng & Lien,[50] after using various evolutionary algorithms in spatial layout design, introduced the honeybee algorithm as the most efficient optimization algorithm in this field. Additionally, Karaman *et al.*[41] used a combination of evolutionary algorithms to design the optimal shell for a hospital. Also, Halawa *et al*[2] proposed the most optimal light and routing in medical centers using the genetic algorithm, particle swarm optimization (PSO) and SA.

Fundamental Approaches in AI

In the early to mid-twentieth century, following the advent of computers and the broad theoretical discourse surrounding them, some AI scientists undertook extensive research to achieve smart machines. These efforts gave rise to comprehensive studies based on theories from the philosophy of mind, cognitive psychology, computer engineering, and, in short, discussions in 'cognitive science'. This culminated in the emergence of a branch of philosophical studies known as the philosophy of AI.[51]

Researchers have observed many similarities between the mind and the computer. In their view, digital computers represent the best model for studying how information processing occurs in the human mind. Therefore, based on functionalism, the mind can be considered a very complex computer that processes information step by step, sequentially. Alternatively, from a perspective inspired by neuroscience, information processing occurs in parallel rather than sequentially.[52] Accordingly, the advocates of the first idea are called symbologists, who generally believe that information processing should occur in the form of a systematic transformation of physical structures that represent information carriers. The second group, known as connectionists, considers information processing possible through the operation of neural networks. They believe that this process does not need to be implemented by separate and independent structures; rather, it can be distributed as patterns of weights and connections within the neural network.[53] Based on these two ideas, two main approaches have emerged in the construction of intelligent machines: symbolic and sub-symbolic.

In the golden years, often referred to as the period following the advent of computers, the dominant paradigm of AI was the symbolic approach, which was considered a method based on problem-solving and reasoning. However, in the 1980s, sub-symbolic AI began to advance and has continued to be of interest in recent years.[54] The cornerstone of this approach is based on simulating the neural system of the human mind and focusing on the learning capabilities of machines. These two approaches have experienced their ups and downs over the years, each with distinct components, advantages, and disadvantages [Table 1]. According to Dreyfus,[55] neither can be considered superior to the other. In certain areas, the symbolic approach demonstrates considerable strength, whereas in others, the sub-symbolic approach excels. Therefore, experts believe that the solution to all issues cannot be found in a single approach.

Table 1. Features of the symbolic and Sub-symbolic (connectionist) approaches [52,53]

Feature \ Approach	Sub-symbolic	Symbolic
Components	**Neural Networks** (Mimicking the human brain) **Training Data** (Labeled data) **Algorithms** (For training and optimizing the model)	**Knowledge Base** (A repository of rules and facts) **Inference Engine** (Based on logical rules) **Rule-based Systems** (For information processing)
Advantages	**High Adaptability** (Flexibility in dealing with new data) **Complexity of Management** (Managing extraction and pattern formation processes) **Automatic Feature Extraction** (The ability to automatically learn features) **Noise Robustness** (High tolerance to noise)	**Interpretability** (The justifiability of a reasoning process) **Expert Knowledge** (Enabling the encoding of expert knowledge) **Logical Reasoning** (Drawing conclusions based on rules) **Rule-Based Approach** (Explicitly representing rules for modification)
Disadvantages	**Lack of Interpretability** (The decision-making process is often unclear (black box)) **Data Dependency** (The quality of the input data significantly impacts the results) **Computational Resources** (Requires significant time for training and optimization) **Data-driven** (Cannot provide satisfactory answers without sufficient and appropriate data)	**Lack of Scalability** (Difficulty in performing well when dealing with large amounts of data) **Lack of Adaptability** (Inability to flexibly accommodate new rules) **Difficulty in Knowledge Acquisition** (Challenges in encoding expert knowledge) **Inability to Handle Uncertainty** (Deficiencies in managing uncertain information)
Algorithm	Artificial Neural Networks, Machine Learning, Evolutionary Algorithms, Cellular Automata, Multi-agent Systems	Expert Systems, Natural Language Processing, Knowledge Engineering, Shape Grammar, Logic Programming

Since the goal of AI is to simulate various aspects of human cognitive processes,[6] researchers are striving to adopt comprehensive approaches in which symbolic and sub-symbolic methods complement one another rather than compete. This way, they can mitigate the limitations and shortcomings of each approach with the advantages of the other. These integrated methods and techniques aim to bridge the gap between the two [Figure 3].

Iko & Kotraki[56] state that the main idea is to build a system that can combine the advantages of both—namely, the power of reasoning and inference with the ability to learn from the environment. Lallement *et al.* [52] believe that symbolic approaches can solve problems that require high cognitive power, and that hybrid algorithms are more effective for performing everyday tasks. Just as humans deal with and solve both types of problems simultaneously, machines must also be able to address both challenges. As a result, both approaches should be utilized. Bermudez[54] refers to these techniques, which integrate symbolic and sub-symbolic theories, as the Neuro-Symbolic Integration (NSI) approach, in which both systems can perform high- and low-level human cognitive processes in a complementary manner. With this explanation, the following section will examine strategies for combining these two AI fundamental approaches.

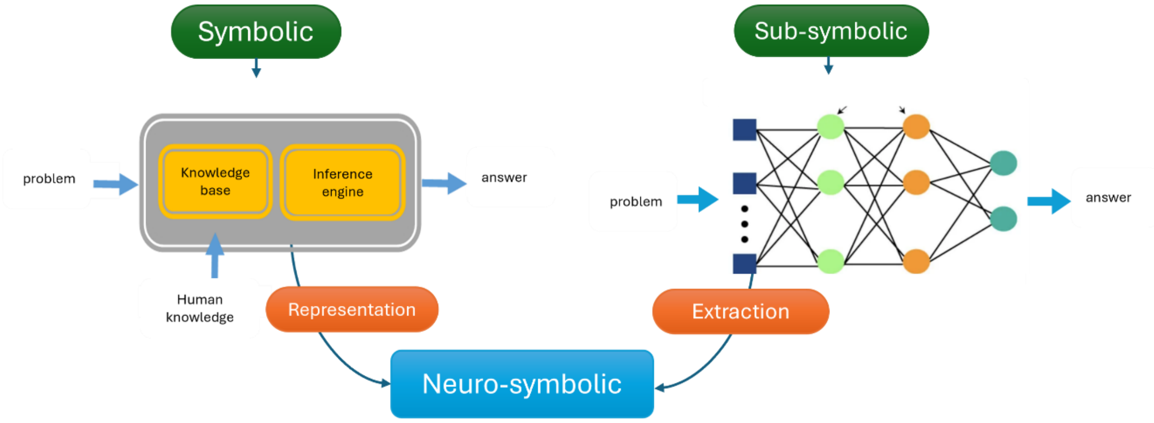

Figure 3. Symbolic vs sub-symbolic [2,56]

Strategies of the Neuro-symbolic integration (NSI)

To combine the symbolic and connectionist approaches, numerous methods and techniques have been employed in research. Most of the symbolic and connectionist systems used in studies thus far can be integrated within a unified approach. In studies related to this topic, strategies have been proposed to combine these two approaches, among which the hybrid strategy and the unified strategy have been the most popular [Figure 4]. In a hybrid strategy, two or more symbolic and sub-symbolic techniques are combined within an overall architecture, but they remain independent and are implemented in parallel, such as neuro-fuzzy systems with the aim of synergizing fuzzy logic and neural networks. In the unified strategy, one approach is the basis, and the capabilities of the other one are added to it. For example, the unified Neuro-symbolic system includes a neural network as the main component that uses symbolic knowledge in processing.[57] According to these two strategies, various classifications of these systems have been introduced by researchers [Figure 4]. Katz[58] presented the most famous Neuro-symbolic taxonomy at the association for the advancement of AI, which is illustrated in [Table 2] and [Figure5].

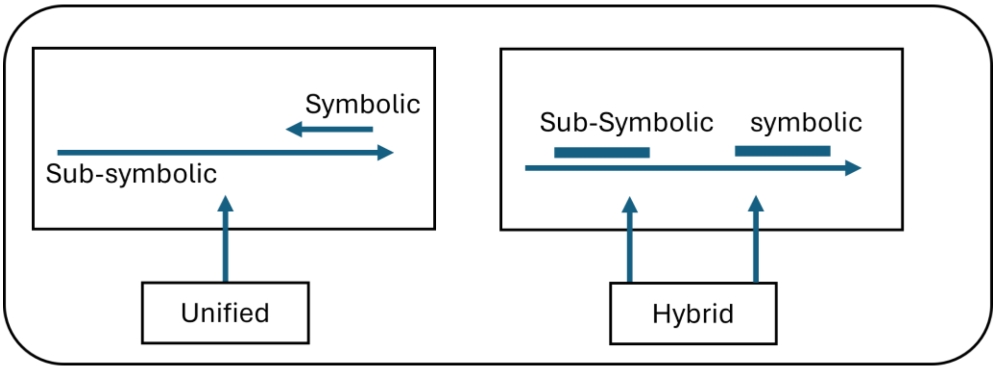

Figure 4. Hybrid vs unified methods in NSI approach [57-59]

Table 2. Overview of 6 methods of NSI strategies [56-59]

Strategies	Methods	Description
Hybrid	*1-Symbolic-neuro-symbolic*	As part of the usual deep learning process, all symbols are transformed into vector embeddings, which are then processed by neural models to generate symbols.
	2-Neuro-symbolic-neuro	A neural network model is created using symbolic knowledge. The neural network's initial weights are assigned to several types of symbolic knowledge.
	3-Neuro; symbolic	In the parallel pipeline, neural and symbolic systems are given distinct tasks and exchange the information they have extracted to enhance the performance of either the individual or the collective systems (e.g. neuro-symbolic concept learner, deepProbLog).
Unified	*4-Symbolic [neuro]*	Refers to symbolic solvers that use neural models as subroutines, such as the neural state estimator, such as the Monte Carlo tree search.
	5-Neuro[symbolic]	Combinatorial symbolic reasoning is carried out via the neural network model. This is accomplished either by focusing on specific symbols at a given moment or by understanding the relationships between the symbols (e.g. GNNs).
	6-Neuro$_{symbolic}$	The network's loss function is regularized via a transition of symbolic logic principles. Tensor Product Representations and Logic Tensor Networks (LTNs) both have these rich transformation and logic embeddings.

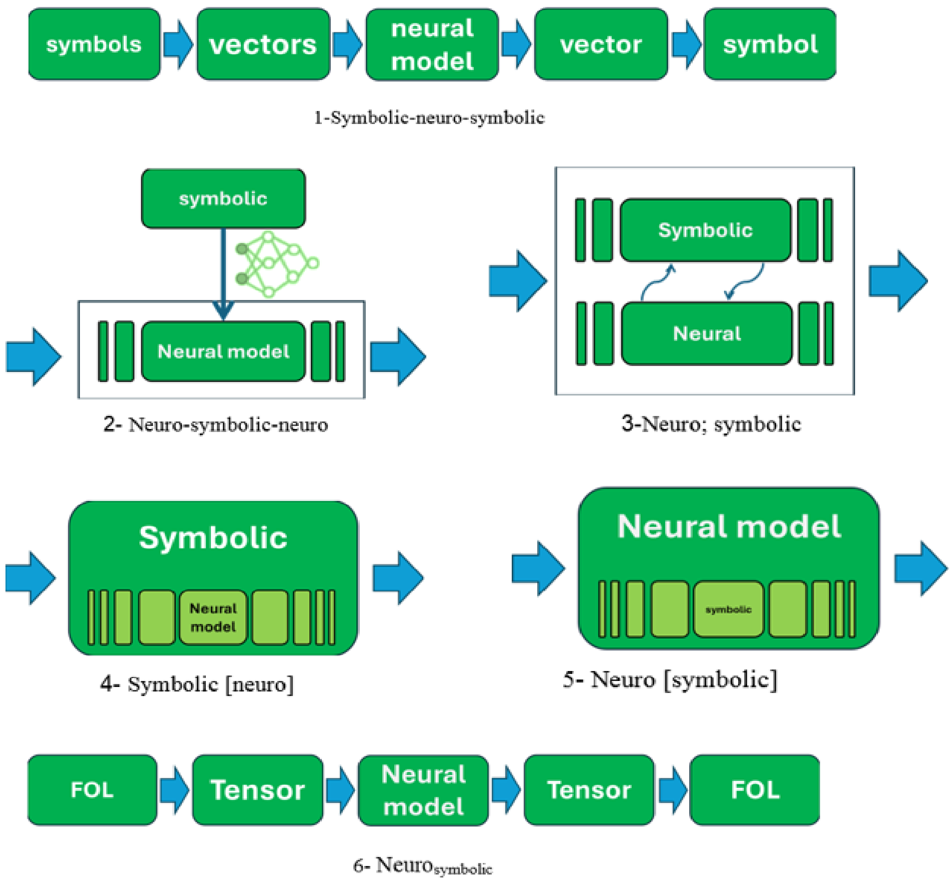

Figure 5. Neuro-symbolic Integration (NSI) approach

AI-based Generative Design Process

Numerous methods have been developed to enhance the architectural design process systematically.[19] However, these methods were primarily defined for humans. Even after the advent of computer-aided design (CAD) methods, the common design process for various applications, including hospitals, did not differ significantly from the pre-computer era. As a result, after several decades, the design process is still largely carried out by humans on paper copies, which are then transferred to computers by the user through software. This process cannot be considered a true collaboration between the architect and the computer, as the computer is still viewed as a tool in the hands of the architect.[60] In recent years, with the introduction of AI technology, there have been attempts to position AI as a colleague alongside the designer.

However, it has primarily been tested in research and studies rather than being able to perform architectural activities alongside the designer practically. The most important reasons for this, in addition to the lack of collective will to achieve this goal,[61] include insufficient training in algorithmic architecture and the lack of necessary skills among architects to communicate effectively with machines. This communication is facilitated by programming languages, as well as knowledge of mathematics, statistics, probabilities, and data science. [44] The consequence of this deficiency is the absence of methods for the generative design process of AI-based architecture, which continues to lead to weaknesses in the architectural design of medical centers and hospitals.

The generative design process, or, in other words, the AI-based design process, is one in which an AI algorithm generates design options based on the architect's initial ideas and specific parameters.[45] These parameters for designing a hospital include all the influential components of architectural design, such as the factors mentioned in [Table 1], as well as quantitative data such as regulations, laws, and structural and construction considerations.

In this new design process, instead of entering an exact plan into the system, the designer specifies design parameters and constraints by transferring qualitative and quantitative data to the machine. This can be done through various methods, such as coding within a programming language environment.[44] The system can then suggest different design options for various parts of a hospital based on the training it has received. This approach can facilitate the optimization of the design process, [4] easily create complex and optimized designs,[9] and even help generate creative and unique solutions,[62] as algorithms can automate the design generation process and provide new and innovative options. [63] One of the key benefits of generative design in hospitals is that it allows architects to quickly explore and simulate a range of design ideas and alternatives by analyzing a wealth of data. Unlike traditional manual or computer-aided design methods, which can be time-consuming and expensive, generative design automates the process, enabling designers to access a diverse set of images and renderings swiftly.[12] McKnight[64] acknowledges that in the conventional architectural design process, even after the architect has selected the final option which is a long and time-consuming endeavor—he is uncertain whether the best option has been chosen. On the other hand, Bonamici et al. [65] referencing the generative design process introduced by Autodesk Inc., an American multinational software corporation and pioneer of computer-aided design (CAD), argue that despite significant advancements in this field, the designer's experience and knowledge remain the most critical elements of the design process. As a result, bilateral communication between the architect and the machine must be established efficiently. Villagi et al. [66] tested this approach and presented results with a high degree of acceptability. In the generative design process they introduced, the architect had two roles: not only did the architect code the AI models to facilitate the design process, but he or she also maintained full supervision throughout the process.

It can be inferred from the studies reviewed that the overall AI generative process is structured around three main stages: pre-design, design, and post-design [Figure 6]. Nagy et al. [67] contend that while generative design methods have significantly accelerated the process of producing architectural designs, they have not fundamentally altered the basis of the design process. Consequently, these three stages can be aligned with the traditional architectural design process: analysis, synthesis, and evaluation.[38]

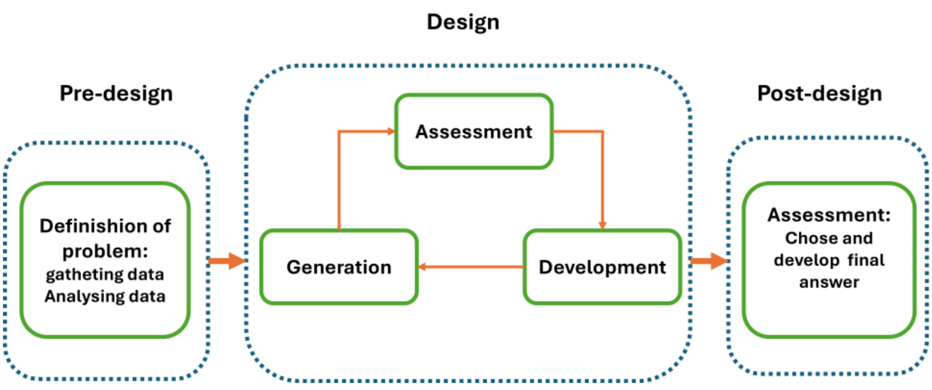

Figure 6. Overview of stages of AI-based generative design process (AI Gen) [64-67]

The generative model consists of three main elements: the human element (the designer), the machine element, and the interaction between the two. The human element is responsible for the first stage of the process. After defining the problem and constraints, the designer enters the second stage. It is important to note that 'designer' does not refer to a human; it refers to an AI system. The designer learns to refine the program with each iteration, bringing it closer to the design goals. After receiving approval from the human element, the machine element subsequently works to improve and develop the final design. Each stage comprises various steps and sub-steps aimed at achieving the desired outcomes, and the architect collaborates with AI to navigate through these steps systematically. These are illustrated in [Figure 7].

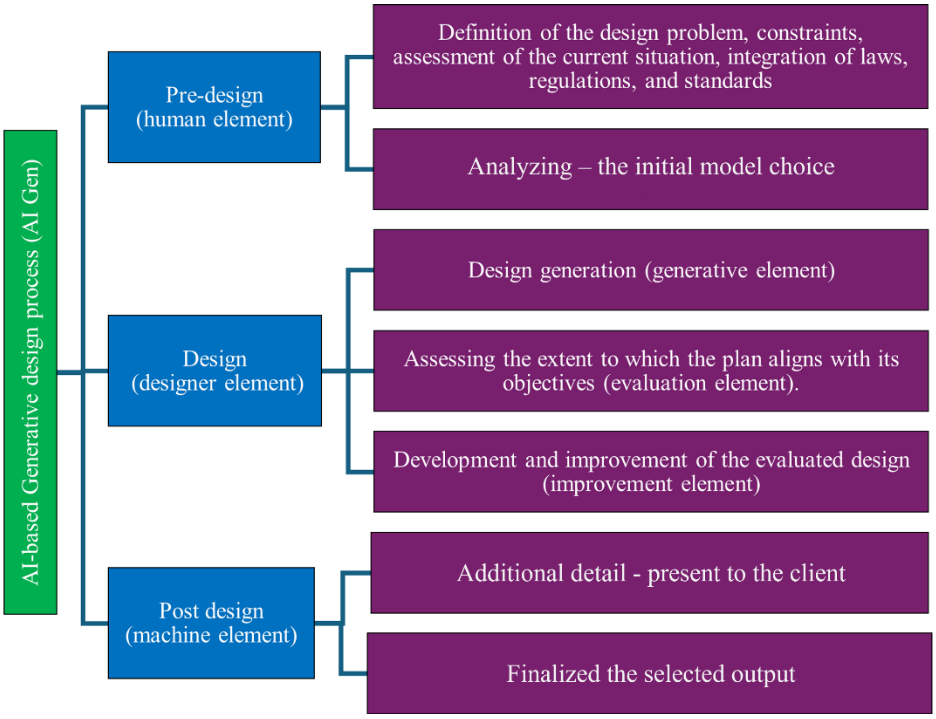

Figure 7. Different steps of the three stages of AI Gen

Discussion

The review and analysis of the findings indicate that there is a need to explain a comprehensive model that encompasses the concept of AI generative design in architecture. Through this model, strategies for integrating the algorithms of each approach, appropriate to the hospital design process, can be introduced. This model is illustrated in [Figure 8], and its components will be discussed in detail below.

Pre-design Stage (Cognition-analysis)

In the AI-based hospital design process, the first phase, titled "pre-design," consists of two steps. The first step is the definition, during which all the data necessary to address the hospital design problem is collected. Some of this data is extracted from the design plan and the subsequent demands, needs, goals, and constraints.[18] The other part is based on predetermined information, such as criteria, standards, laws, and regulations for the architectural design of medical centers, as well as a review of the budget, site, and case studies. This process is carried out by human resources (architect or design team).

The next step in this section is analysis, which involves analyzing the data collected in the first step to begin presenting initial solutions and producing the design. In the conventional hospital design process, the basis for analysis in the second step consists of theoretical foundations, qualitative concepts, and the architect's insights, such as creativity, intuition, style, and worldview. The output of this analysis includes various diagrams, graphs, and initial sketches that aim to achieve the design idea and concept. However, in AI generative design, the analysis step is performed by a machine that has previously become familiar with these principles and concepts due to the nature of AI. The output of this step is a knowledge base.

The knowledge base is a collection of data, rules, relationships, and training samples that function as the model's memory, and the model continually references it during the design process to retrieve information.[44] For each project, a knowledge base must be prepared that aligns with the specific requirements. The process of creating a knowledge base is carried out using existing algorithms from both symbolic and sub-symbolic approaches. Symbolic algorithms have a strong ability to extract features and analyze data, can logically explain the reasons behind their decisions, and draw conclusions through logical reasoning. However, they do face limitations, including the need for the human element to manually define rules and symbols for the symbolic model in advance; if the information is incomplete, inferences cannot be made, and as the volume of data increases, the computations become more complex. In the sub-symbolic approach, machine learning algorithms can provide acceptable outputs in extracting hidden patterns from large dataset.

These algorithms exhibit high accuracy, predictive power, and the potential for automation, allowing them to improve their results each time they encounter new data. These algorithms can perform classification, pattern extraction, and relationship discovery by analyzing similar examples and storing this information in their memory for later reference.[59] However, they require a substantial amount of high-quality data and powerful systems for complex computations.

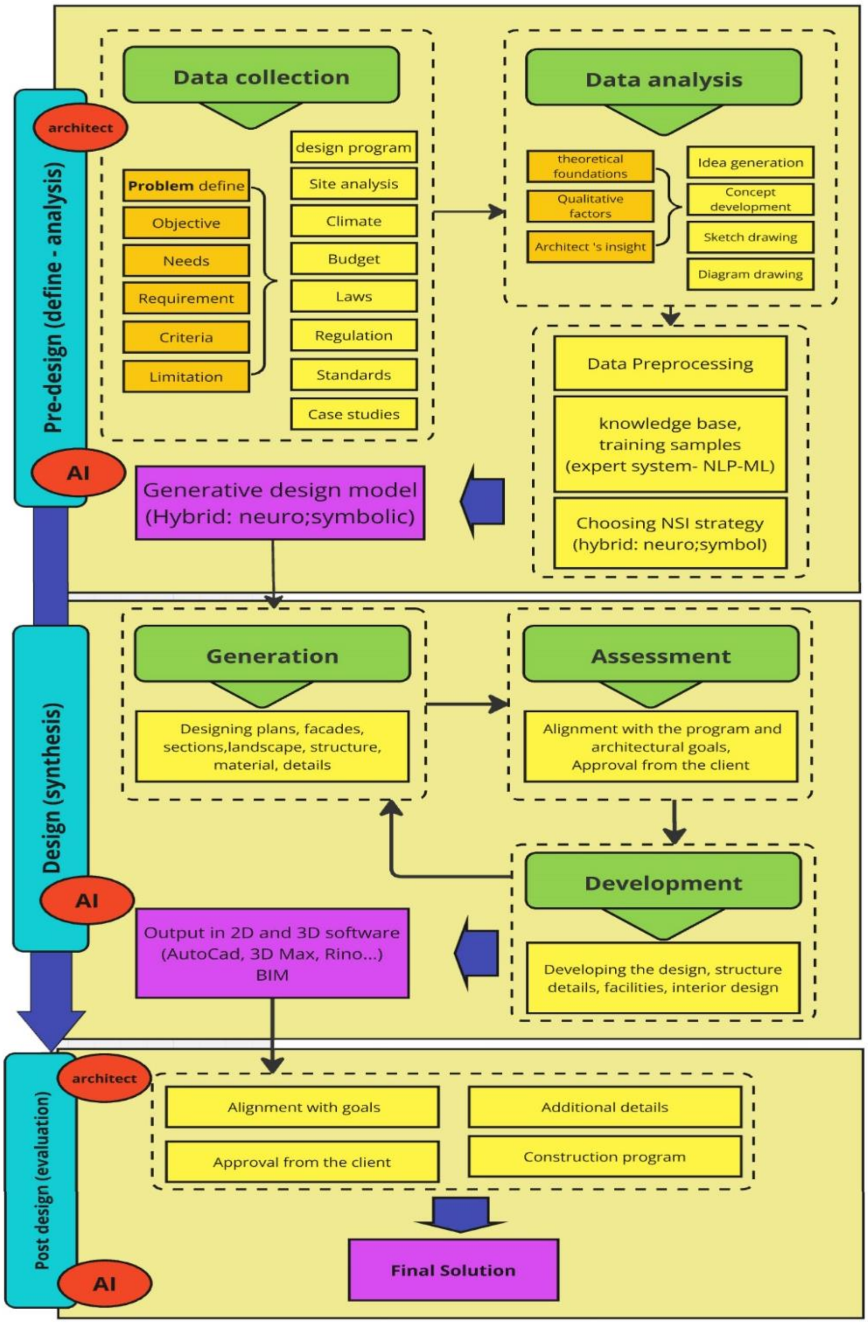

Figure 8. The AI Gen hospital design process through neuro; symbolic method

It should be noted that several technical measures are necessary for data collection and its transfer to the machine, such as pre-processing and post-processing of data, dimension reduction, normalizing, and the use of mathematical formulas for training. These tasks are best performed exclusively by an architect familiar with AI or by a team consisting of an architect and other computer science specialists. It is also important to note that the selection of algorithms for building a knowledge base depends on the type of data collected in the first step. For structured data, such as patient information, hospital-related furniture, dimensions, sizes, standards of the environment, treatment space, rules, regulations, and other quantitative items, expert systems and machine learning algorithms—such as clustering, classification, and regression algorithms—can be used. For unstructured data, such as images of similar samples and text documents, natural language processing algorithms, instance-based algorithms, and neural networks can be used in conjunction.

The Main Model Choice

Another important issue to consider in the first phase of the AI-integrated process and hospital architecture design is the choice of the neuro-symbolic model, along with an appropriate strategy to initiate the production process. As previously mentioned, in earlier studies, this strategy has been used less frequently, with researchers typically designing the architecture using a single algorithm like GA or, at most, combining two algorithms from the same category, for instance, evolutionary algorithms, which cause some challenges. The main challenge of using these algorithms is due to their nature. Evolutionary algorithms have a random nature that can lead to unnecessary mutations.[38] Therefore, with the increase of calculations, the algorithms acted randomly and went out of the rules and regulations set for the spaces (for instance, the standard dimensions of a bedroom). Among the various technical disadvantages of these algorithms are the tendency to become trapped in a local optimum, insufficient mathematical support, uncertainty regarding the final solution (including the possibility of a more optimal answer) and a lack of memory to retain information from previous solutions.[41] While neural networks have gained significant popularity among researchers in recent years, they come with notable drawbacks, the most prominent being the need for a vast amount of training data. Additionally, the lack of interpretability in these networks hinders the ability to logically validate the processes they undergo, particularly when it comes to designing hospital layouts. By employing a unified approach, some of the challenges that researchers faced can be addressed.

When examining strategies for selecting the appropriate method, it is noted that systems using an “integrated strategy” encounter design challenges due to their architectural complexity and exhibit less flexibility in modifying or developing parts of the model. In this approach, the neural network and the symbolic system are fully integrated and operate as a cohesive whole. In contrast, the “hybrid strategy” operates on the principle that neural networks and symbolic systems are developed separately and connected through an interface, offering greater flexibility. This means that components of the system can be changed and developed independently, depending on conditions such as new data entry.[64] Conversely, separating the components facilitates understanding and system analysis. However, the presence of the interface may slightly reduce the system's overall efficiency, and ensuring coordination between the symbolic systems and neural networks may require additional precision and supervision.

Given these considerations, a hybrid strategy appears to be a more suitable choice for the design process of a complex subject such as a hospital. Among the various combinations of hybrid strategies, method number three (neuro; symbolic), stands out as the most effective one [Figure 9]. This approach means that the foundation of the designer's AI model is based on neural networks, with the symbolic system functioning alongside these networks as a knowledge base and an expert system capable of logical reasoning.

Considering the diverse components involved in the hospital design process (see Figure 2), a model is needed that can address complex challenges, such as architectural design. Additionally, as indicated in Table 1, symbolic algorithms are not a suitable basis for the designer's AI model due to their limitations in learning and memory allocation, which results in inadequate performance in improving outcomes, as well as a lack of flexibility and scalability when handling large volumes of data—issues that architects face in hospital design. Consequently, symbolic algorithms will primarily serve as reasoning and inferential components for the model's decisions.[62]

On the other hand, the growth and development of neural networks over the past few decades, along with their effectiveness in handling large amounts of data and their ability to learn from numerous training examples, make them a suitable choice as the main foundation for model architecture. They also demonstrate high speed and accuracy in solving problems. However, they require a substantial amount of data, and the decision-making processes of these networks are often opaque, leading to their characterization as "black boxes". [67] Accordingly, neural networks should be combined with symbolic systems to ensure that the results of the AI model align with the design rules and criteria set by the architect. The specific logic inherent in data analysis, as provided by symbolic systems, can not only reduce the volume of data and, subsequently, the processing time required by neural networks but also enhance their interpretability in delivering results. The characteristics of generativity, pattern recognition, and generalizability enable neural networks to perform effectively in the design generation phase of the architectural design process.[66]

Along with all these considerations, another important issue that should be considered are ethical issues. It’s essential to recognize that ethical issues in AI-driven design encompass a wide range of considerations, including moral questions and practical aspects of accessibility and equity. Like all AI models, they are only as good as their training data. If that data is incomplete or biased, then a biased unfair design is probable outcome.[56] To act against such things, it must:

- Work on a broad and representative dataset; by training AI models using data from various origins to ensure generated designs would be less biased or more inclusive.
- Consist of the needs of a bunch of robust algorithms; employ algorithms that have significant tolerance to uncertainty but are intelligent enough to make the right decision based on seemingly incomplete data.
- Developing ethical guidelines; promoting the ethical structures so that responsible and ethical use of AI is ensured.
- Incorporate human checks; human checks are also essential for monitoring the AI-driven design process and tagging the necessary parameters.

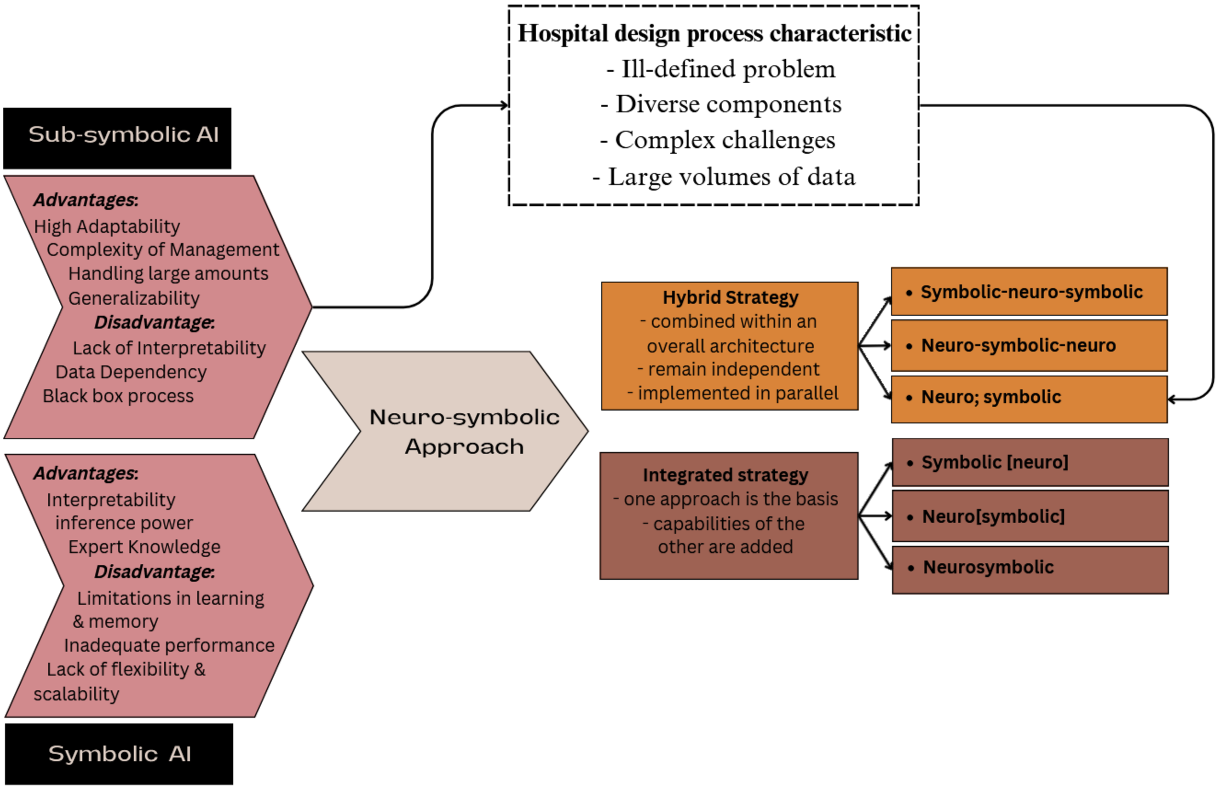

Figure 9. Selection of the main model based on the hospital design characteristics and the neuro-symbolic strategies features

Design Phase Stage (Synthesis)

Following the initial set of actions, the second phase, known as synthesis, prepares the AI model to generate architectural documents automatically. This phase is divided into three steps. In the first step, the design generation begins, and the model offers solutions to the architectural problem based on its learned experiences. After the generation, the second step involves evaluating all possible states produced by the generative model. In this step, algorithms assess the proximity of each option to the design goals, allowing for the elimination of unsuccessful choices. In the third step, the evaluated design is improved and made detailed. The entire document is then ready for the next stage. Throughout the synthesis phase, much like in the human design process, the AI model continuously iterates between these three steps, ultimately delivering an improved output aligned with the desired goals.

In the integrated design process of architecture and AI, the synthesis phase is entirely the responsibility of the machine. It is dependent on the model's underlying architecture, which may include a variety of machine learning algorithms, such as K-means clustering or instance-based algorithms, deep learning algorithms like Graph Neural Networks or Generative Adversarial Networks, and evolutionary algorithms such as Genetic Algorithms or Particle Swarm Intelligence, as well as their combinations.

Following this phase, the designs generated by the model can be exported to traditional architectural design software such as AutoCAD and Revit. Additionally, certain outputs—including diagrams, graphs, and plans—can be displayed in coding environments like Python. In recent years, the emergence of Building Information Modeling (BIM) software, particularly Revit, has resulted in a growing preference for its outputs over other software options.

It is crucial that spatial, environmental, and structural considerations work in parallel and support one another. According to Weber et al.,[68] software such as Revit can comprehensively present these aspects through detailed executive plans and graphic representations. Additionally, various factors must be considered in the design of different hospital spaces, including patient rooms, inpatient wards, surgical rooms, ancillary areas, and administrative offices. Key issues such as energy use, daylighting, waste management, and greenhouse gas emissions are also critical and should be addressed by selecting an appropriate strategy during the hospital design process. This comprehensive approach should occur alongside the generation of architectural documents by the model.

Post-design (Evaluation) Stage

After the design phase, the architect reevaluates the final solution using AI algorithms and statistical tools, incorporating additional details as needed. During the evaluation stage, as mentioned in the ethical issue above, the architect can interact with the initially created database to make modifications and achieve a more refined final design.[69] At this point, the architect is presented with a reduced number of design options, as undesirable alternatives have already been eliminated during the evaluation stage of the previous phase. The selected output that meets the desired objectives is optimized, and with the approval of both the architect and the client, it is finalized as the solution. Following this selection, AI algorithms can further assist the architect and project stakeholders with construction challenges, project scheduling, and the analysis of new data by referencing the knowledge base.

Conclusion

This study presents an integrated process for AI-based hospital design. Using neuro-symbolic strategies, this process leverages the strengths of both symbolic and sub-symbolic approaches. This integrated methodology holds significant potential for generating innovative and optimal architectural designs that address the complex needs of hospitals.

In this approach, the architect serves as the human element, responsible for providing data to build a knowledge base, supervising the production process, analyzing and enhancing the generated design, and ultimately making the final decisions regarding the outcomes. This study shows that AI algorithms, when implemented through a hybrid strategy and method number three (neuro; symbolic), can deliver acceptable outputs in collaborative partnership with the architect. However, implementing this approach comes with challenges, including the need for vast quantities of high-quality data, substantial computational costs, and the complexities involved in designing and constructing the foundational architecture of the AI model.

Given the rapid advancements in AI, future research should emphasize practical, interdisciplinary collaboration between architects and other relevant experts in the healthcare field to develop more effective hospital designs.

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