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Architectural spatial layout design for hospitals: A review

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ABSTRACT

The design of hospital spatial layouts is a critical aspect of healthcare architecture, directly influencing patient outcomes, staff efficiency, and the overall quality of care. A well-designed hospital layout is essential for ensuring smooth operations, minimizing errors, and improving both patient and staff experiences. This paper reviews the significant advances in the field, particularly focusing on the transition from traditional design methods to the integration of computational techniques and machine learning (ML) in hospital layout planning. Despite these technological advancements, there remains a notable gap in the full adoption and optimization of these methods to effectively address the inherent complexities of healthcare environments. This review identifies that while computational methods and machine learning-driven approaches have brought precision and innovation to hospital design, the challenge lies in balancing these technologies with the expertise and insights of human designers. Moreover, the need for interdisciplinary collaboration between architects, healthcare professionals, and engineers is emphasized as crucial for the successful implementation of advanced design strategies. Insights from this review highlight the potential of future research to bridge the existing gaps, proposing directions for the continuous integration of technology in hospital layout design.

1. Introduction

Hospitals stand as some of the most intricately designed structures, created with the purpose of fulfilling the diverse requirements of healthcare delivery. The layout of a hospital significantly affects numerous operational aspects, such as efficiency, patient care, the well-being of the staff, and the overall quality of healthcare services. Ulrich et al. [1] highlighted the critical role of the physical setting in healthcare environments, noting that strategically designed facilities can markedly improve the level of services provided. The layout design of the hospital directly influence components like the allocation of nurses' time, navigation within the facility, the flow of patients, and the risk of overcrowding. Therefore, the design of hospital layouts is crucial, as it directly contributes to overcoming operational challenges and ensures the delivery of high-quality healthcare services.

Besides its fundamental significance, the design of healthcare facilities involves a complex and detailed process. According to Hicks et al. [2] point out that the complexity of healthcare facility design goes beyond mere physical space arrangement; it includes managing the dynamic movement of patients, staff, visitors, equipment, and the flow of information within the facility. The way spaces are configured significantly influences the facility's effectiveness, guiding the movement patterns that affect how accessible areas are, and shaping human behaviour and interaction. As a result, a key challenge in designing hospitals is understanding how these spatial arrangements impact human choices, mobility, and the overall efficiency of operations and activities [3].

Designing hospitals is a critical, evidence-based, and multidisciplinary endeavour for delivering high-quality medical care. This process, involving architects, healthcare professionals, and engineers, aims to create spaces that promote healing, prioritize patient

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care, and ensure operational efficiency. Key to the design is the integration of mechanical, electrical, and technological systems, alongside measures for infection control and the crafting of healing environments through thoughtful interior design. Early design decisions are essential to establish a seamless flow for all users within the facility, thereby reducing waiting times, ensuring ease of movement, and addressing critical aspects like privacy, noise control, and natural lighting. However, achieving these goals can be challenging due to the complex spatial relationships within healthcare settings [4]. The layout design and optimization process seeks to navigate these complexities by strategically arranging spaces to meet design objectives while fostering an efficient, safe, and patient-centred healthcare environment.

Traditional and computational design methods, including Facility Layout Planning, have been pivotal in evolving hospital layout design strategies. These methods have progressively incorporated advanced technologies, including machine learning (ML), to enhance the generation and evaluation of hospital floor plans. Spatial network analysis and simulation modelling offer quantitative assessments of hospital functions, visibility, accessibility, patient flow, and staff flow, providing valuable insights into the effectiveness of layout designs.

This paper aims to conduct a comprehensive review of studies applying various methodologies for creating hospital layout designs. It seeks to trace the evolution of architectural spatial layout generation methods, design how hospital spatial layouts according to different criteria and examine the resolution of performance criteria in hospital floor plan design.

This review focuses on the spatial layout of hospitals, particularly examining how the design process has transitioned from traditional methods to computational techniques, and ultimately to machine learning (ML) driven approaches. The objective is to analyse the evolution of architectural and specifically hospital spatial layout design, highlighting how each stage has contributed to more efficient and sophisticated layout planning.

This review addresses several key questions.

- How have architectural spatial layout design methodologies evolved with new technologies?
- What historical shifts in tools and techniques have influenced the development of architectural floor plans?
- What are the current methods and tools used in hospital spatial layout design, and how have they evolved with technology advancements?
- How are emerging technologies such as machine learning (ML) influencing the methodologies used in architectural and hospital spatial layout design?

The main contribution of this article is to discuss in detail the development and changes in the design methods of architectural spatial layouts, compared to previous review studies in this field, and to examine hospital spatial layout design thoroughly considering this information. It also examines studies on machine learning in hospital spatial layout design, in addition to previous reviews. Furthermore, because of all the reviews, detailed conclusions will be drawn about the challenges of hospital spatial layout design methods and future directions.

2. Methodology

This study's research methodology follows to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The literature examined in this review includes peer-reviewed journals, books, and doctoral dissertations released from 1965 to 2023, identified through databases like Scopus and Google Scholar. The resources were divided into two main categories: the first involves resources related to the architectural spatial layout design, and the second is resources dedicated to designing hospital spatial layouts.

For the first category regarding architectural spatial layout design, no systematic review has been conducted. This section has been limited in scope, focusing only on important sources to understand the evolution of architectural and hospital spatial design over time.

For the second category, which involves hospital spatial layout design, a systematic review has been conducted. For the literature search, the keywords employed were “hospital layout”, “healthcare facility layout”, paired with terms like “design”, “planning”, “problem”, “automation”, “optimization”, “generation”. A search filter mechanism was applied to identify literature featuring these keywords within the paper's title, abstract, and keyword section, and which were written in English. After selecting appropriate literature databases, exclusion criteria were applied, removing articles that were either not fully accessible or did not align with the thematic focus of this paper. Additional sources were incorporated by examining the reference lists of articles already chosen.

In the comprehensive search for the second category, the author evaluated 55 studies, including journal articles, and selected 7 for detailed review in this paper. The selection criteria were based on two main factors: first, the study's relevance to hospital building typologies, and second, its exploration of new issues and dimensions in hospital design. Specifically, the chosen publications clearly described the design challenges they addressed or the new insights they provided. Most of the studies were sourced from notable journals, including 8 from the Health Environments Research & Design Journal (HERD), 5 from the Journal of Building Engineering, and 3 from Automation in Construction.

In this paper, the literature on architectural and specifically hospital spatial layout design is categorized to systematically address different aspects of architectural challenges and solutions. The classification begins with a general overview of architectural spatial layout design, transitioning into more specialized discussions on computational design methods and the integration of machine learning (ML) in architectural spatial layout design.

Firstly, this paper explores architectural spatial layout design in section 3, examining the fundamental concepts and historical evolution of spatial layout design in architecture. It lays the groundwork by discussing traditional methods, computational methods, facility layout planning methods and the subsequent shift towards ML-driven techniques, setting the context for understanding the specific complexities of hospital layout design.

Secondly, this paper systematically reviews the evolution of hospital spatial layout design in section 4, focusing on the shift from manual to automated design processes, and highlights the significant advancements in architectural design methodologies. It details the role of early CAD systems, the application of algorithmic space planning, and the integration of modern software and optimization algorithms that have dramatically transformed architectural practices. Additionally, the paper explores how facility layout planning techniques, originally developed for manufacturing, have been adapted to optimize hospital layouts for better efficiency and effectiveness. It also examines the latest advancements in applying machine learning (ML) particularly through the use deep neural networks, in hospital spatial layout design. By categorizing and discussing these technological and methodological advancements, this paper aims to provide a clear and comprehensive understanding of current trends and future directions in hospital spatial layout design. In Fig. 1, a classification of issues associated with layout design is presented, forming the basis for the examination of methods used in architectural and hospital spatial layout design.

3. Architectural spatial layout design

The architectural space layout design process is vital for shaping how buildings are experienced and used, focusing on spatial relationships and geometric forms to meet client needs [5]. This process balances multiple, sometimes conflicting criteria, including solar exposure, efficient circulation, aesthetics, and sustainability [5]. Given its iterative nature, architects use methods like sketching and digital modelling to refine their designs, addressing diverse objectives [6]. There has been a shift towards automated layout design and optimization to manage the complexities of designing complex structures like hospitals. This shift leverages computational design and machine learning to enhance the design process, reflecting a broader trend towards technological integration to improve efficiency and reduce errors [6]. In summary, the architectural space layout design process is crucial in the architectural design phase, balancing diverse criteria, and evolving through technological advancements to address its inherent challenges.

3.1. Computational design methods for architectural spatial layout design

The evolution of architectural space layout design from manual to automated processes reflects significant advancements in computational design, driven by the integration of prototypes, sophisticated programming, and optimization formulas [5]. This shift began in the 1960s with milestones like Sutherland's [7] Sketchpad, the first CAD system, and Armour and Buffa's algorithmic space planning method, CRAFT, which laid foundational principles for computational design despite their limitations in geometric descriptions and user interfaces. Also, Alexander [8,9] introduced of computational concepts into architecture laid the foundation for computational design, influencing both software programming and architectural practices. Negroponte [10] explored CAD in projects like URBAN II and URBAN V showcasing the potential of technology to enhance architectural design and predating its widespread adoption in the industry. These contributions were crucial in integrating computational methods into architectural design, fostering a collaborative approach between computer scientists and architects. Furthermore, modularity in architectural design has been key in applying systematic and mathematical principles to streamline and economize construction. Modularity emerged from traditional design practices and was popularized by the modernist movement and architects like Le Corbusier, aiming for mass production and stan-

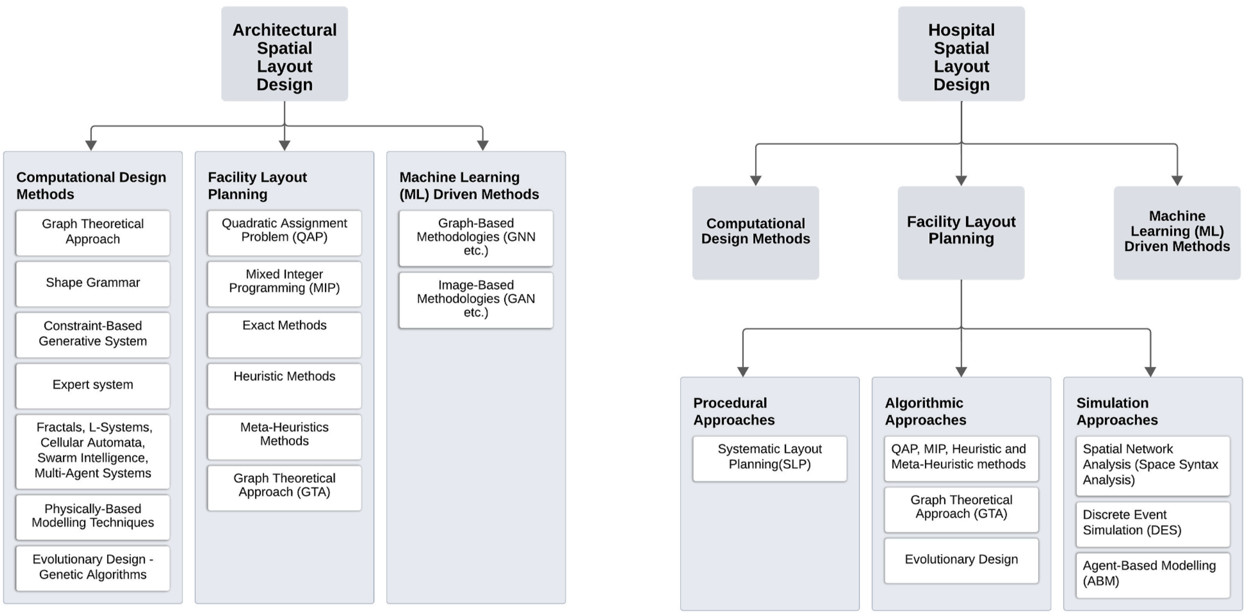

Fig. 1. Architectural and hospital spatial layout design review taxonomy, image source: author.

dardizing building parts to improve design and construction efficiency. Since the late 20th century, parametric design has profoundly impacted architectural practices, streamlining the creation of complex, adaptable designs using rules and parameters for swift modifications and heightened customization [11]. Despite its revolutionary impact, parametric design has encountered obstacles such as managing numerous variables and the need for extensive computational resources, leading to criticisms of design oversimplification. Chaillou [12] proposed that the integration of artificial intelligence (AI) could address these challenges, facilitating a more comprehensive and holistic approach to design. Also, Mitchell [13] outlined generative algorithms have transformed computational design using computational power for creativity and problem-solving. Generative design employs algorithms to automate solution creation, offering multiple solutions within specific constraints, applicable in architecture, engineering, and product design. In addition to these developments, Building Information Modelling (BIM) has revolutionized architectural design by managing a building's lifecycle from planning to renovation, enhancing collaboration, and data-driven decisions. Integrating with computational design, BIM enables the creation of complex, efficient designs, transforming how buildings are conceived and constructed.

The evolution of architectural space layout design has been notably influenced by applying graph theory and computational methods, beginning with Buffa's [14] study on functional diagrams and extending to Levin's [15] efforts on automating the design process. Krejcirik [16] conducted further exploration into the optimization of planned spaces through computer-aided design, followed by Weinzapfel et al. [17], who utilized geometric definitions and their relationships as design constraints for 3D spatial arrangements. Eastman [18] introduced the "space planning problem (SLP)" as a conceptual challenge within the architecture field. In the 1970s, the foundational efforts to create automated systems for generating architectural space layouts were rooted in graph theory, as outlined in the works of Levin [15] and Grason [19]. Levin [15] wrote a book focused on using graphs to find the best architectural layouts. Grason [19] introduced graph-based representations of floor plans for improving computer-assisted space planning. Roth et al. [20] initiated the process by converting graphs into rectangular floor plans, though their method didn't support automatic design generation. Also, Roth and Hashimshony [21] explored into the application of graph algorithms to overcome challenges in architectural design. Subsequent research expanded the application of graph algorithms to tackle architectural problems, with notable contributions like the development of algorithms for generating rectangular duals of triangulated graphs by Kozminski and Kinnen [22], and the enhancement of these algorithms by Bhasker and Sahni [23] for more efficient floor plan generation. Medjdoub and Yannou [24] introduced a method combining initial topological solutions with dynamic spatial organization, while Martin [25] proposed a three-step process involving the creation of adjacency graphs, room positioning, and resizing. Marson and Musse [26] utilized hierarchical treemaps for floor plan production, and Shi et al. [27] applied the Monte Carlo Tree Search method for the initial design phase. Wang et al. [28] developed a method to reinterpret existing floor plans by adjusting room connections, leading to the creation of new layouts. Wang and Zhang [29] introduced an innovative approach using graph transformations and dual graphs. This method facilitates the customization and generation of floor plans, providing a systematic framework for architectural design modifications. These studies collectively highlight the importance of graph theory in creating and optimizing architectural space layouts, demonstrating its impact on the field. Also, graph theory's role in architectural design has evolved to include AI and ML, enabling predictive and innovative optimization of spatial layouts through extensive data analysis.

Beyond graph theory methods, in the late 1970s, Stiny and Gips [30] introduced the concept of shape grammars, offering a rule-based framework for analysing and generating designs. This approach uses shape rules for transforming shapes and a generation engine for rule application, serving purposes from analysing design patterns to creating new design languages. Stiny and Mitchell [31] applied it to reinterpret Andrea Palladio's architectural plans, while Koning and Eizenberg [32] used it to define rules for Frank Lloyd Wright's designs. Colakoglu [33] and Duarte [34] further applied shape grammars to design Hayat houses and replicate Álvaro Siza's Malagueira residences, respectively. As an alternative method, Li et al. [35] proposed a constraint-based generative system for automated architectural spatial layout, focusing on optimizing floor plans through nonlinear programming to meet a set of predefined constraints. Flemming et al. [36] introduced an expert system designed to generate and evaluate architectural floorplans, using a comprehensive approach that includes generation, evaluation, control strategies, and processing stages to refine the final design. Arvin and House [37] introduced a transformative concept in space layout planning by employing physically based modelling techniques to create an interactive and responsive design process.

On the other hand, some researchers address ill-defined architectural design problems using evolutionary algorithms like genetic algorithms (GAs), which generate and evaluate numerous design alternatives to identify optimal solutions based on criteria such as functionality, light access, and energy efficiency through iterative cycles. The concept of evolutionary architecture, initiated by Frazer [38], led to significant advancements in design methodologies. Jo and Gero [39] introduced an evolutionary design model focusing on the structured capture of design knowledge to solve specific challenges, applying it to optimize large office layouts with genetic algorithms. Elezkurtaj and Franck [40] further developed this by presenting a generative design system using genetic algorithms, offering an architectural software-like interface for easier user interaction. Nagy et al. [41] advanced the field with a multi-objective genetic algorithm for office space planning, considering various architectural performance criteria. Although their method showed promise, it highlighted the need for faster computational processes to generate and optimize designs effectively.

3.2. Facility layout planning for architectural spatial layout design

The facility layout planning problem, a key area of study across industrial engineering, management science, and architecture, focuses on optimizing space layouts to improve production systems. This involves strategically organizing production components within a physical space to enhance compatibility with the production process [42]. The challenge encompasses arranging physical departments and resources to meet various objectives and adhere to constraints such as space shape, size, and orientation [43,44]. Efficient facility layouts significantly boost productivity and efficiency [45], whereas inadequate designs result in increased work in process and prolonged production lead times [46]. Tompkins et al. [47] outline a methodical facility layout design process to enhance operational efficiency, productivity, and cost savings. This process begins with setting clear objectives and analysing relationships and space needs. It progresses through developing and assessing various layout plans, choosing the best option, and implementing it while ensuring the design remains flexible for future adjustments and improvements.

The primary focus in optimizing facility layouts is on minimizing material handling costs (MHC), a major portion of operating expenses in manufacturing, which can be significantly reduced through efficient layout designs [46–48]. Pérez-Gosende et al. [42] outline the optimization model's objectives, including reducing MHC and flow distances, alongside other goals like improving departmental adjacency and maximizing space use [48]. This holistic approach aims to enhance productivity and operational efficiency. The method selection for facility layout planning hinges on the facility's unique characteristics, goals, and constraints. Cubukcuoglu [49] explains that strategies adapt to various factors, such as departmental area needs (equal or unequal), layout configurations (number of rows and floors, either single, double, or multiple), objectives (single or multiple), and layout types (static, with consistent material flow, or dynamic, with changing material flow or demand), among other specific conditions.

To tackle facility layout planning challenges, a variety of methods are used, including the quadratic assignment problem (QAP), mixed integer programming (MIP), graph theory approaches, heuristic and metaheuristic strategies, and simulation-based methods. These methods aim to optimize layouts for operational efficiency and effectiveness. The QAP, introduced by Koopmans and Beckmann [50], provides a mathematical framework for optimizing department placement to minimize factors such as time, cost, and flow between departments. It has applications in various settings, including hospital layout planning [51,52]. The QAP's limitation of assuming equal-sized departments has been addressed by adaptations that divide departments into uniform grids, increasing problem complexity [53,54]. The Quadratic Set Covering Problem (QSCP) offers an alternative for accommodating different department shapes [55]. Continuous representation using MIP allows for flexible positioning of departments of varying sizes, offering more adaptable layout designs [56]. Montreuil [57] introduced the initial MIP model for continuous facility layout problems, incorporating both integer and continuous variables to design layouts with varying department sizes. This model overcomes QAP limitations and utilizes a range of optimization strategies, including exact, heuristic, and metaheuristic algorithms, genetic algorithms, simulated annealing, tabu search, particle swarm optimization, ant colony optimization, and integer linear programming. Exact methods find optimal solutions but are suitable for smaller problems due to scalability issues [58]. Heuristic methods offer quicker, near-optimal solutions without guaranteeing the best solution, while metaheuristic methods enhance heuristic strategies by integrating insights from AI and other fields [59]. Simulated annealing, genetic algorithms, tabu search, ant colony optimization, and particle swarm optimization are widely used for facility layout problems. Simulated annealing was first applied to QAP by Burkard and Rendl [60], and tabu search was introduced by Glover [61], proving effective for complex issues [62]. The graph theoretical approach (GTA) models facility layouts using vertices for facilities and edges for flows or connections, ensuring spatial arrangements reflect necessary functional relationships [63,64]. The main objective is to develop layouts that adhere to specific adjacency requirements among activities.

3.3. Machine learning (ML) for architectural spatial layout design

Artificial Intelligence (AI) encompasses the development of machines capable of performing tasks that typically require human intelligence, including critical thinking, problem-solving, and learning from experience. Tracing its roots back to the 1940s with foundational work by McCulloch and Pitts [65] and Turing's [66] Turing Test, AI has evolved through significant milestones and periods of enthusiasm and scepticism. The field has seen breakthroughs from the inception of neural network models to the emergence of deep learning in the 2010s, leading to human-level performance in tasks like image and speech recognition. Machine learning (ML), a critical subset of AI defined by Samuel [67], focuses on enabling computers to learn from data without explicit programming. It shifts from traditional programming to a model-based approach that predicts outcomes on new data, encompassing two main phases: training and testing. ML is categorized into supervised, unsupervised, semi-supervised, and reinforcement learning, each with specific applications ranging from data classification to decision-making through trial and error. The machine learning workflow involves several key steps: defining the problem, collecting, and preparing data, selecting, and training a model, evaluating its performance, and deploying it for real-world use. This process is pivotal for creating efficient and accurate models capable of addressing complex problems by learning from historical data and applying learned insights to new situations. Deep Learning (DL), a branch of machine learning, utilizes multi-layered neural networks to analyse and learn from complex data patterns, effectively simulating human cognitive processes. There are different types of Deep Neural Networks, each distinguished by their performance capabilities and the principles they use to derive outputs.

The advancement of artificial intelligence (AI) in architecture has seen significant evolution, moving from early experimental stages to becoming a fundamental component of architectural practice and education. Initially, pioneers like Negroponte [10] at the MIT Media Lab's Architecture Machine Group showcased the potential of AI in architecture through projects like URBAN II and URBAN V, laying the groundwork for Computer-Aided Design (CAD). These projects underscored a collaborative approach between architects and AI, with the latter managing rules and the former defining parameters. Cedric Price expanded the notion of AI in architecture with his project, the Generator, introducing the idea of self-adjusting buildings and positioning machines as independent design agents. This shift underscored the growing complexity and autonomy of AI in architectural design. Chaillou [68] notes that these early innovations by Negroponte and Price have been pivotal in shaping the ongoing discussion about the role of AI in architecture.

Machine learning (ML), a subset of artificial intelligence (AI), has significantly advanced architectural design, analysis, and construction processes, fostering a shift towards more innovative, efficient, and data-driven methodologies. This impact is particularly notable in design optimization, building visualization, simulation, and performance-based design. Tamke et al. [69] underscores ML's role in enhancing design flexibility and innovation, facilitating comprehensive analyses of complex datasets, and improving decision-making processes. Additionally, Alammar and Jabi [70] highlight ML's application in optimizing energy consumption in adaptive facades, demonstrating its utility in early design evaluation. Ko et al. [71] review the implementation of ML in architectural spatial layout planning, illustrating its benefits in generating detailed and efficient layout models, minimizing design errors, and fostering a collaborative human-AI design approach.

Machine learning (ML) in architectural design has significantly evolved the discipline, broadly categorized into image-based and graph-based methodologies. Image-based ML techniques leverage the visual capabilities of neural networks, like Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs), to generate and analyse architectural visuals. These methods are effective in recognizing patterns in extensive floor plan archives, thereby optimizing design workflows and expediting project completion. This approach is instrumental in tasks ranging from the conceptualization of designs to environmental simulations. Graph-based ML techniques, on the other hand, use graph data structures to represent and analyse the relationships and structure of architectural elements. These techniques, supported by Graph Neural Networks (GNNs), excel in understanding the fundamental logic of a floorplan, capturing complex structural and abstract concepts well beyond simple geometric interpretation. This methodology provides deeper insights into the spatial and semantic relationships inherent in floor plans, aiding in more comprehensive analyses of structural layouts. Both approaches utilize the strengths of neural networks to revolutionize architectural processes, enhancing tasks like design conceptualization, space organization, structural evaluation, and environmental modelling. The integration of these ML techniques into architecture not only fosters innovation in design practices but also enhances efficiency and depth in architectural planning and analysis.

Recent developments in AI for architectural design have led to innovative approaches for space layout planning and floor plan generation, primarily using Generative Adversarial Networks (GANs), Graph Neural Networks (GNNs), and other methodologies. Generative Adversarial Networks (GANs) have revolutionized generative architectural design since Goodfellow's [72] introduction, spawning various advancements like CGANs, iGAN/GVM, and Pix2Pix, which broadened their application in architecture. Also, Huang and Zheng [73] utilized Pix2PixHD for architectural element translation. Additionally, research by As et al. [74] applied deep learning to generative concept design using data from BIM-based software, converting it into graph representations for innovative design generation. Further exploration into GANs' potential in architecture includes studies by Peters [75] on room arrangement, Newton [76] utilizing a dataset of Le Corbusier's works for floor plan creation, and Wu et al. [77] developing a data-driven approach for generating residential floor plans. Chaillou [12] discussed the statistical approach to architectural design using GANs, emphasizing a holistic design process. Lastly, innovations in indoor scene generation, such as the variational autoencoder by Li et al. [78] and the PlanIT framework by Wang et al. [79], showcase the versatility and depth of GAN applications in architecture. Kim et al. [80] utilized GANs for converting raster images into annotated pairs, enhancing indoor layout extraction from floor plans. Zhao et al. [81] explored floor plan generation for emergency departments using DCGAN, pix2pix, and CycleGAN, finding CycleGAN most effective for its single-image training capability and adaptability in architectural design. Luo and Huang [82] introduced FloorplanGAN, combining vector-based generation with raster-based discrimination for flat layout creation. Parallelly, the application of GNNs in architecture, Hu et al. [83] introduced Graph2Plan, a framework that uses Graph Neural Networks (GNNs) to automate architectural layout generation, improving design efficiency and flexibility by incorporating user-defined constraints (see Fig. 2). In mixed-method approaches, Nauata et al. [84] pioneered an approach in architectural design using graph constrained GANs integrated with GNNs for space layout planning, which improved realism, diversity, and constraint adherence in house layouts. They further advanced their model with House-GAN++ [85], enhancing architectural design technology. This method initially involved generating raster data and then vectorizing it post-process. Liu et al. [86] addressed limitations in geometric detail capture and user customization by introducing a method that combines a Graph Convolutional Network (GCN) with an auto-regressive transformer to directly produce vector-based space layouts, marking a significant improvement in architectural design generation. Dong et al. [87] employed GNNs with EdgeGAN to analyse room relationships within floor plans by isolating walls. Rahbar et al. [88] combined agent-based modelling with deep learning, using pix2pix for spatial layout conversion from heat maps, demonstrating accuracy in meeting design constraints. Azizi et al. [89] developed a technique using attributed graphs with LSTM and VAE for floor plan embedding, validated by its ability to match similar layouts. Aalaei et al. [90] advanced architectural layout generation with graph constrained conditional GANs, focusing

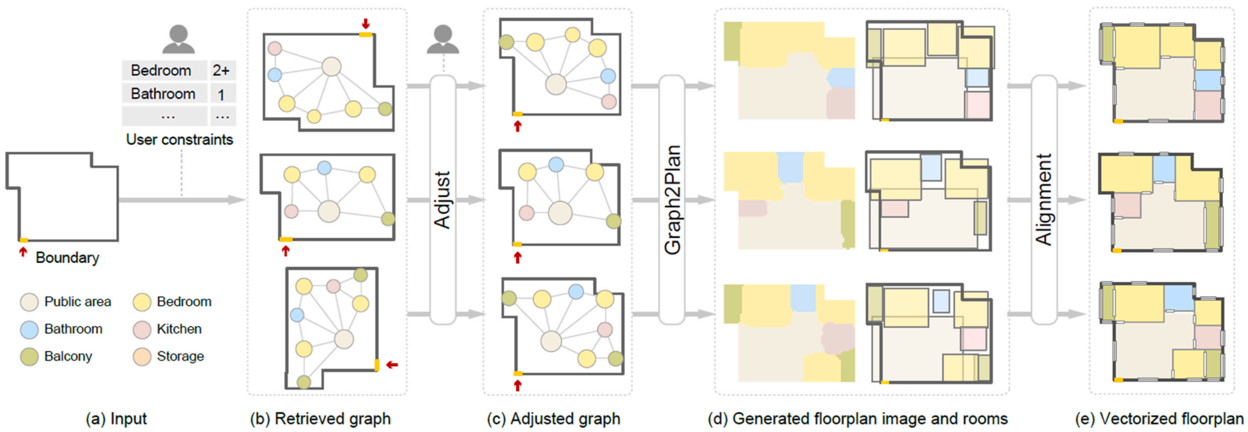

Fig. 2. Graph2Plan framework, image source: [83].

on input flexibility and model generalizability, addressing the limitations of previous studies like [83] by enhancing design process control and adaptability to various conditions. These developments showcase significant advancements in the application of GANs, GNNs, and deep learning algorithms for architectural design and layout generation.

4. Architectural spatial layout design for hospitals

Hospitals represent intricate structures. The planning of spatial layouts for hospitals is a critical aspect of their design process. Particularly during the early phases, the organization of spaces plays a vital role and significantly impacts the functional efficiency of the building. Hospital layout planning (HLP) is crucial due to the architectural complexity and multifunctionality of healthcare facilities, requiring a multidisciplinary approach that incorporates clinical, spatial, and stakeholder considerations [91,92]. Effective HLP seeks to optimize facility components to boost service quality and patient satisfaction, facing challenges like aligning medical processes with physical spaces and achieving multiple objectives [93–95]. Recently, there has been an increasing focus on research dedicated to the spatial organization of healthcare facilities [96]. In a recent study, Jia et al. [97] conducted a systematic review of literature focusing on decision support methods for designing hospital layouts, specifically using spatial network analysis and simulation modelling. The study highlights a critical gap in directly linking hospital design challenges to spatial layouts and underscores the need for clear layout representation and standardized methods for evaluating design assessments. It emphasizes the importance of cross-referencing design challenges with appropriate assessment methods to improve hospital layout decisions. Jamali et al. [91] carried out the initial thorough examination of the subject from an architectural view, offering a framework for architects and healthcare designers to critically assess Hospital Layout Problems (HLPs) and their ethical considerations. Halawa et al. [98] conducted a systematic review focusing on evidence-based design in healthcare facilities, highlighting the use of techniques such as mathematical and simulation modelling, statistical analysis, space syntax analysis, heuristics, Lean Six Sigma, machine learning, fuzzy logic, Markov chains, along with reviews, observations, and surveys. Benitez et al. [96] carried out a systematic review of existing research on the planning of spatial layouts in healthcare settings. This review uncovers the diverse methodologies and tools utilized to tackle layout planning challenges in the healthcare industry. Sadek and Shepley [99] analysed and discussed the effectiveness of Space Syntax and its recently developed spatial metrics that offer precise descriptions of different layout typologies, specifically emphasizing healthcare facilities. Additionally [100], introduces Space Syntax to healthcare designers, administrators, and researchers, reviewing its application in healthcare research and suggesting future possibilities.

In this section of the paper, we methodically examine several key aspects of hospital spatial layout design and facility layout planning, focusing on computational design methods. We explore the transition from manual to automated processes, highlighting significant advancements and how techniques originally developed for manufacturing have been adapted for healthcare. This includes a range of methodologies such as procedural, algorithmic, and simulation methods. The final part of the section addresses the latest advancements in machine learning (ML)-supported design methods for hospitals, presenting case studies and the application of ML techniques.

4.1. Facility layout planning for hospital spatial layout design

Although facility layout planning (FLP) has its roots in manufacturing, its application within the healthcare sector is growing. Nonetheless, research focused on healthcare layout planning (HLP) is still scarce and often led by disciplines beyond architecture [91,101]. Operations research (OR) methods, including optimization and simulation, support the development of optimal or robust layouts by addressing the complex problems inherent in HLP within feasible computational times [102,103]. Techniques are divided into procedural, algorithmic, and simulation categories, each with its own strengths and limitations for hospital design [104–106]. A holistic approach, integrating these methods, could provide a comprehensive solution, incorporating static and dynamic factors of healthcare environments. The literature emphasizes the importance of modelling and optimization in HLP, highlighting the application of mathematical programming, simulation, and lean manufacturing tools to enhance healthcare facility efficiency and outcomes [46,49,91,96,98].

4.1.1. Procedural approaches

Hospital layout design benefits from procedural approaches that merge qualitative experiences with quantitative data, aiming to create spaces that are operationally efficient and conducive to the human experience. Procedural approaches to hospital layout design are a methodical process that breaks down the design into sequential steps, each being addressed in order. Key methodologies in this domain have been developed by Reed [107], Muther [108], and Apple [109], with Muther's Systematic Layout Planning (SLP) being particularly influential for its comprehensive planning framework. The relationship chart, a core tool within SLP, is widely used for its effectiveness in optimizing spatial arrangements. The effectiveness of procedural hospital layout design depends on generating quality alternatives by experienced designers and incorporating expert input, with the challenging final step being the evaluation and selection of designs among multiple objectives.

4.1.2. Algorithmic approaches – mathematical modelling

Algorithmic approaches to hospital layout design use mathematical models to optimize design objectives and constraints, relying on quantitative data for solution evaluation. Although effective in providing structured solutions, they often need adjustments to address detailed design aspects. These models aim to improve performance metrics while considering physical, legal, and operational constraints. Cubukcuoglu [49] identifies the Quadratic Assignment Problem (QAP) and Mixed-Integer Programming (MIP) as the leading algorithmic optimization strategies in hospital layout design. Additional methods include exact, heuristic, and meta-heuristic approaches.

Researchers have used Quadratic Assignment Problem (QAP) and Mixed-Integer Programming (MIP) methodologies to optimize hospital layouts, focusing on minimizing patient travel and departmental intercommunication costs. Elshafei [51] introduced QAP for clinic locations to reduce patient travel distance, setting a precedent for subsequent studies. Murtagh et al. [110] employed a QAP approach with fixed locations to cut transportation costs via a heuristic method. Butler et al. [111] proposed a two-phase method, combining a quadratic integer goal programming model for layout and bed allocation with simulation modelling. Hahn and Krarup [112] utilized QAP to minimize travel distances between hospital facilities, comparing heuristic and metaheuristic strategies. Yeh [113] tailored QAP for hospital design, employing simulated annealing and Hopfield neural networks for optimization. Amaral [114] developed a MIP model addressing corridor allocation and resource consumption, aiming for compact layouts. Chraibi et al. [115] used MIP and QAP with CPLEX solver to minimize travel and rearrangement costs in operating theatre layouts. Helber et al. [116] presented a two-stage hierarchical approach, using QAP and MIP for departmental and unit placements, accounting for multi-story buildings. Acar and Butt [117] formulated a Mixed-Integer Linear Programming (MILP) model to assign nurses to patients in an oncology unit. Cubukcuoglu et al. [52] optimized hospital layouts using QAP and computational design, enhancing internal transportation efficiency. Also, Cubukcuoglu et al. [95] introduced a generative design workflow combining zoning, routing, and spectral clustering with MIP for optimal floor plans. These studies highlight the application of mathematical optimization in improving hospital layout planning.

Research in hospital layout optimization extends beyond the Quadratic Assignment Problem (QAP) and Mixed-Integer Programming (MIP) to include various algorithmic methods. Arnolds et al. [118] developed a multi-period planning tool using discrete event simulation and heuristics for hospital wards. Arnolds and Nickel [119] advanced this with adaptable ward layouts using mathematical models and a CPLEX solver. Rismanchian and Lee [120] optimized emergency department layouts with process mining and goal programming, demonstrating effectiveness through a CPLEX-solved case study. Arnolds and Gartner [92] modified QAP to consider specific layout constraints, while Chraibi et al. [121] explored adaptive operating theatre layouts.

QAP's NP-hard complexity led researchers to heuristic and meta-heuristic approaches, including genetic algorithms (GA), simulated annealing (SA), tabu search, ant colony optimization (ACO), particle swarm optimization (PSO), and local search algorithms. Gero and Kazakov [122] used GA to reduce hospital layout costs. Su and Yan [123] combined daylight simulations with GA to optimize nursing unit layouts, enhancing environmental quality and operational efficiency. Stummer et al. [124] integrated tabu search with multi-objective decision support for medical department placement. Liang and Chao [125] applied tabu search for layout optimization, focusing on adjacency and travel distances. Cheng and Lien [126] used the particle bee algorithm for departmental preferences and space needs. Safarzadeh and Koosha [127] developed a non-linear MIP model with fuzzy constraints, employing GA to minimize space costs. Huo et al. [128] used NSGA-II with adaptive local search for multi-floor hospital planning. Khatib and Alshboul [129] combined systematic layout planning (SLP) with GA for spatial efficiency.

Alternative strategies include lean principles, simulation optimization, fuzzy constraint theory, and physically based modelling. Wang et al. [130] applied lean principles to enhance emergency department layouts, demonstrating that linear layouts reduce wait times and improve efficiency. Lin et al. [131] used fuzzy constraint theory for operating theatre layouts. Lin and Wang [132] combined SLP with fuzzy AHP for human reliability in theatre layouts. Chaeibakhsh et al. [133] developed a constrained optimization model to redesign hospital rooms, minimizing patient fall risk. Lorenz et al. [134] used physically based modelling for hospital planning, allowing dynamic visualization of layout changes. Gai and Ji [135] combined quantitative analysis with qualitative assessments using intuitionistic fuzzy sets for healthcare facility planning. These approaches demonstrate the use of computational techniques to improve efficiency, service levels, and safety in hospital settings.

4.1.3. Simulation approaches

Simulation modelling techniques such as spatial network analysis (SNA), discrete-event simulation (DES), and agent-based modelling (ABM) are extensively used in hospital layout design. These methods address operational and spatial challenges by depicting dynamic activities, patient movements, resource usage, and interactions within hospitals. Jia et al. [97] emphasize that space syntax analysis (SSA) assesses layout designs in terms of visibility and access, while simulation modelling provides quantitative data on hospital operations.

Extensive reviews in the academic literature focus on SSA and simulation methods in hospital layout planning. Jia et al. [97] conducted a systematic review on decision support systems for hospital layout design, categorizing the literature into five key issues: overcrowding, patient wait times, visibility and staff interaction, wayfinding, and hospital-acquired infections. Sadek and Shepley [99] reviewed SSA tools used in healthcare facility design, while Haq and Luo [100] explored Space Syntax in improving wayfinding, staff flows, spatial cognition, and layout effectiveness. Jun et al. [136] summarized the application of DES in hospitals, outpatient clinics, and emergency departments.

4.1.3.1. Spatial network analysis (SNA) - space syntax analysis (SSA). Space Syntax, introduced by Hillier and Hanson [137], involves tools for analysing spatial configurations in buildings and urban areas. It quantifies spatial characteristics to understand how spaces influence human activities and interactions [138]. SSA is applied across disciplines, including healthcare, urban design, and sociology, to improve spatial environments by optimizing patient flow, staff efficiency, and accessibility [139,140]. In healthcare design, SSA aids in hospital navigation, nurse movement analysis, privacy, evacuation planning, cost minimization, staff-patient interactions, patient satisfaction, and hand sanitizer usage influenced by floorplans [140]. It emphasizes managing proximity and accessibility to address design challenges [99].

SSA's utility in wayfinding within hospitals was demonstrated by Peponis et al. [141], who showed how layouts impact navigation efficiency. Tzeng and Huang [142] used SSA to study wayfinding behaviour in outpatient areas through axial-line mapping and isovist analysis. Haq and Luo [100] reviewed SSA applications in healthcare, focusing on visitor navigation, nurse movements in Medical-Surgical Units (MSUs), patient privacy, evacuation strategies, and layout improvements. SSA also optimizes hospital layouts by studying nurse movement patterns. Hendrich et al. [143] analysed how unit layout affects nurses' time in patient rooms using spatial analysis. Choudhary et al. [93] developed a model to predict nurse movement patterns and travel speeds based on layout connectivity and integration. Visibility from nurses' areas is crucial for patient monitoring. Advanced SSA software, incorporating agent-based simulation models, evaluates lines of sight. Lu et al. [144] introduced targeted visual connectivity to quantify visibility in a neuro ICU, showing how SSA can optimize strategic areas like nurse stations. Lu and Zimring [145] further explored visibility analysis to forecast nurse locations (see Fig. 3). Johanes and Atmodiwirjo [146] used heat maps to study visibility in healthcare settings, while Hadi and Zimring [147] assessed visibility in ICUs, highlighting the impact of corridor design on staff visibility.

4.1.3.2. Discrete event simulation (DES). Discrete event simulation (DES) replicates real-life processes, facilities, or systems, particularly in healthcare, for modelling performance and capacity management. Jun et al. [136] and Gibson [148] highlighted DES's utility in simulating healthcare delivery processes, determining facility capacities, and analysing patient movement. Gibson [148] used DES to improve service quality and productivity by creating an efficient work environment for healthcare staff. Vos et al. [149] evaluated hospital layout designs' impact on patient and goods flow using DES, aiming to enhance operational outcomes in healthcare delivery.

4.1.3.3. Agent-based modelling (ABM). Agent-based modelling (ABM) is the process of developing computational models to simulate the behaviours and interactions of autonomous agents within a given system. These agents, which may symbolize individuals such as patients and healthcare providers like hospital staff, exhibit unique characteristics and behaviours. By employing dynamic simulation, decision-makers could witness the evolution of patterns and system behaviours over time. Before implementation, this method allows for experimentation with different scenarios, adjustments to the layout, and the pursuit of an effective hospital design.

Wurzer [150] focused on process and agent-based simulation, addressing critical aspects of hospital planning, including urban context, adjacency, traffic separation, location, size, proportion, orientation, and wayfinding. The study also emphasized the importance of early-stage simulation in hospitals for ensuring visibility, accessibility, wayfinding, space placement, dimensioning, and the management of movement, circulation, and traffic. Also, Wurzer et al. [151] developed a simulation tool using agent-based modelling to evaluate how different hospital layouts affect treatment delivery and patient flow. They used real treatment data to test various layout scenarios, aiming to optimize hospital efficiency and patient care through strategic space planning.

In addition to the individual simulation and optimization techniques discussed earlier, some researchers have adopted a combined approach. For example, Morgareidge et al. [152] utilized both discrete event simulation (DES) and space syntax analysis (SSA) simultaneously. By integrating DES, a lean tool, with SSA, they aimed to enhance process flow and restructure the Emergency Department (ED) space. This dual-method approach allows for a more holistic analysis and optimization strategy, capitalizing on the strengths of each method to improve the overall efficiency and layout of healthcare facilities. Also, Li et al. [106] proposed a novel decision-support methodology for designing healthcare facility layouts, integrating multi-objective optimization with simulation-based performance evaluation. The approach realistically evaluates user interactions within a surgical ward using Building Information Modelling (BIM) and agent-based modelling. Given the complex nature of hospital layout design, which involves diverse and sometimes conflicting criteria, employing multiple approaches is crucial for effectively addressing this intricate design challenge. Therefore, a variety of strategies are necessary to navigate the complexities of the design process.

4.2. Machine learning (ML) for hospital spatial layout design

Research on layout design using machine learning (ML) techniques has mainly focused on residential buildings, while studies on hospital buildings are limited. Zhao et al. [81] developed an AI method for emergency department (ED) layout design by first gathering a dataset of ED designs and then selecting over 100 high-quality layouts as training data for various Generative Adversarial Network (GAN) models. The models—DCGAN, pix2pix, and CycleGAN—are evaluated to find the most effective for creating functional ED layouts, with assessments focusing on architectural and algorithmic effectiveness. They highlighted the unique challenges in designing emergency department (ED) layouts, emphasizing the complexity added by the need to manage various flows like clinical

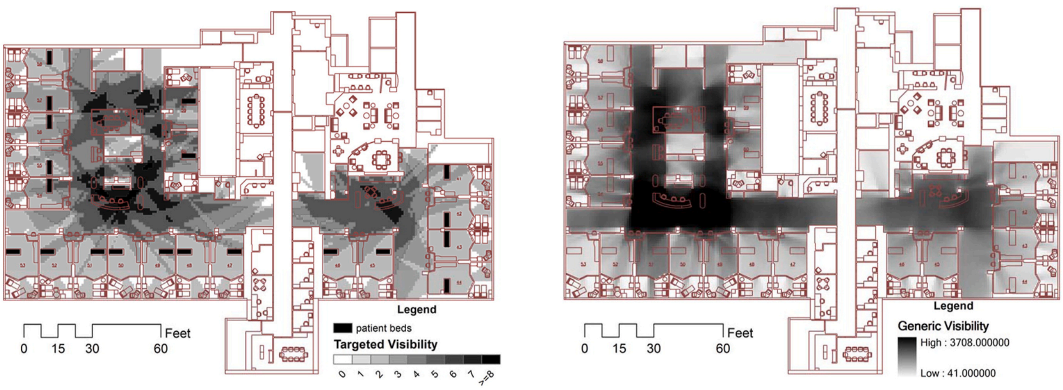

Fig. 3. Targeted visibility and generic visibility analysis, image source: [145].

processes and patient movement. Achieving an optimized design at the initial phase is difficult, often requiring many iterations. The study notes the emerging role of machine learning (ML) as a decision-making tool that can analyse large datasets and predict future trends, offering a promising solution to the complexities of ED layout optimization.

Zhao et al. [153] discussed two artificial intelligence-based methods to enhance hospital layout design, focusing on operating departments. The first method, Healthcare Systematic Layout Planning (HSLP), applies systematic planning and genetic algorithms to optimize layouts, resulting in precise but somewhat rigid designs. The second method uses a Generative Adversarial Network (GAN), specifically pix2pix, to create innovative and applicable layouts from a trained dataset of existing designs. Both methods aim to reduce the architects' workload in the early design stages and demonstrate the potential of intelligent design in medical architecture. Zhou et al. [154] developed a method to automate the design and optimization of hospital layouts. They incorporated key parameters such as adjacency preference scores and infection risk coefficients to tailor the designs to be effective in both standard and emergency public health scenarios. The methodology involved generative design techniques that automatically propose multiple layout configurations based on predefined criteria and constraints. They employed data-driven machine learning approaches as part of their generative design approach. Then, to evaluate and select the optimal layout among the proposed configurations, the researchers used a multi-objective deviation analysis. This analysis helps in balancing various design objectives, such as maximizing operational efficiency and minimizing infection risks, making the final layout choice best suited for handling everyday healthcare needs as well as emergency situations.

In conclusion, while artificial intelligence and machine learning provide innovative tools for optimizing hospital layout design, the complexity and unique requirements of healthcare environments mean that these technologies are not a one-size-fits-all solution. They require careful implementation and continuous refinement to truly meet the demands of hospital layouts. The potential of AI to enhance architectural planning in this field is significant, yet it must be leveraged thoughtfully to address the specific challenges and variability inherent in hospital layout design.

5. Challenges and future directions in hospital spatial layout design

Designing hospital layouts involves navigating a complex array of challenges and considerations that extend beyond simple architectural concerns to encompass patient safety, staff efficiency, and adaptable use of space. As healthcare continues to evolve, driven by technological advancements and changing healthcare policies, the strategies for hospital layout design must also adapt. This section explores three key areas that present both challenges and future directions with the potential to significantly impact hospital layout design: Computational Design Methods, Facility Layout Planning, and the application of Machine Learning (ML) in Hospital Layout Design.

5.1. Computational design methods in hospital spatial layout design

While computational design methods provide advanced tools for architectural space layout, they face numerous challenges that limit their practical application in hospital layout design. Lobos and Donath [5] critically reviewed the current state of architectural space layout planning, identifying a significant gap between method development and field application. They emphasized the importance of integrating these methods more closely with architectural practices and suggested enhancing user involvement, simplifying complex algorithms, performing in-depth problem analyses, and developing specialized tools for different types of buildings. The necessity of an interdisciplinary approach that merges traditional design with modern engineering techniques was also highlighted, along with the need for architect training in both design and technology. Das et al. [155] introduced the Space Plan Generator, mainly for major healthcare facilities. Its application, however, is mostly confined to large and complex buildings due to the detailed input required, which significantly extends the design time. This tool exemplifies the common issue of needing explicit detail for every design aspect, which can lead to overlooking important yet subtle elements essential for effective floorplan design. Du et al. [156] noted that although various methods and tools have been explored for automatic space layout generation, their adoption within the architectural community has been limited. They suggested that much of the research has been too focused on facility layout without adequately addressing the diverse functions and specific needs of different building types. Zhao et al. [81] discussed the narrow focus of previous hospital layout research on staff assignments, which does not fully address the comprehensive needs of hospital design. This contrasts with the more developed automated house plan generation, indicating a significant gap in research focus. Okhoya et al. [157] and Aalaei et al. [90] further critiqued the current approach of defining architectural problems with rigid mathematical models, which fail to capture the complexity and variability inherent in architectural design. They advocated for a more data-driven approach that reflects the real-world application of past designs and historical data in solving contemporary design challenges.

In summary, the integration of computational design methods in hospital layout design presents both challenges and opportunities. These include the need for more intuitive tools that align closely with architectural workflows, improved user involvement, simplified algorithms, and better integration with big data analytics and CAD, BIM systems. Future research should focus on developing methods that are adaptable, user-friendly, and capable of handling the complex requirements of hospital design.

5.2. Facility layout planning in hospital spatial layout design

Facility layout planning in hospital layout design poses unique challenges as it aims to optimize space for patient care, staff efficiency, and safety. While several studies have explored different aspects of facility layout planning in healthcare settings, there is a noted gap in effectively managing large and diverse datasets specific to hospitals [116]. Hospital layouts typically involve solving highly complex QAPs, where the task is to assign a set of facilities to locations in a way that minimizes the total cost of moving between facilities while maximizing the closeness of related units. This mathematical problem is notoriously difficult to solve due to its computational complexity and the intricate nature of hospital operations [52]. Halawa et al. [98] discuss the complexities of healthcare facility design, particularly the challenges due to variability and dynamic human factors. They criticize the field for its lack of interdisciplinary approaches, noting that while operations research and healthcare engineering focus on using simulation and optimization to improve layouts and workflows, these methods often neglect practical architectural constraints. The study also points out that relying solely on mathematical programming is insufficient, as it bases decisions on limited metrics like travel distance, missing broader and more nuanced aspects of effective design.

In conclusion, addressing the challenges and future directions in hospital layout design necessitates a multidisciplinary approach that integrates innovative methodologies, automation, and optimization techniques to establish efficient, safe, and patient-centred healthcare environments.

5.3. Machine learning (ML) in hospital spatial layout design

Machine learning (ML) has emerged as a transformative tool in architectural practice, offering the potential to automate routine tasks, enhance design efficiency, and stimulate creative processes. In the early stages of design, ML facilitates the exploration of innovative solutions by analysing vast datasets, thereby fostering a synergistic relationship between human designers and AI technologies. This is particularly relevant in the context of hospital spatial layout design, where ML has demonstrated its capacity to improve the functionality of critical spaces by informing floor plans with data-driven insights. However, despite these advancements, the application of ML in hospital design is not without significant challenges and potential risks, particularly given the sensitive nature of healthcare environments.

The design of hospital layouts necessitates an exceptionally high level of precision, as spatial configurations can profoundly impact patient health outcomes, the effectiveness of treatments, and the productivity of medical staff. The current ML methods used to generate hospital layouts are often characterized by a "black box" nature, where the underlying decision-making processes are not easily interpretable. This lack of transparency raises concerns about the reliability of ML-generated designs, as these systems may produce outcomes that do not adequately address the complex and nuanced requirements of healthcare settings. For instance, ML algorithms may fail to account for critical factors such as patient flow, staff interactions, and the psychological effects of spatial design on patient well-being, all of which are essential for creating safe and effective healthcare environments.

Additionally, the reliance of ML models on large datasets introduces further complications. Managing complex and diverse data sets for architectural projects requires significant preprocessing, posing a challenge due to the complexity and time consumption involved. The integration of ML with Building Information Modelling (BIM) presents a potential solution, suggesting design improvements based on large datasets. However, transforming BIM data for ML compatibility, especially for Graph Neural Networks (GNNs), remains a challenge [71]. Also, the quality and representativeness of the training data are crucial; if the data is incomplete or fails to capture the full range of hospital design challenges, the resulting layouts may be suboptimal or even detrimental.

The architectural field currently lacks clear evaluation methodologies for ML, making it challenging to validate and trust AI-driven decisions. Architects also face difficulties integrating ML into design workflows due to the complexity of computational models and the need for a deep understanding of ML processes. Overcoming these challenges requires targeted education and tools to bridge the gap between architectural creativity and ML proficiency. A hybrid approach that combines human expertise with machine capabilities is crucial in architectural spatial layout planning (ASLP), particularly in hospital design. This strategy ensures that while ML enhances efficiency and creativity, it is complemented by the critical judgment of architects, who play an essential role in interpreting and refining AI-generated designs. By maintaining this balance, the hybrid approach ensures that hospital layouts are not only innovative but also meet the rigorous standards required for patient care and staff efficiency, ultimately leading to safer and more functional healthcare environments.

In conclusion, machine learning (ML) offers significant benefits for architectural practice, especially in optimizing hospital layout designs. However, challenges such as data complexity and the opacity of ML algorithms need addressing. For effective implementation, architects should pursue a hybrid approach: combining ML insights with human expertise to enhance design accuracy and creativity. It is advisable for professionals in hospital layout planning to integrate ML gradually, focusing on areas where it can provide clear benefits, and to invest in training to bridge the gap between architectural knowledge and ML skills. This strategy will ensure that ML contributes positively to hospital design, improving both functionality and efficiency.

6. Conclusion

This review has highlighted significant advancements in hospital spatial layout design, emphasizing the integration of computational methods, facility layout planning, and machine learning (ML) techniques. The evolution of these methodologies marks a shift from traditional approaches to data-driven and automated processes, offering new opportunities for optimizing hospital environments. A key insight is the growing importance of hybrid approaches that merge the precision of computational tools with the expertise of human designers. This synthesis is crucial for addressing the complex challenges inherent in hospital layout design.

The main findings from this review include the following:

Technological Gaps and Mixed Methods: Despite progress in computational design and ML-driven approaches, a significant gap still needs to be in fully adapting these techniques to architectural spatial layout design, especially for complex structures like hospitals. The specific planning requirements of hospitals complicate the integration of these methods. Current approaches are insufficient to address the complexities of hospital spatial layouts, necessitating future research that develops targeted tools for these challenges. Combining ML with facility layout planning, optimization, and simulation may offer a more comprehensive approach, providing broader perspectives and more accurate spatial solutions. Additionally, spatial layout design techniques successfully applied in other building types should be explored for hospital design. This review provides a comprehensive examination of these methods and their potential application in hospitals.

Interdisciplinary Collaboration and Human-Machine Synergy: Collaboration between architects, healthcare professionals, and engineers is crucial to ensure that technological innovations are balanced with human expertise. The synergy between human designers and computational tools is essential for addressing the intricate challenges of hospital spatial planning. This hybrid approach ensures that technological solutions remain practical and sensitive to context.

Dataset Limitations: A significant challenge in applying ML to hospital design is the lack of high-quality, representative datasets. Developing comprehensive, well-evaluated datasets is critical for advancing future hospital designs. Instead of focusing solely on generating new layouts, future research should emphasize combining ML with evaluation methods to refine and assess existing designs. Robust datasets sourced from BIM systems and other architectural tools can accelerate design processes and improve the reliability of spatial planning solutions.

In summary, this review outlines the potential of computational methods and ML in hospital spatial layout design, while also identifying areas requiring further exploration. Developing targeted, interdisciplinary approaches that balance technological innovation with human judgment will be essential for creating hospital environments that are both functional and conducive to healing. Addressing these gaps will enable future research to harness advanced technologies more effectively, improving operational efficiency and patient care in hospital settings.

CRediT authorship contribution statement

Aysegul Ozlem Bayraktar Sari: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Wassim Jabi:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Aysegul Ozlem Bayraktar Sari reports a relationship with Ministry of National Education of the Republic of Türkiye that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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