

Article

AI-Driven BIM Integration for Optimizing Healthcare Facility Design

Hamidreza Alavi ^{1,*} , Paula Gordo-Gregorio ² , Núria Forcada ² , Aya Bayramova ³ and David J. Edwards ^{3,4} 

¹ Department of Engineering, University of Cambridge, Cambridge CB3 0FA, UK

² Group of Construction Research and Innovation (GRIC), Department of Project and Construction Engineering (DPCE), Universitat Politècnica de Catalunya (UPC), 08222 Terrassa, Spain; paula.gordo@upc.edu (P.G.-G.); nuria.forcada@upc.edu (N.F.)

³ Department of the Built Environment, Birmingham City University, Birmingham B4 7XG, UK; ashhyrgul.bayramova@mail.bcu.ac.uk (A.B.); drdavidedwards@aol.com (D.J.E.)

⁴ Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2092, South Africa

* Correspondence: sa2194@cam.ac.uk

Abstract: Efficient healthcare facility design is crucial for providing high-quality healthcare services. This study introduces an innovative approach that integrates artificial intelligence (AI) algorithms, specifically particle swarm optimization (PSO), with building information modeling (BIM) and digital twin technologies to enhance facility layout optimization. The methodology seamlessly integrates AI-driven layout optimization with the robust visualization, analysis, and real-time capabilities of BIM and digital twins. Through the convergence of AI algorithms, BIM, and digital twins, this framework empowers stakeholders to establish a virtual environment for the streamlined exploration and evaluation of diverse design options, significantly reducing the time and manual effort required for layout design. The PSO algorithm generates optimized 2D layouts, which are seamlessly transformed into 3D BIM models through visual programming in Dynamo. This transition enables stakeholders to visualize, analyze, and monitor designs comprehensively, facilitating well-informed decision-making and collaborative discussions. The study presents a comprehensive methodology that underscores the potential of AI, BIM, and digital twin integration, offering a path toward more efficient and effective facility design.

Keywords: digital twins; BIM; facility design; artificial intelligence; PSO; layout optimization



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1. Introduction

The effective design of buildings and healthcare facilities depends on successful collaboration among various stakeholders, including architects, engineers, and users. However, the complexity of modern architecture poses challenges to collaboration and often leads to constraints and limitations in the design process [1,2]. Conventional design approaches often treat different stages of the design separately, leading to suboptimal outcomes. The preliminary design of healthcare facilities heavily relies on user involvement and feedback to meet specific needs and requirements [3,4].

Layout planning (LP) plays a crucial role in optimizing space utilization within a building or facility and minimizing total space requirements. Hospital layout planning (HLP), a specialized form of LP, focuses on designing efficient layouts for healthcare facilities [5,6]. Researchers have investigated different methods to optimize the layouts of healthcare facilities. For instance, Chraïbi et al. [7] implemented intelligent decision systems to optimize healthcare processes and improve the efficiency of staff at an operating theater. They utilized PSO to achieve nearly optimal layouts for large-sized instances.

Additional studies have also focused on addressing optimization challenges in healthcare facility layout planning. Arnolds and Gartner [8] utilized data-driven critical pathway

mining to support strategic healthcare management decisions. Vahdat et al. [9] focused on minimizing patient walking distances in healthcare clinics through data-driven simulation optimization approaches. Zhao et al. [10] proposed intelligent design processes based on healthcare systematic layout planning and generative adversarial networks for the functional layout of operating departments in general hospitals. Halawa et al. [11] focused on designing healthcare facility layouts with pod structures using a framework of algorithms. They utilized electronic healthcare record (EHR) data to forecast patient flows and applied a three-phase framework. The initial phase utilized process mining algorithms to predict patient flow, the second phase employed simulation modeling, and the final phase addressed the uneven area facility layout problem. The outcome was an optimized layout prediction for the facility.

While these studies have contributed significantly to the optimization of facility layout planning, there exists a critical gap in the literature regarding the integration of BIM with these models. BIM is a digital representation of physical and functional characteristics of elements or spaces in a building. BIM provides a powerful platform for displaying high-quality data and integrating various platforms [12,13]. Throughout a facility's life cycle, BIM uses 3D, parametric, and object-based models to produce, store, and utilize coordinated and compatible data. Better documentation, more teamwork and work flexibility, and up-to-date information throughout the entire life cycle can all be provided by BIM, which serves as a primary resource for decision-makers [14,15]. BIM implementation is a subject of research in a variety of areas, including sustainability [16], strategy planning [17], retrofit planning [18,19], preventative maintenance planning [20,21], building systems analysis [22,23], and energy management [24–26].

With advancements in technology and the emergence of BIM, there is an opportunity to enhance this process by integrating AI algorithms with BIM models. This integration can facilitate efficient data collection, enhance data quality, and enable the visualization of layout solutions, ultimately assisting decision-makers in making informed choices [27,28]. Moreover, it allows for the optimization of facility layouts, minimizing transportation distances for personnel and equipment, improving safety, and maximizing efficiency. However, the current literature lacks comprehensive studies that have fully explored the integration of BIM with AI techniques for layout planning [29].

Several studies have acknowledged the advantages of integrating AI techniques with BIM for facility layout planning. For instance, Lu et al. [30] investigated the integration of BIM with optimization algorithms for sustainable building design and demonstrated the potential of using AI techniques to enhance energy efficiency and minimize resource consumption. They emphasized the benefits of coupling BIM with AI algorithms to support decision-making in the early stages of the design process. In the context of facility layout planning, BIM has been primarily used as a tool for visualization and clash detection rather than for optimization purposes. Gai et al. [31] proposed an AI-based optimization approach for hospital ward layout planning. They integrated BIM with machine learning algorithms to optimize the spatial allocation of patient rooms, medical equipment, and nursing stations. The results demonstrated the effectiveness of the proposed approach in reducing travel distances for professionals and enhancing the overall workflow efficiency. Moreover, Zhang [32] explored the integration of BIM with deep reinforcement learning (DRL) algorithms for optimal layout planning in outpatient departments. They developed a framework that combined BIM data and DRL techniques to generate layout solutions that minimize walking distances for patients and maximize the utilization of space. The study demonstrated the potential of AI-driven layout optimization to improve the patient experience and operational efficiency of healthcare facilities.

While there has been limited research on the integration of AI algorithms with BIM, the primary motivation for this study is the perceived significance and potential value of such integration in advancing facility design. Traditional methodologies in facility design often rely on manual processes and lack the dynamism required to adapt to evolving industry needs. This study introduces a paradigm shift by integrating artificial intelligence tech-

niques, particularly optimization algorithms, with BIM and digital twin technologies. The aim is to foster interoperability between PSO code, BIM software, and digital twins, thereby empowering facility design with the advantages offered by these combined paradigms. By doing so, we extend the possibilities of healthcare facility design, making it more dynamic, data-driven, and adaptable to the evolving needs of the healthcare industry. The framework is designed to be extendable to DT technology in the future. DT technology enhances the optimization of design processes by providing real-time simulation capabilities before physical construction begins. This approach can be particularly beneficial in real-world scenarios, such as optimizing hospital layouts during health crises like the COVID-19 pandemic. By predicting hospital admissions and managing space efficiently, DT technology can ensure that facilities adapt to changing demands and maintain optimal functionality. The proposed framework will automatically create a 3D BIM model from the results of a design optimization algorithm, reducing the time and effort required for manual BIM creation. Additionally, the integration of digital twins provides real-time monitoring and simulation capabilities, further enhancing design capabilities and operational efficiency. This research seeks to optimize the layout planning process in healthcare facilities and improve the effectiveness of the early-stage design process by combining the strengths of AI techniques, BIM, and digital twins. Hence, healthcare facilities can benefit from improved design outcomes, enhanced efficiency, and better decision-making support. The proposed framework's adaptability can be further refined to dynamically respond to changing healthcare needs, particularly during public health emergencies, suggesting temporary layout modifications to accommodate surge capacity or isolation requirements.

2. Materials and Methods

In pursuit of the primary objective to bridge the gap between AI-driven optimization algorithms, BIM software (Autodesk Revit 2024), and digital twin technologies, this study employs a three-step methodology. This method establishes a way to improve compatibility between different areas. The process involves a series of organized steps that aim to enhance the compatibility between PSO algorithms, BIM software, and digital twins. This enables advanced 3D BIM visualization and real-time monitoring. The following steps delineate the procedural framework as shown in Figure 1:

- Data Requirement and Parameter Creation in BIM:

This initial stage involves identifying the necessary data inputs and establishing parameters within the BIM environment to support the implementation of AI algorithms.

- AI Algorithm Implementation:

In the next phase, AI algorithms are deployed to optimize and enhance the functionality of BIM models by leveraging data collected in the previous stage.

- Data Integration and Visualization:

After algorithmic processing, the integrated data are visualized within the BIM environment, enabling stakeholders to interact with and analyze the information effectively.

- Connection to Digital Twin Technology:

The processed data are then fed into digital twin technology, facilitating real-time monitoring and simulation capabilities for improved decision-making and operational efficiency. This structured approach ensures coherence between PSO algorithms, BIM software, and digital twins, while also supporting advanced visualization and monitoring capabilities essential for modern construction and operational processes.

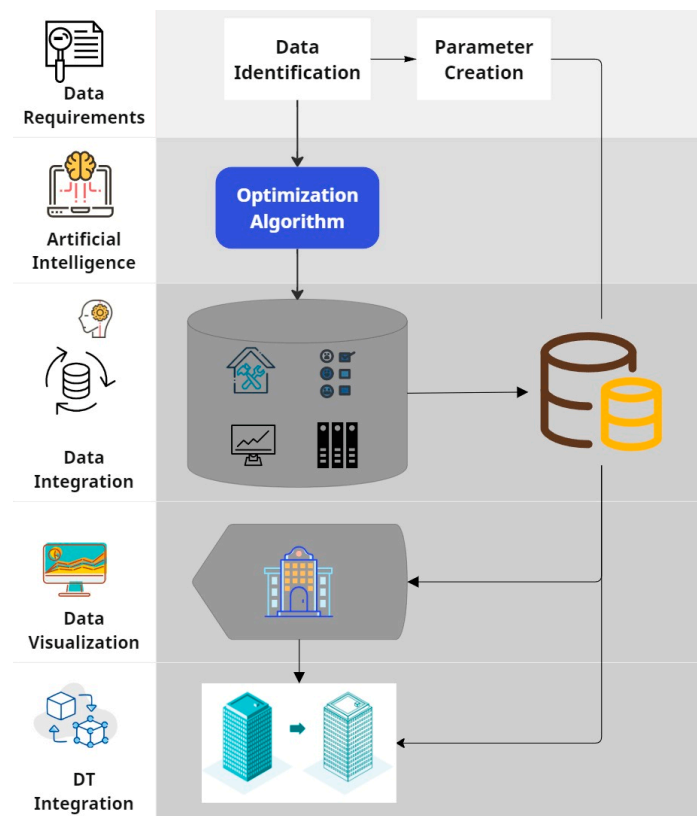


Figure 1. Process of AI-driven digital twin integration.

2.1. Data Requirement

The first step involves identifying essential data requirements. While traditional BIM systems are good at providing spatial and building information, they often do not fully accommodate the comprehensive data needed for designers. Once the data requirements are established, the methodology incorporates an “optimization algorithm”. This algorithm utilizes data obtained through techniques such as PSO and other AI-driven methods. The algorithm’s data requirements include parameters such as room dimensions, spatial constraints, and patient flow probabilities, which are crucial for successful implementation. The goal is to generate optimized 2D layouts through an iterative optimization process. This process takes into account important factors such as space utilization, circulation flow, and accessibility, resulting in refined healthcare facility designs.

2.2. Data Integration

After obtaining optimized 2D layouts, the next step is 3D BIM visualization. At this stage, a script is meticulously developed using Dynamo, a powerful visual programming module deeply integrated within Revit. Dynamo, with its node-based approach, interprets the outputs generated by the optimization algorithm. It imports the relevant data extracted during the data requirement phase and facilitates the creation of a comprehensive 3D BIM model within Revit. This dynamic process enables designers to iteratively adjust design parameters, explore various design options, and evaluate their implications for different facets of healthcare facility design.

2.3. Data Visualization

This stage is crucial for facilitating a thorough understanding of the layout solutions and enables further analysis and evaluation of their spatial arrangement. The 3D visualizations generated within the BIM environment serve as a powerful tool for designers and stakeholders alike. The final phase focuses on the integrated capabilities of digital twins to provide real-time, interactive representations of the facility, enabling continuous

optimization and scenario testing. The integrated PSO and Dynamo workflow, combined with digital twin technology, allows for iterative optimization and refinement of layouts. This approach provides flexibility to explore various design options, evaluate their implications, and make data-driven decisions. Moreover, the methodology incorporates the use of Dynamo Player, which extends further options for customization. For instance, designers can select the typology of walls, flooring materials, and even define specific levels within the healthcare facility. This additional flexibility is particularly useful in accommodating varying design scenarios and preferences. This methodology integrates data requirement analysis, optimization algorithms, and 3D BIM visualization, offering a comprehensive approach to enhance healthcare facility design optimization. The ensuing sections of this paper explore the practical application and findings of this integrated approach, shedding light on its potential to transform design processes and decision-making in the healthcare sector.

3. Implementations

The implementation of the proposed framework within the BIM and digital twin environment is a systematic process comprising three fundamental steps, as illustrated in Figure 2.

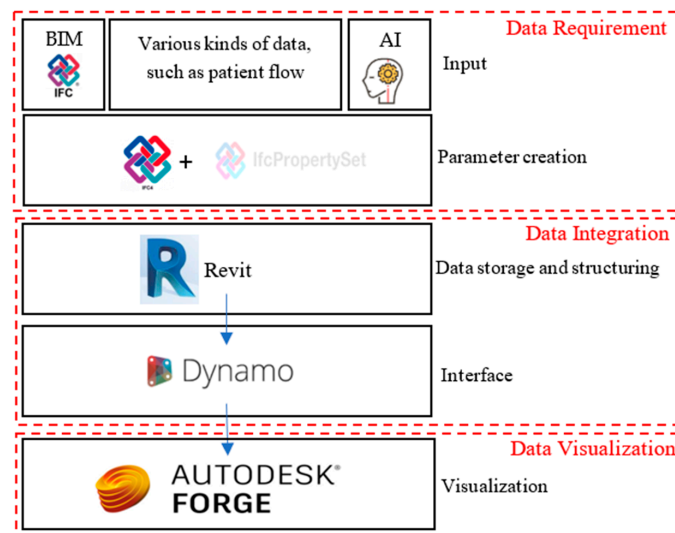


Figure 2. System architecture for the integration.

3.1. Data Requirements

A PSO algorithm was meticulously crafted to accommodate input data derived from a proposed hospital clinic and to generate optimized 2D layouts, integrating the global best positions for each room while delineating their respective x and y coordinate systems. The software components pivotal in executing these critical functions are given as follows: PyCharm editor, primarily used for the development of the optimization algorithm within the Python programming language; Autodesk Revit, which serves as the core BIM software; and Dynamo, a visual programming extension seamlessly integrated into Revit, further augmenting its capabilities.

This study undertakes an approach that integrates vital insights and data derived from the work of Halawa et al. [11]. Halawa's research, focusing on the utilization of electronic health record (EHR) data to forecast patient flows and optimize facility layout predictions, stands as a testament to the intricate relationship between data-driven healthcare facility design and efficient layout planning.

It is crucial to emphasize that while Halawa's research primarily delved into AI-driven predictive modeling, the primary emphasis of this study centers on the interplay and integration of various data sources and the broader framework of data interoperability.

In this context, the data insights obtained from Halawa’s work take on a significant role as an essential input source for the PSO algorithm. By subjecting these data to various scenarios and integrative processes, our study validates the cohesive integration of BIM technology, further substantiating the imperative aspect of data interoperability within this context. The approach aspires to showcase the potential of seamless data exchange and integration within healthcare facility design, contributing to a comprehensive understanding of the nuanced and interconnected facets of data-driven healthcare facility management and design.

This research proposes the utilization of synthetic data in lieu of actual clinic data in the initial stage, which is subsequently transformed into an analyzable format. Table 1 provides a comprehensive list of rooms along with their respective sizes. According to Halawa et al. [11], raw EHR data contains patient IDs, encounter dates, provider information, department visits, appointment lengths, rooming, and checkout times. After preprocessing the data, patient pathways are created. The researchers used an algorithm with probabilistic deterministic finite automata (PDFA) to identify key pathways from the preprocessed data.

Table 1. Room list and room sizes.

Unit/Room	Unit Count	Width [cm]	Length [cm]
Check-in	1	500	700
Waiting area	1	1000	900
X-ray room	1	1000	800
Cast room	1	2000	900
Exam room	1	900	840
Physician work area	1	1500	850

Table 2 represents a patient pathway that can encompass the stages of check-in, waiting, X-ray, and cast. To calculate the probability of a patient following this pathway, the product of transitional probabilities and the probability of reaching a final state is computed by traversing the path from the starting point to the endpoint. Consequently, this is represented as $10/10 \times 10/10 \times 9/10 \times 3.5/10 = 3.15/10$, resulting in a total probability of 31.5% (see Table 3).

Table 2. Patient flow overall probability.

Description	Flow Variant	Probability
Check-in—Waiting—X-ray—Cast	CWXC	31.5%
Check-in—Waiting—X-ray—Exam	CWXE	25.0%
Check-in—Waiting—Exam—Physician	CWEP	13.0%
Check-in—Waiting—Cast—Exam	CWCE	13.5%
Check-in—Waiting—X-ray—Physician	CWXP	12.0%
Check-in—X-ray	CX	5.0%
SUM		100.0%

While the present study employs a fixed number of rooms and predetermined probabilities as inputs, it is worth noting that the data can easily be modified to accommodate dynamic inputs, such as varying numbers of rooms and diverse scenarios of movements within a clinic or similar environments.

The PSO algorithm requires initial solutions to initiate the exploration of the solution space. While previous research has shown that the quality of the initial solution can influence the final solution and tends to achieve early convergence toward the best solution, this study strategically opted for a totally random layout suggestion. The purpose was to assess the robustness and adaptability of the PSO algorithm within the healthcare facility design context, aligning with the broader goal of introducing a framework for the integration of AI algorithms and BIM models.

Table 3. Probability matrix of movements of patients.

Check-in	Waiting	X-ray	Cast	Exam	Physician	Total Probability
1	1	0.9	0.35	0	0	0.315
1	−1	0.5	0	0.5	0	0.250
1	1	0	0	0.26	0.5	0.130
1	1	0	0.9	0.15	0	0.135
1	1	0.24	0	0	0.5	0.120
1	0	0.05	0	0	0	0.050
					SUM	1.000

In this step, a continuous encoding method was used to represent the layout, where each room corresponds to a sequence of activities based on the patient flow probabilities and movement probabilities between rooms. The rooms were randomly placed within the available space, considering their dimensions and locations along the x and y axes. The simulation was run with specific settings and the results were visualized through optimized layout solutions.

3.2. Data Integration

Once the optimized layouts were generated using the PSO algorithm, they were integrated into the BIM using Dynamo. The PSO-generated layouts were imported into Dynamo, where they were represented as a collection of rooms with their respective dimensions and positions. Dynamo's visual programming capabilities were then utilized to extract relevant information from the layouts, such as room adjacency matrices, distance matrices, and room coordinates. Each node represents a specific action or operation, such as importing data, manipulating geometry, or generating complex algorithms. Dynamo has evolved into a comprehensive platform that enables designers to explore visual programming, solve practical design problems, and automate and optimize processes visually within Revit. It has transformed from being a separate tool to being deeply integrated within Revit, making it more accessible and user-friendly for designers.

The integration of Dynamo within Revit enables the creation of a streamlined workflow for generating optimized 3D BIM visualizations and enables designers to automate repetitive tasks, manipulate complex geometries, and perform data-driven design. The script developed in Dynamo interprets the output from the optimization algorithm, importing relevant data into Revit, and generating a 3D BIM model, as illustrated in Figure 3. The Dynamo script has been included in Appendix A. With the ability to modify design parameters and explore different design options iteratively, designers can optimize layouts and evaluate their impact on various factors such as space utilization, circulation flow, and accessibility. The visual programming script employed in this study follows the subsequent steps:

First, the output generated by the algorithm is converted into CSV files, which are then read into Dynamo. The second step involves reading these data into separate lists for each room. Each list contains the x and y coordinates for the center point of the respective room, as well as the x and y coordinates for two corner points. Similarly, in the third step, lists are created to represent the outline of the area. Moving forward, the fourth step involves feeding the room lists into a function that calculates the distances between rooms in the x and y directions. Additionally, coordinates for the two corner points and center points are generated. However, the coordinates for the corner points are not utilized further. To ensure accurate placement of the wall rectangles, a coordinate system is established from the center of the rooms. The fifth step focuses on generating x and y coordinates for each corner point, as well as lines representing each side and the rectangle. While the rectangle is relevant for subsequent steps, the lines are not utilized further. The final step in the script, as the sixth in the overall sequence, entails creating floors and walls for both the outline and individual rooms.

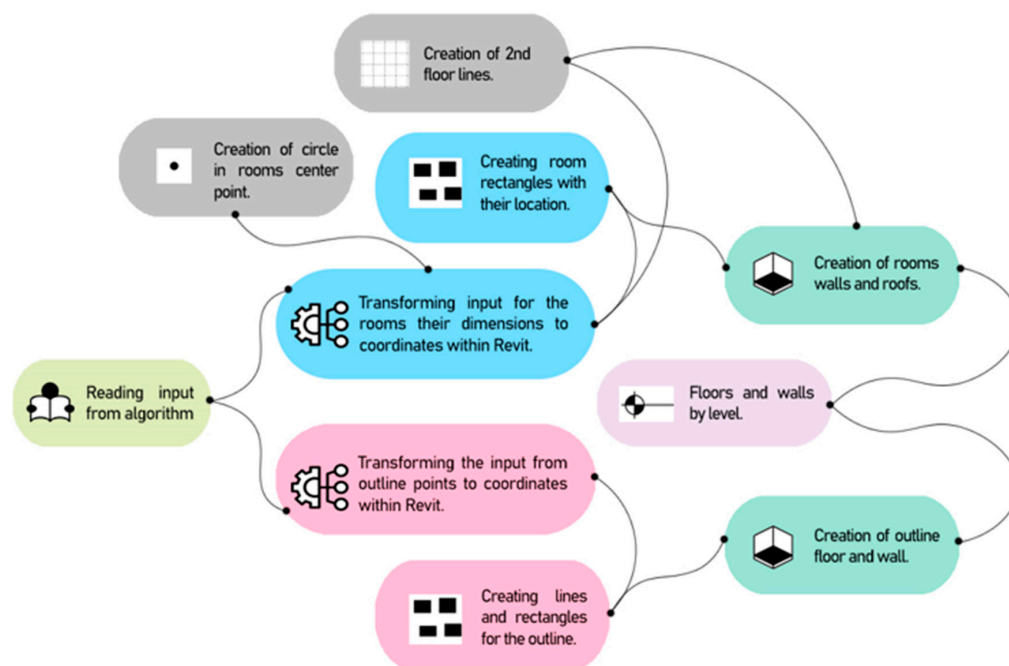


Figure 3. Flowchart for integration.

3.3. Data Visualization

The 3D visualizations of the optimized layouts within the BIM environment not only provide a clear representation of the spatial arrangement of the clinic rooms but also facilitate further analysis and evaluation of the layout solutions. Moreover, the integrated PSO and Dynamo workflow allows for iterative optimization and refinement of the layouts. This iterative approach enables the exploration and evaluation of alternative layout solutions by modifying the input parameters of the PSO algorithm and re-running the optimization process. Consequently, the layout design for the clinic continuously evolves, leading to an improved and more tailored spatial arrangement.

Furthermore, the incorporation of digital twin technology improves the BIM environment by enabling real-time monitoring and simulation of the facility's performance. This integration promotes a deeper understanding of the facility's operations, facilitating better-informed decision-making and more responsive design adjustments.

By employing the PSO algorithm and Dynamo in tandem, a series of simulations may be conducted to generate a BIM model based on the optimized 2D layout. The workflow involves using the PSO output in the form of comma-separated value (CSV) or JSON files, allowing for flexibility in data formats, as an input for Dynamo. Furthermore, the Dynamo automation tool, supplemented by the Dynamo Player, offers additional customization options (Figure 4). These include the selection of wall and floor typologies, definition of levels, and the ability to choose the AI optimization technique to be implemented. For instance, in this case, the PSO algorithm is applied; however, the methodology is adaptable to other AI algorithms. To utilize an alternative AI algorithm, the results should be first converted into CSV or JSON files. This dynamic approach empowers designers and facility managers with the capacity to experiment with different design configurations and AI optimization strategies, enhancing the versatility of the layout design process.

The framework is enhanced by integrating digital twin technology, which enables real-time monitoring and simulation. Digital twins continuously update the facility's performance, allowing stakeholders to make data-driven decisions based on real-time data. This real-time interaction is visualized using Autodesk Forge, a cloud-based platform that integrates BIM models with various data sources to create a comprehensive digital twin environment. Autodesk Forge allows for the visualization of 3D models linked with

real-time data, improving the ability to continuously monitor, analyze, and optimize the facility's performance.

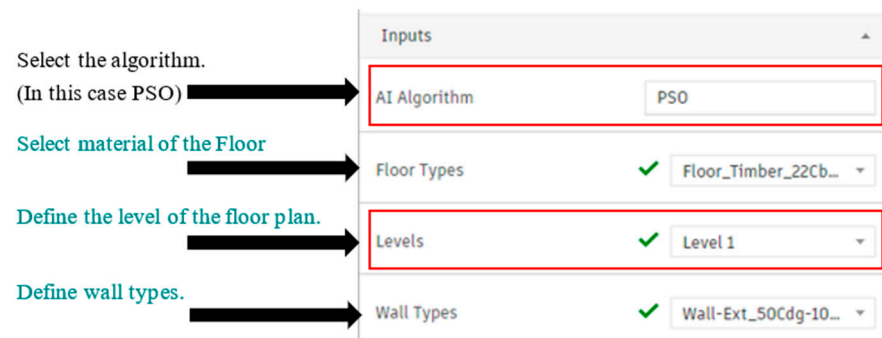


Figure 4. Additional customization options for BIM AI.

The PSO algorithm is iterated upon multiple times. In this study, 10 iterations were conducted, resulting in the generation of a 2D layout with substantial distances between clinic rooms. The outcome aptly demonstrates the effectiveness of the proposed methodology. Figure 5 showcases the optimized 2D layout obtained through the application of the PSO algorithm and the subsequent automated creation of the BIM model through the Dynamo script in Revit.

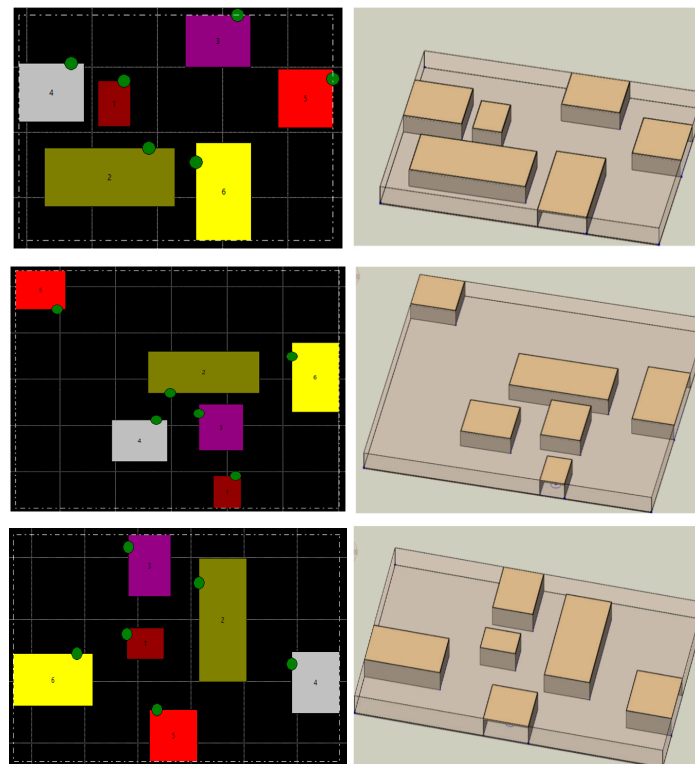


Figure 5. Automated creation of the BIM models (right) from optimized 2D Layouts (left).

This adaptable approach not only streamlines the layout design process, but also enables stakeholders to make informed decisions, explore different design configurations, and harness the potential of AI algorithms and digital twins within a BIM environment.

4. Discussion

The effective design of healthcare facilities is crucial for meeting the needs of patients and healthcare providers, ensuring optimal functionality, and improving patient experiences. Traditional design approaches have often separated different stages of the process,

leading to suboptimal outcomes. Specifically, the initial design of healthcare facilities heavily relies on user involvement and feedback to meet specific requirements. Optimizing the layout of healthcare facilities is essential for efficient space utilization and minimizing space requirements. The integration of AI techniques, particularly optimization algorithms, with BIM systems has the potential to revolutionize the design process. This integration streamlines data collection, enhances data quality, and enables the visualization of layout solutions, empowering decision-makers to make informed choices.

This study emphasizes the importance of using an integrated approach to streamline the design process, reduce time and labor costs, and enhance cost-effectiveness. It also highlights potential areas for future research, particularly exploring generative design techniques within the BIM framework. This study aims to inspire further advancements in healthcare facility design practices. While previous research has focused on using AI algorithms to optimize healthcare facility layouts, this study takes a novel approach by fully integrating AI algorithms with BIM technologies. It emphasizes the advantages of seamless data interoperability between these two domains. This integration can bridge the gap between data-driven design and efficient layout planning, offering a comprehensive understanding of healthcare facility design optimization. The advantages of integrating functional plans into a BIM model are extensive. Through the use of IFC, both a seamless exchange of data and interoperability across various software platforms are facilitated. This integration allows for the creation of a 3D model that empowers end-users to select materials for walls and floors through an intuitive interface. The model also supports generative design, streamlining the rapid creation and assessment of multiple design options. Furthermore, it enhances sustainability efforts by enabling CO₂ calculations and environmental impact assessments, thereby optimizing the building's lifecycle from design to operation, as well as maintenance efficiency and environmental sustainability. Moreover, utilizing BIM at this stage is not excessive. It can be used not only for the design phase but also for operational stages, such as renovating buildings, to address issues similar to those encountered during the COVID-19 pandemic. This enables predictive space management and optimization, guaranteeing that the facility can adapt to changing demands.

The PSO algorithm has been integrated with BIM through Dynamo visual programming to optimize the layout of hospital clinics. The resulting 3D BIM models offer valuable insights for stakeholders during the preliminary design phase, allowing them to make informed decisions based on a comprehensive understanding of the facility's layout. This methodology enables iterative adjustments to design parameters and the exploration of various design options. Furthermore, digital twin technology enhances the BIM environment by enabling real-time monitoring and simulation of the facility's performance. This continuous feedback loop ensures that the design dynamically adapts to real-world conditions and evolving healthcare needs. Stakeholders can interact with the real-time data and make data-driven decisions by visualizing digital twins in platforms like Autodesk Forge, further improving operational efficiency and patient care.

To contextualize this innovation, it is instructive to compare it with the existing systems detailed in the introduction of this paper. Chraibi et al. [7] utilized PSO in an operational context, enhancing staff efficiency in operating theaters. Unlike their approach, which primarily focused on operational efficiency within a confined scope, our integration extends to comprehensive facility design, leveraging BIM to enhance the spatial and functional adaptability of healthcare environments. Arnolds and Gartner [8] explored the impact of data-driven critical pathway mining on strategic decisions in healthcare management. Our approach builds on this by not only utilizing data-driven methods but by integrating these insights with dynamic BIM models and digital twins, thus providing a more robust and flexible platform for real-time decision-making and scenario simulation. Vahdat et al. [9] concentrated on minimizing patient walking distances using simulation-optimization techniques. Our study extends this concept by employing AI to automate the optimization process, thereby not only addressing patient movement but also optimizing the overall spatial layout, which can dynamically adjust to the changing needs of the facility. The

incorporation of AI into the design process represents a significant advancement over traditional methods. AI-driven design within BIM enables the rapid generation of multiple design alternatives, facilitating well-informed decision-making. The process's accuracy and reliability are enhanced through the use of IFC models, ensuring comprehensive data exchange and interoperability. This approach benefits various stakeholders, including patients, hospital staff, civil engineers, designers, and facility owners. Patients receive improved care through optimized space management, hospital staff experience reduced workload during peak times, and owners achieve cost savings and increased efficiency. Furthermore, sustainable design practices enabled by generative design benefit the environment. This innovative methodology is not only replicable but also supported by Dynamo scripts, which can guide other researchers.

The proposed framework for healthcare facility design integrates AI-driven optimization algorithms with BIM and digital twin technologies, offering significant advancements over existing techniques. Traditional methods often require manual adjustments and subjective decision-making, leading to increased time and costs despite improvements from data-driven critical pathway mining and simulation optimization approaches. In contrast, the proposed framework automates the layout design process through PSO algorithms and Dynamo visual programming, significantly reducing the manual effort and time required for data collection and BIM model creation. This automation allows designers to focus on higher-level decisions and iterative improvements. Furthermore, the integration of robust visualization capabilities for BIM and the real-time monitoring of digital twins enables comprehensive visualization, analysis, and monitoring of designs. This approach facilitates well-informed decision-making and collaborative discussions. The proposed framework also excels in layout optimization by iteratively optimizing space utilization, circulation flow, and accessibility, resulting in 3D BIM models that provide valuable insights for stakeholders. Additionally, the framework's adaptability allows for dynamic adjustments to design parameters, accommodating various design scenarios and responding to evolving healthcare needs, such as public health emergencies. This ensures that the facility design is not only efficient and effective but also flexible and resilient.

The integration of AI and BIM in healthcare facility design opens up possibilities for future research. Researchers can explore the application of generative design techniques within the BIM framework to maximize its potential for optimization purposes. By leveraging AI and generative design in BIM, healthcare facility designs can become more efficient, accurate, and adaptable to the evolving needs of the healthcare industry. This ultimately leads to improved patient experiences and operational effectiveness. All in all, the integrated approach to healthcare facility design optimization showcased in this study highlights the potential benefits of combining AI-driven algorithms with BIM and digital twin technologies. The ability to visualize and optimize layouts iteratively significantly enhances the design process, empowers stakeholders, and sets the stage for future research into more sophisticated AI-driven design approaches within the BIM framework.

5. Conclusions

This study demonstrates the potential of integrating AI algorithms with BIM and digital twin technologies to optimize healthcare facility layouts. By automatically integrating AI into the BIM framework, researchers can leverage the capabilities of BIM from the early stages of the design process, resulting in improved efficiency and effectiveness.

The proposed methodology combines PSO algorithms with BIM using Dynamo visual programming. This integration allows for creating optimized 2D layouts and transforming them into detailed 3D BIM models. By combining these technologies, it not only facilitates meaningful discussions and informed decision-making during the initial design phase, but also takes advantage of the clash detection, quantity takeoff, and visualization capabilities of BIM. Furthermore, the use of digital twins enhances the framework by enabling real-time monitoring and continuous optimization, ensuring that the facility dynamically adapts to real-world conditions and evolving needs.

The use of BIM in healthcare facility design offers several advantages. By creating a digital representation of the facility, BIM enables stakeholders to visualize and analyze designs in a virtual environment, identifying potential conflicts or inefficiencies early on. Additionally, BIM allows for the selection of wall types and the calculation of material quantities, aiding in accurate cost estimation and facilitating efficient procurement processes. Designers can utilize BIM's clash detection capabilities to identify and resolve clashes between different building elements, ensuring coordination and avoiding costly errors. Furthermore, BIM enables the analysis of different scenarios based on factors such as cost, energy efficiency, and sustainability, providing a more holistic view of the design. Moreover, the integration of digital twin technology with BIM allows for real-time interaction with the facility's performance data, promoting better-informed decision-making and more responsive design adjustments. This real-time capability is particularly valuable in accommodating varying design scenarios and responding to dynamic healthcare needs, such as during public health emergencies.

While the initial results are promising, it is important to acknowledge the limitations of this study. Currently, the focus is on integrating AI-driven BIM, with plans to incorporate DT technology in future work. It is crucial to conduct further research to fully integrate DT capabilities and validate the approach in real-world scenarios. Continuously assessing the accuracy and reliability of the AI algorithms is necessary to ensure optimal performance. Subsequent work will aim to address these limitations and explore the complete potential of DT technology in healthcare facility design. This study highlights opportunities for future research by emphasizing the use of generative design techniques within the BIM framework. By taking maximum advantage of BIM capabilities and integrating AI algorithms, researchers can further enhance optimization and design processes in healthcare facilities, leading to improved patient experiences and operational efficiencies. While limitations exist, such as the need for accurate input parameters and exploration of the approach in various healthcare contexts, the proposed methodology offers a promising avenue for advancing healthcare facility design practices and realizing the benefits of BIM. While this study does not currently utilize DT technology, an AI-driven BIM integration framework is crafted to facilitate future DT integration. The potential for DT integration is intended to provide real-time simulation and optimization capabilities, thereby enhancing the design, operation, and maintenance phases of healthcare facilities. Future research should focus on validating the methodology in different settings, refining data collection processes, and exploring the full range of opportunities that arise from the integration of AI and generative design techniques in BIM. In addition, this study anticipates the incorporation of augmented reality (AR) applications into the BIM AI framework. This advancement would enable stakeholders to visualize and interact with proposed layouts in real-world contexts, providing an immersive experience that enhances decision-making and the understanding of spatial implications.

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Appendix A

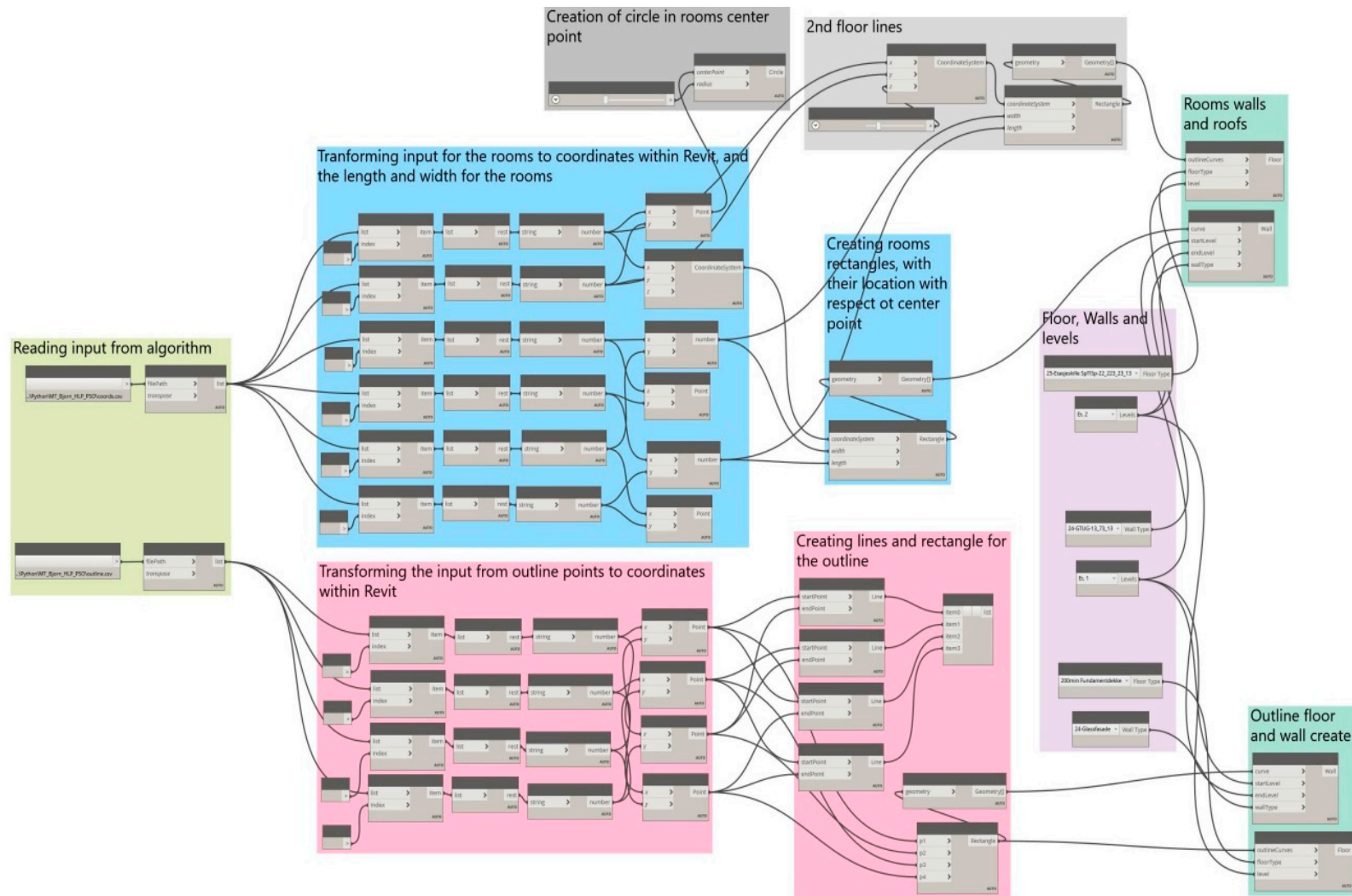


Figure 1. Dynamo Script for Interpreting Optimization Algorithm Output and Generating 3D BIM Model in Revit.

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