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A Computational BIM-Based Spatial Analysis Method for the Evaluation of Emergency Department Layouts

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Abstract

This paper introduces a novel BIM-based computational workflow that embeds spatial analysis directly within the Building Information Modelling (BIM) environment to support the evaluation and design of hospital emergency department (ED) layouts. Conventional analyses often depend on external software and repeated data exchange, which limit efficiency and integration with the design process. The proposed method integrates space syntax principles into Revit through Dynamo and custom Python scripts, enabling automated calculation of spatial measures linked to healthcare-specific performance indicators. The workflow was applied to two UK-based ED floor plans in a comparative case study, assessing patient-oriented aspects such as wayfinding, emergency access, and spatial privacy, alongside staff-oriented factors including workstation accessibility and visibility. Results were validated against DepthmapX to ensure consistency and reproducibility. The findings demonstrate that a BIM-native approach can streamline spatial analysis by eliminating import–export cycles, enhancing design iteration, and supporting post-occupancy evaluation. The significance of the study is in providing a decision-support framework for architects and healthcare planners in both designing new and evaluating existing ED layouts, where spatial configuration directly affects efficiency and user experience. Its main contribution is a reproducible workflow that enables real-time evaluation and strengthens the link between spatial analysis and evidence-based healthcare design.

Keywords: building information modelling; computational design; spatial analysis; spatial layout evaluation; space syntax; healthcare design; emergency department

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1. Introduction

1.1. Aim and Scope of the Study

The layout of hospital environments plays a critical role in shaping patient outcomes, staff efficiency, and the overall quality of care. In emergency departments (EDs), where time-sensitive decisions and spatial complexity intersect, design choices strongly influence wayfinding, privacy, accessibility, and visibility [1]. Poor wayfinding in crowded EDs can increase patient stress, delay care, and divert staff from clinical tasks [2]. Privacy is often compromised by open or poorly organised layouts, whereas clear spatial partitions and visual separations help maintain confidentiality and comfort [3]. Accessibility is equally essential: patients need clear pathways and well-positioned triage stations, while staff require direct access to supplies, equipment, and critical spaces to ensure timely care [1]. Visibility enhances safety through improved supervision and reduces risks by facilitating face-to-face communication among staff [4]. Together, these factors shape patient flow, strengthen staff performance, and contribute to positive healthcare outcomes.

Although space syntax and related spatial analysis methods have been applied to healthcare facilities, they are most often used in post-occupancy evaluation rather than in early design [5]. Their integration into the design process remains limited, with only a few examples applied at the building scale [6].

This study introduces a computational workflow that integrates spatial analysis directly into the Building Information Modelling (BIM) environment, enabling real-time performance evaluation of hospital ED layouts. Developed in Revit–Dynamo, the method embeds space syntax principles through custom Python scripts and applies the AVA (Accessibility and Visibility Analysis) package to compute key metrics—including step depth, metric distance, connectivity, integration, and isovist area—without exporting to external tools. The framework allows scenario-based evaluations from both patient and nurse perspectives, aligning spatial metrics with healthcare-specific indicators such as wayfinding, accessibility, privacy, and visibility. By embedding spatial logic into the design process, it supports evidence-based decision-making, facilitates post-occupancy evaluation (POE), and promotes iterative, data-driven design within BIM environments.

1.2. Research Gap and Contribution

Spatial analysis methods such as space syntax have been widely used to evaluate healthcare layouts [7]. However, most analyses are conducted using standalone tools such as DepthmapX, which operate outside BIM environments and do not integrate with the architectural design process [8]. This separation reduces the ability to evaluate spatial configurations dynamically and limits the usefulness of spatial feedback during early design stages [9].

Despite the increasing adoption of BIM in architecture, very few methods integrate spatial analysis directly within BIM workflows. One of the earliest attempts was ArchiSpace, a BIM-based system developed by Li et al. [8], which automatically generated spatial topology and enabled real-time space syntax analysis during the early design stage. While innovative, it was limited to 2D topologies, lacked IFC/Revit integration, and offered only a narrow set of metrics. More recently, Ugliotti and Shahriari [10] proposed a BIM-based approach for measuring spatial depth and interaction levels in hospital settings. Although valuable, this work focuses narrowly on depth analysis and does not provide a generalisable, multi-criteria evaluation framework.

This study addresses these gaps by proposing a reproducible computational workflow for BIM-integrated spatial analysis. Unlike conventional approaches requiring manual data transfers, the method operates entirely within the BIM model. Implemented in Revit with Dynamo and Python, it leverages the AVA (Accessibility and Visibility Analysis) package to automate the calculation of spatial metrics such as step depth, metric distance, visibility, connectivity, integration, and isovist area.

The workflow supports real-time, scenario-based assessments of critical user journeys, such as patient movement from waiting areas to treatment rooms. By combining spatial logic, visualisation, and user-specific feedback within one environment, it enhances BIM as a platform for evidence-based design. The method also extends beyond the design phase to support post-occupancy evaluation (POE). Its reliability was verified by cross-checking results with DepthmapX, confirming consistency across platforms.

Unlike previous approaches that often focused on isolated user perspectives or single spatial criteria, the proposed framework offers a more integrated evaluation approach. It enables a deeper understanding of how spatial configurations affect both operational efficiency and user experience in emergency departments, and provides a systematic means to compare, assess, and optimise design alternatives.

1.3. Research Questions

This study is guided by the following research questions:

- How can Building Information Modelling (BIM) be integrated with spatial analysis (space syntax) methods to evaluate the performance of hospital emergency department layouts, and which spatial metrics are most relevant for assessing critical design factors such as accessibility, visibility, and privacy from both patient and nurse perspectives?
- How can the proposed BIM-based workflow be validated, and what are its main advantages and limitations compared to conventional space syntax tools?

1.4. Paper Structure

Section 2 reviews relevant literature on hospital design, space syntax methods, and BIM-based spatial analysis. Section 3 outlines the methodological design, including the conceptual framework, spatial variables, evaluation criteria, and the BIM-based workflows developed in Revit–Dynamo with the AVA package. Section 4 presents the analysis of two ED layouts in the UK, demonstrating the spatial metrics and visual outputs related to wayfinding, emergency access, privacy, accessibility, and visibility. Section 5 discusses the findings in relation to traditional space syntax tools and implications for evidence-based healthcare design. Section 6 concludes with contributions, limitations, and future research directions.

2. Literature Review

Hospital design is a complex process that must balance functionality, safety, and efficiency while addressing the needs of both patients and staff. Patient-centred design requires careful consideration of accessibility, proximity, wayfinding, security, and privacy, as these factors directly influence healthcare delivery. Well-designed spatial layouts enhance patient recovery, improve safety, and support staff performance [1,11,12].

Given this complexity, space syntax has become a widely applied method in healthcare facility research. It provides quantitative measures of spatial configuration—including movement, accessibility, visibility, and circulation patterns—allowing designers and researchers to evaluate how layouts influence performance [13]. In addition, spatial analysis has been employed in post-occupancy evaluation (POE) to assess whether built environments meet intended functional goals and to inform future design decisions [14].

At the same time, Building Information Modelling (BIM) has become increasingly important in delivering complex healthcare projects [15,16]. BIM provides a data-rich framework that supports integrative, evidence-based analysis and enables early design decisions that enhance hospital functionality and efficiency [16]. When combined with spatial analysis, BIM allows performance metrics such as accessibility and visibility to be evaluated directly within the design environment, strengthening the feedback loop between design intent and healthcare outcomes [10].

2.1. Overview of Spatial Analysis and Space Syntax

Spatial analysis is an essential methodology in urban and architectural research, providing tools to examine how spatial configurations shape human behaviour. Methods such as agent-based modelling, GIS-based analysis, and network analysis have been applied to evaluate connectivity, accessibility, and movement. Among these approaches, space syntax is one of the most established. It examines how spatial configurations influence human behaviour, including movement, visibility, and interaction. By representing the built environment as a network of spaces and connections, it enables both entire layouts and individual rooms to be quantitatively evaluated [13,17]. These configurational measures provide a basis for statistical analysis of architectural floor plans and have been shown to explain 60–80% of movement patterns [18].

The measures are typically calculated using software such as DepthmapX, originally developed by Turner [19] and later enhanced by Tasos Varoudis at University College London (UCL). DepthmapX enables axial, convex, visibility graph (VGA), and segment analyses, generating numerical data and visualisations that capture accessibility, connectivity, and circulation patterns. By quantifying the relationships between all spaces in a system, space syntax offers a systematic way to evaluate how layouts affect efficiency, wayfinding, and user experience [20].

Space syntax provides distinct representation methods by analysing spatial configurations, human movement, interaction potential, and visibility relationships. These representations enable the systematic study of how spatial layouts influence behaviour, accessibility, and connectivity in architectural and urban environments.

Justified graph analysis illustrates the hierarchical depth of spatial relationships within a layout (Figure 1). Spaces are organised by their distance and connectivity from a central reference point, such as a main entrance or key space [17]. Key measures include step depth (accessibility), connectivity (direct spatial links), and integration (spatial centrality).

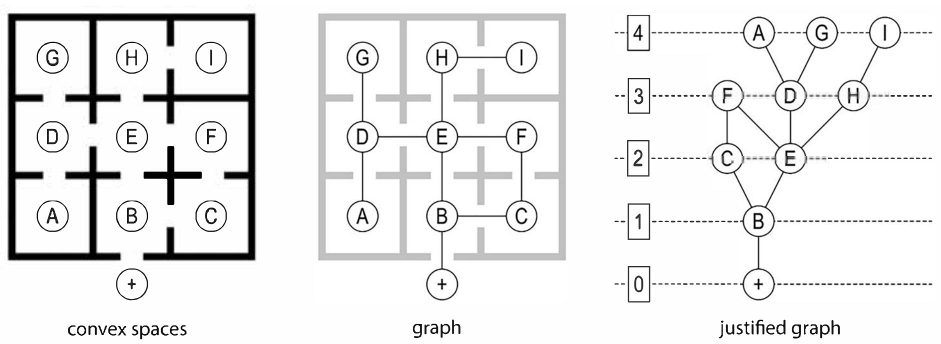

Figure 1. Justified graph analysis (adapted from Daves, Ostwald, and Lee [21]). The letters (A–I) represent individual spaces within the plan, while the numbers (1–4) indicate the depth levels from the entrance (+) in the justified graph. *Adapted with permission from Ref. [21]. Copyright 2021, Higher Education Press Limited Company. Published by Elsevier B.V. under the CC BY-NC-ND 4.0 license (https://creativecommons.org/licenses/by-nc-nd/4.0/, accessed on 10 September 2025).*

Axial analysis captures primary movement paths by overlaying the layout with the longest and least numerous axial lines (Figure 2). It evaluates circulation efficiency through measures such as choice (betweenness centrality), which identifies likely routes for movement, and integration, which shows how well a path connects within the network [17]. *Convex analysis* represents spaces as convex polygons to assess openness, interaction, and permeability between connected areas (Figure 2) [22]. Key measures include connectivity, evaluating the number of linked spaces, and integration, assessing accessibility within the system. *Visibility graph analysis—VGA* examines visibility relationships across an entire spatial setting, supporting the evaluation of wayfinding, surveillance, and spatial connectivity (Figure 2) [23]. Key measures include visual integration, which assesses the overall visibility of a space within the system, and visual step depth, which captures the number of steps needed to reach a visually connected space. *Isovist analysis* evaluates visibility and spatial perception from a given location [24]. Key measures include isovist area, which quantifies the extent of visible space, and perimeter, which captures the boundary length of the visible area. These measures are useful for assessing wayfinding complexity and surveillance potential. *Agent-based analysis* simulates human movement by modelling virtual agents navigating a spatial layout according to predefined behavioural rules (Figure 2) [25]. Key measures include agent density, which shows movement concentration, and path choice probability, which identifies preferred circulation routes. These spatial measures offer insights into spatial organisation, accessibility, and visibility. Their detailed definitions and applications in evaluating hospital layouts will be further discussed in Section 3.

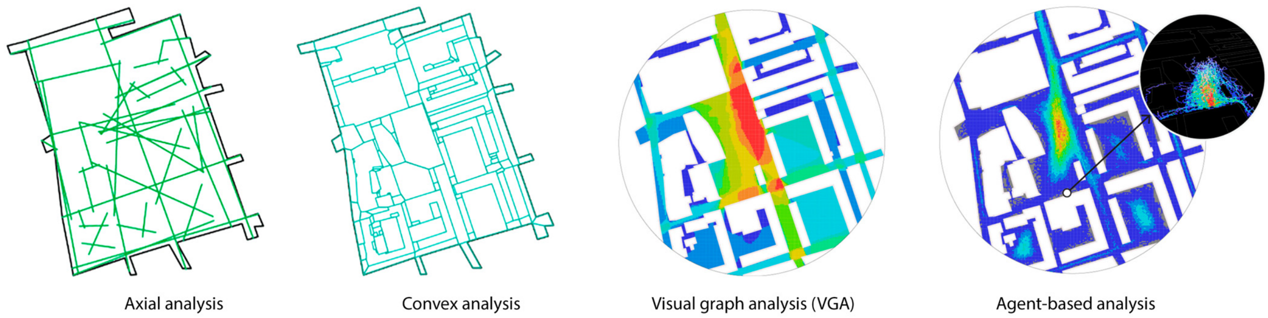

Figure 2. Axial, convex, visibility graph, and agent-based analysis (adapted from Yamu, van Nes, and Garau [26]). In the visibility and agent-based analysis diagrams, warmer colours (red–yellow) indicate higher visibility or movement intensity, while cooler colours (green–blue) represent lower values. The subfigure in the agent-based analysis shows a model where agents are released from a specific location. *Adapted from Ref. [26]. Copyright 2021, the authors. Published by MDPI, Basel, Switzerland, under the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/, accessed on 10 September 2025).*

2.2. Overview of BIM-Based Spatial Analysis Method

Building Information Modelling (BIM) has transformed the architecture, engineering, and construction (AEC) industry by integrating multidimensional information into a single digital representation of buildings. Beyond its role in design and construction management, BIM is increasingly used for spatial analysis, enabling the evaluation of built environments and supporting evidence-based design.

Since BIM captures both geometric and semantic data, it provides a strong foundation for embedding spatial analysis methods such as space syntax directly into the design process. One of the earliest attempts was made by Li et al. [8], who developed ArchiSpace, a BIM-based system that automatically generated spatial topology and enabled real-time space syntax analysis during early design. While innovative, it was limited to 2D representations, lacked IFC/Revit integration, and offered only a narrow set of metrics. Jeong and Ban [27] later showed that the topological relationships between spaces—particularly accessibility and social characteristics—can be assessed in early stages using computational tools. Similarly, Al Sayed et al. [28] argued that embedding space syntax in BIM could improve decision-making by linking spatial organisation with social and environmental performance. In the healthcare sector, Ugliotti and Shahriari [10] demonstrated how BIM-based space syntax analysis can automate the evaluation of spatial depth and interaction in hospital layouts.

BIM has also been applied to other spatial evaluation methods. For example, Lee et al. [29] developed an approach using the Building Environment Rule and Analysis (BERA) language to perform quantitative circulation analysis, enabling systematic comparison of design alternatives. Shin et al. [30] extended this direction by blending measurable indicators such as metric distances, spatial depth, and room dimensions with experiential qualities. Their introduction of the "Weighted Distance (WD)" metric illustrated how BIM can account for both physical and perceptual factors when analysing paths and circulation efficiency. More recently, Zhang et al. [31] applied BIM within a multi-layered evaluation framework for housing design, linking spatial analysis with lifecycle data to support ageing populations and demonstrating the scalability of BIM-based analysis from building-level performance to urban planning strategies.

Despite these advances, limitations of conventional space syntax tools remain. Dursun et al. [9] criticised their lack of interactivity and poor integration with iterative design processes. Nourian et al. [32] responded with a Grasshopper-based toolkit that integrates real-time space syntax analysis, enabling interactive exploration of design alternatives. Yazar et al. [33] developed a similar tool, SpaceChase, which embeds spatial analysis into the design workflow. These approaches highlight the need for flexible, integrated methods that bring spatial analysis closer to the design process itself.

2.3. Overview of Spatial Analysis in Hospital Design and Evaluation

Spatial analysis is a key tool in hospital design and evaluation, enabling architects, planners, and healthcare professionals to assess and improve built environments in ways that support patient care and staff workflows. Hospitals are highly complex facilities, combining diverse functional areas such as inpatient wards, outpatient clinics, surgical suites, and emergency departments. The spatial arrangement of these zones directly affects wayfinding, staff coordination, infection control, and overall patient outcomes [11].

Several reviews have highlighted the role of computational methods in hospital design. Haq and Luo [13] provided an early overview of space syntax applications in healthcare research, outlining its potential and future directions. Sadek and Shepley [34] further examined the accuracy of space syntax measures, emphasising their correlation with behavioural and perceptual outcomes. Jia et al. [7] reviewed spatial decision support systems, noting the value of network analysis and simulation modelling for addressing hospital design challenges. More recently, Bayraktar Sari and Jabi [12] identified a shift from traditional design methods to computational approaches, including spatial analysis and machine learning in hospital planning.

Spatial analysis has been used both in early-stage design decision-making and in post-occupancy evaluation (POE). Within the framework of evidence-based design (EBD), it helps assess the consequences of alternative layouts on patient throughput, staff efficiency, and emergency response times. Applications commonly focus on wayfinding complexity, accessibility between public and clinical areas, and staff visibility. At the same time, POE provides objective feedback on whether built environments meet their intended design goals. Together, these applications demonstrate how spatial analysis links design intent with real-world performance, reinforcing its value as a tool for evidence-based healthcare architecture.

3. Research Design and Methods

This study employs a computational BIM-based spatial analysis approach to assess and compare two emergency department (ED) layouts. It integrates space syntax principles and spatial metrics to evaluate accessibility and visibility through a structured and quantitative method. The spatial metrics used in this study have been previously validated through research demonstrating their correlation with hospital floor plan characteristics and key criteria such as wayfinding, emergency accessibility, and staff efficiency. Rather than exploring new relationships, this research applies established spatial indicators to provide an objective, data-driven comparison of ED layouts.

The research follows a quantitative spatial analysis methodology, integrating Building Information Modelling (BIM) tools, including Revit, Dynamo, Python scripts and the AVA (Accessibility and Visibility Analysis) package, along with the space syntax measures. This computational approach provides a structured framework for evaluating key spatial characteristics. The richness and detail of BIM environments can be used as a point of departure for automating spatial assessments to generate quantifiable insights to inform hospital layout design.

This section outlines the conceptual framework for selecting spatial metrics, the evaluation criteria and challenges associated with emergency department configurations, and the case study process. It describes the computational tools and spatial analysis procedures used to assess and compare the layouts, providing a systematic and evidence-based approach to spatial assessment. A summary of the overall computational workflow used in this study, including BIM-based modelling, spatial metric computation, and result visualisation and output, is presented in Figure 3.

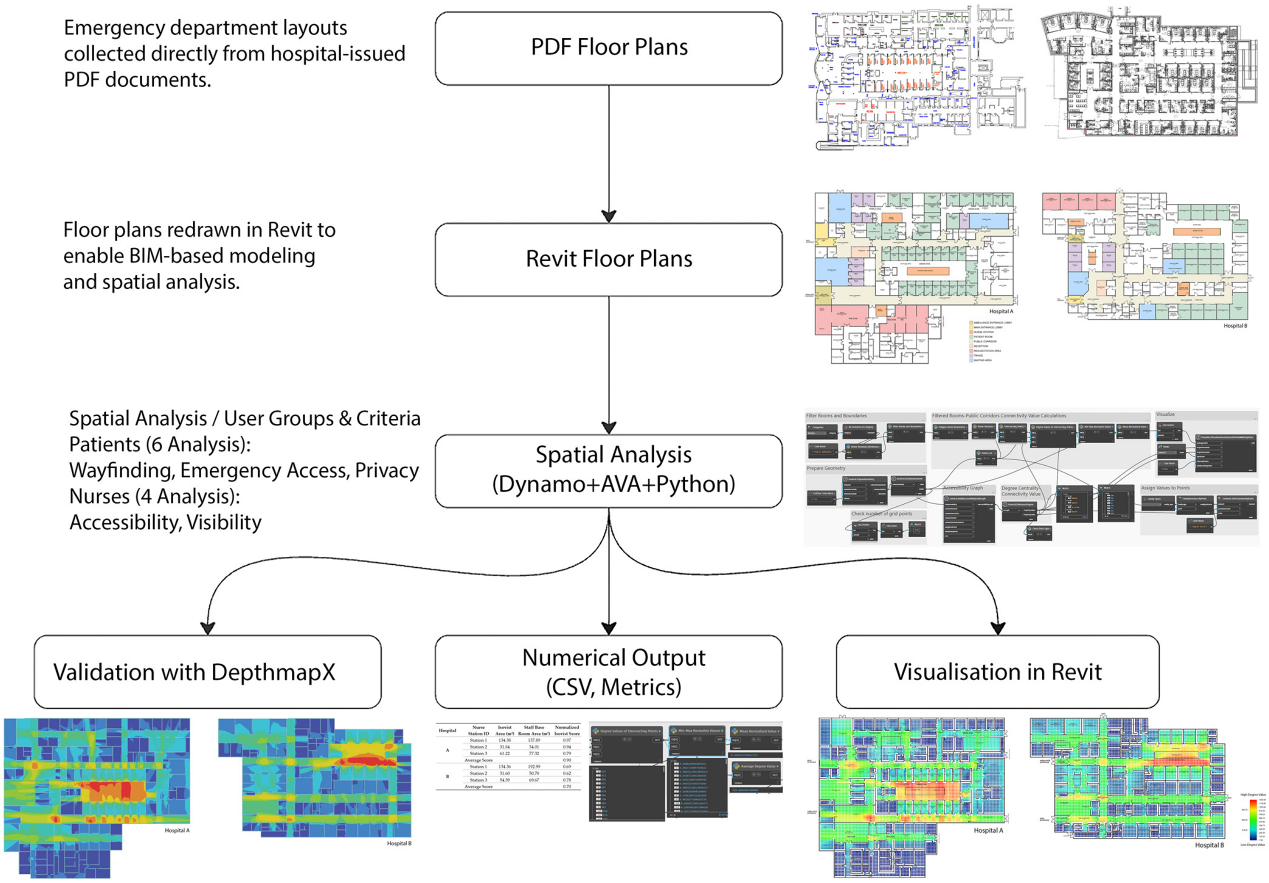

Figure 3. BIM-based workflow for spatial analysis of emergency department layouts.

3.1. Conceptual Framework for Accessibility and Visibility in Hospital Design

Accessibility and visibility are key components of hospital design that critically influence the ability of patients, visitors, and staff to navigate and move through healthcare environments. Accessibility refers to the ease with which an individual can reach a destination [35], while visibility denotes the spatial quality describing how much of an area or surface can be perceived from a given location [24]. These spatial properties directly affect wayfinding, emergency accessibility, and staff efficiency, which are essential for ensuring safe, effective and positive healthcare experiences.

The accessibility of a hospital or healthcare facility is closely tied to its spatial configuration. Elements such as corridors, entrances, waiting areas, and treatment spaces significantly influence movement and visibility. Inefficient layouts can hinder wayfinding, delay emergency responses, and disrupt staff workflow, ultimately impacting service quality and patient safety. In such contexts, spatial analysis techniques provide a structured and validated method to evaluate and enhance layout performance.

In this study, spatial analysis is employed to examine emergency department (ED) layouts, evaluating how effectively they support accessibility and visibility for individuals performing various spatial activities within the department. The analysis focuses on patients and nurses, as these user groups are most affected by spatial configuration due to their reliance on navigation, emergency response, and efficient movement. The specific challenges for each group and the corresponding spatial measures are discussed in Section 3.2.

3.2. Challenges and Assessment Criteria in Spatial Analysis of Hospital Design

The spatial configuration of hospital layouts plays a critical role in patient wayfinding, emergency accessibility, and nurse workflow efficiency. Inefficient spatial design can result in navigation difficulties, longer travel distances, and limited visibility, ultimately affecting patient safety, healthcare delivery, and staff performance.

This section identifies the main accessibility and visibility challenges faced by two key user groups, patients and nurses, and presents the spatial analysis criteria used to evaluate these challenges.

3.2.1. Patients: Accessibility and Visibility Challenges

Patients navigating emergency departments, whether arriving on foot or by ambulance, encounter multiple spatial challenges that influence their experience and access to medical care. Wayfinding, emergency accessibility, and privacy are the primary factors affecting the efficiency of patient care.

This study analyses emergency department (ED) floor plans from the patient's perspective, considering performance criteria related to these factors. Table 1 summarises the criteria, measured attributes, and spatial analysis methods used to evaluate wayfinding, emergency accessibility, and privacy from the patient's perspective.

Table 1. Spatial analysis methods and measured attributes for patient user group.

User Groups: Patients					
No	**Criteria**	**Measured Attribute**	**Spatial Analysis Method-AVA**	**Spatial Measures**	**Analysis Outcome**
1	**Wayfinding**	Connectivity of public corridors	Accessibility Analysis	Connectivity Value (local)	Higher connectivity values indicate spatial understanding and support navigation.
2	**Wayfinding**	Integration of public corridors	Visibility Analysis	Integration Value (global)	Higher integration values indicate overall navigation efficiency.
3	**Wayfinding**	Visibility of reception area from the main entrance	Targeted Visibility Analysis	Targeted Isovist Area	Higher reception visibility values from the entrance indicate easier wayfinding.
4	**Wayfinding**	Step depth and metric distance from main entrance to patient rooms	Visibility & Accessibility Analysis	Visual Step Depth & Metric Distance	Lower step depth and shorter distances indicate easier access to patient rooms.
5	**Emergency Accessibility**	Step depth and metric distance from ambulance entrance to resuscitation area	Visibility & Accessibility Analysis	Visual Step Depth & Metric Distance	Lower step depth and shorter distances indicate shorter routes, and faster emergency response.
6	**Privacy**	Integration of patient rooms	Accessibility Analysis	Integration Value (global)	Lower integration values indicate better privacy.

Wayfinding and Spatial Measures

Wayfinding is a cognitive process that involves navigating from an origin to a destination. It is influenced by environmental conditions [36] and individual behaviour [37]. The architectural layout plays a central role in influencing wayfinding and shape patients' initial perceptions and impressions of the quality of care. The wayfinding experience for the patient is one of the most critical design aspects of healthcare facilities, as it affects patient and visitor perceptions of their overall experience. Navigating a complex hospital can cause stress, missed appointments, and frequent interruptions of staff time to provide directional assistance [2].

Topological and mathematical values derived from the space syntax theory help identify areas that pose wayfinding difficulties and provide a quantifiable understanding of the spatial environment. According to Haq and Luo [4], syntax variables are useful for identifying corridors that are most frequently used by visitors during exploration and wayfinding in hospital buildings. Connectivity, integration, and intelligibility are key space syntax measures that correlate strongly with wayfinding performance [38]. These measures describe the distribution of visual information and accessibility within a spatial layout, which are critical factors for effective wayfinding.

Additionally, Jia et al. [7] demonstrated that the space syntax analysis methodology, with its key concepts of connectivity (degree centrality), integration (closeness centrality), and intelligibility, is highly effective for evaluating accessibility and wayfinding in complex building layouts like hospitals. Visibility analysis, such as isovist analysis, can be used to quantify these spatial properties and their impact on wayfinding [13]. Also, Emo [39] highlighted that depth of view and visibility lines are recognised as key spatial elements for wayfinding. These theoretical perspectives and empirical findings underscore the value of analysing wayfinding through multiple spatial measures that capture different aspects of spatial configuration and user perception.

Based on these theoretical insights, this study employs the following spatial measures to quantitatively assess wayfinding performance within emergency department layouts.

Connectivity is a local space syntax measure that defines how each space is linked to its directly adjacent spaces [40]. It represents the number of spaces connected to a specific space within the overall system and is classified as a static, local metric [22].

Previous studies have demonstrated the importance of connectivity in explaining user movement and spatial understanding. Choi [41] found connectivity to be a strong predictor of repeat visits in museum settings ($r = 0.623$), highlighting its role in directing users toward areas with greater visual access and exploration opportunities. Haq [42] extended this understanding by showing that, in unfamiliar environments, users are naturally drawn to highly connected spaces during initial exploration. In a study of three urban hospitals, Haq and Zimring [40] found that connectivity was the strongest predictor of total space usage ($r = 0.768$, 0.884, and 0.786). Similarly, Aksoy et al. [43] identified connectivity, integration, and step depth as key parameters for assessing wayfinding performance among first-time users in hospital layouts, based on behavioural observations and spatial metrics derived from space syntax analysis.

In this study, the connectivity value of public corridors is analysed to evaluate patient wayfinding by measuring how well these spaces are linked and accessible. Previous research indicates that higher connectivity enhances visibility and spatial understanding, facilitating easier navigation for patients.

Integration measures how easily a space connects to all other spaces within a network, indicating its potential to attract movement or function as a destination. It is a global space syntax measure that evaluates the accessibility of each space within the overall system by considering the number of steps or turns required to reach all other spaces [40]. Integration reflects how each space relates to the entire configuration of a layout.

Researchers have used integration values derived from space syntax analysis to examine public corridor systems and understand how patients navigate hospital buildings. Peponis et al. [44] conducted one of the earliest studies in healthcare environments and found that integration measures explained significant variations in spatial usage within a 100-bed hospital. Haq [42] similarly observed a strong correlation between corridor and intersection use and their integration values ($r = 0.662$) in a 21-storey hospital. In a different context, Choi [41] tracked individuals in museum environments and identified integration as the strongest indicator of presence among first-time visitors. Further, Haq and Girotto [45] analysed the relationship between cognitive representations and real spatial configurations, finding strong correlations between sketch-map integration values and those derived from space syntax in two hospital settings: University Hospital (r = 0.931) and City Hospital (r = 0.876).

In this study, the integration value of public corridors is analysed to assess patient wayfinding by evaluating spatial accessibility and overall cohesion within the emergency department layout.

Isovist analysis represents all the points within an environment that are visible from a specific vantage point in space [24]. In space syntax analysis, isovist measures have been used to identify how entry spaces influence wayfinding, indicating which entrances are more complex in terms of navigation [13]. A targeted visibility (or targeted isovist) analysis focuses on the visibility of specific points of interest rather than the overall visible area. It evaluates how well key spaces can be seen from defined viewpoints.

Ensuring clear visibility of public areas such as reception and waiting spaces is essential to support patient wayfinding. For patients and visitors unfamiliar with the layout, higher targeted isovist values indicate greater visual access and a higher likelihood that the reception area will be easily recognised. This facilitates purposeful navigation, improves spatial orientation, and contributes to a clearer overall understanding of the hospital environment.

In this study, the targeted isovist area was used to examine the visibility of the reception area from the main entrance, representing how easily patients can locate key destinations upon entering the building.

Visual Step Depth analysis examines the relative depth of spaces within a built environment and identifies how many steps are required to reach a specific location from a starting point. In hospital design, lower step depth values indicate greater efficiency, easier wayfinding, and better spatial orientation [46].

Previous studies have explored the relationship between visual step depth and wayfinding performance. Hölscher and Brösamle [47] found a significant positive relationship between measures of step depth and wayfinding efficiency. In their study, step depth from the starting point to the target was a strong predictor of wayfinding difficulty, showing strong correlations (r = 0.77–0.87). Their findings also indicated that fewer visual steps from the entrance to a destination support improved navigation and user performance. Similarly, Vogels [48] identified a strong correlation (r = 0.69) between visual step depth and wayfinding efficiency, highlighting the depth from the main entrance as a key factor in navigation within complex multilevel buildings.

In this study, visual step depth was used to evaluate the ease of access to patient rooms from the main entrance.

Metric distance measures the actual physical length between two points and serves as a direct indicator of travel effort or time. In hospital environments, shorter metric distances help patients and staff move more efficiently and access critical care areas more quickly.

In this study, metric distance was used to complement visual step depth by capturing the physical travel effort between spaces. The combination of visual step depth and metric distance provides a comprehensive assessment of spatial accessibility, reflecting both the number of spatial transitions required to reach a destination and the actual walking distance between spaces. Lower values in both metrics indicate more direct, legible, and user-friendly circulation routes.

Emergency Accessibility and Spatial Measures

Emergency accessibility refers to how efficiently critically ill or injured patients can be transferred to life-saving treatment areas, particularly those arriving by ambulance. Ensuring a direct and unobstructed route to trauma and resuscitation rooms is crucial to minimise treatment delays and improve patient outcomes.

In spatial analysis, emergency accessibility can be quantified through spatial measures that reflect both the directness of movement and the physical effort required to reach critical spaces. Building upon the measures introduced earlier, this study applies **visual step depth** and **metric distance** to assess the efficiency and directness of emergency access routes. Visual step depth reflects the number of spatial transitions required to reach a destination, while metric distance represents the actual physical length of the route. Previous studies have shown that layouts with lower step depth and shorter travel distances enable faster emergency response times and more efficient patient transfers.

In this study, emergency accessibility is assessed by measuring visual step depth and metric distance between the ambulance entrance and the resuscitation area across each emergency department layout. Lower values in both measures indicate more direct and efficient access routes, supporting timely emergency interventions and improved quality of care.

Privacy and Spatial Measures

Privacy, a fundamental human need [49], is an essential consideration in hospital design and encompasses both physical and psychological aspects of patient care. In healthcare environments, privacy provides patients with a sense of safety and respect, contributing to satisfaction, dignity, and overall well-being. The spatial configuration of hospital layouts plays a crucial role in either facilitating or compromising privacy. Poor spatial organisation can lead to excessive exposure, unwanted visibility, and a lack of confidentiality, all of which negatively affect patient comfort. Privacy in hospital design requires both physical separation between space types and controlled access to sensitive areas. For example, spatially isolating patient rooms or treatment cubicles provides a private environment for consultation or care.

In spatial analysis, the **integration** value can be used to evaluate the degree of privacy by indicating how spatially segregated patient rooms are within the overall layout. Integration measures how spatially embedded a location is within a layout and reflects its overall accessibility and exposure to movement and visibility. Alalouch and Aspinall [50] suggest that integration values are effective indicators for evaluating privacy in hospital layouts. Areas with lower integration values tend to have limited visual and spatial connections to the rest of the plan, which corresponds to a higher degree of privacy.

In this study, privacy is assessed based on the integration of patient rooms. The analysis focuses on how the spatial position of these rooms within the overall layout supports their segregation from main circulation routes, thereby enhancing visual and spatial privacy for patients.

3.2.2. Nurses: Accessibility and Visibility Challenges

Nurses play a critical role in hospital operations by providing continuous patient care, coordinating clinical tasks, and responding rapidly to emergencies. The spatial configuration of hospital environments directly influences how nurses move and interact within these spaces. Well-designed layouts support efficient workflows, improve visibility between key functional areas, and enhance coordination among staff. A substantial body of research highlights that spatial design is central to facilitating communication and clinical performance. In this context, accessibility refers to the ease with which staff can reach critical hospital zones, while visibility concerns their ability to monitor patients and activity areas from strategic positions. Together, these factors shape nurses' capacity to collaborate, respond effectively, and move efficiently through hospital environments.

Poor accessibility and limited visibility can have serious consequences for nursing efficiency. Among spatial design elements, the placement of the nurse station is particularly influential in shaping daily workflows. Studies have shown that nurse stations positioned in accessible and visually strategic locations contribute to more effective communication and faster clinical response times [51,52]. When nurse stations are located far from patient rooms or lack visual connection to critical areas, nurses experience increased physical effort and delays that reduce the time available for patient care [34]. Restricted visibility also makes it more difficult to observe patients and respond to urgent situations [50]. These challenges can extend to visitors, who often struggle to navigate visually unclear environments, causing confusion and frequent interruptions for staff assistance [40].

Building on these insights, this study evaluates how hospital layouts can be analysed to support nursing performance through a computational BIM-based spatial analysis approach, drawing on techniques from space syntax. It focuses on performance factors such as ease of movement, visibility to key areas, circulation efficiency, and response time, each of critical to nursing workflows. The study also aims to identify spatial metrics most closely associated with these factors to establish quantifiable indicators of nurse activity within emergency departments. The analysis concentrates on emergency department configurations, with particular emphasis on the positioning of nurse stations. Using spatial analysis tools within a BIM environment, the study examines how specific layout features affect nurse accessibility and spatial awareness. The performance criteria, spatial attributes, and analysis methods applied are summarised in Table 2, providing a structured framework for assessing the impact of spatial design on nursing efficiency in complex healthcare settings.

Table 2. Spatial analysis methods and measured attributes for nurse user group.

User Group: Nurses					
No	**Criteria**	**Measured Attribute**	**Spatial Analysis Method-AVA**	**Spatial Measures**	**Analysis Outcome**
7	**Accessibility**	Integration of nurse stations	Accessibility Analysis	Integration Value (global)	Higher integration values indicate higher nurse accessibility.
8	**Visibility**	Visual Connectivity of nurse stations	Visibility Analysis	Visual Connectivity Value (local)	Higher visual connectivity values indicate greater visibility.
9	**Visibility**	Visibility from nurse stations	Visibility Analysis	Isovist Area	Higher isovist values indicate wider coverage of critical areas and better staff interaction.
10	**Visibility**	Visibility of patient areas from the nurse stations	Targeted Visibility Analysis	Targeted Isovist Area	Higher visibility of patient areas from nurse stations indicates better oversight.

Accessibility and Spatial Measures

Accessibility is a critical factor influencing nurses' ability to provide timely and coordinated care. Beyond its functional importance, accessibility reflects how efficiently staff can move between key areas to perform clinical tasks.

Spatial accessibility can be quantified through **integration** values, which indicate how well a space is connected within the overall layout. Higher integration values correspond to greater connectivity and ease of movement, supporting faster responses and improved coordination among staff [53]. Penn and Hillier [53] demonstrated that more integrated spaces encourage frequent and meaningful communication among occupants. Individuals positioned in accessible, highly integrated areas experience greater visibility and ease of contact, fostering spontaneous collaboration and situational awareness [51]. Rashid et al. [54] demonstrated that visibility and accessibility in open-plan offices enhanced informal interaction and strengthened individuals' sense of belonging. Furthermore, Rashid et al. [55] showed that spatial integration positively influenced occupants' sense of community, with those located near highly integrated spaces feeling more connected.

In healthcare settings, spatial integration has been shown to directly influence nursing performance. Cai and Zimring [52] found that nurses' awareness of patient rooms was positively correlated with the global integration value of their workstation ($r = 0.715$, $p = 0.004$). Gharaveis et al. [56] reported a strong relationship between spatial integration and perceived communication ($r = 1.0$, $p = 0.00$). These findings indicate that nurse stations located in more integrated areas promote efficient movement and better coordination, ultimately supporting patient safety and care quality.

In this study, integration values are used to assess the spatial accessibility and connectivity of nurse stations within emergency department layouts. When multiple stations are present, their combined integration levels are analysed to evaluate accessibility to critical treatment zones, patient rooms, and shared work areas.

Visibility and Spatial Measures

Visibility within hospital environments plays a critical role in supporting nursing efficiency and directly influences patient safety and quality of care. Clear sightlines from nurse stations to patient areas enhance nurses' ability to monitor conditions, detect changes, and respond quickly to emergencies. This spatial awareness is particularly important in emergency departments, where timely observation and communication are essential.

Previous studies have shown that improved visibility increases both staff performance and patient supervision. Greater visual access to patient rooms has been linked to more frequent nurse visits and increased opportunities for direct care [57]. Visibility also facilitates communication and collaboration among healthcare staff, promoting situational awareness and coordination in fast-paced clinical environments [56,58]. Therefore, visibility is not merely a design attribute but a key determinant of effective and safe care delivery.

The visibility of nurse stations can be assessed through spatial metrics that quantify visual access to key patient areas. Measures such as visual connectivity, isovist area, and targeted visibility provide insights into how the spatial configuration supports nurses' ability to monitor patients, maintain situational awareness, and coordinate care effectively.

Visual Connectivity defines how visually connected a point is within its surroundings, based on the number of nodes visible from that location. Higher visual connectivity enhances opportunities for spontaneous interaction and increases spatial awareness among staff [59,60]. Gharaveis et al. [56] also found a positive relationship between visual connectivity and communication ($r = 0.8$, $p = 0.20$) in emergency departments.

In this study, visual connectivity values of nurse stations are measured to assess their potential to support communication, coordination, and patient monitoring.

Isovist Area measures the total extent of space visible from a single point. Larger isovist areas indicate more open and visually connected environments that improve observation and teamwork. Gharaveis et al. [56] identified strong links between isovist area, collaboration, and situational awareness ($r = 0.8$, $p = 0.20$).

In this study, isovist areas are analysed to evaluate the visual reach of nurse stations and their contribution to effective care delivery.

Targeted Visibility, introduced by Lu et al. [61], focuses on specific points of interest such as patient beds rather than overall visual access. This metric showed strong correlations with nurse density ($r = 0.924$) and staff interactions ($r = 0.894$), demonstrating that direct visual access enhances monitoring and response.

In this study, emergency department floor plans will be evaluated to assess the extent to which nurses can observe patients from the nurse station using targeted visibility analysis. This will be measured by calculating the proportion of visible patient beds from the nurse station in relation to the total visible area, providing an objective assessment of patient visibility within the hospital layout.

3.3. Tools and Computational Framework

This section outlines the digital tools and computational framework used to conduct the spatial analyses in this study. The methodology integrates Building Information Modelling (BIM), space syntax principles, and customised scripting to systematically evaluate accessibility, visibility, and privacy within emergency department (ED) layouts.

Autodesk Revit 2025 served as the BIM environment, providing detailed geometry and semantic data of hospital floor plans. Dynamo 3.3.0 was used for visual programming and workflow automation, while Python 3.13 enabled advanced data processing and exporting. Python also enhances flexibility by allowing the analysis to be adapted to different layouts or design scenarios beyond the constraints of visual programming alone. Within Dynamo, the AVA (Accessibility and Visibility Analysis) package (version 0.2.74), developed using the Grafit Spatial Graph Analysis Library [62] facilitated the computation of graph-based spatial metrics such as connectivity, step depth, visual integration, and isovist area. DepthmapX 0.8.0 was additionally used for validation and cross-checking of results. Together, these tools form a unified and repeatable workflow linking spatial configuration to performance criteria that support evidence-based healthcare design.

- ***Limitations of Traditional Space Syntax Tools***

Traditional space syntax software, such as DepthmapX, has been widely used to evaluate connectivity, visibility, and movement patterns in architectural layouts. As an open-source platform, DepthmapX enables visibility graph analysis (VGA), axial analysis, and agent-based modelling to explore spatial relationships and movement dynamics.

However, despite these advantages, DepthmapX presents several limitations that restrict its integration within contemporary BIM workflows. The tool primarily operates in 2D, making it unsuitable for analysing multi-level hospital layouts or vertical circulation. Moreover, its processes such as creating convex maps, generating axial lines, and linking spatial elements are largely manual, time-consuming, and prone to user error.

DepthmapX also lacks real-time data synchronisation, requiring manual re-exporting and updating of models with each design iteration. This hinders its use in iterative design processes. Furthermore, its lack of direct BIM integration often results in fragmented workflows and potential data loss when analysing hospital environments where BIM is a critical design and documentation platform.

- ***Proposed Computational BIM-Based Spatial Analysis Method***

To address these limitations, this study proposes a computational BIM-based spatial analysis method that enables automated, real-time evaluations directly within the BIM environment. The approach integrates space syntax principles into BIM-based workflows, enhancing the efficiency, accuracy, and flexibility of spatial analysis.

Unlike traditional workflows, this model eliminates the need for separate software by allowing spatial analyses to remain dynamically linked to the BIM model. This integration minimises data loss, streamlines analysis procedures, and supports continuous decision-making throughout design development. Key spatial measures such as connectivity, integration, and isovist can be automatically computed and visualised within Revit, enabling designers to assess spatial performance iteratively and in real-time. Through computational automation, the method reduces human error, accelerates spatial data processing, and enables the analysis of complex multi-floor layouts and dynamic scenarios.

Beyond analytical applications, the proposed method also functions as an evidence-based design tool, supporting decision-making across all stages of the design process—from early planning to post-occupancy evaluation (POE). By embedding spatial analysis directly within BIM workflows, designers and researchers can validate hospital layouts against key spatial performance metrics such as wayfinding, accessibility, and staff efficiency. This capability is particularly valuable in healthcare environments, where optimising workflow, emergency accessibility, and patient experience are essential.

In summary, the proposed BIM-integrated spatial analysis framework bridges the gap between spatial evaluation and architectural design. It eliminates the fragmentation of traditional tools, enhances workflow efficiency, and supports data-driven decision-making. By embedding spatial evaluation directly within the BIM environment, this approach provides a cohesive method for enhancing hospital layouts. It strengthens the connection between spatial performance and evidence-based healthcare design.

AVA Package for Spatial Analysis in BIM Workflows

The AVA (Accessibility & Visibility Graph Analysis) package, developed using the Grafit: A Spatial Graph Analysis Library [62], was employed in this study to facilitate spatial analysis within a BIM environment. This tool, integrated with Dynamo, enables isovist analysis, accessibility and visibility graph analyses directly within Revit. By leveraging this package, spatial metrics can be visualised within the BIM model, providing quantitative spatial data for analysis and decision-making.

The AVA package incorporates core concepts from space syntax but does not strictly follow its traditional formulations. Instead, it offers customised metrics for both visibility and accessibility graphs. Although these two analyses share similar computational principles, they differ in several key aspects:

Calculation Height:

- Accessibility analysis is performed at a low height (~0.03 m) to represent movement pathways.
- Visibility analysis is conducted at a specified ViewHeight, where geometry is considered an obstacle.

Connection Rules:

- Accessibility: Nodes are connected if they are on the same level and free of obstacles. Additional connections are defined for stairs and ramps.
- Visibility: Nodes are connected only when there are no obstacles between them.

Connection Inputs:

- The AVA package supports 3D spatial analysis across multiple floors by representing stairs and ramps as weighted connection lines based on stair length and a single turn. Custom connections, including elevators, can also be defined using the Revit adaptive family and integrated into the analysis through tailored weight assignments.

Weighting Input:

The weighting input determines the parameter used for shortest-path optimisation.

- If WeightMatrixId = 0 → shortest paths are calculated based on metric weights.
- If WeightMatrixId = 1 → shortest paths are determined by segment count (topology).
- The RelativeMatrixId allows for optimising one parameter (e.g., metric distance) while also minimising another (e.g., number of segments).

For accessibility analysis, the default optimisation is by metric length of segments (index = 0) and then by topology (index = 1). For visibility analysis, the logic is similar, but the emphasis is typically on minimising topology or turns. Here, the main weight matrix was set to 1, with a relative weight of 0.

Table 3 presents the key spatial metrics and their definitions used in the AVA package for spatial analysis. Figure 4 provides an overview of the key components used in the AVA package for spatial analysis.

Table 3. AVA spatial measures and their corresponding space syntax metrics.

AVA Spatial Measure	Graph Type	Corresponding Space Syntax Measure	Definition
Measure Degree (Degree Centrality)	Accessibility	Connectivity	The number of directly connected nodes.
	Visibility	Visual Connectivity	The number of directly visible nodes.
Measure Depth	Accessibility	Metric Mean Depth	The average shortest metric distance from a node to all other nodes.
	Visibility	Visual Step Depth	The number of visibility steps from a node to all other nodes.
Closeness Centrality	Accessibility	Integration	The sum of shortest paths from a node to all other nodes.
	Visibility	Visual Integration	The sum of visibility steps from a node to all other nodes.
Betweenness Centrality	Accessibility	Choice (Betweenness)	The number of shortest paths that pass through a node.
	Visibility	Visual Choice	The number of shortest visual paths that pass through a node.

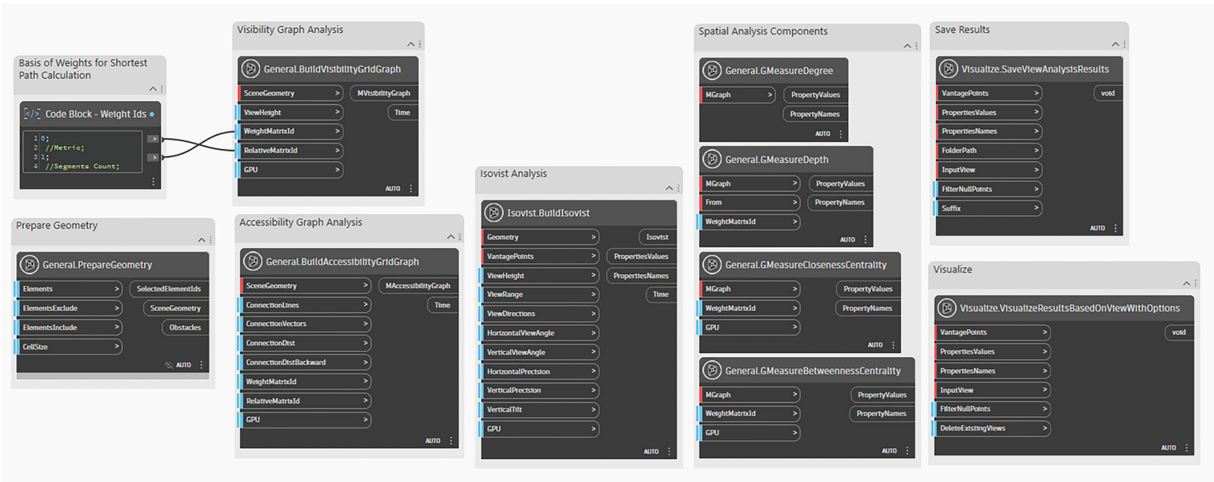

Figure 4. Key spatial analysis components of the AVA package.

The workflow for spatial analysis using the AVA package within a BIM environment follows four main stages, as illustrated in Figure 5.

1. *Prepare Geometry and Generate Grids:* Within Dynamo, the Revit geometry is defined, and a computational grid is generated to discretise the spatial domain. Specific tags are applied to control which elements are included in the analysis. For instance, floors can be tagged as #NonGrid to exclude them from grid generation, while doors and windows are tagged as #IsObstacle to represent closed conditions that block visibility or accessibility. This step ensures that only relevant architectural components are included in the analytical model.

2. *Generate Graph Analysis:* Accessibility, visibility, and isovist graphs are generated to represent different aspects of spatial performance. The accessibility graph calculates the shortest paths between spaces, the visibility graph captures visual interconnections, and the isovist graph defines the visible area from a specific point or node. Together, these graph types form the structural basis for subsequent quantitative analysis.
3. *Calculate Spatial Metrics:* Once the graphs are generated, spatial metrics are computed using the AVA package. These include general graph-based measures such as General.GMeasureDegree, General.GMeasureDepth, General.GMeasureClosenessCentrality, and General.GMeasureBetweennessCentrality. Additionally, isovist-based metrics are calculated for each grid point to quantify visibility and spatial reach. The results are stored in Dynamo and linked to the Revit model for visualisation and evaluation.
4. *Visualize and Export Results:* The analysis results are visualised in Revit using the VisualizeResultsBasedOnView function, enabling real-time interpretation of accessibility and visibility patterns. Values are assigned to grid points for detailed inspection, and results can be exported via SaveViewAnalysisResults (e.g., CSV) for further analysis. The workflow also visualises the shortest paths between key areas, supporting the evaluation of travel efficiency and connectivity.

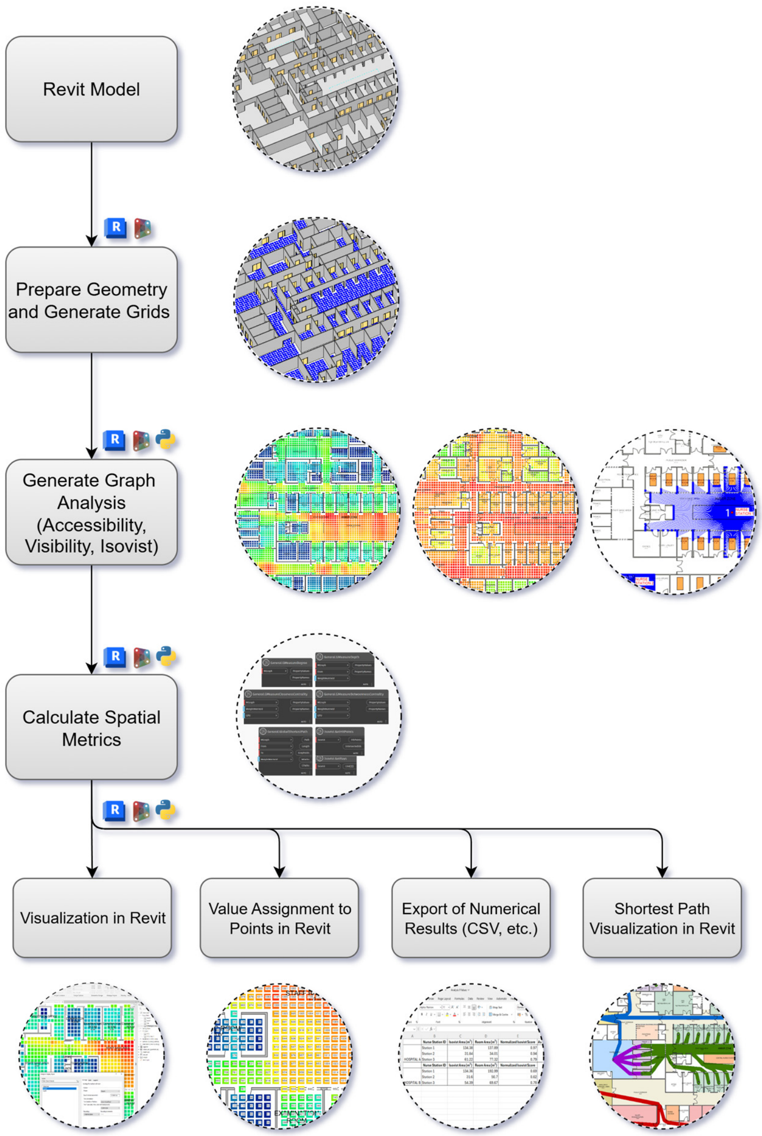

Figure 5. Key steps in the BIM-based workflow for spatial analysis.

4. Case Study: Comparative Spatial Analysis of Emergency Departments

This case study presents a comparative spatial analysis of emergency departments by examining the floor plans of Hospital A and Hospital B (Figure 6). The original floor plans were obtained in PDF format and re-modelled in Autodesk Revit to enable computational analysis. Both hospitals, located in the UK, have single-storey emergency departments, ensuring a consistent basis for comparison.

The two layouts were selected to serve as representative examples for testing and demonstrating the proposed computational workflow, rather than for evaluating specific hospitals. The purpose is to illustrate how the method can be applied to different emergency department configurations in a consistent and replicable way. The developed workflow is designed to be adaptable and scalable to other hospital ED layouts, supporting comparative and performance-based spatial analysis across diverse design scenarios.

This section presents a comparative spatial analysis of two emergency departments, including their spatial configurations, visual outputs, and quantitative results from computational analysis.

Figure 6. Floor plans of the emergency departments in Hospital A and Hospital B.

4.1. Spatial Analysis from the Patient Perspective

This section evaluates the emergency department floor plans from the patient perspective through six computational analyses focusing on accessibility, visibility, and privacy. The first examines corridor connectivity to assess circulation efficiency, followed by visual integration analysis to evaluate spatial coherence and wayfinding. The third measures reception visibility from the main entrance, indicating ease of orientation. The fourth investigates walk-in patient flow across key zones, while the fifth focuses on emergency accessibility between the ambulance entrance and resuscitation area. Finally, privacy analysis of patient rooms assesses their spatial separation and visual isolation. Together, these analyses provide a comprehensive understanding of how emergency department layouts perform across key patient-related spatial criteria.

4.1.1. Analysis 1: Connectivity of Public Corridors

The connectivity analysis of public corridors evaluates their accessibility and role in patient navigation. The degree centrality (connectivity value) measures how many spaces are directly connected to a given corridor, indicating ease of movement. This analysis focuses solely on public corridors as primary circulation elements, assessing their efficiency in facilitating patient flow.

The analysis is performed in Dynamo using the AVA package and a custom Python node (Figure 7). The process begins by filtering and isolating public corridor boundaries. The required grid points for measurement are then generated across the floor plan using the General.PrepareGeometry node. Next, an accessibility graph is constructed through the General.BuildAccessibilityGridGraph node, and degree centrality values are computed for each grid point with the General.MeasureDegree node. Finally, the results are visualised and assigned to corridor points in Revit. A custom Python script is also used to exclude non-corridor areas, ensuring that connectivity values are calculated exclusively for public corridors. This structured workflow enables the quantitative evaluation of circulation efficiency directly within the BIM environment.

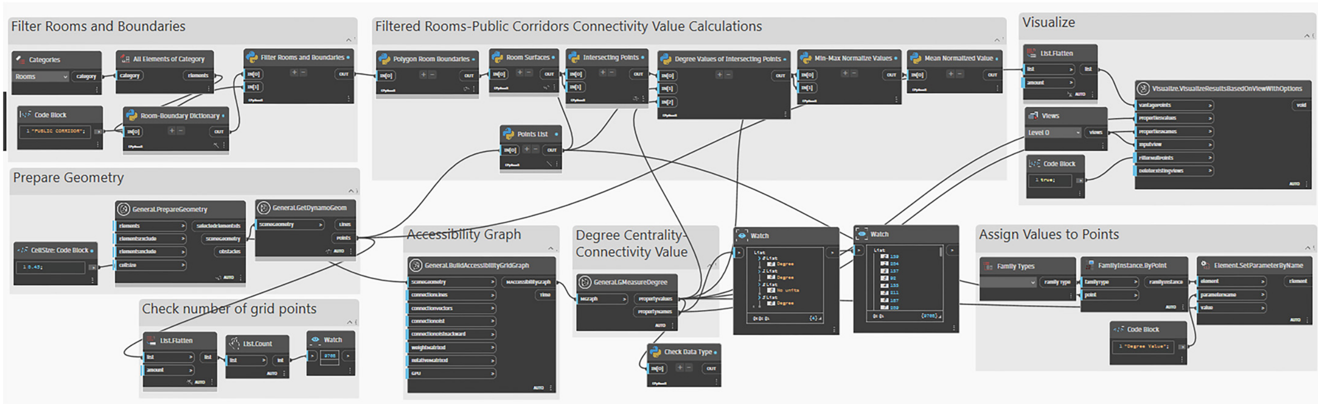

Figure 7. Dynamo script for connectivity analysis of public corridors.

To ensure comparability across different hospital layouts, min–max normalization is applied to the degree centrality values of public corridor spaces. This method rescales corridor-specific data to a 0–1 range, enabling fair comparison regardless of variations in hospital size, layout complexity, or the number of corridor segments. By normalising only corridor points, rather than all grid points, the analysis is kept focused on circulation areas that are critical for wayfinding and patient flow. Hospitals with larger or denser corridor networks may naturally show higher raw degree values, even if their spatial configurations are not inherently more efficient. To address this, corridor-specific degree values are normalised using the formula:

$$X_{\text{norm}} = \frac{X - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}}$$

where X represents the raw degree value of the public corridor point, and X_{min} and X_{max} denote the minimum and maximum degree values among all identified corridor points within the same layout. This ensures that the normalised scores reflect the relative connectivity performance of corridor spaces within their spatial context. After normalization, a set of values ranging from 0 to 1 is obtained for each hospital's corridor system. The mean normalized degree value is then calculated as:

$$\overline{X_{\text{norm}}} = \frac{1}{N}\sum_{i=1}^{N} X_{\text{norm},i}$$

where N is the number of corridor points, and $X_{\text{norm},i}$ is the normalized degree value for the i-th point. This mean value serves as a standardized indicator of corridor connectivity efficiency. A higher mean normalised score indicates better-connected and more navigable corridors, while lower values suggest fragmented circulation networks that may hinder accessibility.

Connectivity results are visualised directly in Revit using a colour-coded floor plan, where red denotes highly connected corridors and blue represents less accessible areas. Each grid point's degree centrality is embedded in the BIM model, allowing both visual and numerical inspection. This dual representation ensures that spatial feedback is readily available and automatically updated with layout changes.

The visual outputs of the analysis (Figure 8) highlight distinct connectivity patterns for Hospitals A and B. As summarised in Table 4, Hospital A has a mean normalised degree value of 0.51, whereas Hospital B achieves a higher score of 0.57, indicating stronger corridor connectivity. Moreover, the spatial distribution of connectivity in Hospital B appears more consistent and evenly spread across the layout, suggesting a smoother circulation flow and greater accessibility.

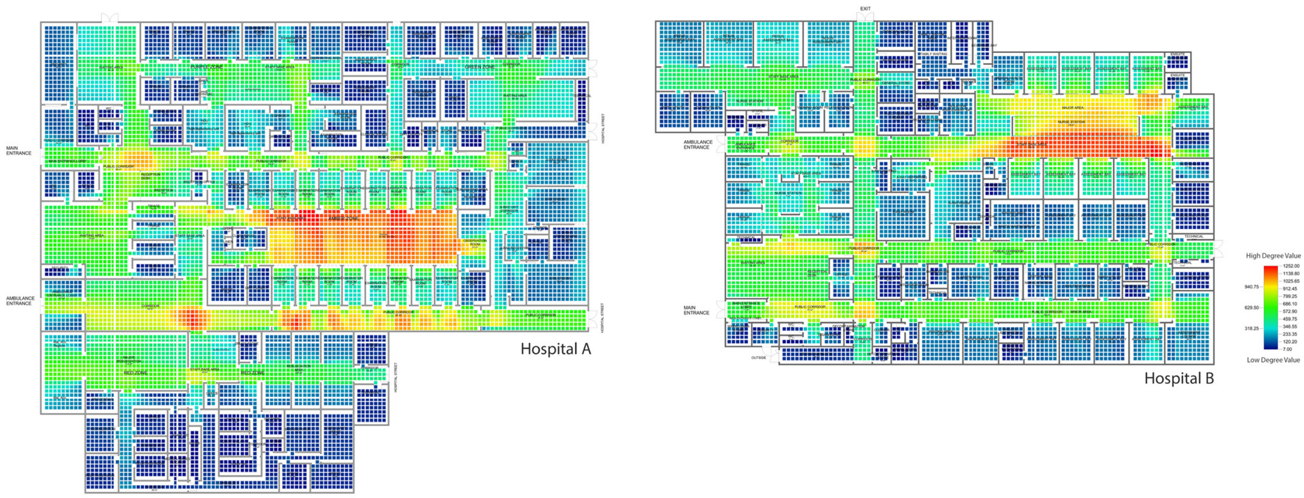

Figure 8. Connectivity analysis visualisation for Hospital A and Hospital B.

Table 4. Connectivity analysis results for public corridors.

Metric	Hospital A	Hospital B
Average Degree—Connectivity Value for Public Corridors	646.65	632.00
Mean Normalized Degree—Connectivity Value (Final Score)	0.51	0.57

- ***Validation of Results with DepthmapX***

To verify the accuracy of the connectivity results obtained through the BIM-based computational workflow, a validation analysis is conducted using DepthmapX 0.8.0. The Visibility Graph Analysis (VGA) function is applied to the same emergency department floor plans to calculate degree values for each grid point and to generate corresponding connectivity maps (Figure 9).

The results produced in DepthmapX are compared with those generated in Dynamo (Figure 8). The spatial distribution patterns of connectivity show a high level of similarity between the two methods. Areas identified as highly connected in the Dynamo analysis also appear as high-degree zones in the VGA results. This strong correlation confirms that the proposed BIM-based workflow produces reliable and consistent outcomes that align with established space syntax methods, validating its applicability for spatial analysis of hospital layouts.

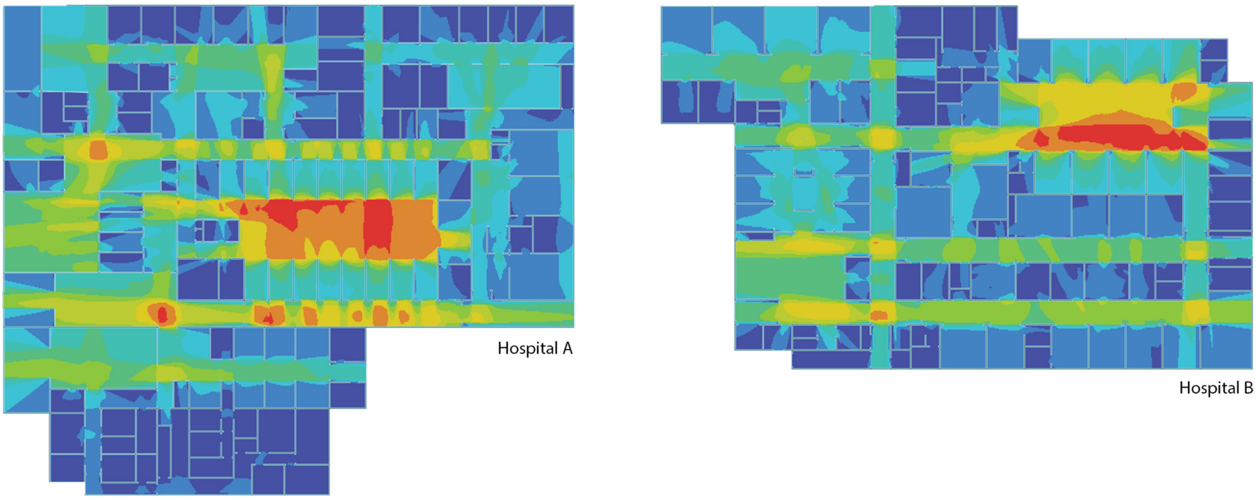

Figure 9. Connectivity analysis of Hospital A and B using VGA in DepthmapX. Warmer colours (red–yellow) represent areas with higher connectivity values, while cooler colours (green–blue) indicate areas with lower connectivity values.

4.1.2. Analysis 2: Integration of Public Corridors

This analysis evaluates the visual integration levels of public corridor spaces, which play a key role in spatial accessibility and wayfinding within emergency department layouts. The analysis is performed in Dynamo using the AVA package and a custom Python script (Figure 10). The workflow consists of four main steps: (1) filtering and isolating public corridor boundaries, (2) generating grid points across the floor plan using the General.PrepareGeometry node, (3) constructing a visibility graph with the General.BuildVisibilityGridGraph node, and (4) calculating integration (closeness centrality) values using the General.MeasureClosenessCentrality node. Finally, the results are visualised in Revit through the Visualize node, providing a systematic and automated way to measure and interpret visual coherence and spatial accessibility within the BIM environment.

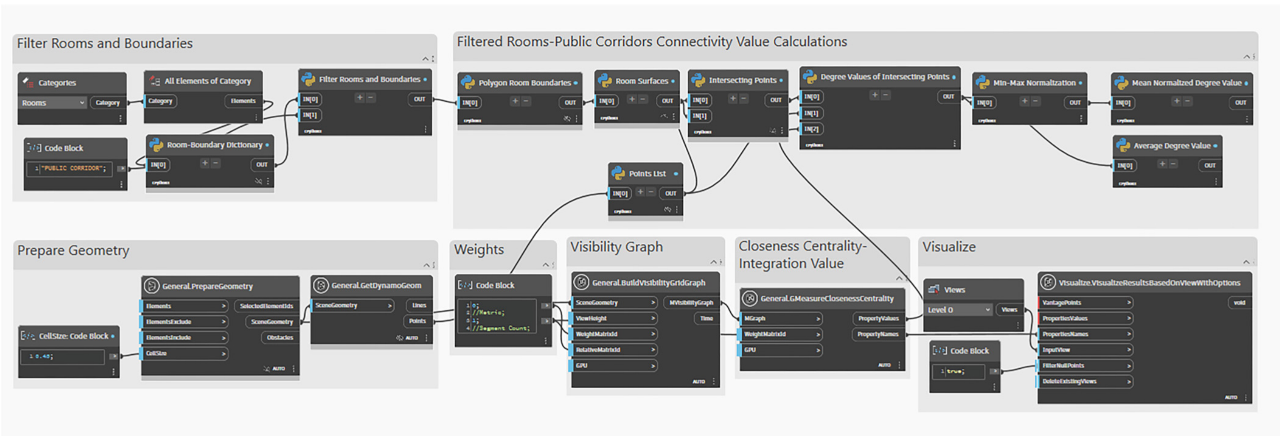

Figure 10. Dynamo script for visual integration analysis of public corridors.

The resulting heatmaps (Figure 11) show the spatial distribution of integration values for Hospitals A and B. Warmer colours indicate areas of higher visual integration, while cooler tones represent less integrated zones. These visual outputs offer a clear depiction of how corridor configurations influence spatial legibility and wayfinding potential.

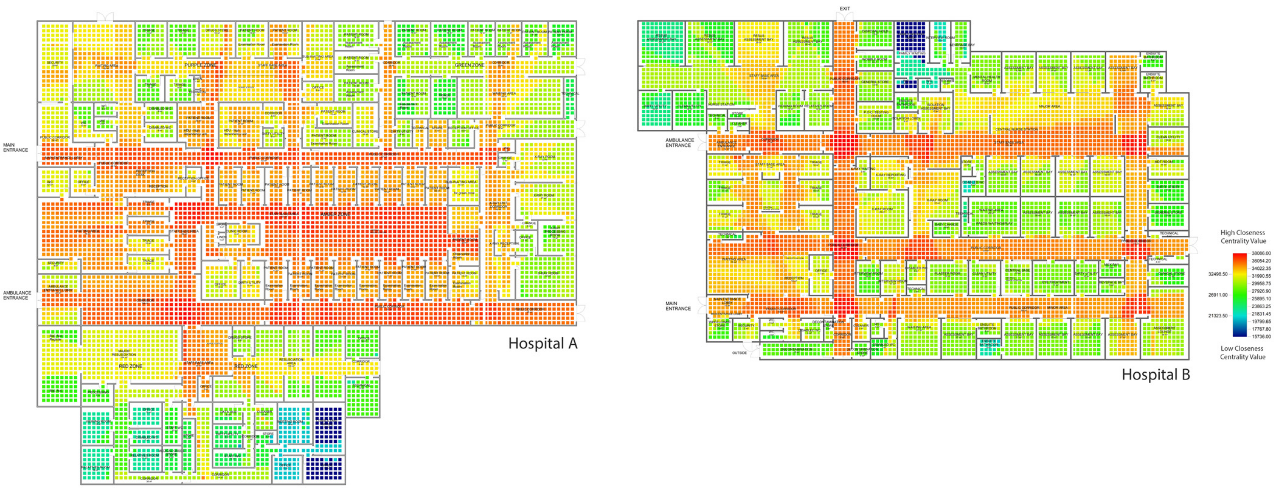

Figure 11. Integration analysis visualisation for Hospital A and Hospital B.

The integration analysis results (Table 5) show that Hospital A exhibits a higher average integration score (49,586.42) and mean normalised value (0.69) compared to Hospital B (35,222.98 and 0.62, respectively). These findings indicate that the public corridor network in Hospital A is more visually cohesive and centrally integrated within the overall spatial system, supporting more efficient wayfinding and better spatial comprehension. In contrast, the lower integration values observed in Hospital B suggest a more fragmented corridor configuration, which may hinder intuitive navigation and reduce overall spatial legibility.

Table 5. Integration analysis results for public corridors.

Metric	Hospital A	Hospital B
Average Degree—Integration Value for Public Corridors	49,586.42	35,222.98
Mean Normalized Degree—Integration Value (Final Score)	0.69	0.62

To validate these findings, an additional space syntax analysis is conducted using DepthmapX 0.8.0. The visual patterns generated in DepthmapX (Figure 12) correspond closely with those produced in Dynamo, demonstrating a strong agreement in spatial integration values across both platforms. This consistency confirms the reliability of the proposed BIM-based methodology and its ability to produce robust and comparable spatial analysis results.

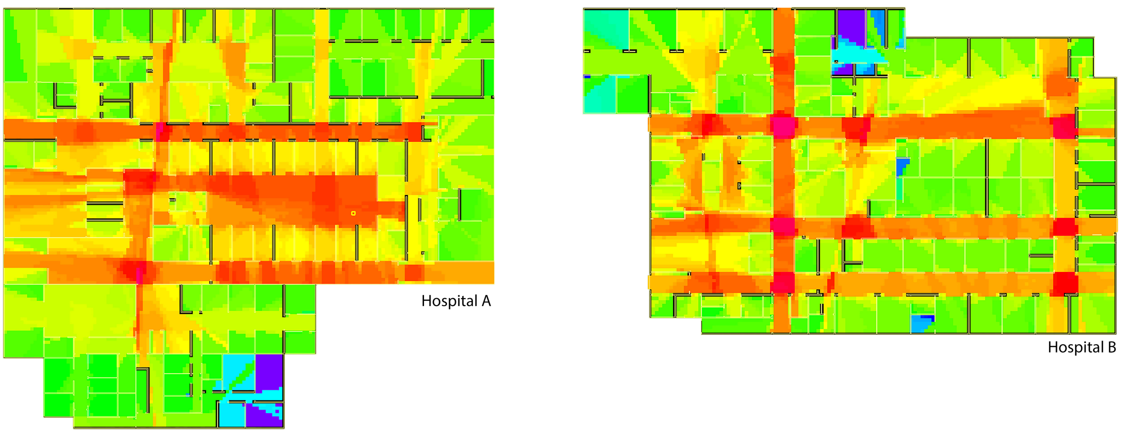

Figure 12. Visual integration analysis of Hospital A and B using VGA in DepthmapX. Warmer colours (red–orange) represent areas with higher integration values, while cooler colours (green–blue) indicate areas with lower integration values.

4.1.3. Analysis 3: Visibility of Reception Area from Main Entrance

This analysis assesses how visible the reception desk is from the main entrance of the emergency department. Visibility strongly influences patients' ability to orient themselves upon arrival, as the reception serves as a visual anchor for initial wayfinding.

The analysis is conducted in Dynamo using an isovist-based method (Figure 13). The workflow involves four main steps: (1) preparing the floor plan geometry and selecting the main entrance as the vantage point, (2) generating isovist rays that simulate lines of sight, (3) identifying how many of these rays intersect the reception desk, and (4) calculating a visibility ratio based on the total number of ray hits. This ratio provides a quantitative measure of visual accessibility.

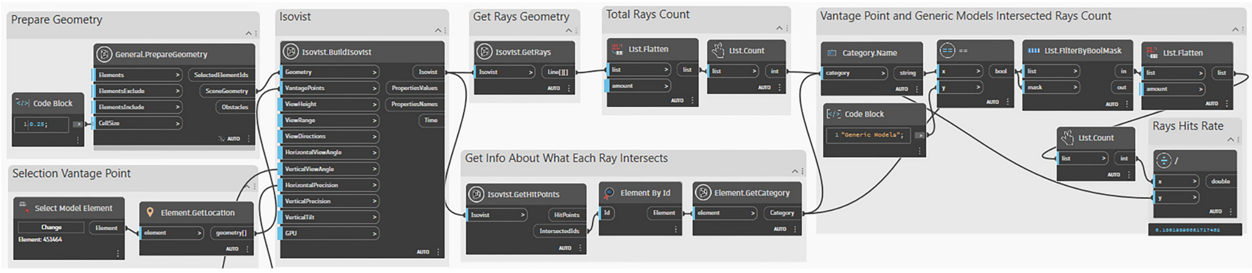

Figure 13. Dynamo script for visibility analysis of reception desk from main entrance.

The Dynamo workflow used for this process is illustrated in Figure 13, and the resulting visibility maps for both hospitals are shown in Figure 14. The results (Table 6) indicate that Hospital A achieves a slightly higher visibility ratio (0.13) than Hospital B (0.11), suggesting clearer visual access from the entrance to the reception area. This improved visibility in Hospital A may enhance patient orientation and reduce initial wayfinding uncertainty. Overall, this analysis highlights how the geometric configuration of the entrance zone can directly influence first impressions and spatial understanding in emergency settings, underscoring the importance of visual access in patient-centred design.

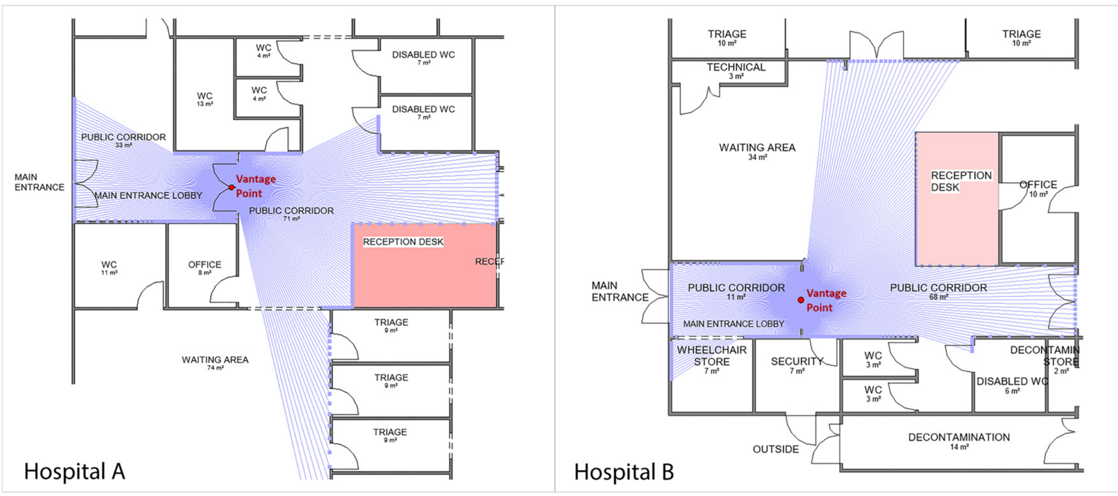

Figure 14. Reception desk visibility in Hospitals A and B. Blue lines represent the isovist rays generated from the main entrance vantage point, illustrating lines of sight toward the reception desk.

Table 6. Visibility analysis results for the reception desk from the main entrance.

Metric	Hospital A	Hospital B
Visibility Ratio (Rays Hits Rate)	0.13	0.11

4.1.4. Analysis 4: Step Depth and Metric Distance Analysis of Walk-In Patient Flow (Main Entrance to Patient Rooms)

This analysis evaluates the spatial accessibility and navigability of emergency department layouts from the perspective of walk-in patients. It focuses on two key spatial metrics: step depth, which measures the number of spatial transitions between key zones, and metric distance, which quantifies the actual travel length between them. The method follows typical patient flow models used in the UK (Figure 15). The analysis is divided into three stages: from the main entrance to waiting areas, from waiting areas to triage zones, and from triage zones to patient rooms such as assessment, examination, or treatment bays. The spaces are grouped according to their spatial proximity and functional role, and distances are measured between their geometric centroids. This structured approach captures representative movement patterns of walk-in patients and allows consistent comparison across different emergency department layouts.

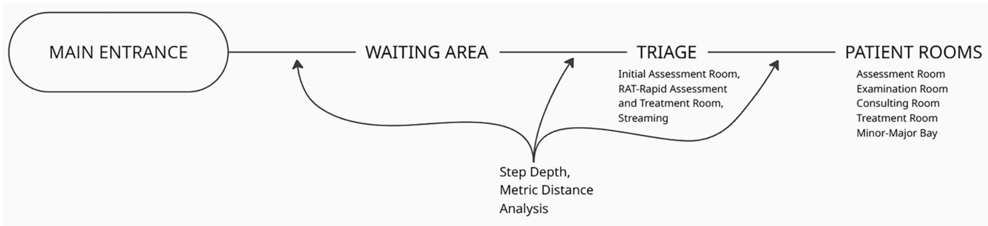

Figure 15. Walk-in patient flow diagram in a UK emergency department.

The analysis is conducted in Dynamo using the AVA package and a custom Python script to calculate both topological and metric distances between key functional zones of the emergency department (Figure 16). A detailed version of this custom Average Paths Python script is provided in Appendix A.

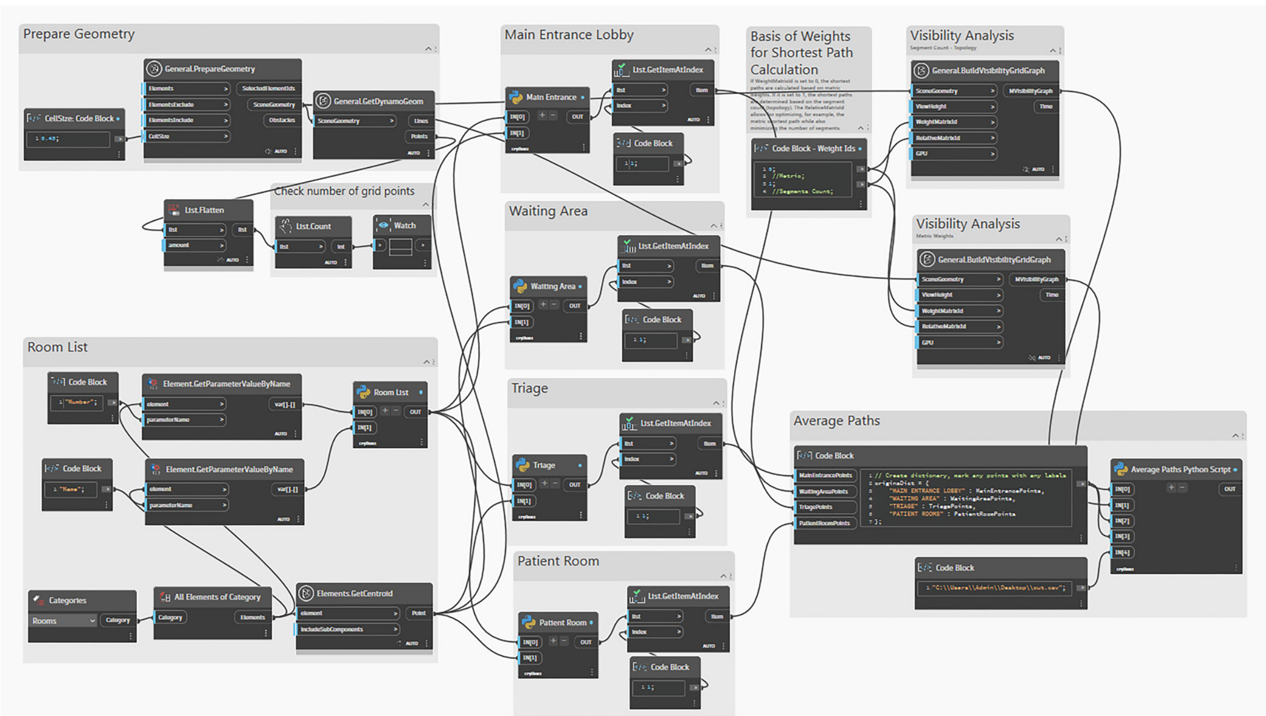

Figure 16. Dynamo script for step depth and metric distance analysis of walk-in patient flow.

The workflow begins by preparing the floor plan geometry and generating a regular analysis grid using the General.PrepareGeometry node. Room data are then extracted and grouped into four functional areas: main entrance, waiting area, triage, and patient rooms, based on their spatial roles. Two visibility graphs are constructed with different weighting schemes: one based on metric distance and the other on step count. These graphs form the basis for computing the shortest paths between zone centroids, allowing the evaluation of both metric and segment-topological accessibility. The Average Paths Python script calculates step depth and metric distance values for each stage of the patient journey. These results quantify and visualise how efficiently each layout supports patient movement within the BIM environment.

The resulting flow paths, visualised for Hospital A and Hospital B (Figure 17), reflect clinically plausible patient movement scenarios and are used in both Analysis 4 and 5. The computed average values for each segment are summarised for comparison (Figure 18). As shown in Table 7, Hospital A demonstrates lower average step depth (2.5) and metric distance (17.18 m) compared to Hospital B (3.4 and 21.75 m, respectively). These results indicate that Hospital A provides a more spatially efficient and topologically compact layout for walk-in patients, potentially improving wayfinding, reducing walking distances, and supporting smoother operational flow in emergency care.

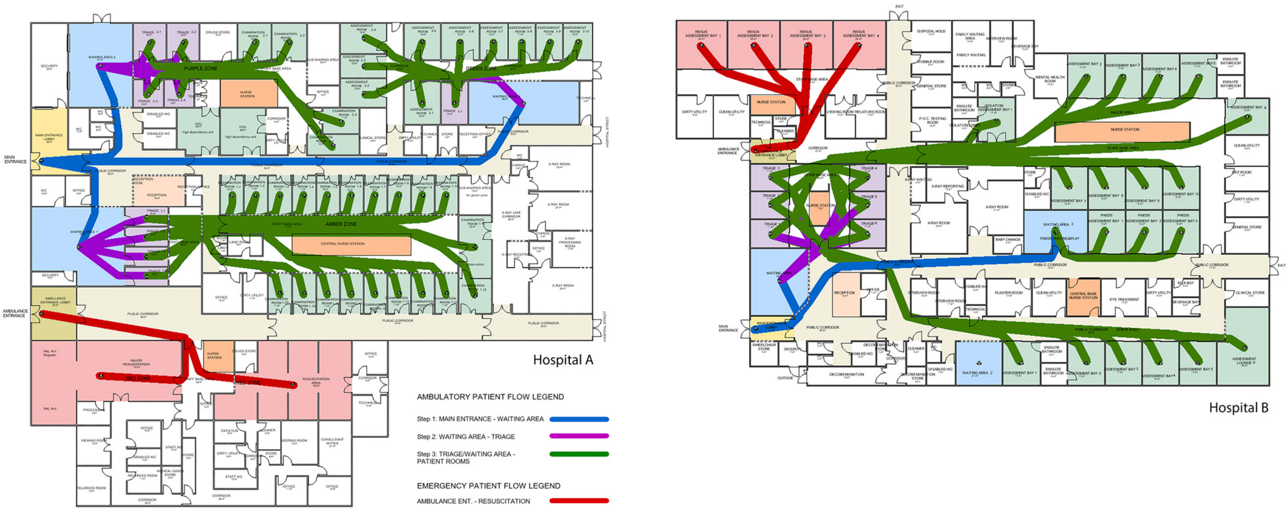

Figure 17. Visualisation of walk-in and ambulance patient flow paths in Hospitals A and B.

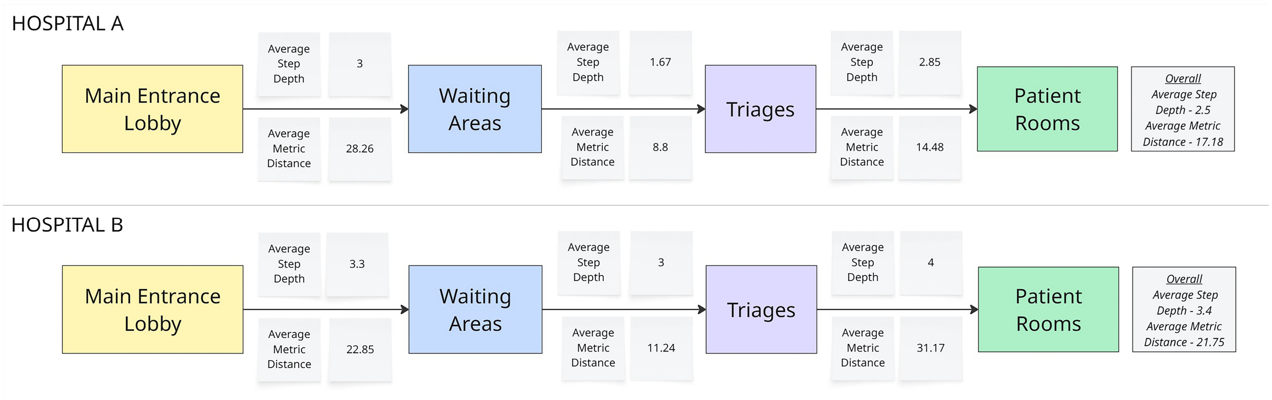

Figure 18. Step depth and metric distance of walk-in patient flow in Hospitals A and B.

Table 7. Step depth and metric distance analysis of walk-in patient flow.

Metric	Hospital A	Hospital B
Overall Average Step Depth	2.5	3.4
Overall Average Metric Distance	17.18 m	21.75 m

4.1.5. Analysis 5: Emergency Accessibility Analysis—Step Depth and Metric Distance of Ambulance Arrivals (Ambulance Entrance to Resuscitation Area)

Emergency accessibility is a crucial factor in emergency department (ED) design, as it directly influences how quickly and efficiently patients can reach critical treatment areas. In time-sensitive cases such as trauma, stroke, or cardiac arrest, even brief delays in internal movement can significantly impact patient outcomes. Therefore, evaluating spatial accessibility within the ED is essential for enhancing patient flow and supporting effective clinical decision-making.

This analysis assesses the spatial accessibility between the ambulance entrance and the resuscitation area, where life-saving interventions are performed on critically ill patients. The objective is to determine how directly and efficiently patients can be transferred from the point of arrival to the area of urgent care. A lower step depth value indicates a more accessible and spatially efficient configuration. The analysis applies the same Dynamo workflow used in Analysis 4 (Figure 16), adapted for this scenario by redefining the origin and destination points for ambulance-based patient flow. The resulting route, visualised as a red path in Figure 17, represents the shortest connection between the two key areas.

As presented in Table 8, both Hospital A and Hospital B show the same step depth value (3), indicating comparable topological accessibility. However, Hospital B demonstrates a notably shorter metric distance (16.71 m) than Hospital A (28.8 m), suggesting a more compact spatial configuration that may facilitate faster emergency response and improve operational efficiency.

Table 8. Step depth and metric distance analysis of ambulance arrivals (ambulance entrance to resuscitation area).

Metric	Hospital A	Hospital B
Overall Average Step Depth	3	3
Overall Average Metric Distance	28.8 m	16.71 m

4.1.6. Analysis 6: Privacy Analysis—Integration of Patient Rooms

Privacy is a critical component of patient care and is strongly influenced by the spatial configuration of hospital environments. This analysis examines how the emergency department layout supports spatial and visual isolation in patient areas, particularly treatment and examination rooms. Spatial privacy is assessed by calculating the integration values of patient rooms. In space syntax analysis, lower integration values indicate greater spatial segregation, which corresponds to higher levels of privacy. The purpose of this analysis is to identify patient areas that may be overly exposed within the overall layout and to inform design adjustments where necessary.

For consistency, the following room types were grouped under the category of patient rooms: examination, assessment, consulting, treatment, observation, isolation, and high dependency units (HDU). This classification standardises the analysis and ensures that privacy levels are evaluated across comparable room types. Resuscitation areas were excluded due to their typically open configurations, which do not support the same degree of enclosure. Similarly, triage rooms were omitted, as they are used for short-term assessments and provide limited privacy.

The computational method follows the same process used in Analysis 2 (Integration of Public Corridors) (Figure 10), with one key difference: instead of filtering public corridor spaces, the analysis focuses specifically on grid points located within the identified patient rooms. As presented in Table 9, Hospital B shows lower average and normalised integration values (30,868.72 and 0.39, respectively) compared to Hospital A (45,034.67 and 0.59). Since lower integration values correspond to greater spatial segregation, these results suggest that patient rooms in Hospital B offer a higher level of spatial privacy.

Table 9. Integration analysis results for patient rooms.

Metric	Hospital A	Hospital B
Average Degree—Integration Value for Patient Rooms	45,034.67	30,868.72
Mean Normalized Degree—Integration Value (Final Score)	0.59	0.39

4.2. Spatial Analysis from the Nurse Perspective

This section presents the spatial analysis of nurse accessibility and visibility in the emergency department (ED) layout. The analysis aims to evaluate how spatial configuration affects nurses' ability to move efficiently, maintain visual awareness of patient zones, coordinate with other staff, and respond effectively within the clinical environment. From the nurse perspective, accessibility and visibility are critical to workflow efficiency, situational awareness, and overall care quality.

Four computational analyses were performed to assess these spatial performance factors within each ED layout. The first analysis evaluates the integration of nurse stations, measuring their spatial accessibility and centrality within the layout. The second examines visual connectivity, identifying how well nurse stations are visually linked to their surroundings and to adjacent activity areas. The third focuses on isovist-based visibility, quantifying the overall visual openness and extent of view from each nurse station. Finally, a targeted visibility analysis measures the proportion of patient areas directly visible from nurse stations, providing an indicator of staff supervision potential and patient safety.

4.2.1. Analysis 7: Integration of Nurse Stations

This analysis evaluates the spatial accessibility of nurse stations by calculating their integration values, indicating how centrally these areas are positioned within the emergency department (ED) layout. The aim is to assess how effectively nurse stations are embedded in the overall spatial configuration, as this influences staff mobility, workflow efficiency, and access to critical care zones. Higher integration values denote stronger spatial connectivity with surrounding spaces, supporting faster movement and improved coordination among clinical staff.

The computational method follows the same procedure used in Analysis 2 (Integration of Public Corridors) and Analysis 6 (Integration of Patient Rooms). An accessibility graph was generated in Dynamo using the AVA package, and the GMeasureClosenessCentrality node was applied to compute integration values for each grid point. Only the points located within nurse station boundaries were selected to ensure that the results specifically represent their spatial characteristics. This approach provides focused insight into how well nurse stations support efficient workflows and rapid staff response within emergency care environments.

The results of the integration analysis are summarised in Table 10. While Hospital A shows a higher average integration value for nurse stations (45,059), Hospital B demonstrates a higher mean normalised integration score (0.64 compared to 0.52 in Hospital A). This indicates that, relative to their internal spatial structure, the nurse stations in Hospital B are more centrally positioned within the layout. Since normalised values account for differences in layout size and spatial distribution, they provide a more balanced basis for comparison. Overall, the results suggest that nurse stations in Hospital B occupy a more connected and spatially integrated position within the emergency department configuration.

Table 10. Integration analysis results for nurse stations.

Metric	Hospital A	Hospital B
Average Degree—Integration Value for Nurse Stations	45,059.01	32,998.14
Mean Normalized Degree—Integration Value (Final Score)	0.52	0.64

4.2.2. Analysis 8: Visual Connectivity of Nurse Stations

This analysis evaluates the visual connectivity of nurse stations within each emergency department (ED) layout using a visibility graph. It measures how effectively nurse stations are visually linked to their surroundings and adjacent clinical areas. The computational workflow was developed in Dynamo using the AVA (Accessibility and Visibility Analysis) package and Python scripts (Figure 19). It involves filtering the floor plan to isolate nurse station boundaries, preparing the geometry and generating the visibility graph. Degree centrality values were calculated to measure the number of direct visual connections between grid points. These values were normalised using the same method described in Analysis 1 (Connectivity of Public Corridors). The results were then visualised to show areas with high and low connectivity.

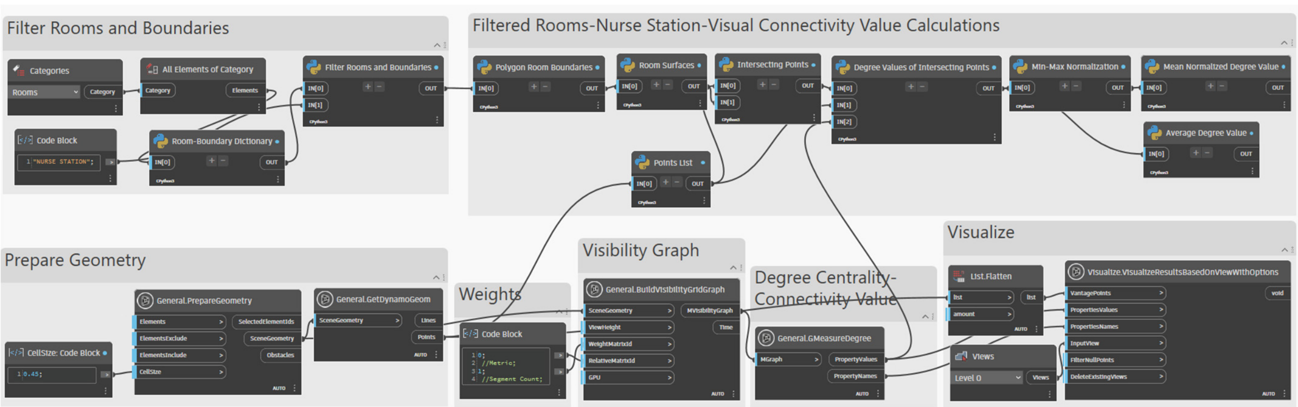

Figure 19. Dynamo script for visual connectivity analysis of nurse stations.

The visual connectivity maps (Figure 20) illustrate the spatial distribution of visibility, with warmer colours indicating stronger visual relationships between nurse stations and adjacent spaces. As shown in Table 11, Hospital A exhibits a slightly higher average visual connectivity value (766.32) than Hospital B (723.16). When normalised, the final scores indicate that nurse stations in Hospital A (0.58) are more visually connected to their surrounding environment compared to those in Hospital B (0.51). These findings suggest that the spatial configuration of Hospital A provides broader visual access from nurse stations, supporting more effective patient monitoring, communication, and coordination among staff.

Table 11. Visual connectivity analysis results for nurse stations.

Metric	Hospital A	Hospital B
Average Visual Connectivity of Nurse Stations	766.32	723.16
Mean Normalized Degree—Visual Connectivity Value (Final Score)	0.58	0.51

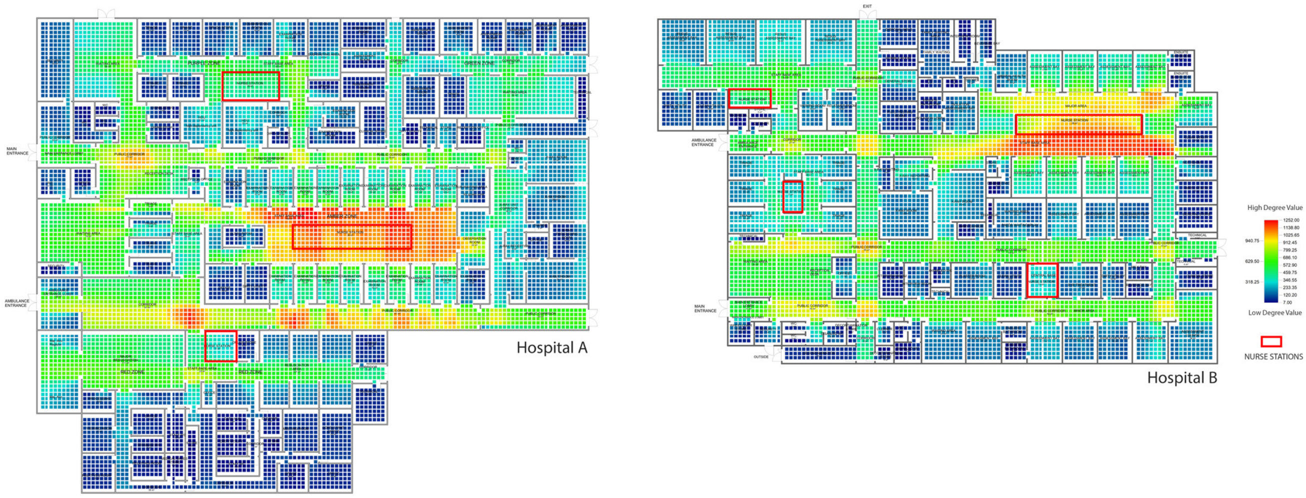

Figure 20. Visual connectivity analysis for Hospital A and Hospital B.

4.2.3. Analysis 9: Visibility from Nurse Stations

This analysis evaluates spatial visibility from nurse stations by calculating the isovist area for each station within the emergency department (ED) layouts. The isovist area represents the total visible surface from a given point and indicates how visually open or obstructed the environment is from the nurse's perspective. To enable meaningful comparison between layouts of different sizes and spatial organisations, each isovist area was normalised using a reference area corresponding to the total floor area surrounding each nurse station (e.g., staff base or care zone) where visibility is most critical. The normalised isovist value was calculated as follows:

$$\text{Normalized Isovist Area} = \frac{\text{Isovist Area}}{\text{Reference Area}}$$

This normalisation ensures that visibility scores are scale-independent and comparable across stations and layouts. Higher values indicate greater visual openness, while lower values suggest restricted sightlines. An average normalised isovist score was then computed by averaging the scores of all nurse stations within each layout, providing a single indicator of how effectively these areas are visually integrated into their surroundings.

The computational workflow, developed in Dynamo using custom Python scripts and the AVA (Accessibility and Visibility Analysis) package, is shown in Figure 21. It involves preparing the geometry and isovist parameters, selecting nurse stations as vantage points, calculating isovist areas through ray-casting, matching each nurse station with its corresponding staff-base area to obtain reference values, and finally computing the normalised isovist and average visibility scores.

The resulting isovist fields (Figure 22) visualise the extent of visibility from each nurse station. As shown in Table 12, Hospital A achieved a higher average normalised visibility score (0.90) than Hospital B (0.70). These findings suggest that the spatial configuration of Hospital A provides a more visually open environment around nurse stations, potentially supporting better supervision, faster response times, and more effective communication within clinical areas.

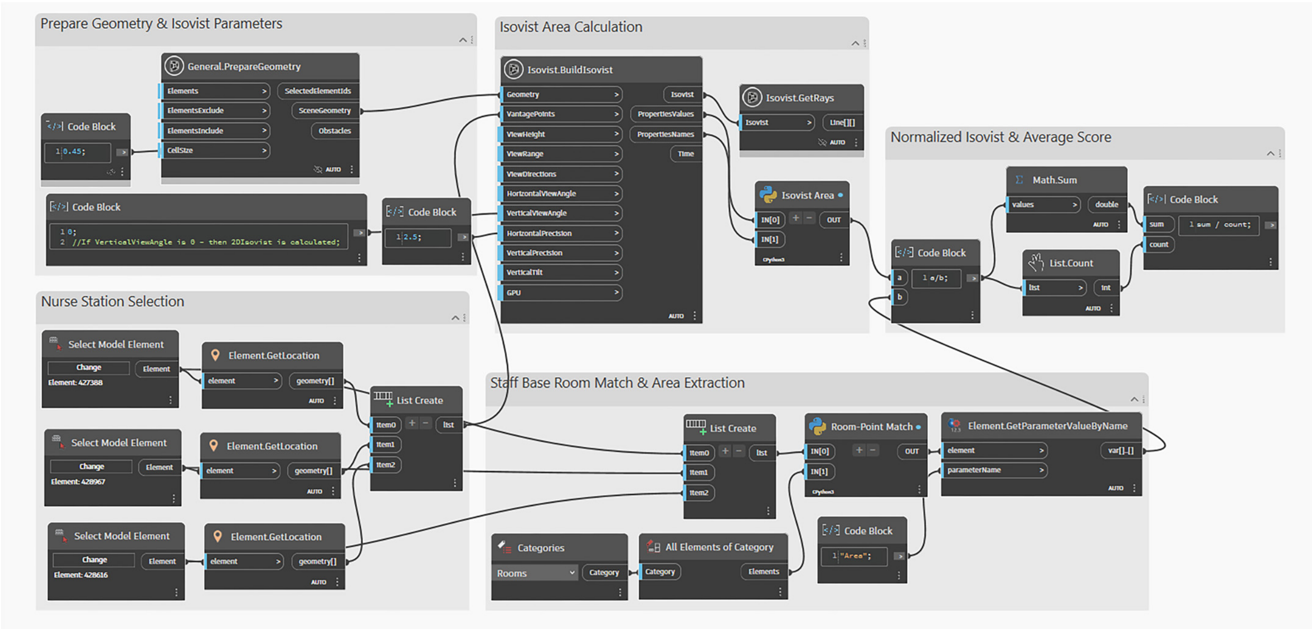

Figure 21. Dynamo script for visibility analysis from nurse stations.

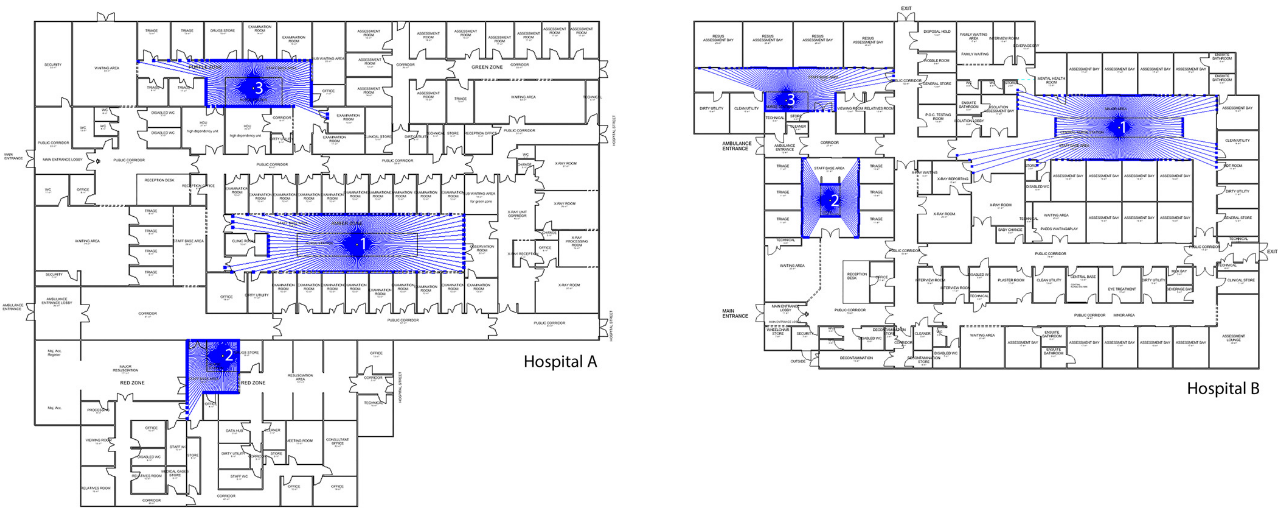

Figure 22. Visibility analysis from nurse stations in Hospital A and Hospital B. The blue lines represent the isovist rays generated from each nurse station, illustrating the extent of visible lines of sight from each vantage point.

Table 12. Visibility analysis results from nurse stations.

Hospital	Nurse Station ID	Isovist Area (m^2)	Staff Base Room Area (m^2)	Normalized Isovist Score
A	Station 1	134.38	137.89	0.97
	Station 2	31.84	34.01	0.94
	Station 3	61.22	77.32	0.79
	Average Score			0.90
B	Station 1	134.36	192.99	0.69
	Station 2	31.60	50.70	0.62
	Station 3	54.39	69.67	0.78
	Average Score			0.70

4.2.4. Analysis 10: Visibility of Patient Areas from Nurse Stations

This analysis evaluates how effectively patient areas can be visually monitored from nurse stations within the emergency department (ED) layout. Continuous visibility is essential for effective supervision, rapid response, and patient safety. The method calculates the proportion of isovist rays emitted from each nurse station that intersect with patient beds, modelled as Generic Models in the BIM environment. This proportion, referred to as the Patient Bed Visibility Rate, quantifies nurses' ability to supervise patient areas from their designated workstations.

The analysis was performed in Dynamo using the AVA (Accessibility and Visibility Analysis) package and Python scripting (Figure 23). Rays were generated through the Isovist.BuildIsovist function, and intersections with patient beds were identified by category filtering. For each nurse station, the number of rays intersecting patient beds was divided by the total number of rays cast, producing a normalised visibility rate. The resulting values were visualised to show how effectively each nurse station overlooks the patient areas (Figure 24). An average visibility score was then calculated for each hospital, allowing comparison of overall spatial supervision potential across the two layouts.

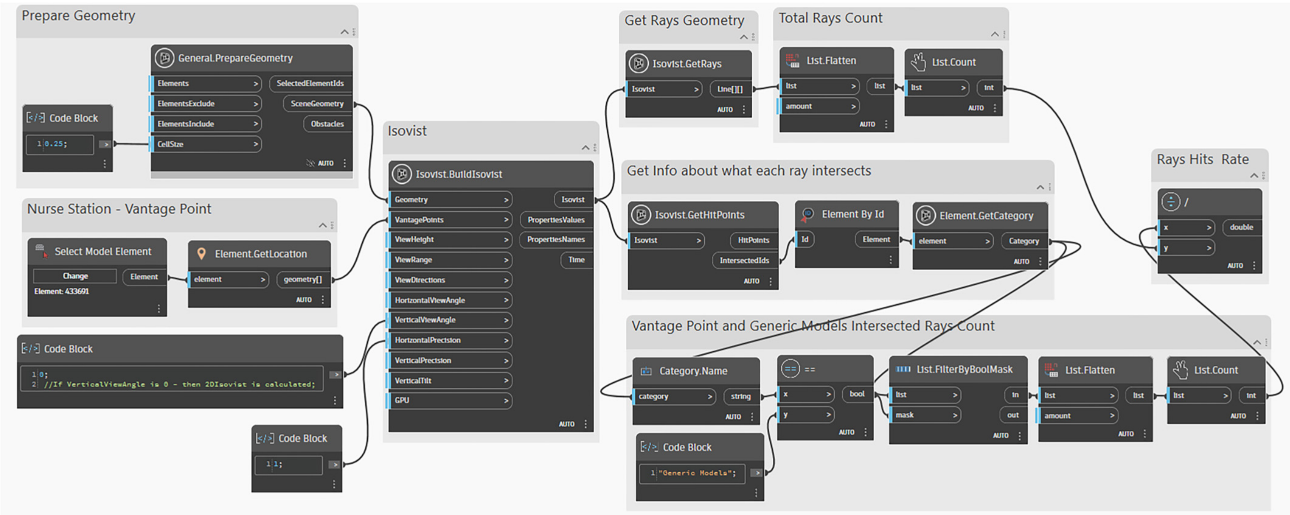

Figure 23. Dynamo script for visibility analysis of patient areas from nurse stations.

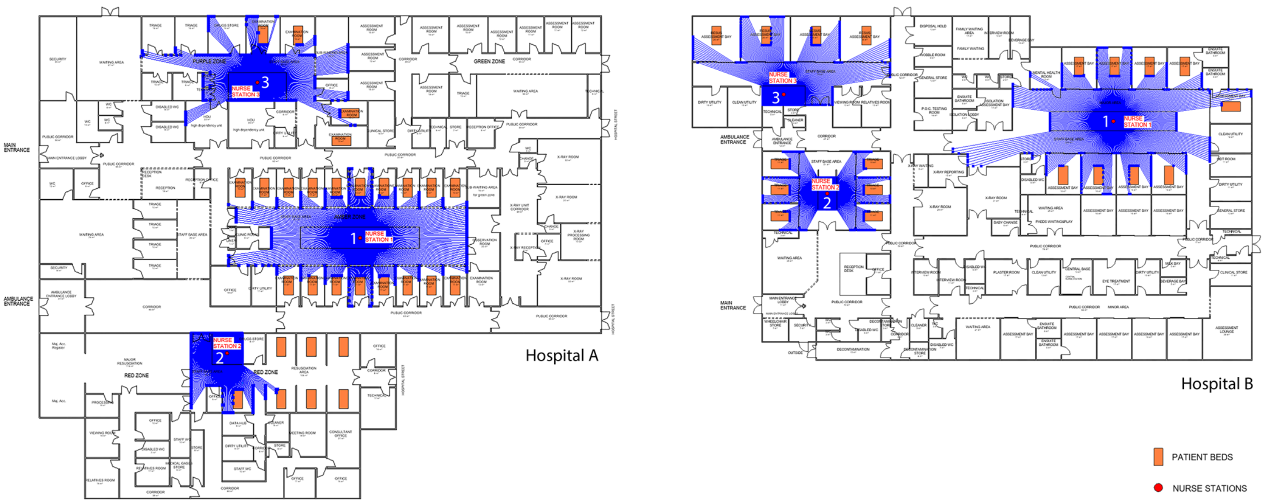

Figure 24. Visibility analysis of patient areas from nurse stations. The blue lines represent the isovist rays generated from each nurse station, illustrating the extent of the visible area within the layout.

As shown in Table 13, Hospital B achieved a higher average Patient Bed Visibility Rate (0.16) than Hospital A (0.10). Within each layout, visibility also varied between stations. In Hospital A, Stations 2 and 3 had lower visibility scores than Station 1, suggesting uneven spatial oversight. In contrast, Hospital B demonstrated more consistent visibility across all nurse stations, indicating a more balanced configuration. These results highlight how the relative positioning of nurse stations and patient beds directly influences visual access, spatial awareness, and the potential for timely clinical response. Overall, this targeted analysis emphasises the importance of aligning staff workstations with patient care zones.

Table 13. Visibility analysis results of patient areas from nurse stations.

Hospital	Nurse Station ID	Total Rays	Rays Hitting Patient Beds	Patient Beds Visibility Rate
A	Station 1	361	74	0.20
	Station 2	361	21	0.05
	Station 3	361	25	0.06
	Average Score			0.10
B	Station 1	361	65	0.18
	Station 2	361	78	0.21
	Station 3	361	29	0.08
	Average Score			0.16

5. Discussion

This section discusses the overall findings derived from the ten spatial analyses conducted on the emergency departments (EDs) of Hospitals A and B. It interprets how spatial configuration influences accessibility, wayfinding, visibility, and privacy from both patient and nurse perspectives. The discussion is structured into three parts: Section 5.1 interprets and compares the spatial results of the two case studies; Section 5.2 discusses the methodological novelty and positioning of the proposed BIM-integrated framework within the wider research context; and Section 5.3 explores the broader implications of these findings for evidence-based healthcare design. Together, these discussions link quantitative outcomes with conceptual insights, addressing both methodological innovation and design performance.

5.1. Interpretation of Spatial Findings

Table 14 summarises the ten spatial analyses conducted for both ED layouts, organised by user group and spatial theme. The discussion interprets how these results relate to patient and nurse experiences, linking spatial metrics with key design concepts such as accessibility, visibility, and privacy. The findings illustrate how spatial configuration shapes operational performance, user orientation, and environmental perception within emergency care settings.

From the patient perspective, wayfinding performance is primarily determined by the legibility and continuity of public corridors. Hospital B records slightly higher connectivity (0.57) but lower integra-tion (0.62) than Hospital A (0.69), indicating that while Hospital B provides stronger local interconnections, Hospital A supports smoother overall circulation. This suggests that Hospital A's corridor network promotes more intuitive movement, reducing route frag-mentation and enhancing navigation efficiency. The reception area in Hospital A is also marginally more visible from the main entrance (0.13 vs. 0.11), providing an initial visual cue for orientation. The walk-in flow analysis shows that patients in Hospital A reach treatment areas with fewer turns and shorter travel distances (2.5 steps/17.18 m) compared to Hospital B (3.4 steps/21.75 m). Collectively, these findings indicate that Hospital A offers a more compact and legible layout that facilitates intuitive wayfinding.

The ambulance-to-resuscitation flow reflects the efficiency of emergency access routes. Both layouts require three steps between the ambulance entrance and resuscitation area, but Hospital B's path is considerably shorter (16.71 m vs. 28.8 m). This demonstrates higher response efficiency through a more direct route from the ambulance bay to critical treatment zones. In contrast, Hospital A's longer route could increase transfer times during emergencies.

Spatial privacy is represented by the integration values of patient rooms. Hospital B's lower integration score (0.39) compared to Hospital A (0.59) indicates stronger spatial segregation, providing greater enclosure and reduced exposure to circulation areas. While this enhances acoustic and visual privacy, it may also increase walking distances for staff and visitors, highlighting the trade-off between privacy and accessibility.

Table 14. Summary of spatial analysis results and spatial concepts for Hospitals A and B.

User Group	Spatial Theme	Analysis	Hospital A	Hospital B	Correlation	Core Concept
Patient	Wayfinding	1. Connectivity of Public Corridors	0.51	0.57	Positive	Spatial legibility & circulation clarity
		2. Integration of Public Corridors	0.69	0.62	Positive	Navigation efficiency
		3. Visibility of Reception from Entrance	0.13	0.11	Positive	Visual guidance & orientation
		4. Walk-in Flow (Step Depth/Metric Distance)	2.5/17.18	3.4/21.75	Negative	Movement efficiency & route length
	Emergency Accessibility	5. Ambulance to Resuscitation (Step Depth/Metric Distance)	3/28.8	3/16.71	Negative	Response efficiency & critical path length
	Privacy	6. Integration of Patient Rooms	0.59	0.39	Negative	Spatial segregation & privacy
Nurse	Accessibility	7. Integration of Nurse Stations	0.52	0.64	Positive	Operational centrality & workflow efficiency
	Visibility	8. Visual Connectivity of Nurse Stations	0.58	0.51	Positive	Visual control & situational awareness
		9. Visibility from Nurse Stations	0.90	0.70	Positive	Visual openness & interaction
		10. Visibility of Patient Beds from Nurse Stations	0.10	0.16	Positive	Targeted supervision & oversight

Nurse accessibility, represented by the integration values of nurse stations, reflects their spatial centrality within the emergency department layout. Hospital B achieves a higher integration score (0.64) than Hospital A (0.52), suggesting more central placement that supports efficient staff circulation and communication. Conversely, the lower integration in Hospital A implies a more peripheral arrangement, which could enhance local visibility but reduce overall accessibility within the circulation system.

Visibility metrics highlight contrasting visual strategies between the two layouts. Hospital A demonstrates higher visual connectivity (0.58 vs. 0.51) and broader isovist coverage (0.90 vs. 0.70), suggesting greater openness and inter-station awareness. This configuration supports efficient coordination and information exchange in dynamic clinical settings. In contrast, Hospital B shows higher visibility of patient beds from nurse sta-tions (0.16 vs. 0.10), indicating enhanced targeted supervision within patient areas. This layout enables localised control and continuous observation of critical spaces, balancing efficiency and safety. The contrast between global visibility (Hospital A) and local monitoring (Hospital B) reflects two complementary design strategies: one promoting openness, the other prioritising focused oversight.

Overall, the analyses reveal a balanced relationship between wayfinding, accessibility, visibility, and privacy. Hospital A performs better in global circulation and spatial legibility, while Hospital B excels in emergency access efficiency and patient-centred privacy. The results suggest differing design priorities: Hospital A favours openness and flow continuity, whereas Hospital B focuses on targeted visibility and spatial containment. This comparison underscores the value of multi-criteria evaluation in ED design, where navigation, supervision, and privacy must be balanced to achieve optimal functional and experiential performance.

5.2. Methodological Contribution and Novelty

The methodological contribution of this study lies in establishing a fully BIM-integrated spatial analysis workflow that combines space syntax principles with real-time design evaluation inside the Revit–Dynamo environment. Previous studies, such as Nourian et al. [32] and Yazar et al. [33], introduced Grasshopper-based toolkits for parametric space syntax analysis. While these methods enabled real-time graph evaluation, they relied mainly on geometric abstractions and did not access the full range of BIM data, including both geometric and semantic information. Similarly, Ugliotti and Shahriari [10] embedded a limited set of syntax indicators, such as depth code, within Revit via Dynamo. However, their framework focused primarily on depth and adjacency, without addressing visibility, multi-user analysis, or context-specific evaluation.

This study extends those approaches by developing a comprehensive, fully BIM-embedded spatial analysis system within the Revit–Dynamo–Python environment. Using the AVA (Accessibility and Visibility Analysis) package, the method automates the computation of metrics including connectivity, integration, step depth, metric distance, and isovist area. These metrics are directly linked to BIM data. Unlike previous tools, the proposed system synchronises geometric and semantic layers, allowing real-time updates as the design evolves.

A key methodological novelty lies in the framework's ability to support multi-criteria and role-specific evaluation. Spatial indicators are categorised by user groups (e.g., patients and nurses) and functional zones (e.g., corridors, nurse stations, patient rooms). This structure captures both operational and experiential aspects of healthcare environments and allows the customisation of metrics for scenario-based evaluation.

From a computational perspective, the integration of Dynamo scripting with Python algorithms enables full automation and reproducibility. Manual steps are minimised, reducing data-handling errors and eliminating the need for export–import operations. The workflow is systematic, scalable, and consistent across layouts of different sizes and complexities. Validation against DepthmapX confirmed the reliability of the results.

Overall, this study advances BIM–space syntax integration from geometry-based analysis to a data-driven and clinically oriented framework. The method enhances analytical precision and efficiency, positioning BIM as a flexible design-support tool that links spatial reasoning with evidence-based healthcare design.

5.3. Broader Implications for Evidence-Based Healthcare Design

The proposed framework has broader implications for architectural design and healthcare planning. By embedding spatial analysis within BIM, it closes the gap between design modelling and performance assessment, allowing spatial quality to be continuously evaluated as the design evolves. Embedding key spatial metrics such as wayfinding, accessibility, visibility, and privacy into the design environment provides immediate feedback on how layout configuration affects user experience and operational performance. Designers can test alternatives in real time, visualise trade-offs between circulation efficiency and privacy, and make informed design decisions based on measurable evidence rather than intuition.

The framework also supports continuous evaluation beyond the design phase. Because spatial indicators remain linked to BIM data, the same analytical models can be reused for post-occupancy evaluation (POE). This enables ongoing monitoring of hospital performance and comparison of intended design outcomes with actual use patterns. Over time, such insights can refine design guidelines and strengthen evidence-based standards in healthcare architecture.

Future extensions could integrate environmental and operational performance indicators. For instance, acoustic comfort may be analysed by linking BIM material properties and spatial adjacencies to sound-transmission models. Daylight access can be assessed through geometric and orientation data in combination with environmental simulations. Infection control performance can be evaluated by combining spatial connectivity and flow data with airflow or occupancy-based simulations. A further direction is full 3D integration: the AVA package and Python workflow can be configured for 3D analysis, multi-level visibility, and vertical circulation. Although technically feasible, this capability was not implemented in the current case studies and remains a promising avenue for future research. Together, these extensions would create a more holistic understanding of how spatial, environmental, and clinical factors interact in healthcare design.

Finally, the framework's flexible structure makes it adaptable to a range of healthcare settings, including outpatient clinics, intensive care units, and general wards. Beyond healthcare, it offers a transferable model for integrating spatial reasoning into complex buildings where safety, efficiency, and user well-being are critical.

Overall, the framework promotes a shift toward a data-driven and human-centred design culture. It embeds analytical intelligence into everyday design workflows, facilitates transparent decision-making, and strengthens the feedback loop between spatial configuration, user experience, and operational performance.

6. Conclusions

This study introduced a computational BIM-based framework for the spatial analysis and performance evaluation of hospital emergency departments. The approach integrates accessibility, visibility, and privacy metrics into a single BIM-embedded workflow within the Revit–Dynamo–Python environment. By automating the computation of spatial indicators and linking them directly to BIM data, the method enables real-time evaluation and evidence-based decision-making during the design process.

Comparative analyses of two emergency department layouts demonstrated how spatial configuration influences both operational efficiency and user experience. Hospital A achieved higher spatial legibility and global circulation efficiency, while Hospital B performed better in emergency access and patient-centred privacy. These findings highlight the importance of balancing wayfinding, visibility, and privacy through multi-criteria evaluation during early design stages.

Beyond analytical results, the study addresses a key limitation in current practice—the disconnection between architectural design and spatial analysis tools. Traditional standalone methods often operate outside the design environment, requiring repeated export–import cycles and manual adjustments that lead to inefficiencies and errors. In contrast, the proposed BIM-integrated workflow supports automated, scenario-based evaluation within a single modelling platform, providing immediate feedback during design development. This integration transforms BIM from a static modelling tool into an active decision-support system for evidence-based healthcare design.

Future research may extend the framework's capabilities by integrating environmental and operational parameters such as acoustic comfort, daylight access, and infection control. The workflow could also be adapted for multi-storey hospitals or linked with real-time occupancy and simulation data to evaluate dynamic clinical scenarios.

Overall, the proposed framework contributes a replicable, scalable, and design-integrated methodology that bridges computational spatial analysis and architectural practice. It promotes a data-driven and human-centred approach to healthcare design, ensuring that spatial quality, user needs, and clinical efficiency are evaluated in alignment throughout the design process.

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Abbreviations

The following abbreviations are used in this manuscript:

AEC	Architecture, Engineering, and Construction
AVA	Accessibility and Visibility Analysis
BIM	Building Information Modelling
EBD	Evidence-Based Design
ED	Emergency Department
GIS	Geographic Information Systems
POEVGA	Post-Occupancy EvaluationVisibility Graph Analysis

Appendix A

This appendix presents the Average Paths custom Python script used to calculate average metric and step distances between rooms and spatial zones.

Table A1. Average Paths Python Script.

```
# Load the Python Standard and DesignScript Libraries
import sys
import clr
clr.AddReference('ProtoGeometry')
clr.AddReference('[DynamoPackages]/AVA/bin/Grafit')
clr.AddReference('[DynamoPackages]/AVA/bin/GrafitRevit')
```

Table A1. *Cont.*

```
from Autodesk.DesignScript.Geometry import *
from Grafit import *
from GraFitRevit import *
import csv

# The inputs to this node will be stored as a list in the IN variables.
dataEnteringNode = IN
# Inputs
visibilityGraphMetric = IN[0]  # Graph object for metric distances
visibilityGraphStep = IN[1]   # Graph object for steps
originsDictionary = IN[2]       # Dictionary<string, List[Point]>
destsDictionary = IN[3]        # Dictionary<string, List[Point]>
outputFilePath = IN[4]

# Extract activity types
originTypes = list(originsDictionary.keys())
destTypes = list(destsDictionary.keys())
activityTypes = list(set(originTypes + destTypes)) # Merge all unique types
numActivities = len(activityTypes)

# Initialize the result table
resultTable = [[None for _ in range(numActivities)] for _ in range(numActivities)]

# Function to convert Dynamo Point to APoint using CWPoint and CRUtils
def convert_to_apoint(dynamoPoint):
    xInInches = dynamoPoint.X / 0.3048
    yInInches = dynamoPoint.Y / 0.3048
    zInInches = dynamoPoint.Z / 0.3048
    return CWPoint(xInInches, yInInches, zInInches)

# Helper function to find the closest node
def get_closest_node(graph, point):
    cw_point = convert_to_apoint(point)
    result = graph.ClosestNodeToPointDyn(cw_point)
    return result.Item1, result.Item2

# Calculate average distances and steps
for i, typeFrom in enumerate(activityTypes):
    origins = originsDictionary.get(typeFrom, [])
    for j, typeTo in enumerate(activityTypes):
        if j <= i:
             continue
        destinations = destsDictionary.get(typeTo, [])
        if not origins or not destinations or i == j:
            continue
        metricDistances = []
        stepCounts = []
        for origin in origins:
             graphFromIndex, nodeFromIndex =
get_closest_node(visibilityGraphMetric, origin)
            for destination in destinations:
                graphToIndex, nodeToIndex =
get_closest_node(visibilityGraphMetric, destination)
                metricDistance =
visibilityGraphMetric.GetShortestPathDistance(
                    nodeFromIndex, graphFromIndex, nodeToIndex, graphToIndex, 0
```

Table A1. *Cont.*

```
)
        stepDistance = visibilityGraphStep.GetShortestPathDistance(
          nodeFromIndex, graphFromIndex, nodeToIndex, graphToIndex, 1
)
                print(f"step distance from origin {typeFrom} to destination
{typeTo} = {stepDistance}")
                metricDistances.append(metricDistance)
                stepCounts.append(stepDistance)
        avgMetric = sum(metricDistances) / len(metricDistances) if
metricDistances else 0
        avgSteps = sum(stepCounts) / len(stepCounts) if stepCounts else 0
        resultTable[i][j] = avgMetric * 0.3048
        resultTable[j][i] = avgSteps

with open(outputFilePath, mode="w", newline="") as file:
    writer = csv.writer(file, delimiter=";")
    header = [""] + activityTypes
    writer.writerow(header)
    for i, row in enumerate(resultTable):
        writer.writerow([activityTypes[i]] + row)

# Assign your output to the OUT variable.
OUT = resultTable
```

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