Digital Twin-Based Hospital Layout Optimization for Patient Flow Improvement

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Abstract: Hospitals operate in highly dynamic environments where patient demand, clinical workflows, and resource availability vary continuously, making effective layout planning a persistent challenge. The traditional approaches used in hospital layout design often don't incorporate real-time operational variability. This results in congestion, longer waiting times, and inefficient resource utilization. Therefore, this paper proposes hospital layout optimization using Digital Twin–based framework that integrates spatial data with operational data. The Digital Twin approach helps in understanding hospital layout and identifying the alternatives solutions by varying different parameters without disrupting the operations. This study simulates the original hospital layout and alternative - three patient pathways. The simulation results show the bottleneck department (imaging department) before and after intervention of introducing three parallel patient pathways. The results show the effectiveness of Digital Twins as a decision-support tool for data-driven and adaptive layout planning. This proposed methodology is applicable to hospital design, renovation, and operational reconfiguration, offering a practical framework for improving patient flow, operational efficiency, and infrastructure resilience.

Keywords: Digital Twin; hospital layout optimization; patient flow; discrete event simulation; patient pathways; waiting time;

Introduction

Hospitals are interconnected systems where physical space, clinical processes, and human interactions are closely interrelated.

Patient wait times, staff productivity, and the efficient use of vital resources are all directly impacted by the layout of departments, diagnostic facilities, and circulation corridors. Overcrowding, excessive patient transportation, and delays in the provision of care are frequently caused by inadequate spatial planning.

Static floor layouts, empirical principles, and professional expertise are the main components of traditional hospital layout design. These methods provide a basis for preliminary planning, but their capacity to adapt to shifting operational conditions—such as varying patient demand, emergency scenarios, and changing clinical workflows—is constrained. Layout planning techniques that take operational behavior into account have become crucial as modern healthcare systems prioritize efficiency, flexibility, and patient-centered care.

Digital Twin technology provides a means to represent physical systems through virtual models that reflect real-world processes and interactions. Within healthcare, Digital Twins have been applied to study patient flow, assess operational policies, and support decision-making under uncertainty. Applying this concept to hospital layout planning enables spatial configurations to be evaluated within a dynamic and data-driven framework, which motivates the present study [1],[2].

Related work

Initial studies related to optimization of hospital layouts mostly utilized discrete-event simulation to model the flow of patients and highlighted operational constraints. These studies highlighted how simulation models could effectively represent random arrival patterns and variability in service, which facilitated performance assessment across various scenarios [3][4].

Nonetheless, spatial factors were frequently addressed in a limited or indirect manner. Subsequent research merged facility layout planning principles with simulation methods to evaluate the adjacency of departments and distances traveled by patients [5],[6]. Although this combination enhanced spatial assessment, many of these models remained static and failed to sufficiently consider changing operational conditions or real-time system dynamics [7].Recently, Building Information Modeling (BIM) has been utilized in the design of healthcare facilities to create precise geometric and spatial representations of hospital structures. While BIM improves spatial accuracy and visualization, it generally does not include methods for integrating operational dynamics and feedback from current hospital activities. [8].

Digital Twin–based approaches overcome these shortcomings by integrating spatial models, operational data, and simulation within a unified framework. Recent healthcare studies have demonstrated the effectiveness of Digital Twins in optimizing ward operations, managing intensive care unit capacity, and improving patient throughput [9-13]. However, much of the existing literature emphasizes operational improvements rather than explicitly addressing hospital layout design, revealing a gap that this work seeks to address.

Key Contributions

The key contributions of this work are summarized as follows:

1. A structured Digital Twin framework proposed for hospital layout optimization that integrates spatial layout and operational processes.

2. A simulation-based methodology to evaluate multiple layout alternatives under varying demand conditions.

3. Quantitative performance assessment using patient-centered and operational metrics relevant to healthcare environments.

4. Experimental evidence demonstrating the effectiveness of Digital Twins in improving layout-related performance indicators.

Method, Experiments and Results

In this section, we present, the methodology, hospital system description, Digital Twin Modeling Framework, algorithm for simulation and then propose the intervention of adding three parallel patient pathways to the hospital workflow to compare the performance parameters. Figure 1 shows the methodology of this study.

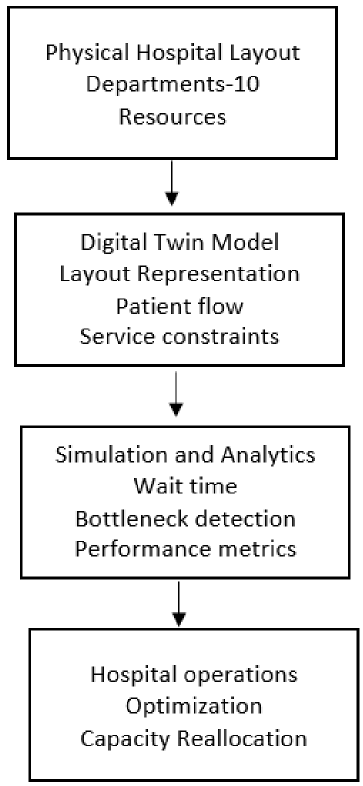


Figure 1. Study Methodology

Hospital System Description

The hospital is modeled as a sequential patient-care system consisting of ten functional departments, representing a typical outpatient care pathway. The departments, arranged in patient flow order, are:

1. Registration
2. Triage
3. Consultation
4. Laboratory
5. Imaging
6. Diagnosis
7. Treatment
8. Billing
9. Discharge
10. Pharmacy

Patients enter the system through registration and proceed sequentially through all departments until exiting after pharmacy services. Each department is modeled as a service station with limited capacity and stochastic service times, capturing real-world operational variability.

Digital Twin Modeling Framework

The proposed Digital Twin integrates layout logic, process behavior and operational performance metrics into a unified virtual model. The Digital Twin consists of:

- Physical Layer: Representation of hospital departments and their service capacities.
- Operational Layer: Patient arrivals, queuing behavior, and service processes.
- Analytical Layer: Performance evaluation using waiting time and congestion metrics.

Patient arrivals follow a stochastic process, and service times at each department are modeled using bounded random distributions derived from realistic outpatient service durations.

Simulation-Based Layout Evaluation

This structure allows the Digital Twin to evaluate layout-induced congestion effects, especially when departments with high service demand (e.g., imaging or treatment) are poorly positioned or under-capacitated. Also parallel patient pathways are introduced in the simulation.

Algorithm: Digital Twin–Based Hospital Layout Simulation

```
Initialize simulation clock t ← 0
Initialize queues and servers for each department di ∈ D
while t < T do
   Generate patient arrivals based on stochastic arrival process
   Assign new patients to Registration department
   for each department di in patient care sequence do
       if server available at di then
          Begin service and record waiting time
      else
         Place patient in queue
      end if
  end for
Advance simulation clock
end while
Compute average waiting time for each department
Identify departments with maximum congestion/bottlenecks
```

Intervention

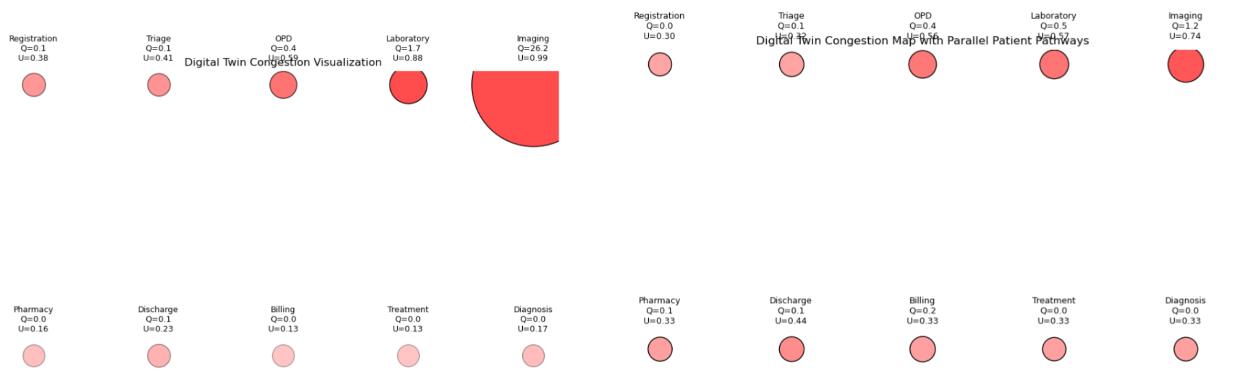
The following new parallel pathways for patients were introduced.
1. Registration→Triage→Consultation→Lab→Billing→Pharmacy
2. Registration→Triage→Consultation→Imaging→Billing→Pharmacy
3. Registration→Triage→Procedure→Ward→Billing→Pharmacy

Results

The proposed Digital Twin framework was evaluated on a hospital layout consisting of ten interconnected departments, ranging from patient registration to pharmacy. Discrete-event simulation was used to emulate patient arrivals, service processes, and resource constraints over a full operational horizon. Parallel patient pathways were incorporated to reflect realistic clinical workflows.

In the baseline layout, significant queue accumulation was observed at imaging department (Figure 2), leading to increased average waiting times and uneven resource utilization. Animated congestion visualization revealed persistent bottlenecks. The introduction of multiple patient pathways reduced the bottleneck at imaging department thereby reducing the average wait time for patients (Figure 3).

These results validate the effectiveness of the Digital Twin in identifying spatial inefficiencies and evaluating alternative layout configurations prior to physical implementation.



(a) before *(b)after*

Figure 2. Bottleneck comparison of all department before and after adding multiple patient pathways

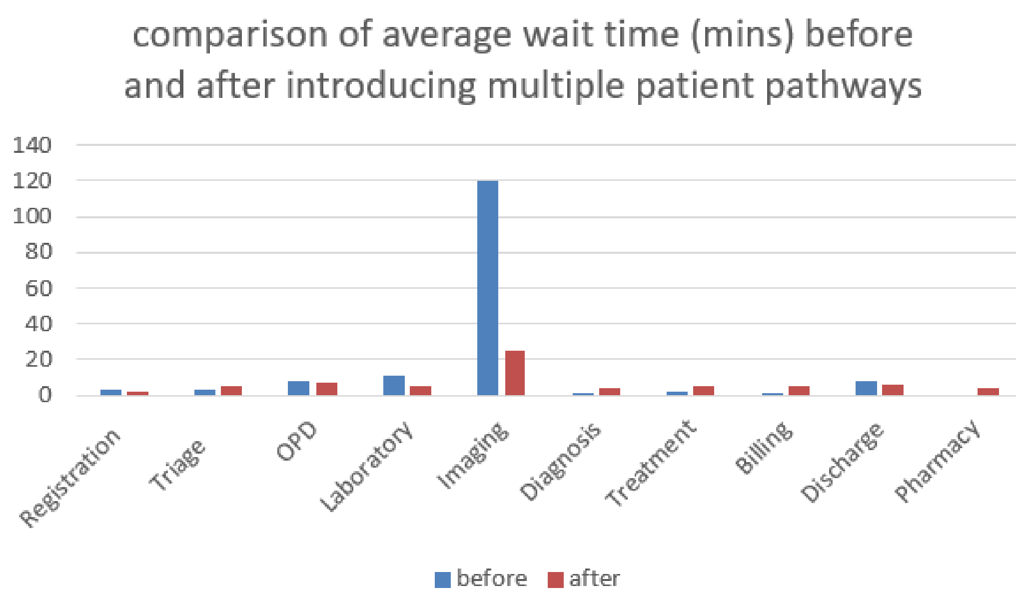


Figure 3. Wait times in all department before and after adding multiple patient pathways

Discussions

The findings demonstrate that Digital Twin–based simulation provides an effective decision-support mechanism for hospital layout planning by capturing both spatial relationships and time-dependent operational behavior. The study shows that inefficient spatial configurations can intensify congestion and bottlenecks despite adequate service capacity, indicating that layout design plays a critical role in patient flow efficiency. Layout optimization supported by a Digital Twin approach leads to shorter patient travel paths and reduced waiting times without the need for additional physical or human resources, thereby improving continuity of care delivery. The inclusion of parallel treatment pathways increases the representational accuracy of the model and captures the inherent variability present in clinical workflows. In addition, the proposed framework is designed to accommodate future enhancements such as priority-driven routing, emergency case management, and adaptive layout adjustments, making it suitable for sustained performance improvement in hospital settings.

Conclusions

This work introduced a Digital Twin–enabled simulation framework for the analysis and optimization of hospital layouts involving ten interrelated departments. By combining discrete-event simulation with dynamic visualization, the framework successfully represented patient movement, congestion hotspots, and patterns of resource utilization under realistic operating conditions. The findings indicate that inefficiencies in spatial design—particularly in areas serving high patient volumes—can substantially increase waiting times even when service capacity is sufficient.

The implementation of parallel patient pathways alleviated congestion in critical departments and improved overall flow consistency without necessitating additional infrastructure or staffing. These results demonstrate the effectiveness of the Digital Twin framework in identifying system bottlenecks, comparing layout alternatives, and supporting evidence-based decisions prior to physical changes. The framework also provides a scalable basis for future development, including priority-aware routing, emergency patient integration, and real-time adaptive reconfiguration, enabling continuous enhancement of hospital operational performance.

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