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EVALUATION AND SELECTION OF HOSPITAL LAYOUT BASED ON AN INTEGRATED SIMULATION METHOD

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ABSTRACT

Space planning and management, as an important part of facility management in the hospital context, is closely related to patient flow and patient behavior. The lack of consideration of such interdependencies would complicate movement patterns of end-users during consultation and treatment process, and as a result, reduce the hospital operational efficiency. To facilitate better space planning and management in hospitals, this study integrates discrete-event simulation and agent-based simulation to examine and evaluate different layout designs. The constructed simulation models take into account the patient flow and patient behavior. At the same time, on-site surveying and monitoring data as well as realistic medical information are used as inputs for the simulation model. Simulation results including patient lead time and facility utilization were used for hospital layout selection. This research provides a new approach to layout design selection and contributes to more effective and efficient space planning and management in healthcare facility.

1 INTRODUCTION AND BACKGROUND

Currently, healthcare systems have become large, complex and very dynamic environments. The efficiency and performance of the healthcare environments have also become focuses (Mcclure and Lafayette 2017). Actually, layout is one of the key items of building design performance. There has been a considerable amount of post-occupancy research investigating healthcare layout and how to it affects important indicators related to patients or departments, such as the patient time in the system and efficiency of nurses providing care (Khadem et al. 2008; Lather and Messner 2019). It is worth noting that factors including space layout, patient behavior, and medical procedures interact and relate to each other, and ultimately affect efficiency and performance of healthcare environments. The evaluation of hospital layout cannot ignore such interdependencies.

Medical architects are increasingly concerned about the evidence-based design decision making process (Burmahl et al. 2017). Unfortunately, due to changes in the healthcare industry and services, existing facilities seem to be unable to serve as the "evidence" for evidence based design of new facilities (Mcclure and Lafayette 2017). The design of healthcare facilities often does not have a single correct answer. In practice, hospital layout scheme is commonly generated, compared and finally determined based on experiential judgments of experts, benchmarks, design aspects and legal regulations (Arnolds et al. 2012; Chraibi et al. 2019).

There are a large number of studies involving the hospital layout, and the topic is often the planning and/or optimization of hospital layout through operations research. The decision making methodologies including technique for order preference by similarity to ideal solution (TOPSIS) and fuzzy TOPSIS (Yang and Hung 2007), preference selection index (Maniya and Bhatt 2011), AHP (Chakraborty and Banik 2007), DEA (Yang and Kuo 2003), GRA (Kuo et al. 2008), etc., were proposed for selection of facility layout design. Most of the research on layout evaluation and selection is aimed at factories or construction sites. Huertas et al. (2007) presented a model to estimate and evaluate the operational costs of alternative layouts for large capacity warehouses. Youngsup (2010) developed the spatial layout evaluation model for the integrated design environment based on BIM technologies. Few studies have focused on evaluation and selection of hospital layout design alternative. Mcclure and Lafayette (2017) developed the layout evaluation simulation protocol, which provides a complete methodology for using computer simulation to support the evaluation of healthcare facility design alternatives. The research also used agent simulation model to detect emergency behavior.

For those existing mathematical approaches of operations research, on the one hand, they greatly simplify the complexity of problem and it is difficult to reflect the complex, variable, dynamic and multidimensional nature of the healthcare systems; on the other hand, it remains difficult to solve to optimality for large-sized instances due to the exponential growth in the required computational effort and associated working memory (Tayal et al. 2017). In addition, research often overlook the impact of patient behavior and patient flow on the layout. Different stakeholders have different objectives and hence hold different perceptions of performance. The selection of alternatives must be considered to strike a balance between better patient satisfaction and the efficiencies required by providers (Brailsford and Vissers 2011). In this context, integrated simulation is gaining acceptance as a source of evidence.

This research integrates Discrete Event Simulation (DES) and Agent-Based Simulation (ABS) to help managers examine and compare different spatial layout schemes through the modeling of patient behavior, patient flow, and the establishment of evaluation indexes. Finally, the feasibility and practicability of the methodology is verified by a case about the spatial layout of the orthopedic patient clinic. On-site surveying and monitoring data and realistic medical data are used in this case model.

2 RESEARCH DESIGN

In order to better demonstrate the application of simulation in hospital layout selection, this study chose a case of actual orthopedic patient layout design comparison. Figure 1 illustrates the steps and sequence of layout design selection by computer simulation.

Description of the orthopedic clinic. In order to provide better environment and services, Shanghai 6th People's Hospital plans to build a new patient building, with orthopedics clinic on the second and third floors. The orthopedic clinic operates from 8:00 am to 4:00 pm, and about 1,500 patients visit orthopedic departments daily. The rate of patients' arrival varies from time to time. The main facilities of the orthopedic clinic include waiting rooms, consultation rooms, X-ray inspection rooms, ultrasound inspection rooms, registration rooms for inspection, inspection control rooms, pharmacy and other functional areas. The consultation room is divided into expert doctor consultation room and general doctor consultation room. According to past statistics from orthopedic clinic in the healthcare information system, the number of patients arriving at the specialist consultation room in the morning was approximately 670, and the number of patients in the general consultation room was 1,000. The number of patients in the afternoon session was 330 and 500, respectively.

There are two proposed new spatial layout schemes designed by design institute that both meet the requirements of medical building regulations. The difference between the two layout schemes is the setting of the inspection rooms. The X-ray inspection rooms in Scheme A are all arranged in the second floor, and the ultrasound inspection rooms are all arranged on the third floor. While in the Scheme B, the X-ray and the ultrasound inspection rooms are evenly arranged on the both floors.

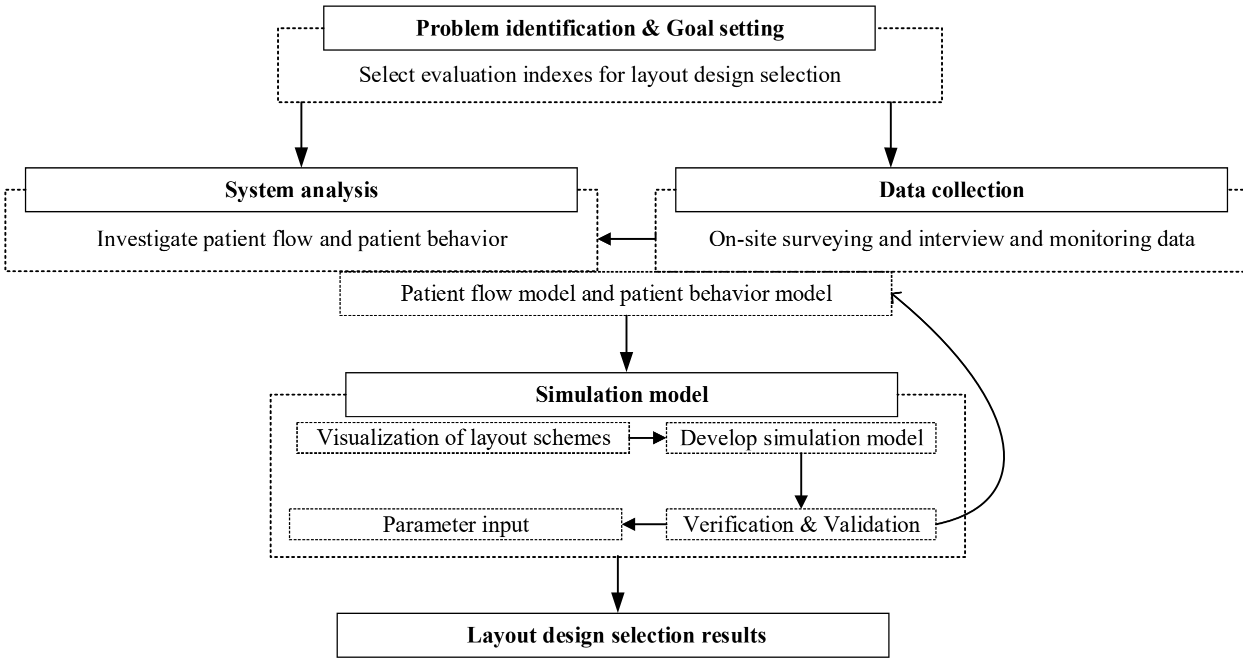


Figure 1: The process of layout design selection.

Evaluation indexes of the layout design selection. The pros and cons of layout designs depend on the evaluation indexes chosen. Reviewing relevant literature, layout designs are usually evaluated from the perspective of the patient and the clinic. The evaluation indexes from the patients' perspective include patient time in the system, patient waiting time, patient travel distance, patient throughput, and so on. And the clinics always care about the resource (healthcare personnel, medical facilities, etc.) utilization efficiency.

Combining the previous research and actual operational needs of the decision makers in the orthopedic clinic of Shanghai 6th People's Hospital, the following indexes were selected: (1) the patient average time in the system; (2) the facilities utilization rate.

Patient flow analysis. Patient flow is the process by which a hospital implements basic medical service functions. It is the internal medical service process and procedures of the hospital. Patient flow affects the quality and effectiveness of the spatial layout, and the correlation and uniformity of them determine whether the hospital building can be better used for medical treatment. The lack of consideration of such interdependencies would cause confusion in the internal processes of various medical functional units. Temporarily changing the layout design during the construction phase would cause huge waste of construction investment. Therefore, in the comparison and selection of layout design alternative, it is necessary to make full consideration of the corresponding patient flow. In addition, due to the different rehabilitation process or needs, the patient flow has some certain randomness. In order to truly reflect patient flow, on-site surveying and data processing are necessary.

According to interviews with staffs, close observation of the daily operations of similar orthopedic clinic, and collection past data of clinic, the patient flow of the orthopedic clinic in this case is obtained, as is shown in Figure 2.

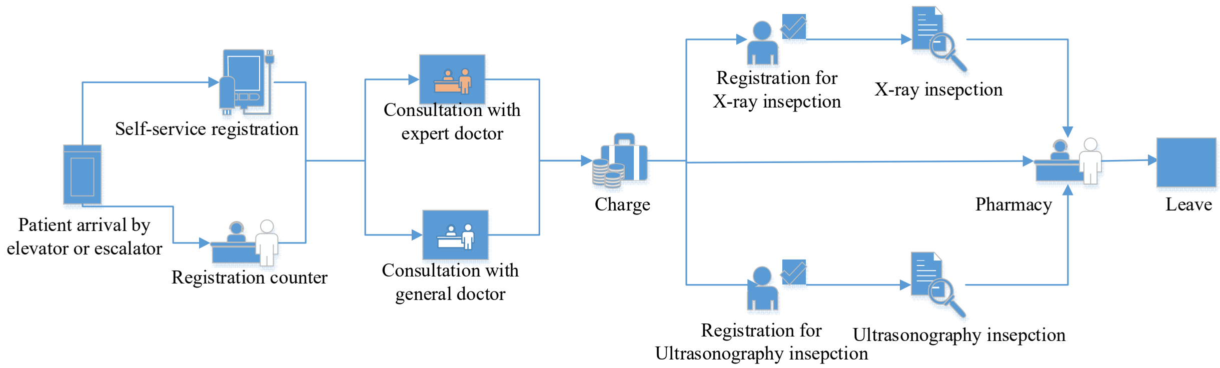


Figure 2: The patient flow of the orthopedic clinic.

Patient behaviors analysis. Space layout planning is closely related to user behaviors. Villa et al. (2014) emphasized that the coordination between behavior patterns and layout is the focus of current research and practice. In the process of medical treatment, patients have two types of behaviors: registration, diagnosis, payment, medicine, rehabilitation and other functional behavioral patterns; and observation, communication, waiting for others, rest, recreation and other non-functional behaviors. The simulation model can depict these behaviors according to the purpose.

According to the on-site survey results and monitoring data, escalators and elevators are the main means of transportation for patients to reach the floor of orthopedics clinic. The ratio is almost 2:1.

Simulation model. Recently, the use of computer simulation for decision-making has exhibited a rising trending (Kittipittayakorn and Ying 2016). Simulation models enable us to explore different hypothetical scenarios that are hard and expensive to be examined in real-world situation. Healthcare management want "proof" during any decision-making process, simulation offers that proof. Simulation allows users to estimate the performance of spatial layout design before expending resources to implement those designs.

DES is a computer-based methodology that provides an intuitive and flexible approach for representing complex systems. According to Konrad et al. (2013), DES offers perhaps the most powerful and intuitive tool for the analysis and improvement of complex healthcare systems. DES model in this paper represents the patient flow. But using only DES is insufficient to model human behavior since the possible path of the entity is predetermined in a DES model (Kittipittayakorn and Ying 2016). ABS has been proposed to model the human discretion factor in a simulation model. It is a new approach for modeling systems of autonomous, interacting agents. An agent can be described as an autonomous entity that makes decisions based on a set of rules (Escudero-Marin and Pidd 2011). In the system, agents communicate with one another; they adapt and change their behavior based on the outcome of the interaction. The integration of DES and ABS can take advantage of both approaches. In order to support DES and ABS and allows us to efficiently combine it with other modeling approaches, the simulation model is implemented in AnyLogic 8. It supports a good combination of DES and ABS. It also can be animated in 2D/3D, allowing concepts and ideas to be more easily verified, communicated, and understand.

Relevant experiments were carried out on the data obtained from field investigation and monitoring to ensure the stability and independence. At the same time, the distribution of these data is also determined by the Kolmogorov-Smirnov test, and input as parameters into the integrated simulation model. The same parameter setting runs the simulation model on two layout designs separately. Table 1 lists the main parameters.

Table 1: Parameter values in the simulation model.

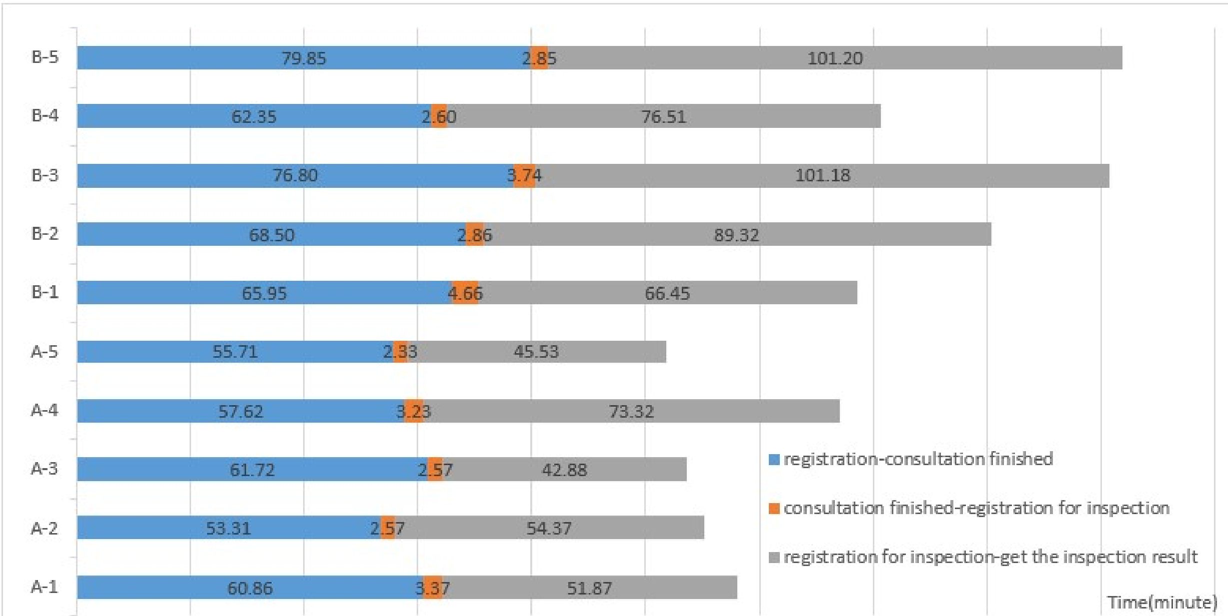
Parameter	**Value (min)**	**Parameter**	**Value(min)**
Registration time	Uniform (0.6, 0.9)	Ultrasonography inspection	Uniform (14, 16)
Consultation time	Uniform (5, 7)	Waiting for inspection result	Uniform (28, 32）
Charge	Uniform (0.5, 0.8)	Get the inspection report	Uniform (0.5, 1）
Registration for inspection	Uniform (0.5, 0.7)	Escalator running time	Uniform (0.15, 0.18)
X-ray inspection	Uniform (2.8, 4.1)	Lift time (including open door)	0.17

In order to make the model conform to actual hospital situation, it is assumed that patients start to queue at 7:00 am at the registration center. When the registration center can be available at 8:00 am, the patients can go through the relevant treatment process. For patients registered on the spot, if they wait to see the doctor for more than 3 hours, they will temporarily leave the hospital. These assumptions are defined through discussions with the hospital staffs, in order to make model generally conform to the actual situation. The demand for X-ray and ultrasonography inspection is provided by the hospital managers.

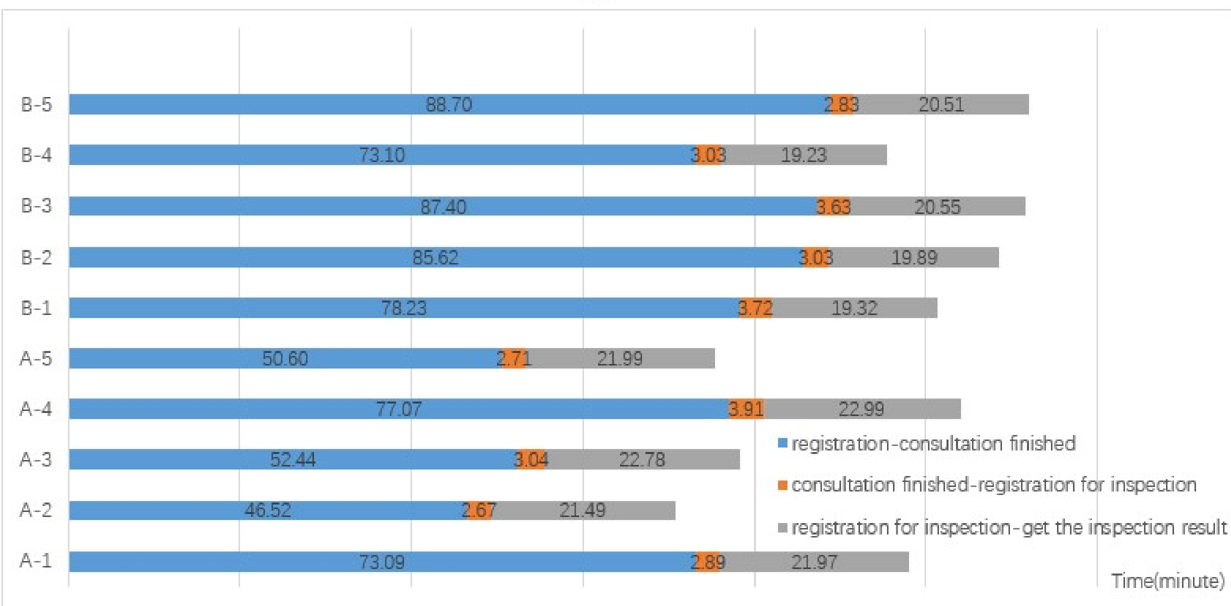
3 RESULTS

Finally, the simulation models of two layout designs are constructed through the comprehensive characterization of the physical space, patient behavior and patient flow. In order to reduce the impact of random distribution, each layout schemes was operated several times and the results were averaged. The duration of each simulation is 7 days. The simulation model is validated by comparing data generated by the model and data collected from the orthopedic department. The results meet the 95% confidence level. After the simulation, the data of selected evaluation indexes is output and optimal layout design is finally determined.

The patient average time in the system. The results show that Scheme A is more efficient than the Scheme B in average time in the system, whether it is X-ray inspection (Figure 3 (a)) or ultrasonography inspection (Figure 3 (b)). We separately counted the three periods of time: registration to consultation finished, consultation finished to registration for inspection, registration for inspection to get the inspection result. For X-ray inspection patients, the average time in the system of Scheme A and Scheme B is significantly different in the third period. And for ultrasonography inspection, the difference is in the first period.



(a)



(b)

Figure 3: The patient average time in the system in scheme A and scheme B.

The facilities utilization rate. Take X-ray facilities rate as an example. For the Scheme A, the X-ray facilities are basically in operation in most cases, while the X-ray facilities on the third floor of the Scheme B often appears to be idle. At the same time, the facilities utilization of the two floors in Scheme B is unbalanced. As is shown in Figure 4. So Scheme A is more efficient than the Scheme B.

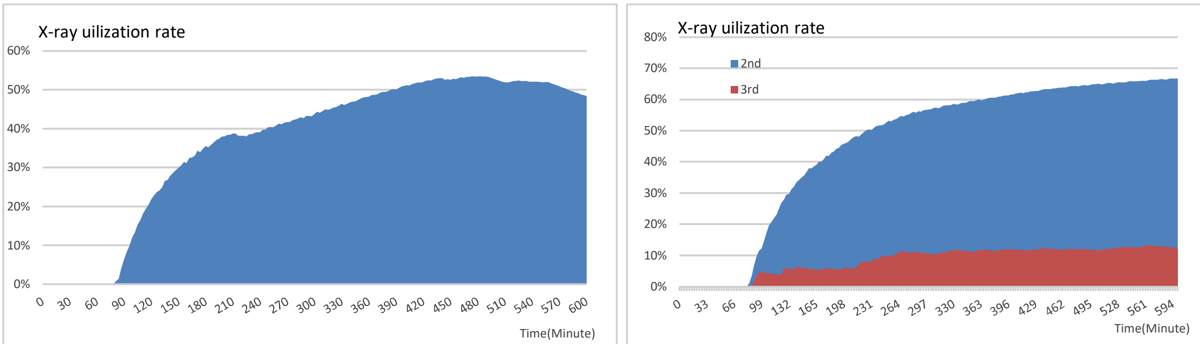


Figure 4: The facilities utilization rate in scheme A and scheme B.

4 CONCLUSION AND FUTURE WORK

The design of current hospital buildings relies heavily on owners' needs and industry practical experience, as well as the choice of layout design. In the practice, experienced hospital planners and architects develop several layout designs after consulting with the hospital managers. They finally together determine the final layout design through discussion. However, in general, there is no violation of hygienic and safety standards in all alternative schemes, and the selection of result often depends on the subjective preference of the decision-makers. This is understandable and frustrating because the information needed to make the right choices is challenging to gather and difficult to interpret. In some cases, data is unavailable. In others, the sheer volume of raw data overwhelms decision-makers, leading to more questions than answers. In order to make the scheme comparison and selection reasonable and scientific, this study integrated DES and ABS simulation models to help selection of layout design alternative. The different designs can be tested with prototypes before documentation for construction. This study shows that simulation models can be useful decision-support tools for healthcare facilities management. The increasing interest in the integration of simulation approaches may be explained by the increasingly complex nature of the problems being faced. Computer simulation is an efficient approach to study such a complex system.

Although our results suggest that the integration of DES and ABS can help layout planning, there are several important limitations to discuss. First, since this research provides only one example, more case studies implementing the model are needed for external validity. Second, the proposed simulation model only generates a method of evaluating a layout scheme but does not generate solutions themselves. Finally, the proposed simulation model does not yield an answer. It merely provides a set of the system's responses to different operating conditions, and so the results need to be well interpreted and understood before any changes are implemented.

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