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ORIGINAL SCIENTIFIC REPORT

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A discrete-event simulation model for assessing operating room efficiency of thoracic, gastrointestinal, and orthopedic surgeries

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Abstract

Background: In hospital management, pinpointing steps that most enhance operating room (OR) throughput is challenging. While prior literature has utilized discrete event simulation (DES) to study specific strategies such as scheduling and resource allocation, our study examines an earlier planning phase, assessing all workflow stages to determine the most impactful steps for subsequent strategy development.

Methods: DES models real-world systems by simulating sequential events. We constructed a DES model for thoracic, gastrointestinal, and orthopedic surgeries summarized from a tertiary Chinese hospital. The model covers preoperative preparations, OR occupation, and OR preparation. Parameters were sourced from patient data and staff experience. Model outcome is OR throughput. Post-validation, scenario analyses were conducted for each department, including: (1) improving preoperative patient preparation time; (2) increasing PACU beds; (3) improving OR preparation time; (4) use of new equipment to reduce the operative time of a selected surgery type; three levels of improvement (slight, moderate, large) were investigated.

Results: The first three improvement scenarios resulted in a 1%–5% increase in OR throughput across the three departments. Large reductions in operative time of the selected surgery types led to approximately 12%, 33%, and 38% increases in gastrointestinal, thoracic, and orthopedic surgery throughput, respectively. Moderate reductions resulted in 6%–17% increases in throughput and slight reductions of 1%–7%.

Conclusions: The model could reliably reflect OR workflows of the three departments. Among the options investigated, model simulations suggest that improving OR preparation time and operative time are the most effective.

KEYWORDS

discrete event simulation, efficiency, hospital management, operating room, operations research

1 | INTRODUCTION

The operating room (OR) provides indispensable healthcare services and plays an important role in healthcare facilities. Improving OR efficiency and throughput benefits patients by reducing patient wait time and financial burden, resulting in higher patient satisfaction.[1,2] In addition, the OR operation accounts for a significant portion of a hospital's costs and income, thus OR efficiency is critical to a hospital's operations and financial health.[1,3]

Like many countries, China also faces the urgent need to improve OR efficiency. The national demand for healthcare services is expanding rapidly, especially due to its aging population.[4] In 2020, more than 67 million surgeries were performed across the country. China's healthcare system must become more accessible and efficient to accommodate the rising demand under limited resources.[5]

Improving OR efficiency is challenging because the OR is a complex and unpredictable environment that requires the coordination of many factors, such as operational and resource factors.[1,6–12] The surgery workflow depends on the multi-layered interactions of nurses, anesthesiologists, surgeons, as well as patients.[1,6–12] Infrastructure and surgical equipment are examples of resource factors that may fail or may be insufficient.[1,6–12] Furthermore, the workflow itself may be inefficient due to issues such as poor scheduling of surgical cases or excessive time spent moving between places.[1,6–12]

Due to these various factors, OR management has gradually adopted decision optimization tools used by the manufacturing industry,[1] such as discrete event simulation (DES).[13] DES is a computer simulation technique which models real-world health systems using networks of events (such as hospitalization and discharge) and queues (such as a patient queue).[14] Simulations enables healthcare providers to explore "what-if" scenarios by simply adjusting inputs, without real-world consequences.[15] Providers can then evaluate the potential effects of different interventions and identify the most beneficial scenario based on specific criteria.[16] Furthermore, DES can handle the inherent variability and uncertainty of real-world healthcare systems by generating stochastic distributions instead of using fixed input values.[17]

We developed a DES model that combines the workflows of thoracic, gastrointestinal, and orthopedic surgeries to represent a general OR workflow. By varying one step in the workflow at a time while keeping others constant in different scenarios, we can analyze how enhancements to individual steps influence throughput. While prior studies have employed DES to evaluate specific strategies in areas recognized as needing improvement, such as resource allocation and surgery scheduling,[3,18–23] our research takes a different approach. We aimed to assist the OR nursing department in pinpointing which areas to work on by identifying steps that hold significant potential for impactful improvements on overall throughput. Furthermore, we explicitly model certain tasks handled by the OR nursing department, which were not considered or broadly categorized into larger tasks in earlier research.

2 | MATERIAL AND METHODS

2.1 | Setting and model perspectives

This study was conducted at Renji Hospital Affiliated to Shanghai Jiaotong University School of Medicine, a tertiary hospital in Shanghai, China. The hospital has a total of more than 2000 beds and 75 ORs across four campuses, with an annual total of approximately 70,000 surgery cases. Our study was conducted at the east campus, which is equipped with 49 ORs. These ORs are fully staffed and operational for 10 h each workday. The appendix (p1) provides a more detailed description of estimated overall OR capacity and utilization.

The OR nursing department is responsible for perioperative nursing care as well as logistical activities such as transporting patients between service locations and cleaning the surgical equipment and ORs. In this study, we developed a decision analytic tool to assist the OR nursing management team in the analysis of different options to optimize efficiency.

At Renji Hospital, each surgical department is allocated a certain number of ORs each day in the week, as shown in Table 1, with one to three ORs scheduled each day for thoracic surgery, two to five each day for gastrointestinal surgery, and four each day for orthopedic surgery. These ORs were rarely utilized for non-elective surgeries (urgent, emergency, and add-on cases due to emergent situations), as the hospital has separate ORs dedicated for non-elective surgeries. Further details are described in the appendix (p2).

All ORs open at 8:00 a.m. each day. Surgeons typically do not use the ORs for the entire day due to other tasks. There is no strict rule to determine their daily total work time. When surgeons stop surgery work for the day, the ORs will be made available to other surgical departments.

This model focused on simulating the operation of thoracic, gastrointestinal, and orthopedic surgeries, most of which are inpatient surgeries. The model structure reflects a generalized workflow common across the targeted surgical departments. Different parameterizations are applied to simulate a specific department. The model's outcome is OR throughput (total number of surgeries) during the observation period. The effects of different workflow improvement options were assessed using scenario analysis.

TABLE 1 Number of ORs designated to each department on each workday.

Workday	Thoracic	Gastrointestinal	Orthopedic
Mon	3	4	4
Tue	2	2	4
Wed	2	5	4
Thu	3	4	4
Fri	1	4	4

2.2 | Model structure

The model simulates the flow of inpatient surgery patients on the day of surgery, starting from preoperative preparation, and ending when the OR is ready for the next patient. The number of ORs open each day is modeled according to the schedule in Table 1. From the perspective of the OR, there are always patients waiting in the queue due to the high demand for surgeries in top hospitals. Therefore, the model draws patients from an unlimited pool. For each patient in the simulation, a surgery type is selected randomly. This selection is made using the sample () function in *R*,[24] which randomly chooses a surgery type based on the available surgeries, with the likelihood of each surgery being chosen weighted by its respective proportion in the data. As the daily total work time is variable, the model implements a time limit for starting new surgeries. No new surgeries are started after this time limit, but surgeries started before the time limit will be completed.

The simulated patient moves through four major events and two minor events, which are marked in Figure 1. More details are specified in the appendix.

2.3 | Model inputs

Real-world patient operative time data of thoracic, gastrointestinal, and orthopedic surgeries were collected from 2021/06/01 to 2021/08/31 and categorized according to department and surgery type. A nurse was assigned to document the time each patient entered and exited the OR, along with the specific OR number and the patient's hospitalization ID. The time data was linked with the specific type of surgery through the hospitalization ID. Simulation of surgery type and operative time are detailed in the appendix. Parameter values relating to type and operative time are shown in Table 2.

Parameters relating to the processing times of the remaining parts in the simulated workflow were obtained through an interview with the head nurse. These parameters are explained in the appendix, and values are shown in Table 2.

2.4 | Model verification and validation

A flowchart of the model is shown in Figure 2. The model was verified and validation by consultation with the head nurse and by comparing simulation results with real-world results. Further details are provided in the appendix (p6).

2.5 | Scenario analysis

Scenarios involving processing time improvements for each stage of the summarized OR workflow were selected based on OR nursing team feedback and literature review. Each scenario was simulated 1000 times, and the average OR throughput of these scenarios were then compared. The evaluated scenarios included: (1) improving preoperative patient preparation time; (2) increasing PACU beds; (3) improving OR preparation time; (4) use of new equipment to reduce operative time of one surgery type. The basis for these scenarios and the parameter value changes are summarized in Table 3. More details regarding scenarios involving the use of new equipment are specified in the appendix.

3 | RESULTS

3.1 | Model verification and validation

According to the head nurse, the generalized OR workflow, as shown in Figures 1 and 2, was able to reflect the actual workflow. After model verification, each of the three departments was simulated 1000 times, and the average OR throughput over 1000 iterations was compared with the actual number of surgeries. The total cases of thoracic, gastrointestinal, and orthopedic surgeries in the actual data were 402, 559, and 529, respectively, and the average simulated throughputs of the three departments were about 400, 552, and 521, which was a difference of less than 2%, as shown in Table 4.

3.2 | Scenario analysis results

The OR throughputs of the three surgical departments in each scenario are shown in Table 4. Among the three scenarios concerning changes in process and resources (i.e., improving the preoperative patient preparation process, increasing PACU beds, and improving OR preparation time), the improvement in OR throughput did not vary significantly among departments. Reducing OR preparation time gave the largest benefit, increasing the OR throughput by approximately 3%–5% across the three departments,

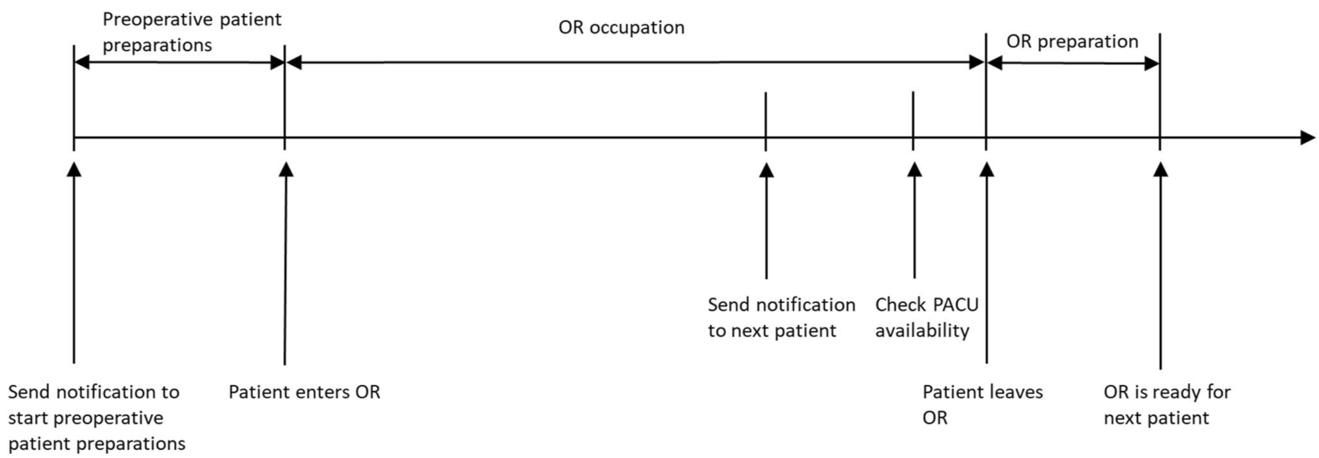

FIGURE 1 Generalized OR workflow diagram.

followed by improving the preoperative patient preparation process, which increased OR throughput by approximately 2%–4%. The least improvement was seen in the scenario with increased PACU beds, resulting in a less than 2% increase in OR throughput. Direct reduction in operative time of selected surgery types (radical gastrectomy, pneumonectomy/segmentectomy/lobectomy, and internal fixation surgery) was the most beneficial to OR throughput, and the extent of improvement was associated with the magnitude of operative time reduction. In thoracic and orthopedic surgeries, the large improvement scenario increased OR throughput by more than 30%, while that of gastrointestinal surgeries increased by approximately 12%. The moderate improvement scenario increased the throughput of thoracic and orthopedic surgeries by approximately 10% and 17%, respectively, while the throughput of gastrointestinal surgeries increased by approximately 6%.

4 | DISCUSSION

We developed a DES model for Renji Hospital's OR nursing department to pinpoint optimization opportunities in the OR workflow. Since the department needs to support multiple surgical departments, the model captures common essential elements from the three departments' OR processes. We then applied a one-factor-at-a-time method, altering one OR workflow step per scenario to isolate and evaluate the effect of each component on system throughput.

We evaluated several optimization strategies, ranging from operational (improving preoperative patient and OR preparation times) to resource factors (increasing PACU beds and using new equipment to reduce operative time). Simulations showed that reducing OR preparation time had a greater impact than the preoperative patient process. Patient preparations typically occur alongside skin closure of the preceding surgery and OR preparation, so this can typically be completed before the OR is ready, making OR preparation the primary bottleneck between surgeries. Thus, decreasing OR preparation time would likely yield more significant performance gains.

Our simulations indicate that OR throughput improvement depends on time savings per surgery and the patient coverage of these improvements. While new equipment reduced operative time similarly across surgical departments, gastrointestinal surgeries saw the least throughput improvement. This is because the time reduction targeted radical gastrectomy for gastric cancer, which represents less than half of all gastrointestinal surgeries, even though it is the second most common type. This is due to the diversity of gastrointestinal surgeries, such that even the most common surgery accounts for less than half of the total. In contrast, the predominant surgeries in thoracic and orthopedic departments account for 60%–70% of their total, leading to more significant throughput improvements when their operative times were reduced. Adding PACU beds, affecting only 10% of patients, had the least impact on throughput.

Our research brings a new perspective to OR workflows using DES. Previous studies have utilized DES to determine the best strategy for optimizing specific areas needing improvement, such as different combinations of surgery prioritization during scheduling.[3,18–23] Our study takes a step back to focus on an earlier planning stage, to find which areas of the OR workflow have the most potential to enhance throughput. Identifying these key areas lays the groundwork for developing and refining strategies tailored to these areas, enabling informed decisions on resource allocation and prioritization.

Additionally, our model is designed from the perspective of the OR nursing department. As a result, it highlights tasks like pre-operative patient preparation

TABLE 2 Input data.

Parameter Operative time	Patient N	Patient %	Distribution[a]	Distribution parameter values (minutes) Mean	SD	Min	Max	Data source
Thoracic surgeries	402							
Pneumonectomy/ segmentectomy/lobectomy	303	75.37%	Truncated lognormal	129.02	60.30	40	407	Real data
Wedge resection	23	5.72%	Truncated lognormal	99.91	82.25	50	417	Real data
Biopsy	23	5.72%	Truncated lognormal	89.13	64.11	19	271	Real data
Radical esophagectomy for esophageal cancer	24	5.97%	Truncated lognormal	328.58	103.35	149	553	Real data
Lumpectomy	29	7.21%	Truncated lognormal	111.10	55.21	30	251	Real data
Gastrointestinal surgeries	559							
Cholecystectomy	5	0.89%	Truncated lognormal	192.80	133.28	76	412	Real data
Radical colectomy for carcinoma of the colon	256	45.80%	Truncated lognormal	198.44	68.91	29	465	Real data
Appendectomy	6	1.07%	Truncated lognormal	158.17	61.13	68	226	Real data
Other	69	12.34%	Truncated lognormal	141.13	91.91	30	495	Real data
Hernia repair	13	2.33%	Truncated lognormal	133.00	74.95	71	343	Real data
Radical gastrectomy for gastric cancer	206	36.85%	Truncated lognormal	220.73	76.17	44	447	Real data
Pancreaticoduodenectomy	4	0.72%	Truncated lognormal	316.50	163.19	154	490	Real data
Orthopedic surgeries	529							
Internal fixation surgery	335	63.33%	Truncated lognormal	137.45	53.69	3	380	Real data
Internal fixation removal	87	16.45%	Truncated lognormal	58.54	31.42	7	188	Real data
Hip arthroplasty	15	2.84%	Truncated lognormal	162.60	31.38	100	228	Real data
Arthroscopic repair	13	2.46%	Truncated lognormal	134.08	41.77	71	205	Real data
Arthroscopic meniscus repair	10	1.89%	Truncated lognormal	97.20	22.29	57	134	Real data
Other	69	13.04%	Truncated lognormal	129.72	76.53	18	490	Real data
Other parameters				**Mode**	/	**Min**	**Max**	
Preoperative patient preparation	/	100.00%	Triangle	20	/	15	60	Head nurse
Additional waiting in OR	/	10.00%	Triangle	32.5	/	5	60	Head nurse
OR preparation	/	100.00%	Triangle	27.5	/	25	30	Head nurse
				Constant	/	/	/	
Patient notification lead time	/	100.00%	Constant	20	/	/	/	Head nurse

[a]Distribution: In the simulation, values are randomly selected from these distributions rather than using fixed values.

and OR setup, which fall under the responsibilities of OR nursing. These tasks, often merged or not considered in prior studies, are treated distinctly in our model. This distinction allows the OR nursing department to assess the impact of optimizing these specific tasks, a perspective not offered by previous models.

Given that we have distilled common elements from three distinct surgical departments to create a generalized OR workflow, this model holds potential for adaptation to other hospitals. Once a hospital ascertains that their OR workflow aligns with the structure of our model, the primary task becomes data collection to update the input parameters.

Cost considerations could also be integrated into the model, so that different approaches are compared on their cost-effectiveness. At present, we can qualitatively estimate the cost level for some approaches. Previous research has explored the implementation of structured practices to reduce non-operative time, such as better preoperative patient preparation and faster OR preparation.[25,26] The financial investment for adopting these approaches would be minimal. Conversely, adding

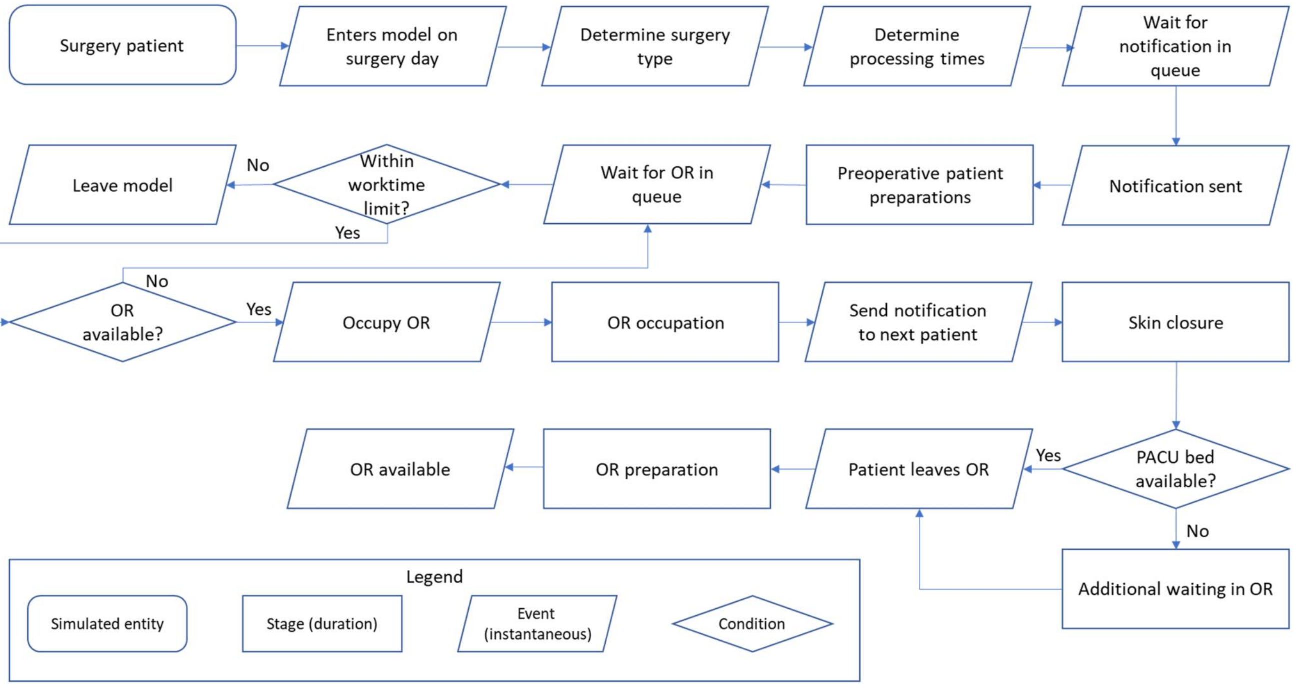

FIGURE 2 Model flowchart.Simulated entity: Represents the patient, the primary entity moving through the modeled OR process.Stage (duration): Denotes a continuous status or phase that a patient undergoes, lasting between two specific events.Event (instantaneous): Signifies a specific moment or occurrence that triggers a change in the patient's or system's status.Condition: Represents a decision point where the workflow can branch based on certain criteria or outcomes. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Scenarios.

Scenarios	Potential improvements	Parameter value changes
Improving the preoperative patient preparation process	Expert opinion: Avoid excessively long preparation times, keeping most cases under 25 min	Preoperative patient preparation: Set maximum value to 25 min
Increasing PACU beds	Expert opinion: Increase PACU capacity to avoid additional waiting in the OR	Whether additional waiting in OR required: Set as a constant with value of 0
Improving OR preparation time	Literature: OR turnover time can be reduced by 6–12 min[25,26]	Preparation time: mode, minimum, maximum reduced by 10 min, that is, set to 15, 17.5, and 20 min, respectively
Use of new equipment to reduce operative time		
Thoracic surgery	Literature: In pneumonectomy/segmentectomy/lobectomy, the use of three-dimensional imaging, laser-assisted resection, and powered staplers has been reported to reduce operative time by 16.2–52.8 minutes[29–34]	Pneumonectomy/segmentectomy/lobectomy operative time: mean, minimum, maximum reduced by:
• slight improvement		15 min
• moderate improvement		35 min
• large improvement		50 min
Gastrointestinal surgery	Literature: In radical gastrectomy, the use of three-dimensional stereoscopic visualization, ultrasonic dissection, and stapler anastomosis has been reported to reduce operative time by 7.5–62 minutes[35–39]	Radical gastrectomy operative time: mean, minimum, maximum reduced by:
• slight improvement		10 min
• moderate improvement		35 min
• large improvement		60 min
Orthopedic surgery	Literature: In internal fixation surgery, the use of surgical robots has been reported to reduce operative time by 60 min[40]	Internal fixation operative time: as base case minimum value was 3 min, this was reduced to 1 min; mean and maximum reduced by:
• slight improvement		10 min
• moderate improvement		35 min
• large improvement		60 min

TABLE 4 Base case and scenario analysis results.

	Thoracic surgeries			Gastrointestinal surgeries			Orthopedic surgeries		
		Difference from base case			Difference from base case			Difference from base case	
Scenario	Cases	Cases	%	Cases	Cases	%	Cases	Cases	%
Model validation									
Base case scenario	400.49	/	/	552.10	/	/	521.39	/	/
Real data	402.00	1.51	0.38%	559.00	5.42	0.98%	529.00	7.61	1.46%
Scenario analysis									
Improving preoperative patient preparation	410.52	10.03	2.51%	566.54	12.96	2.34%	541.51	20.12	3.86%
Increasing PACU beds	407.07	6.58	1.64%	560.05	6.48	1.17%	528.86	7.47	1.43%
Improving OR preparation	419.54	19.05	4.76%	571.58	18.00	3.25%	544.20	22.81	4.37%
Reducing operative time									
Improved surgery type	Pneumonectomy/ segmentectomy/lobectomy			Radical gastrectomy for gastric cancer			Internal fixation surgery		
Slight improvement	427.76	27.27	6.81%	560.68	7.10	1.28%	544.17	22.78	4.37%
Moderate improvement	468.01	67.52	16.86%	580.41	26.83	4.85%	571.92	50.54	9.69%

PACU beds, which our results show has limited impact on throughput, is more costly. Therefore, structured practices should be prioritized over increasing PACU beds.

These cost-effectiveness evaluations can be subsequently incorporated into hospital-based health technology assessments (HTA) to guide management in procurement decisions. HTA is a multidisciplinary process that synthesizes evidence regarding the efficacy, safety, cost-effectiveness, and other properties of a health technology. This aids decision-makers in optimizing healthcare services within limited budgets.[27] As hospitals face increasing pressure to efficiently use resources, HTA is gaining traction globally,[27] including in China.[28] DES models, such as the one described in this study, can be leveraged in hospital-based HTA decision process, especially as they are already prevalent in HTA for cost-effectiveness comparisons.[27]

This study has some limitations. Several model parameters were sourced from interviews with the OR head nurse, relying on individual experience. We used this approach as the OR nursing department had informally reviewed the OR workflow, lending some objectivity to the head nurse's estimates. To reflect uncertainty, we modeled these estimates as random variables with triangular distributions, reporting the standard deviation from 1000 iterations in our results. Additionally, we compared model results against real-world data for accuracy. Although this does not eliminate error, we believe it would not substantially alter the conclusion, given the relatively brief duration of these steps in the total operative times.

In addition, the model currently omits cost inputs. Future adaptations can incorporate economic evaluations for hospital-based HTA, aiding management in diverse scenarios such as equipment procurement, ward design, and resource allocation.

5 | CONCLUSION

We developed a DES model based on the OR workflow of thoracic, gastrointestinal, and orthopedic surgeries at our institution. Model simulations suggest reducing OR preparation time and operative time are more impactful than reductions in preoperative patient preparation or increasing PACU beds. The effect of reducing operative time depends on both the magnitude of service time reduction and the proportion of patients affected. Furthermore, this model could potentially be populated by input data from other institutions to help identify specific improvement opportunities suitable for different settings.

AUTHOR CONTRIBUTIONS

Zhongchen Pu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation; Writing – original draft; Writing – review & editing. **Shuqing Wu**: Conceptualization; Formal analysis; Investigation; Methodology; Software; Visualization; Writing – original draft; Writing – review & editing. **Yi Han**: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation; Writing – review & editing.

CONFLICT OF INTEREST STATEMENT

Shuqing Wu and Yi Han have received research support from Johnson & Johnson Medical (Shanghai) Ltd. Zhongchen Pu declares no conflict of interest.

DATA AVAILABILITY STATEMENT

Data used in this study are available for research only. Data requests will be reviewed by the review committee of Renji Hospital Affiliated to Shanghai Jiaotong University School of Medicine.

ETHICS STATEMENT

No ethical approval required for this study.

INFORMED CONSENT

No informed consent required for this study.

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SUPPORTING INFORMATION

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