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Operating room design using agent-based simulation to reduce room obstructions

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Abstract

This study seeks to improve the safety of clinical care provided in operating rooms (OR) by examining how characteristics of both the physical environment and the procedure affect surgical team movement and contacts. We video recorded staff movements during a set of surgical procedures. Then we divided the OR into multiple zones and analyzed the frequency and duration of movement from origin to destination through zones. This data was abstracted into a generalized, agent-based, discrete event simulation model to study how OR size and OR equipment layout affected surgical staff movement and total number of surgical team contacts during a procedure. A full factorial experiment with seven input factors – OR size, OR shape, operating table orientation, circulating nurse (CN) workstation location, team size, number of doors, and procedure type – was conducted. Results were analyzed using multiple linear regression with surgical team contacts as the dependent variable. The OR size, the CN workstation location, and team size significantly affected surgical team contacts. Also, two- and three-way interactions between staff, procedure type, table orientation, and CN workstation location significantly affected contacts. We discuss implications of these findings for OR managers and for future research about designing future ORs.

Keywords Operating room design · Surgical safety · Agent-based simulation · Markov chains · Statistical analysis · Operations research · Operations management

Highlights

Highlights summarizing the methods and findings of this research:

- We create a quantifiable metric (*total number of surgical team contacts*) that is a pseudo-measure of disruptions. These contacts quantify how often two operating room (OR) surgical team members have the potential to impede each other's ability to deliver care.
- We construct a generalized, agent-based simulation model that can accept as input several design factors (both room-based and procedure-based) in order to evaluate the impacts of OR designs on safety and quality outcomes.
- We evaluate the impact of OR design and other systems factors on patient safety outcomes using this simulated environment.
- This research provides new insights into the placement of objects in the OR from a surgical flow perspective.
- Policy makers can weigh the benefits of "reduced contacts" with recommended design location based on communication and coordination, in setting guidelines for the location of the OR table, Circulating Nurse workstation and OR doors.

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1 Background and literature

1.1 Motivation

This study examines how the physical environmental characteristics of the operating room (OR), along with characteristics of the procedure being performed, can influence the safety of the surgical team and patients. We focus specifically on how these design characteristics affect the unobstructed mobility of the OR surgical team. The physical environment of the OR including the layout of the OR and specific design features can directly affect the processes performed in the OR and consequently affect the quality of care delivered [1, 2]. While prior research by the management science community has recognized the importance of both scheduling management and patient flow in achieving efficient delivery of clinical care in the OR [3–8], this research focuses on improving the safety of clinical care by examining the effects of the OR physical environment on performance.

Studies show that OR design factors affect both the risk of surgical site infection (SSI) and preventable surgical errors [9, 10]. Infection control in the OR has been extensively researched [11], focusing on environmental control factors [12–14], the number of door openings [15–18], physical movement in congested areas [19–21], and stringent aseptic technique protocols [22]. Unnecessary movements within the OR have been shown to increase the microbial level [21, 23], which can lead to an increased risk of SSIs. In one study, the risk of preventable surgical errors increased as observable surgical flow disruptions increased [9]. Such disruptions tend to occur due to poor team communication and high noise levels [24–26], poor placement of equipment and materials [27], insufficient accounting of human factors [27, 28] and inefficient layout of the room [27, 29–32]. However, there is limited understanding of how the physical environment of the OR itself might directly or indirectly affect the risk of SSI and preventable surgical errors.

Operating room layout and design can play an integral role in how a procedure is carried out and how flow disruptions can be minimized. Lee [33] suggests that larger rooms can help the surgical team perform an efficient procedure. However, the team size and equipment present during a procedure interacts with the room size [34]. Room size, team size, and amount of equipment can all contribute to clutter and crowding, which are main causes of disruptions in the OR, and thus a potential hazard to patient safety [2, 27, 30, 35]. While it is often not clear whether such obstructions would lead to a disruption, or to a surgical error, models of error prevention in hazardous environments indicate that there is a correlation between these small events and significant and dangerous errors [9, 27]. Thus, it is important to examine how the physical environment of the OR might affect team member movements and contacts within the OR because these affect patient safety and quality of care.

Despite past research aimed toward improving room layout and providing recommendations to minimize SSI, there remains a lack of evidence demonstrating how these physical environment factors affect safety and efficiency performance.

1.2 Supporting research and new contributions

Our goals in this paper are:

1. To describe and illustrate the use of a quantifiable pseudo-measure of disruptions – *total number of surgical team contacts*. These contacts quantify how often two surgical team members have the potential to impede each other's ability to deliver care in the OR.
2. To formally propose and describe a generalized, agent-based simulation model that can accept as input several design factors (both room-based and procedure-based) to evaluate the likely impacts of OR designs on safety and quality outcomes.
3. To evaluate the likely impact of OR design and other systems factors on patient safety outcomes using this simulated environment.

In recent years, researchers began to address how environmental factors in the OR affect safety and efficiency. Bayramzadeh et al. [36] investigated work patterns, movement, and flow disruptions encountered by the circulating nurse (CN). Specific findings included observations on whether movement involved single vs. multi zone, what activities were being performed, and which zones were most frequented in relation to the CN workstation. They incorporated a computer-based simulation model to illustrate dynamic movements of the CN throughout the OR, and to visually compare CN movement patterns in the OR across different surgery types and different ORs using spaghetti diagrams. However, no statistical analysis was performed, and the CN workstation location was not considered relative to other OR design factors. Taaffe et al. [37] presented an initial investigation into how computer-based simulation modeling can be used to assess design performance, specifically for room size, shape and OR table orientation individually. This study did not include additional relevant factors such as number of OR doors and type of surgery, and it did not provide statistical comparisons on other factors such as CN workstation location and surgical team size. Moreover, there was no predictive model provided for assessing the impact of all environmental factors simultaneously. *In this research, we formally introduce the original playback simulation model, we present the methodology for transitioning to the more generalized, stochastic simulation model, and we provide a statistical model and data analysis that allow a full set of OR design elements to be considered simultaneously.*

We adopt what is considered a hybrid modeling approach. Hybrid simulation models have become more commonplace in recent years, with a thorough review provided by Brailsford et al. [38]. Early uses of hybrid simulation can be found in supply chain management [39–41], with their purpose being to create new capabilities and knowledge by combining more than one simulation technique. Chahal and Eldabi [42] is the earliest and most cited example of describing how to combine multiple simulation methods, in particular discrete event simulation and system dynamics.

This research is a form of hybrid simulation; however, what we develop is an agent-based simulation model at the first level, which contains multiple processes modeled using a discrete event simulation framework. Hybrid simulation in healthcare is becoming more common, yet there are still gaps in how this modeling framework is being used in research [43]. We offer our methodology and research contribution to help address this gap.

2 Methods

This study investigates which OR design factors influence unavoidable contacts during a surgical procedure. The study was conducted in three phases: (1) data collection, coding, and video analysis, (2) development of an agent-based, discrete event simulation model, and (3) statistical analysis summarizing both descriptive and predictive results. This section summarizes the methodological approach to each phase.

2.1 Data collection and coding

For this study, the team used video data from 23 surgical cases from a 700-bed academic hospital in the Southeastern US [1, 21, 31, 36, 37]. (Note: this study was approved by the Institutional Review Board at the partnering Medical University.) Our research team chose a convenience sample that targeted three types of adult General Laparoscopic surgeries (denoted as “Adult G-LAP” throughout the paper, with 16 cases in total) and three types of Pediatric Otolaryngology, or head and neck, cases (denoted as “Peds OTO” throughout the paper, with 7 cases in total). There were significant resources required to set up, observe, and then document observations for every surgery. In order to focus on two distinct categories, we selected several cases over consecutive days in four specific operating rooms. The health system partner was particularly interested in pediatric cases as any lessons learned could serve as input to the new outpatient facility that was under construction at the time. Ultimately, this study informed the design of the new outpatient facility. Having these two categories of surgeries allowed us to make a comparison to identify if surgery type influences any of the output metrics.

Four video cameras (one in each corner of the OR) simultaneously recorded activities in the OR starting with patient entry thru patient exit from the OR. The activities of each surgical team member (surgeon, resident, anesthesiologist, circulating nurse, scrub tech, nurse anesthetist, and other support staff/technicians) were comprehensively recorded using Noldus Media Recorder, as part of the Noldus Observer XT 12 software (www.noldus.com/observer-xt). This software allows for recording of multiple camera views simultaneously, which can then be reviewed simultaneously to generate a coding of each subject’s location, activity, and movement. Using a pre-established code (a categorization of locations in the OR, a list of possible activities, and the possibility to record elements potentially modified by the activities, along with disruptions to surgical flow), each subject was coded second-by-second during each recorded surgery. The OR was organized into different functional zones to identify and code which part of the room the subject was in at any point in time (Fig. 1). Conceptually, the OR surgical team already view the OR as consisting of functional zones that separate sterile, circulating and other work zones. This helps reduce intrusions into areas designated as sterile during surgery and the risk of a break in aseptic technique and potential SSI [44]. This separation of the OR into zones to track movement has been suggested in prior research [27, 29, 45]. Movements were recorded as subjects moved from one zone to another. Tasks performed in each zone were recorded as falling into one of these categories: patient-related, equipment-related, materials and supplies related, and information related. The entire team, including clinical staff at the hospital partner, were involved in our decisions for how to track and collect movements and activities of actual procedures.

Workstation zones (e.g., Surgeon’s Workstation) were labeled according to which surgical team members were the primary users of the zone (surgeon, circulating nurse, and anesthesiologist). Transitional zones referred to those areas within the OR generally used for moving between OR locations. Supply zones contained back-up and some specialty surgical supplies, and support zones contained mobile furniture and equipment used intermittently during surgery. Door zones were classified based on the restricted or semi-restricted access areas outside the OR. Additionally, the surgical zone included the areas on either side of the OR table and the foot of the table. Each OR contained the same set of zones, but the zone size and zone layout varied based on the room dimensions.

2.2 Modeling framework

To capture data on the movements and activities of the surgical team inside the OR, discrete event, agent-based simulation was used. The agents represent individual surgical team

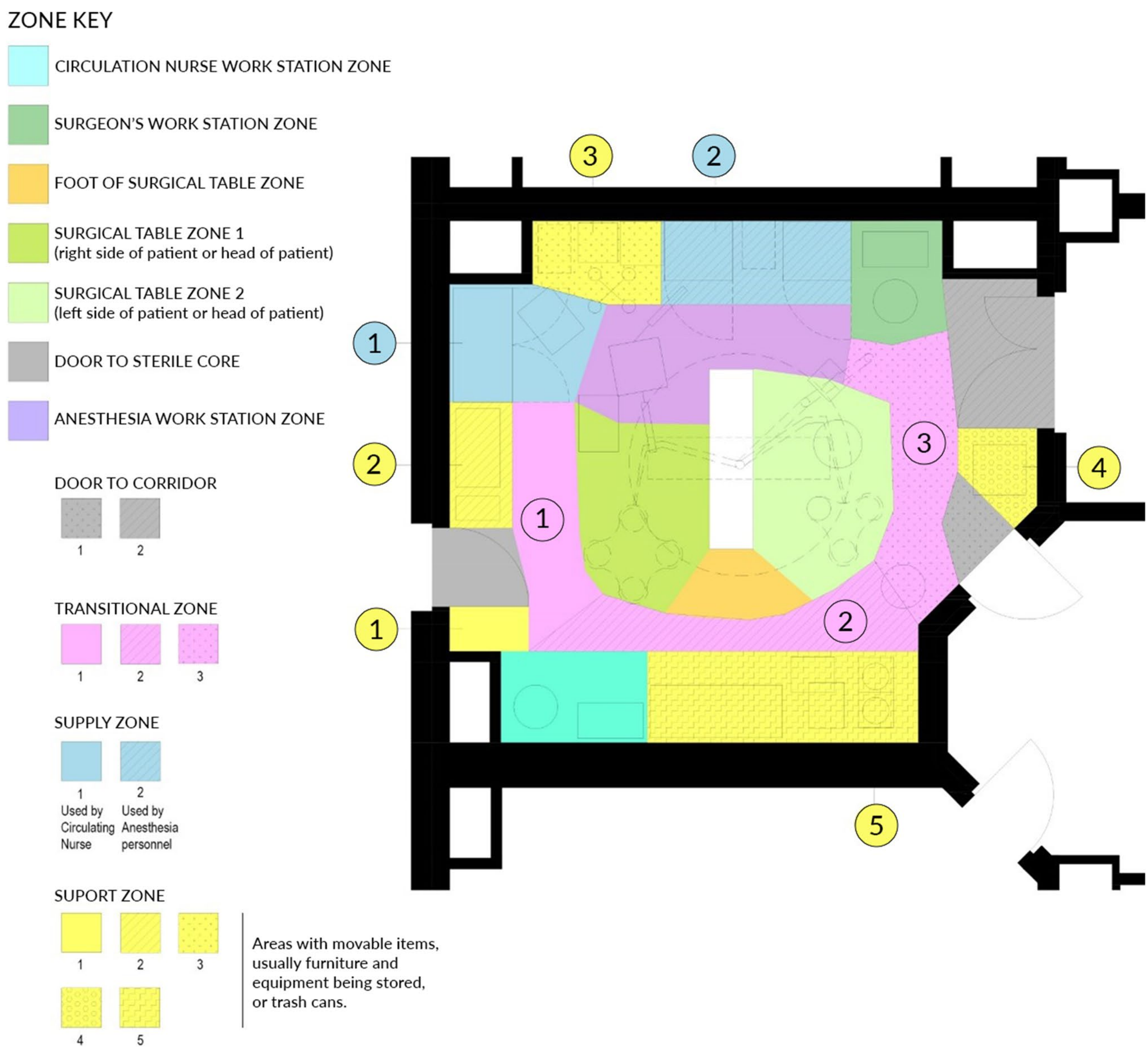

Fig. 1 Sample zone locations in a sample OR

members and the uniqueness of their respective activities and zone-to-zone transitions. Their location and movement can also be affected by the movements of other surgical team members during a procedure. Walls and stationary objects were included in the layout to account for movement restrictions. Such boundary creation, along with collision avoidance based on a social force algorithm inherited in the simulation model [46], are features of the AnyLogic software platform selected to enable a more realistic representation of flow and movement inside the OR. This software was chosen for its flexibility in modeling complex systems, and its Java programming language with object-oriented programming construction. It also has a built-in algorithm that accounts for collision avoidance, which is particularly desirable when describing the walking paths and the congestion experienced by the subjects as they move through the defined operating room space in the model. Such a feature provides an expedient solution to our modeling goal. Two simulation models were constructed in this study: a playback model and a generalized model. Details of the simulation model and design of the study are reported in a separate document, following the Strengthening the Reporting of Empirical Simulation Studies (STRESS) guidelines.

2.2.1 Playback simulation model

The playback model uses data directly from pre-processed spreadsheets derived from the coding of recorded surgeries and simulates the movement of surgical team members from zone to zone as described in the spreadsheet log (cf. Appendix Table 6). In other words, the model replays the actual procedure by reading the subject role, subject location (i.e., zone), and “entrance-to-exit” dwell time in that zone from the file source and executing each record of subject / zone / dwell information in the dataset. There is still a probabilistic component in this approach – the “travel” time required to move from one zone to another. Depending on boundaries and other agent locations, the simulated travel time required could increase or decrease from what occurred in the actual procedure. To ensure that the playback model matches the recorded surgery, we remove this probabilistic component by adjusting in the simulation the remaining “activity” time (dwell time – travel time) in the destination zone, such that the simulated departure to the next zone (according to the spreadsheet log) would occur at the time as planned in the spreadsheet log. This keeps the dwell time in the simulation equal to the dwell time in the spreadsheet log.

This model was built because the performance measures of interest, total number of surgical team contacts and total distanced traveled, cannot be measured by only watching or coding actual videos; the model provided an accurate mapping tool that can collect these measures and draw visual representations of staff movements via spaghetti diagrams. We thus placed significant effort in ensuring the model was an accurate representation of the real system, considering that our primary metrics were related to staff movement. The physical environment (i.e., OR layout and design specifications) is a computer-based representation of the actual room, and the frequency, length and timing of zone visits are modeled just as they appeared in the actual case. As such, the playback model is a replica of the real system, matching staff movement second-by-second, therefore it also serves as a validation tool for the generalized probabilistic model through visual and statistical comparisons of model output. Validating the generalized model to a simulated replica of the real system is an innovative use of simulation tools.

The playback model has two disadvantages: first, the number of possible simulation runs is limited to the set of procedures that were videotaped and subsequently coded. The sample size must then be large enough (e.g. 25–30) to allow for appropriate statistical analysis, and this can be difficult to obtain. Second, it does not accept detailed modification or swapping of functional zone locations. For example, assume a subject wants to move between two zones by going through several other zones. By changing the destination zone, the model should be able to readjust the zones in between to reach the destination zone. In the playback model, this cannot be done since the agent follows the pre-recorded transitions.

Overcoming such limitations of the playback model requires the introduction of (1) a refined data set that can be adapted to a variety of zone layouts within an OR, and (2) a generalized simulation model that captures natural randomness that might occur during a surgical procedure. In the generalized model, we use the playback model as a starting point and incorporate randomness into the transition from origin to destination, instead of mapping out the exact zone-to-zone travel paths used by the playback model. The playback model is thus a building block of the generalized model, using the same agents and their behaviors in the same environment.

2.2.2 Refining the data set for the generalized simulation model

The advantage of the simulation is that the locations and layout of the OR can be virtually tested. But to use the playback model input data for the generalized model, the data had to be refined. For example, consider a specific path taken by a surgical team member in traveling from Support Zone 5 to Supply Zone 2 for the next activity (see Fig. 2), where she/he goes through Transitional Zone 2, Surgical Table Zone 2 and stays for a short period of time in Anesthesia Workstation Zone. If Supply Zone 2 were relocated or moved as part of a test of a new OR design layout, the path that the surgical team member follows to travel from Support Zone 5 to Supply Zone 2 would likely be different from the original path. However, the playback model is not capable of adjusting such intermediary zone visits as it is a playback of actual zones visited in the observed and coded procedures. In other words, the playback model is dependent on all zones that the subject visited in the historical data set. Thus, for the generalized model, we need to transform the dataset so that the sequence of zone visits is stripped of these intermediary zone visits, and only the destination zones where an activity is performed are retained.

To generalize the model, we took the following steps to transform the dataset and retain only the zone visits where an activity had been performed (destination zones). All other zone visits are removed from the list. This meant that the agent was free to select the best feasible route at the point in time during the surgical procedure that the activities were performed. The best feasible route is derived from the social force algorithm, in which the agent attempts to choose the most direct path, while adjusting and updating its path based on the position of the other agents and obstacles [46]. Clinical staff supported the decision to represent the flow in the simulation with the Zone Visits Selection Procedure (cf. Appendix 2 for the detailed steps of the procedure).

Consider again the sample path from Fig. 2. The subject moves from Support Zone 5 to Supply Zone 2 with intermediate visits to Transitional Zone 2, Surgical Table Zone 2, and the Anesthesia Workstation Zone. Step 1 removes

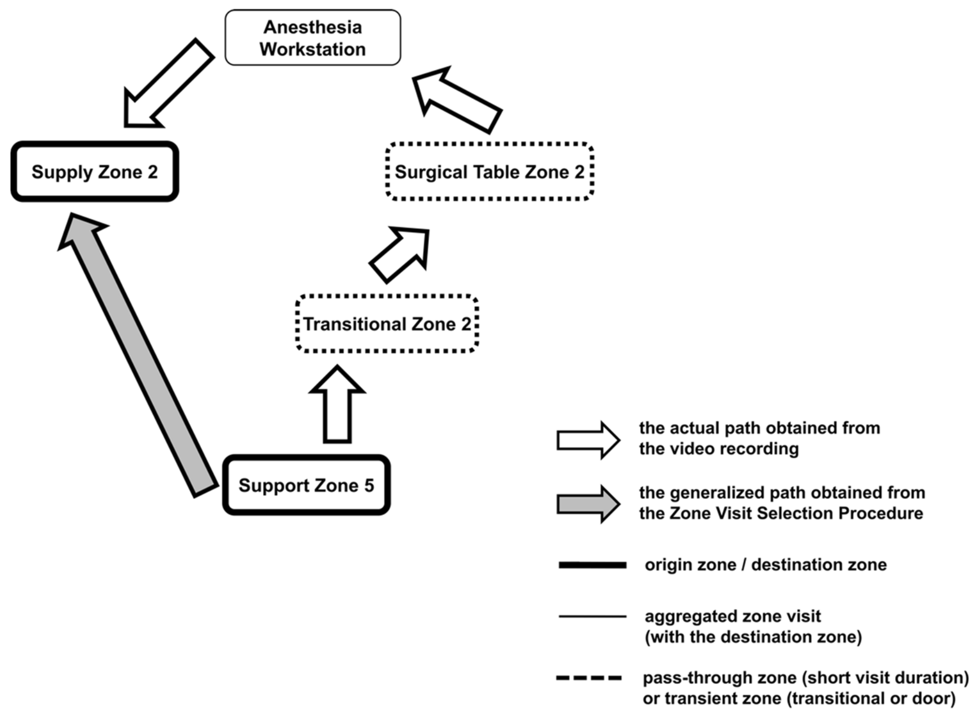

Fig. 2 Movement via exact path vs. destination zones only

the surgical table zone as a pass-through zone, and step 2 eliminates the transitional zone. The anesthesia workstation and the supply zone are both members of Group 6, but the dwell time in the anesthesia workstation zone is found to be shorter. Thus, Supply Zone 2 becomes the destination zone for this subset of zone visits, the dwell time from the anesthesia workstation is assigned to Supply Zone 2, and the anesthesia workstation zone is removed from the path. In the updated path, Support Zone 5 is labeled as the origin zone and Supply Zone 2 is labeled as the destination zone.

2.2.3 The generalized, probabilistic model

We now propose a generalized version of the playback model. The generalized model capitalizes on the detailed, zone-level movements of subjects based on coded data from all procedures, while allowing for randomness in zone dwell times and zone transitions. Adding these two sources of randomness in the model provides the means to study any number of OR layouts; the historical data is no longer tied to a specific layout, as was the case with the playback model.

Similar studies in the literature suggest that a thorough analyses of movements (i.e., tracking frequency and duration of visits in the room) can help build a generalized simulation model where subjects move according to a series of transition matrices [47, 48]. Various types of Markov chains have been used to model the transmission of data across various states of microscale systems such as sensor or wireless networks [49, 50]. The same framework can be applied to study movement in a macroscale system such as traffic flow in an urban region [51, 52]. We apply this methodology to the system under study, where a subject moves across a set of zones according to a specific transition matrix.

Using this probabilistic approach, the pattern of movement resulting from the simulation model will be random and unique for each replication performed, and the model output will likely not match how movement occurred for any single surgical procedure. However, as Section 2.3 will illustrate, the summarized subject movements and key performance measures indicate that the model approximates the actual data from the playback simulation well.

The existence of Markovian behavior can generally be understood from the movement patterns of the surgical team, and determining a subject's next zone is solely based on where the subject is currently located. Such transition probability matrices within this modeling framework are specified based on team member type and phase of the procedure– pre-operative, intra-operative, and post-operative, based on the coded data from the recorded surgeries. To illustrate, Fig. 3 shows the transition probability matrix of the scrub tech during the intra-operative phase for Adult G-LAP procedures, with the last row denoting the mean dwell time in the corresponding zone. The resulting information was obtained based on the data refinement process presented in Section 2.2.2. For the scrub tech, the work is performed primarily around the OR table. There are also frequent but short visits to Support zone 1.

The stochastic simulation model is a probabilistic generalization of the playback model and is capable of being

	Support zone 1	OR Table 1	OR Table 2	CN Workstation	Foot of OR Table	Support zone 2	Surgeon's workstation	Out of Room
Support zone 1	0.41	0.57	0.01	0.00	0.00	0.00	0.00	0.01
OR Table 1	0.51	0.39	0.01	0.03	0.04	0.00	0.00	0.01
OR Table 2	0.33	0.33	0.33	0.00	0.00	0.00	0.00	0.00
CN Workstation	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Foot of OR Table	0.25	0.00	0.00	0.00	0.25	0.25	0.25	0.00
Support zone 2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Surgeon's workstation	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Out of Room	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00

Dwell time (seconds)	Support zone 1	OR Table 1	OR Table 2	CN Workstation	Foot of OR Table	Support zone 2	Surgeon's workstation	Out of Room
Mean	9	82.6	101	28.9	15.9	13.4	5.7	53.7
(Standard deviation)	(0.31)	(1.28)	(2.47)	(0.49)	(0.53)	(0.18)	(0.18)	(1.62)

Fig. 3 Transition probabilities and dwell times (mean and standard deviation): Scrub tech, intra-operative phase, Adult G-LAP

applied to procedure- or team-specific inputs. The strength of this modeling approach does depend on the size of the dataset. Having a large dataset (23 procedures and over 50 hours of recorded movements) will ensure more reliable summary data being used within each transition matrix.

Note that the above transition matrix and dwell times applies to all instances (subjects) of a particular type that are in the model. In larger or more complicated OR procedures, there might be additional anesthesia providers, surgeons, residents, or medical students, and it is reasonable to expect that they will have a similar pattern of movements in the room to their counterparts, as discussed with the clinical partners. However, duration of stay and the order in which they visit zones might be different. To address model robustness, we varied transition matrix input parameters and found that the output performance did not change by more than 5% when input parameters varied by ± 30%, which indicates adequate robustness in our context. Thus, we can conclude that the model is reasonably robust in response to slight changes in the transition matrix, so that our results are not dependent on the estimates of transitions probabilities.

2.3 Validation of the probabilistic model

The objective is to verify (both visually and statistically) if the two modeling methodologies are reasonably similar according to a set of occupancy metrics that illustrate the level of movement and traffic patterns within an OR, namely *total distance traveled* (*TDT*) and *total number of contacts* (*TNC*).

TDT measures the total distance walked inside the room by all OR team members and is a straight-forward calculation, and TNC counts the number of "bumps" experienced by the OR surgical team. These bumps or contacts do not necessarily lead to disruptions, though there may be higher likelihood of occurrence due to the proximity of the tasks being performed. For example, if the two team members happened to be standing next to each other for an extended period of time, the model could potentially register an inordinate number of contacts simply because of their fixed locations. For this reason, TNC was measured by monitoring the distance between any two subjects as they move from one location to another. When a subject passed by another subject within a pre-specified threshold (0.6 m), a contact was recorded. The threshold value was determined by observing several taped procedures for the frequency of team members coming into close contact with each other. This observation was compared against the results being recorded in the simulation for various settings of the contacts threshold. If both subjects are performing activities within the same zone, the interaction is not counted as a contact. Although every contact is not an indicator of disruption, TNC can be used as a reasonable measure of congestion or room obstructions.

We developed the simulation models to allow the second-by-second updating of team member location within the OR. Figure 4 shows the patterns of movement generated by the playback and probabilistic models for a CN involved in two procedures which took place in the same room. The top two figures are simulations of actual surgical procedures from the original dataset. Observe that the density of movement within those two procedures is higher on routes connecting the two doors and through the transitional area. The bottom two figures show only two realizations of the generalized model in

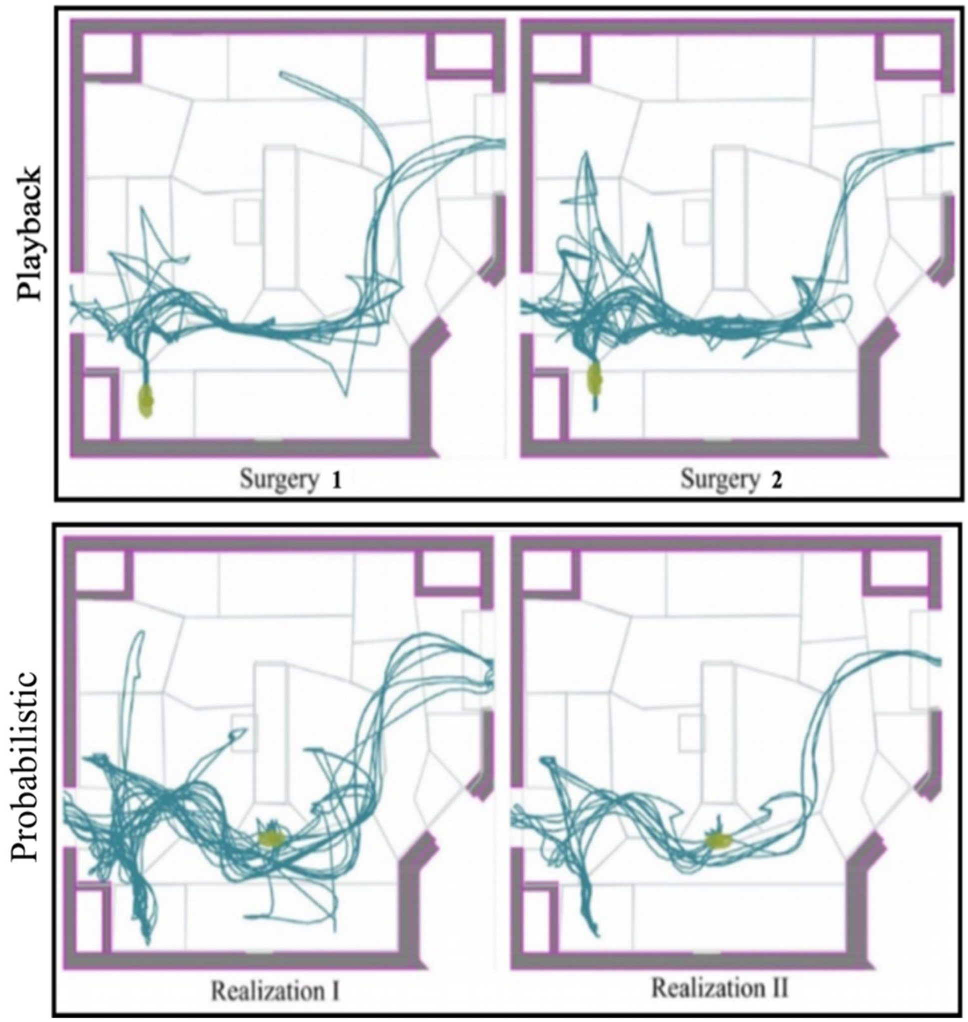

Fig. 4 The movement patterns of a nurse in both playback and probabilistic models

the same room. Again, these two realizations are not exact representations of any procedures from the historical dataset, but rather two replications resulting from the generalized model, which is still using the historical data through the transition probability matrices and dwell times. We note that the pattern and density of movements are very similar. It is possible that a specific zone is infrequently visited by a nurse in the playback model while the same zone is not visited at all for a single realization when using the generalized model. This could result because the zone has a low probability of occurrence and might not be visited in every realization. Also, as Fig. 4 shows, the spaghetti diagrams do not capture direction of movement. However, at the aggregate level, we consider each spaghetti to capture both directions, so it is in fact similar to a round trip between two destinations.

The movement patterns of the surgical team members, as expressed with the transition matrices (Fig. 3), were derived from the large dataset of recorded movements from over 50 h of recorded surgeries (spreadsheet log illustrated in Appendix Table 6), thus ensuring well-grounded estimates. The two performance metrics (TDT and TNC) were used to assess the quality of the probabilistic model when compared with the playback model. To determine the number of simulation replications to perform using the probabilistic model, for both the validation and subsequent analysis of results, an estimate of acceptable variability in output measures was required. Consider an example where the average total distance traveled (TDT) is 300. In discussions with frontline staff and the research team, we chose to allow no more than 2% error in the mean estimate from the true mean, and we assumed a desired standard deviation of no more than 15. With a power of 90%, type-1 error of 5%, standard deviation of 15, and an error of 2%, the sufficient sample size is estimated to be 48 [53]. For all analyses, a total of 50 replications were conducted. Please also refer to the Supplementary file: Section 4.3 of the STRESS document.

Table 1 introduces four statistical tests that were used to compare the two models with respect to TDT and TNC.

Table 1 Four statistical tests together with their type and use

Test Name	Type
Student's t test (t)	Parametric
Chi-squared (χ^2)	Parametric
Wilcoxon signed-rank (W-S)	Nonparametric
Kolmogorov–Smirnov (K-S)	Nonparametric

Table 2 Statistical test result (p-values) for "Playback vs. Probabilistic" model comparison (n = 5 or n = 7 team members)

Test name	Total Distance Traveled (TDT)		Total Number of Contacts (TNC)	
	n = 5	*n = 7*	*n = 5*	*n = 7*
Student's t test (t)	0.75	0.38	0.72	0.28
Chi-squared (χ^2)	0.27	0.04	0.27	0.05
Wilcoxon signed-rank (W-S)	0.87	0.05	0.40	0.33
Kolmogorov–Smirnov (K-S)	0.33	0.27	0.77	0.97

Since the playback model only generates one simulation result for each surgical procedure in the dataset, we used bootstrapping to make 35 playback data points out of the actual sample of size 23. And to compensate for the relatively low sample sizes, two nonparametric tests were chosen. According to Table 2, almost all *p*-values are substantially greater than 0.05 (with only one p-value equal to 0.04). Considering the similarity in CN movements from the visual representation in Fig. 4, along with the collection of statistical tests in Table 2, there is significant support that the models produce similar results and the general, probabilistic model will be an effective analytical tool.

While both TNC and TDT performance measures were used in the validation phase, the value of the generalized model and the statistical approach can be understood through a focused study on TNC. Furthermore, we focus our analysis on TNC as a quantifiable pseudo-measure of disruption and safety, since the focus of this paper is on the relationship between OR designs and safety and quality outcomes. Our analysis proceeds with analysis and discussion of TNC as our measure of study.

2.4 Multiple linear regressions: additive model and higher-order terms

To further understand the factors that predict TNC, we employed multiple linear regression by considering both an additive model and models that include higher-order terms. After fitting each model, residual analyses were conducted to ensure that the normality [54] and homoscedasticity [55] assumptions were tenable. An ordinary least squares multiple linear regression [54] was conducted using the simulation output TNC as the dependent variable. The predictors were room size, room shape, OR table orientation, CN workstation location, team size, number of doors in the OR, and procedure type. Each variable was entered simultaneously. We report semi-partial correlations (*sr*), which represent the unique relationship between a predictor and the outcome variable of interest. Stated differently, it is the linear relation between a single predictor and the outcome, with the effects of all other predictors removed from the focal predictor. Lastly, for parsimony and to gain a more nuanced understanding of how the predictors interacted to influence TNC, we fitted models with two-way interaction terms and three-way interaction terms based on the guidance of subject matter experts in healthcare.

3 Results

In a prior study by the research team, a set of comparisons was conducted to answer specific questions about how the shape and size of the OR room, as well as orientation of the OR table, affected safety and efficiency [37]. While the insights were valuable, only a single factor at a time was manipulated, and there was no predictive modeling where all factors were considered simultaneously. In this research, we offer a complete statistical treatment to measure how room congestion and obstructions (observed through TNC) are affected by the various physical environment factors, as well as the interaction (or combination) of these factors. We can then use the findings with our previous knowledge of the relationships between the performance measures to infer the effect of the factors investigated here on these performance measures.

The aim of this section is to identify changes in TNC as a function of changes to the layout, staffing, or procedure. Each change in variable setting introduces a new model configuration to test. However, to maintain a reasonable set of unique design scenarios to test using computer simulation, only the most critical set of variables was considered. Table 3 presents the list of independent variables that were used for analysis. These variables were selected based on their likelihood of playing a role in room design, layout, and ultimately congestion. The first two are room size and room shape, each with two settings to consider. The third variable is the OR table orientation – to be positioned vertically, angled, or horizontally. The CN workstation location, team size, number of doors, and procedure type all have two settings as described in the table. In particular, the "beside the wall" location was a corner location closest to the foot of the OR table. The base staffing level of five included the following members: surgeon, anesthesiologist, circulating

Table 3 Independent variables or predictors

Variable Name	Values Taken
Room Size	Small / Medium
Room Shape	Rectangular / Square
OR Table orientation	Vertical / Angled / Horizontal
CN workstation location	Foot of OR table / Beside the wall
Team size	5 / 7
Number of doors	1 door / 2 doors (diagonally placed)
Procedure type	Pediatric / Adult

nurse, scrub tech, and nurse anesthetist. When adding two team members to the room, we considered an additional member for the anesthesia team and an additional member for the surgeon team.

In total, there were 192 scenarios to simulate based on all combinations of the factors. Fifty replications per scenario were conducted, and common random numbers (CRN) were used across the scenarios as a variance reduction technique. This section provides both the descriptive and predictive results of the simulation analysis, with a focus on TNC. All analyses are based on the generalized, stochastic simulation model, and its associated zone-to-zone transition probabilities and durations. Throughout the analysis, the variable names in Table 3 will be used.

3.1 Scenarios with the highest / lowest TNC

Table 4 presents the top ten highest and lowest average TNC with a 95% confidence interval estimate for each scenario. From this snapshot of the "top ten" and "bottom ten" it appears that room size, procedure type, and team size all play an important role. Notice that all ten scenarios with the highest TNC have a small room, Peds OTO procedure, and 7 team members, while all ten scenarios with the lowest TNC have a medium room, Adult G-LAP procedure, and 5 team members. The remaining factors do not have such clear results, indicating that they are either not influential or that they are dominated by these three. We note that the CN workstation location beside the wall appears more frequently in the bottom ten (i.e., the smallest TNC set), while the CN workstation location at the foot of the OR table appears more frequently in the top ten (i.e., the largest TNC set.)

Table 4 Top and bottom 10 combinations of factors with respect to Total Number of Contacts (TNC) (Average across 50 replications)

Test Case	Room Size	Room Shape	OR Table Orientation	# of Doors	Procedure Type	Team Size	CN Workstation Location	TNC	95% Confidence Interval
192	Small	Rect[1]	Vertical	1	Ped	7	Foot	68.4	(64.9–71.7)
191	Small	Rect	Vertical	2	Ped	7	Foot	68.2	(64.7–71.8)
190	Small	Rect	Horizontal	1	Ped	7	Foot	67.8	(64.5–71.0)
189	Small	Rect	Angled	1	Ped	7	Foot	64.5	(61.5–67.5)
188	Small	Rect	Angled	2	Ped	7	Foot	60.6	(57.5–63.8)
187	Small	Square	Angled	1	Ped	7	Foot	60.0	(57.2–62.7)
186	Small	Rect	Vertical	1	Ped	7	Wall	59.2	(56.7–63.1)
185	Small	Square	Horizontal	1	Ped	7	Foot	59.4	(56.4–62.6)
184	Small	Square	Vertical	2	Ped	7	Foot	59.3	(55.8–62.7)
183	Small	Square	Vertical	1	Ped	7	Foot	59.2	(56.6–61.9)
***									
10	Medium	Rect	Angled	1	Adult	5	Wall	12.2	(11.3–13.1)
9	Medium	Square	Angled	1	Adult	5	Wall	12.1	(11.1–12.9)
8	Medium	Square	Angled	1	Adult	5	Foot	11.8	(11.1–12.7)
7	Medium	Square	Horizontal	2	Adult	5	Foot	11.3	(10.6–12.2)
6	Medium	Rect	Horizontal	1	Adult	5	Foot	11.1	(10.3–11.8)
5	Medium	Rect	Vertical	1	Adult	5	Wall	11.1	(10.2–11.8)
4	Medium	Square	Vertical	2	Adult	5	Wall	10.8	(10.2–11.7)
3	Medium	Square	Horizontal	1	Adult	5	Wall	10.3	(9.6–10.1)
2	Medium	Rect	Horizontal	2	Adult	5	Wall	10.2	(9.4–10.1)
1	Medium	Rect	Angled	2	Adult	5	Wall	9.7	(9.2–9.9)

[1]Rectangle

3.2 Multiple linear regression: additive model

The overall model has TNC as the dependent variable and the following predictors: room size, room shape, OR table orientation, CN workstation location, team size, number of doors in the OR, and procedure type. This model was statistically significant, $F(8,11,323)=2{,}834.68$, $p<0.0001$, and explained 66.7% of variance in TNC. All predictors were statistically significant except for number of doors in the OR. Thus, a second multiple linear regression was conducted with all predictors but excluded number of doors in the OR. The overall model was statistically significant, $F(7,11,324)=3{,}239.92$, $p<0.0001$, and explained 66.7% of variance in the dependent variable. All predictors were statistically significant at the 0.0001 level.

Table 5 summarizes the fitted models. Focusing on the main effects model, when holding the other predictors constant, increasing the team size from five to seven increased TNC by 16. Compared to the medium room, the small room resulted in an average increase on TNC by 13. Compared to Adult G-LAP procedures, Peds OTO procedures resulted in an average increase of 13 TNC. Compared to the CN workstation located at the foot of the OR table, the CN workstation beside the wall resulted in an average decrease on TNC by 7. Although the remaining predictors were statistically significant, the predicted average change in TNC was not as large. For example, compared to an angled OR table orientation, a horizontal OR table orientation resulted in an average increase on TNC by 1.

In Table 5 (top panel), among the main effects, the largest semi-partial correlation, or the single largest unique predictor of TNC, came from team size ($sr=0.52$), followed by room size ($sr=$-0.41), procedure type ($sr=0.41$) and CN workstation location ($sr=$-0.22). These results corroborate what we observe in the coefficient values of the main effects.

3.3 Multiple regression: higher-order terms

Given the statistically significant main effects terms in the previous section, we explored whether the inclusion of higher-order terms contributed significantly to predicting TNC. For example, including all possible interaction terms among the predictors resulted in a model with 95 terms (overall $R^2=0.739$) and was statistically significant, but explained only an additional 7% of variance compared to the additive model above (see top panel of Table 5) with only 7 terms (overall $R^2=0.667$). The estimated parameters for the higher-order terms are presented in Table 5.

When the two-way interaction terms were added to the main effects model, the overall model was significant, $F(21,11,310)=1334.27$, $p<0.0001$, $R^2=0.712$. In addition, the $\Delta\ R^2=0.045$ was statistically significant, $F(14,11,310)=127.70$, $p<0.0001$. Although a number of two-way interaction terms were statistically significant, we

Table 5 Multiple Regression Results Predicting Total Number of Contacts (TNC) from Room Size, Room Shape, OR Table Orientation, Circulating Nurse (CN) Workstation Location, Team Size, and Procedure Type

Regressor	*B*	*T*	*sr*
Main Effects: model $F(7,11,324)=3239.92^{***}$, $R^2=0.667$			
Size [m]	-13.13	-76.47***	-0.41
Shape [s]	-1.50	-8.73***	-0.05
ORT [h]	1.03	4.88***	0.03
ORT [v]	3.37	16.03***	0.09
CNW [w]	-7.00	-40.75***	-0.22
Team [7]	16.37	95.36***	0.52
Type [p]	13.00	75.70***	0.41
Two-way Interactions: model $F(21,11,310)=1334.27^{***}$, $R^2=0.712$			
Size [m] × ORT [h]	0.12	0.31	< 0.01
Size [m] × ORT [v]	0.18	0.46	< 0.01
Size [m] × CNW [w]	1.93	6.03***	0.03
Size [m] × Team [7]	-7.04	-22.04***	-0.11
Size [m] × Type [p]	-2.10	-6.59***	-0.03
ORT [h] × CNW [w]	-0.45	-1.14	-0.01
ORT [v] × CNW [w]	1.10	2.82**	0.01
ORT [h] × Team [7]	3.44	8.81***	0.04
ORT [v] × Team [7]	1.62	4.14***	0.02
ORT [h] × Type [p]	-2.34	-5.99***	-0.03
ORT [v] × Type [p]	4.73	12.10***	0.06
CNW [w] × Team [7]	-1.58	-4.93***	-0.02
CNW [w] × Type [p]	-2.70	-8.47***	-0.04
Team [7] × Type [p]	8.40	26.32***	0.13
Three-way Interactions: model $F(31,11,300)=933.99^{***}$, $R^2=0.719$			
Size [m] × ORT [h] × CNW [w]	0.50	0.65	< 0.01
Size [m] × ORT [v] × CNW [w]	-2.70	-3.49***	-0.02
Size [m] × ORT [h] × Type [p]	5.57	7.20***	0.04
Size [m] × ORT [v] × Type [p]	1.37	1.77	0.01
Size [m] × Team [7] × Type [p]	-2.21	-3.50***	-0.02
Size [m] × CNW [w] × Type [p]	-3.31	-5.24***	-0.03
ORT [h] × CNW [w] × Type [p]	9.01	11.66***	0.06
ORT [v] × CNW [w] × Type [p]	5.25	6.80***	0.03
ORT [h] × Team [7] × Type [p]	3.48	4.50***	0.02
ORT [v] × Team [7] × Type [p]	0.73	0.94	< 0.01

sr = semi-partial correlation. All regressors were dummy-variables. The level coded 1 appears in brackets. Conditions for Room Size (Size) were small/medium (m); for Room Shape (Shape), rectangular/square (s); for OR Table Orientation (ORT), angled/horizontal (h)/vertical (v); for CN Workstation Location (CNW), at the foot of the OR table/beside the wall (w); for Team Size (Team), 5/7; for Procedure Type (Type), Adult G-LAP/Peds OTO (p). $^{**}p<0.01$. $^{***}p<0.001$.

plotted the largest effects to better understand the nature of the two-way interaction. Figure 5 presents the interaction between team size and procedure type, as well as the interaction between team size and room size. The first plot (Fig. 5(a)) suggests that the increase in TNC from 5 to 7

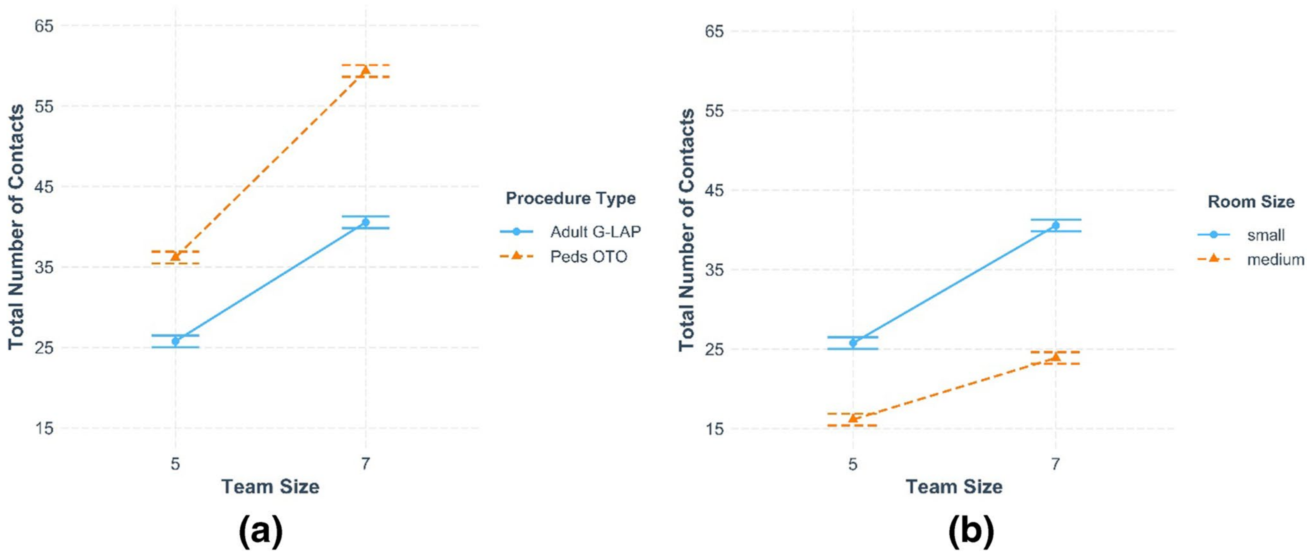

Fig. 5 Two-way Interaction between Team Size and (a) Procedure Type or (b) Room Size

team members was more pronounced for Peds OTO procedures than Adult G-LAP procedures. The second plot (Fig. 5(b)) indicates that the increase in TNC from 5 to 7 team members was exacerbated by a small room size.

Figure 6 presents the interaction between procedure type and OR table orientation, as well as the interaction between procedure type and CN workstation location. Although Adult G-LAP procedures tend to result in lower TNC than Peds OTO procedures, it deserves noting that the vertical OR table orientation resulted in the largest TNC for Peds OTO procedures while resulting in the smallest TNC for Adult G-LAP procedures. Moreover, while there may be no difference in TNC among the three different OR table orientations for Adult G-LAP procedures, it appears that a horizontal OR table orientation may be preferable for Peds OTO procedures. Based on the second plot (Fig. 6(b)), it should be evident that positioning the CN workstation location against the wall can minimize TNC.

When three-way interaction terms were added to the previous model, the overall model was significant, $F(31,11,300) = 933.99$, $p < 0.0001$, $R^2 = 0.719$. In addition, the $\Delta\ R^2 = 0.007$ was statistically significant, $F(10,11,310) = 27.57$, $p < 0.0001$. Although the magnitude of the effects of the three-way interactions appeared small, it is worth exploring, to better understand the complex ways that the predictors interacted. In Fig. 7, a set of three-way interactions is presented. Namely, we illustrate how TNC is affected by OR table orientation, procedure type, and each of the following: (a) CN workstation location, (b) team size, and (c) room size. Clearly, for Adult G-LAP procedures,

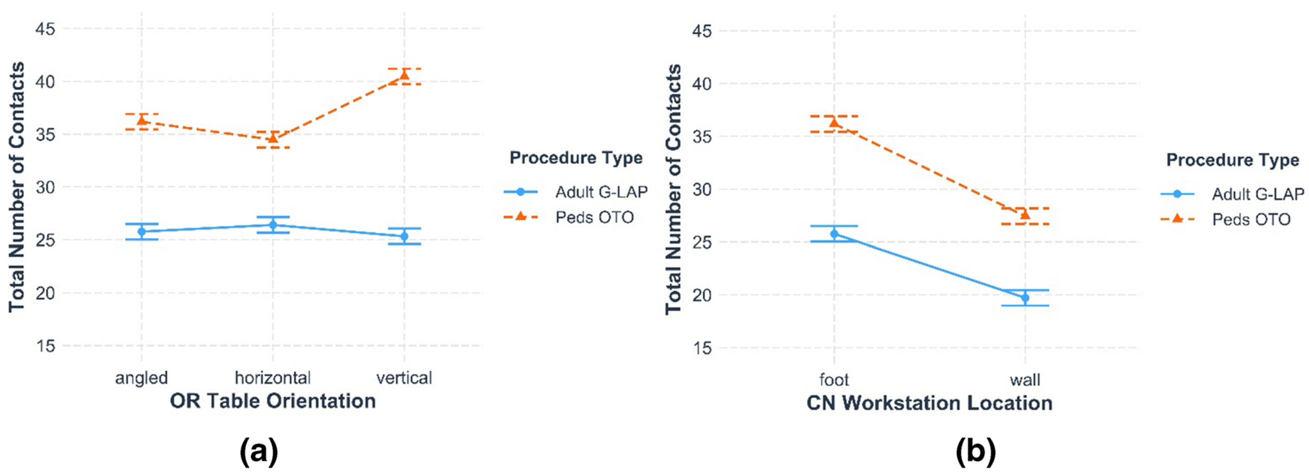

Fig. 6 Two-way Interaction between Procedure Type and (a) OR Table Orientation or (b) CN Workstation Location

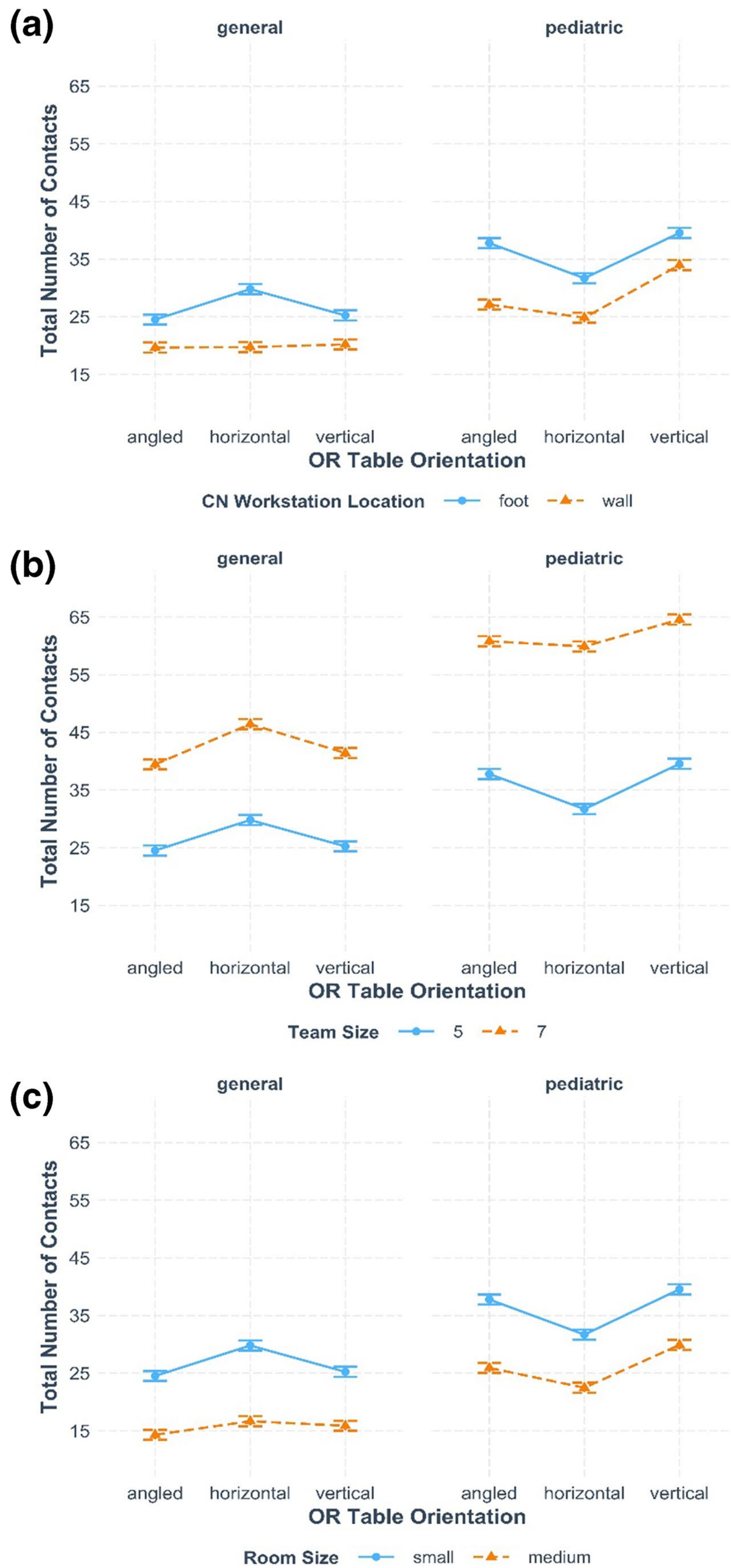

Fig. 7 Three-way Interaction between (1) OR Table Orientation, (2) Procedure Type, and (3) either CN (**a**) Workstation Location or (**b**) Team Size or (**c**) Room Size

it makes little difference on TNC how the OR table is oriented, when the CN workstation is located beside the wall (Fig. 7(a), left panel). However, for Adult G-LAP procedures, if the CN workstation is located at the foot of the OR table, then the OR table orientation should not be horizontal. This interaction is quite different for Peds OTO procedures such that a horizontal OR table orientation is preferable, especially if the CN workstation is located at the foot of the OR table. The three-way interactions in Fig. 7(b) and (c), accounting for either team size or room size, provide similar results to Fig. 7(a) in that the horizontal.

OR table orientation was preferred during Peds OTO cases. Similarly, the horizontal table orientation resulted in the highest TNC for Adult G-LAP cases, with a slight preference to the angled table orientation over vertical table orientation. Lastly, we again note that while there were significant differences in TNC based on table orientation, these differences were smaller than those observed when focusing on team size, room size, procedure type, or CN workstation location.

4 Discussion

This study examined how the OR's physical environment affects surgical team flow and safety during surgical procedures. The outcome variable used, TNC, is a pseudo risk measure. Although not all contacts result in bumps or trips, increased contacts will increase these risks. Prior research shows that a significant number of complications in today's ORs are related to congestion and room layout, and incidental contacts among surgical team members can affect patient and surgical team safety [9, 27, 56]. There is a need for an efficient OR procedural design that can reduce flow disruptions and infection risks. We find that disruptions during surgical procedures due to congestion and clutter can be meaningfully reduced with an OR layout that allows OR team members to move more freely without contact with others. Our findings highlight how TNC measures from simulation experiments can provide insight into how layout, occupancy, and key procedure-based inputs affect congestion and team member movement. We identify factors contributing to the number of contacts during surgery and identify both the most influential factors and the more subtle factors that affect surgical procedures in an OR.

The first key take-away from the main effects is that OR design modifications can effectively reduce TNC, most notably through OR size and CN workstation location. However, OR size is difficult to adjust post-construction, and it is desirable to bring the CN closer to the surgical table to provide greater visibility and improve communication and coordination among the surgical team. Equally important is the finding that the surgical team size has the greatest effect on TNC, despite this not being an OR design factor. Taaffe et al. [37] considered the team size factor, but the simultaneous consideration of all the factors in this study indicates its relative importance. The preeminence of team size has implications for managing the OR space in terms of how leaders in anesthesia and surgery provide staffing recommendations to limit the overcrowding of the OR. This will also impact work design to organize the space for tasks being performed. Another important consideration is that even in situations where a procedure can be completed with a smaller team than originally planned, this could lead to an increased amount of distance traveled by each team member, and the result on TDT by all team members is not clear. Furthermore, distance traveled and number of people in the OR should be considered in the light of prior research, which suggests that team member movement is an important contributor to microbial load volumes, possibly more important than number of people in the OR [21].

From an OR design perspective, it is worth noting that OR size is the most important factor, followed by location of the CN workstation, and that other considered factors (table orientation and room shape) only have a limited effect. This confirms the previous finding in Taaffe et al. [37] that room size plays an important role in the outcome performance measure of TNC, and informs us on the dominant role of room size relative to other OR design factors. Also, whether there was one or two OR doors did not make a difference on TNC. OR designers can thus focus effort on room size and CN workstation location, and account for other safety and structural organization considerations when deciding on the number of OR doors. While a workstation at the foot of the surgical table was associated with more TNC, it is ideal from the perspective of providing situational awareness to the CN, since it enables a clear line of sight to the surgical table, whereas locating the workstation besides the wall forces the CN to have their back turn to the surgical table. Thus, OR designers need to consider solutions that will improve situational awareness and communication for the CN, such as monitors or mirrors, while minimizing contacts. This corroborates a prior finding on CN workstation placement [37]. Besides TNC, room size has implications for distance traveled and team member movement, and consideration for the CN workstation is supported by the fact the CN has a relatively high foot traffic role.

From a change management perspective, one of the first steps is to locate the nature of the change on the change spectrum, in terms of complexity, magnitude and impact [57]. A change in OR size is an infrastructural element that can only be considered for new OR construction or a major renovation, and this is a complex and transformational change, whereas both the surgical team size and the CN workstation location, especially if a mobile workstation is adopted, are structural elements that can be adapted over time in existing ORs, and represent incremental and adaptive changes. As such, managing these two variables that represent a simple change is the most effective way to manage TNC. To the extent that it is possible, managing the number of additional team members present should be prioritized, followed by positioning the CN workstation that both supports communication and coordination as well as reduced contacts. We recognize that locating the CN at the foot of the bed provides a better line-of-sight to the patient and the team, which supports the CN's role to monitor the procedure and communicate with the OR surgical team.

Type of surgery also plays an important role in TNC. This is evident when comparing Peds OTOs and Adult G-LAPs, and this factor that was not considered in prior studies. Certain procedures require more movement of team members compared to other procedures. In these procedures, individuals are required to move about the OR more to obtain various supplies, adjust equipment, and provide support during the procedure. This was illustrated by the consistent result that the Peds OTO procedures resulted in higher total contacts than the Adult G-LAP procedures. The team observed more frequent movements, and varied movement patterns, for the Peds OTO procedures. One limitation is that these procedures were often performed in a particular OR, possibly influencing the historical data for zone-to-zone movements and dwell times in each zone. Nevertheless, since we find that Peds OTO cases generate substantially more TNC, we can take it into account, and to the extent that there are different sizes of rooms in the surgical suite, we should recommend assigning Peds OTO cases (and other high foot traffic cases) to larger ORs.

From the two-way interactions, we can make the following conclusions. In light of Fig. 5(a), the observation that the increase in TNC from 5 to 7 team members was more pronounced for Peds OTO procedures, combined with the fact that Pediatric procedures resulted in greater TNC than Adult G-LAP procedures, suggests that it is all the more relevant to avoid having additional team members present in the OR for procedure types that already have a relatively high number of TNC. Figure 5(b) confirms the intuition that the smaller the OR, the more impact that surgical team size will have, and adding team members should be kept to a minimum, to the extent possible. In addition to the important result that a horizontal table orientation is preferable for Peds OTO, Fig. 6(a) suggests that procedures with higher TNC are more sensitive to table orientation. Also, while we did not find statistical difference in table orientation for Adult G-LAP procedures, the mix of Peds OTO and Adult G-LAP procedures being performed may be considered to choose which orientation minimizes TNC at the aggregate level, to avoid having to change table orientation between procedure types.

The three-way interactions give us more insights regarding table orientation, which is also considered in Fig. 6(a). From Fig. 6(a), we conclude that horizontal reduces TNC, particularly for Peds OTO procedures, and CN workstation against the wall further reduces TNC. Figure 7(a) confirms this conclusion, but it also suggests that if the CN workstation is at the foot of the OR table, then there is a stark difference regarding OR table orientation: horizontal is significantly better than the other two orientations for Peds OTO procedures (high foot traffic type of procedures), whereas horizontal is significantly worse than the other two orientations for Adult G-LAP procedures. We observe a similar contrast between Peds OTO and Adult G-LAP procedures for the other two variables (team size and room size): regardless of surgical team size, and regardless of room size, the opposing results regarding table orientation hold, in that a horizontal table orientation minimizes TNC for Peds OTO but results in the most TNC for Adult G-LAP. Note that there is often a default table orientation by procedure type. Even though the surgical team deemed feasible the tested scenarios, any recommendations would need to support what can ultimately be implemented by the surgical team.

5 Conclusions

A combination of discrete event and agent-based simulation was employed to track movements and locations within the OR for individual surgical team members, which enabled us to capture an interaction statistic not previously reported in the literature – *total number of contacts* (TNC). The model transformation from *playback* to *probabilistic* created the opportunity for this modeling approach to be applied in a much broader sense at our healthcare institution partner. Based on all of the factors presented in this research, the goal was to determine significance of individual factors as well as the level of contribution of each factor towards the contacts observed during the course of a procedure.

While room size, procedure type, and surgical team size contribute significantly (both statistically and in magnitude) to total contacts, other design-related factors such as CN workstation location and OR table orientation also played significant but more minor roles. Such a level of discrimination in factor analysis was previously not available in the design research community. While the model can produce useful results, we note a few limitations. In this research, we present findings on the number of contacts as the model's sole performance measure of interest. As was briefly mentioned, we also collected data on total distance traveled and the number of surgical team transitions into the surgical zone. These measures would also be worthy of further analysis. In addition, there are many process-related factors that would be worthy of study, such as patient flow to increase on-time starts, task handoffs and team coordination and cooperation, and task assignments. Combining these metrics with layout and design options would be logical candidate areas for further research. Finally, our measure of contacts (TNC) can be further refined using empirical designs to gather data to be able to distinguish between contacts to hand off supplies and materials and those contacts more likely to lead to bumps or trips.

Appendix 1: Table 6

Table 6 A snapshot of a spreadsheet log for an actual surgery (S01-ART5-Preoperative)

Time (hh:mm:ss)	Duration (seconds)	Subject	Location
...	...	...	...
00:16:32	5.11962	RN, circulating	Circulating Nurse Workstation
00:16:38	1.19991	RN, circulating	Door to Sterile Zone
00:16:38	1.75987	Scrub Nurse	Transitional Zone
00:16:39	48.6763	RN, circulating	Out of Room
00:16:45	3.11977	Scrub Nurse	Transitional Zone
00:17:28	0.279979	RN, circulating	Door to Sterile Zone
00:17:29	2.19983	RN, circulating	Circulating Nurse Workstation
00:17:32	2.51981	RN, circulating	Transitional Zone
00:17:36	6.55951	RN, circulating	Surgical Table 1
00:17:42	9.47929	RN, circulating	Transitional Zone
00:17:52	11.1192	RN, circulating	Surgical Table 1
00:18:04	3.43974	RN, circulating	Transitional Zone
00:18:08	8.59936	RN, circulating	Circulating Nurse Workstation
00:18:10	1.87986	Scrub Nurse	Transitional Zone
00:18:12	1.95985	Anesthesiologist 1	Door to Corridor
00:18:14	47.3165	Anesthesiologist 1	Transitional Zone
00:18:18	0.359973	RN, circulating	Door to Sterile Zone
...	...	...	...

Appendix 2: Zone Visits Selection Procedure

Step 1 – Remove zone visits with short durations:
Starting with the full dataset of zone visits, discard all entries where the zone visit is less than 15 seconds, as this is a pass-through visit only. This will avoid considering such visits as destinations in the final path, since there was no sustained activity observed there in the video recordings.

Step 2 – Remove transient zone visits:
Discard all remaining transitional and doorway zone visits from the travel path of a subject since these cannot be conceptually considered destination zones. The associated duration of these zone visits is assigned to the nearest functional zone (distances are measured between the central points of two zones). The video recordings of the 23 procedures indicate that the occurrence of activities in these zones is low, and a reassignment of activity greater than 15 seconds occurred less than 6% of the time. (This reduced the zone count from 19 to 13 zones, each contained in at least one group in the next step.)

Step 3a – Aggregate zones into zone groups:
Based on proximity and functionality, identify zone groups where an opportunity exists to select a single zone to represent activity. These zone groupings do not need to be mutually exclusive. The zone groups identified for the OR in Figure 1 are:

Group 1.CN Workstation, Support Zone 1, Support Zone 5
Group 2.Support Zone 2, Supply Zone 1, Support Zone 3
Group 3.Supply Zone 2, Surgeon Workstation, Anesthesia Workstation
Group 4.Surgical Table 1, Foot of Table
Group 5.Surgical Table 2, Foot of Table, Anesthesia Workstation
Group 6.Supply Zone 2, Support Zone 3, Anesthesia Workstation

Step 3b – Aggregate zone visits within zone groups:
For each subset of consecutive zone visits within a zone group, identify and denote the zone visit with the longest duration as the destination zone. All durations of the other zone visits of the subset are assigned to the destination zone, and the zone visits are removed from the dataset.

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Availability of data and material Data used within this research is protected under an IRB protocol approved by the Medical University of South Carolina.

Code availability Simulation models were developed in AnyLogic and are available upon request.

Declarations

Ethics Approval This research received IRB approval from the Medical University of South Carolina.

Conflicts of interest/Competing interests The authors have no relevant financial or non-financial interests to disclose.
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