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SIMULATION-BASED DESIGN AND TRAFFIC FLOW IMPROVEMENTS IN THE OPERATING ROOM

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ABSTRACT

A simulation model was created to model the traffic flow in the operating room. A key research challenge in operating room design is to create the most efficient layout that supports staff and patient requirements on the day of surgery. The simulation allows comparison of base model designs to future designs using several performance measures. To develop the model, we videotaped multiple surgeries in a set of operating rooms and then coded all activities by location, agent and purpose. Our current analysis compares layouts based on total distance walked by agents, as well as the number of contacts, measured as the number of times agents must change their path to accommodate some other agent or physical constraint in the room. We demonstrate the value and capability of the model by improving traffic flow in the operating room as a result of rotating the bed orientation.

1 INTRODUCTION

The operating room (OR) is a sensitive and high-risk environment. It is estimated that major complications after surgery occur in 3-22% of inpatient surgeries in industrialized countries, where around half of these adverse events were determined to be preventable (WHO 2009). It is no wonder that both surgeons and nurses have expressed frustration with the way the design of the OR affects work flow negatively.

Layout is an important factor when designing an OR since it can highly affect the flow of staff and materials during surgery (Palmer et al. 2013). However, little is known about the design of the OR and how it can improve performance outcomes (Joseph et al. 2017). More than half of the movements during robot-assisted surgeries can be eliminated with an improved OR layout (Ahmad et al. 2016). Although there is no clear study about the nature of surgical flow disruptions (SFD) in the OR (Wiegmann et al. 2007), layout-related features such as improper placement of equipment and poor utilization of space and furniture result in disruptions (Palmer et al. 2013). Another study found that ORs with an innovative layout experience shorter case times and higher throughput (Sandberg et al. 2005). It has been shown that poor layout of the OR have the potential to increases SFDs and may also increase surgical site infections (SSIs) in the OR (Wahr et al. 2013).

Each layout contains a number of functional zones, where each zone has been defined based on the key activities that take place in that particular zone. The literature in OR planning and design mainly considers three zones: the anesthesia zone, the circulating zone, and the sterile zone (Joseph et al. 2017). However, to better address activities in the OR, we consider 17-20 zones depending on surgery type. According to these zones and the placement of materials, an ideal layout might be attained by increasing the OR size to accommodate more equipment and larger teams (Schneider 2012) but an analytical approach is required to get a sense of the performance of the layout.

Among operations research techniques, simulation may be the only alternative to provide solutions to complex problems. For example, it is not possible to obtain closed form solutions for complex queuing systems in OR, but they might be readily obtained with simulation methods. The idea is to model the behaviour of individual elements in the system.

We develop a simulation model to study the flow of Patient, Equipment, Materials, Staff and Information (PEMSI) during surgery. The model not only tracks location and PEMSI activities for human and object agents, but also accounts for contact avoidance as the agents move within the OR. The research question is how to create the most efficient layout that supports staff and patient requirements on the day of surgery. The goal of this research is to develop a decision tool that can inform and validate future operating room designs. The model allows us to statistically compare base model OR designs to future designs using several performance measures.

The remainder of this paper is structured as follows: first, we present the method we used to obtain data as input for the simulation model. Then we will describe how the model is developed. In the next section we will have some preliminary results by comparing three different layouts using the simulation model. Finally, we will conclude by addressing limitations of the model and how the model can be further developed to give more reliable results.

2 METHOD

We observed and collected data on 35 surgeries at the Medical University of South Carolina (MUSC). Next, we coded videos of surgeries using *Noldus Observer XT*. Video coding is the process of observing and analyzing video files in an observational research. In the OR, video coding helps us to code subjects, log events, and create valuable qualitative and quantitative results. These videos were recorded in four ORs for the person's role, location, and PEMSI activity using a map of designated zones for each OR. Each OR had its own map with zones designated based on which type of activity was performed in that zone or who visited it most often. This coding was exported to an Excel file and used as an input for the simulation model. The main objective of the coding was to develop measures to analyze the risks to both the patient and staff safety that exist within the PEMSI flows.

Subjects can be either human or object agents. Human agents are surgeons, doctors, circulating or scrub nurses, anesthesiologists, cleanup technicians, or other staff that occasionally enter the OR. Also object agents are carts, trash cans, or any other types of objects that are being used in the OR. Obviously, the list and number of subjects might change from surgery to surgery. In this study, subjects were coded by location and activity during surgery. If the agent is performing more than one activity at a time, we gave the priority to the most important activity occurring.

Locations (zones) were defined according to the type of function conducted in them. Also, areas within the OR that share the same function (i.e. left side and right side of the surgical table) have been differentiated in coding, since tracking movement among these locations (flow) was important. Each surgery is carried out in an OR with seven types of zones based on where staff are typically stationed and the location of supplies and equipment. These zones are:

- head/foot of the surgical table and surgical table zones 1-2
- anesthesia work station zone,
- circulating nurse work station zone,
- support zones 1-6,
- supply zones 1-2,
- transitional zones 1-3,
- door 1-2 to corridor and door to sterile core.

The ”surgical table zones 1-2” denote the sides of the operating table. The ”supply zones 1-2” consist of cabinets containing supplies. The ”support zones 1-6” contain movable items, usually furniture and equipment being stored or trash cans. The ”transitional zones 1-3” are the circulation areas and connect most of the zones together. The rest of the zones were clearly named by the type of function they have. The reason of differentiating more areas for each type of zone is to define locations more specific and meaningful in terms of the movement of subjects in the OR.

According to Figure 1, we use the OR map (zone map) to code agents by their location. Finally, we use the exported data (Excel file) and the OR map as input for the simulation model. The number of zones in the OR map is almost identical for each OR; however, each OR might have less or more zones depending on the surgery taking place in that OR. In fact, each OR can have unique locations and some zones may go unused.

Figure 1: The process of preparing materials for the simulation model.

To date, there are no clear measures of how these PEMSI workflows interact within the OR. We first develop measures of the performance of the PEMSI workflows in the OR and measures of the coordination between these workflows (i.e., their interactions). Then we use the PEMSI workflow performance and coordination measures to identify control mechanisms, which maximize PEMSI workflow coordination and minimize workflow interruptions and disruptions and risks to patient and staff safety. We are interested to identify how various physical constraints imposed by the OR design affect the PEMSI workflows in the OR. Revised layouts will be tested through the simulation model. Currently, we have defined the following two performance measures:

$$\textit{total distance traveled} = \sum_{i \in \{\text{moving agents}\}} \text{distance traveled by agent } i$$

$$\textit{total number of contacts} = \frac{\sum_{i \in \{\text{moving agents}\}} \text{number of contacts experienced by agent } i}{2}$$

total distance traveled measures the total distance traveled by all agents in the OR. To compute this performance measure, we use the log files of the software. *AnyLogic* automatically writes all essential statistics of the model in the log files. The model execution log contains information about agents, message arrivals, their parameters, movement, event occurrences, resource usage, etc. However, a function was created to go through the model execution log and display the total distance walked by all agents at each point of surgery time.

total number of contacts is defined as the number of contacts experienced by each agent. To offset double counts, we divide the summation by two to get the true number of contacts in the system. When two agents pass by each other, if the distance between them is less than 0.3 meter (approximate diameter of a person), then we count it as a contact. To do this, we create a matrix of distances at each point of time and check whether the distance between any two agents is below the threshold level. Note that this threshold might be subjective; however, we tested the model for different threshold levels and observed realistic animation movement at this setting.

It has been shown that environmental factors such as congestion and clutter in the OR negatively affect surgical performance (Ofek et al. 2006, Fanning 2005). In this situation, movements by staff and surgical team often gets obstructed and this in turn increases human errors (Railsback et al. 2006). Although every contact is not an indicative of disruption, the performance measure ”total number of contacts” is a reasonable indicator of congestion.

3 THE SIMULATION MODEL

In this paper, the traffic flow in the OR is modeled mainly using agent-based simulation. An agent-based simulation is a type of computational modeling methodology for simulating the behaviour of agents whose attributes are accessible during the simulation (Railsback et al. 2006). The model actually reads the data and moves agents accordingly and does not have any sources of randomness. The real-time playback has two main advantages over other randomized simulation models. First, it realistically visualizes the OR in which agents are moving. Second, it exactly follows the inter-dependencies of tasks, whereas other randomized simulation models are not able to do this due to the complexity of activities in the OR.

The simulation model was constructed using *AnyLogic*. This software has a higher-level library, called *Pedestrian Library*, for simulating pedestrian flows in a physical environment. It allows creating models of buildings and structures such as an OR. This Library allows the creation of a flexible model in order to collect basic and advanced statistics, and effectively visualize the process. The library consists of two main parts: environment and behavior. Environment includes different areas, walls, services, queues, and other resources. Behaviour is defined using some physical rules in the defined environment. The advantage of AnyLogic’s pedestrian library is that it uses a social forces model so that agents’ paths do not overlap, they cannot walk through walls, and they can go to attractors in the designated areas.

The model has the same layout as the operating room where the surgery was performed. Each zone is represented by an area in the OR map. According to Figure 2, the model reads the coded surgeries from the Excel file and performs a surgery playback by creating an agent to represent each person who was in the surgery video. Some performance measures were set for the simulations output to be able to compare OR layouts. The log function in AnyLogic automatically records the total distance walked by each agent, and the number of times agents get within a certain threshold of each other, along with how many people are in each zone at each time. Another functionality of the simulation is that it can create a traffic density map to see which areas are occupied most in addition to various graphs and charts that show different parameters during surgery.

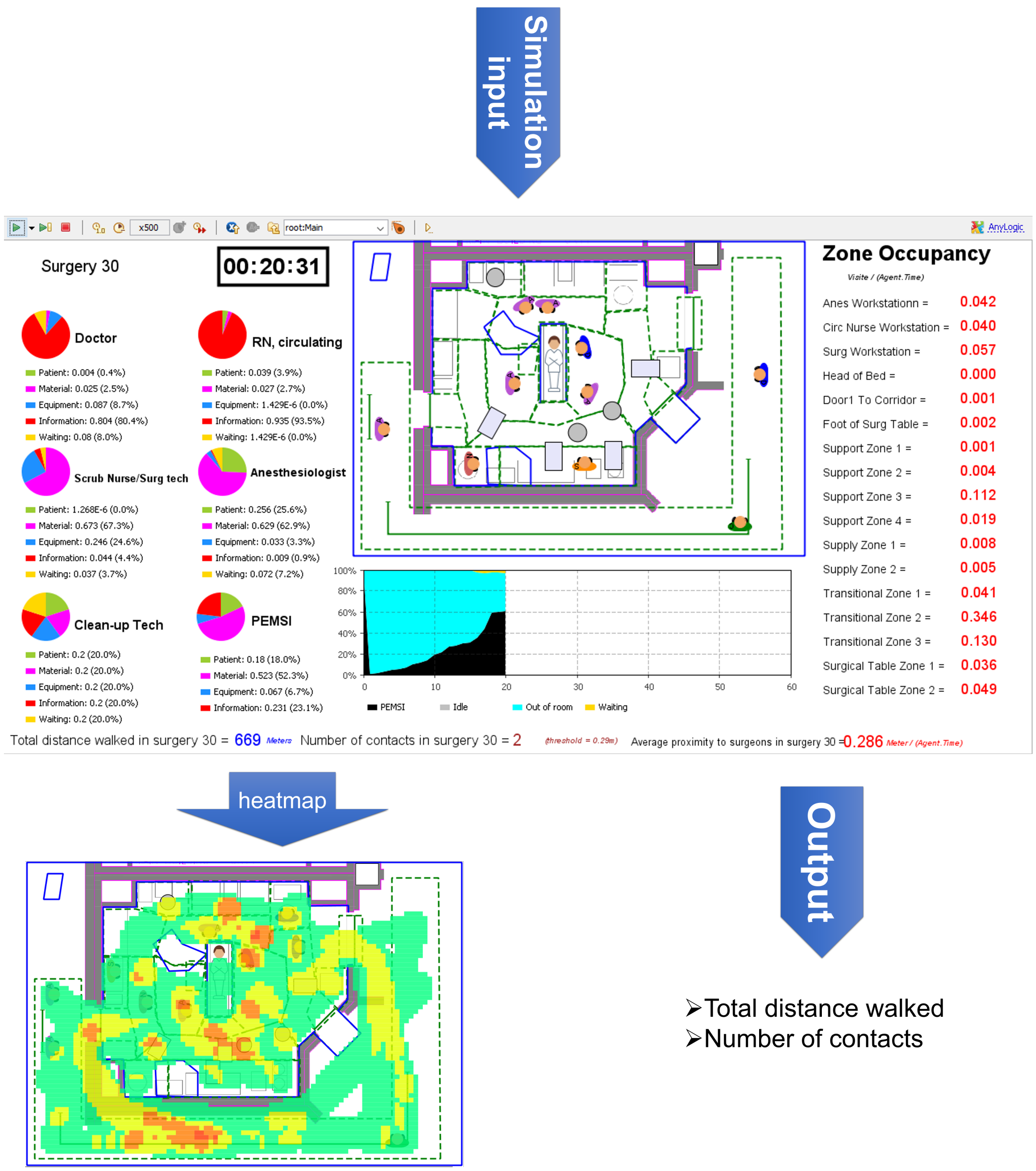

Figure 2: The simulation model reads data, and then moves agents accordingly.

4 PRELIMINARY RESULTS

Two layout changes were designed in order to use the simulation to statistically compare layouts. As Figure 3 shows, these changes included rotating the bed 90 degrees (L2), and moving the surgical boom to the other side of the bed (L3). The figures below depict these changes.

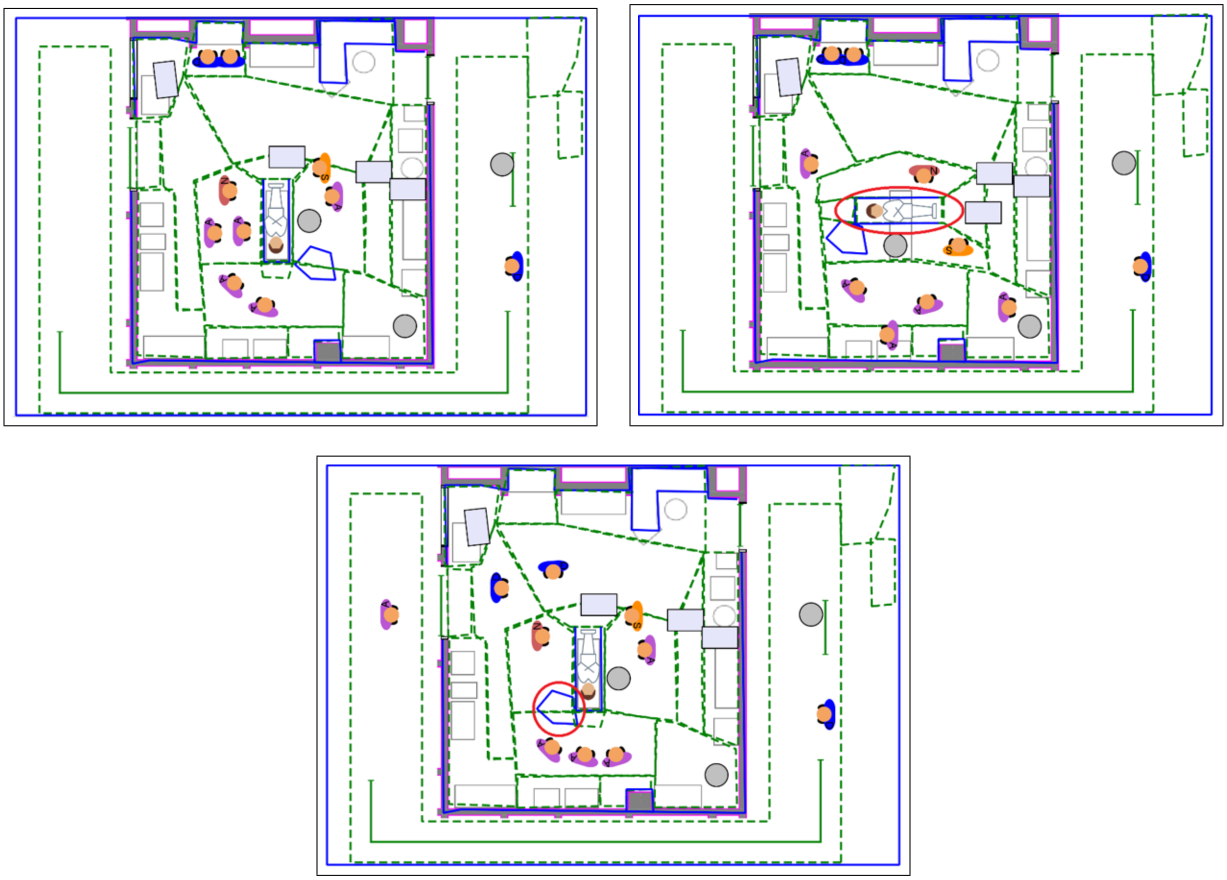

Figure 3: Three layouts to be compared: top-left: base layout (L1), top-right: rotating the bed 90 degrees (L2), bottom: changing the position of surgery boom (L3).

In order to test the model, in addition to observing the simulation animation, the performance measures were tested on these three layouts. In addition to observing the simulation animation, the performance measures were tested on the three layouts presented by Figure 3. To do so, the model was run for 18 surgeries carried out in the same OR. The shortest surgery and longest procedures required 84 minutes and 238 minutes, respectively, with an average length of 143 minutes. Note that this sample set of 18 runs are playbacks of 18 actual surgeries.

As expected, both performance measures *total distance traveled* and *total number of contacts* significantly increased with surgery time, according to Figure 4. This is however trivial since a surgery gets longer, it is expected to have more distance walked and more contacts. As we see, *total number of contacts* has a significant quadratic trend as well. This indicates that as surgery gets longer, the rate of experiencing a contact increases. One explanation might be agents get tired in a longer surgery and thus the possibility of having a contact increases. In other words, we expect to see more contacts as we go towards the end of the surgery.

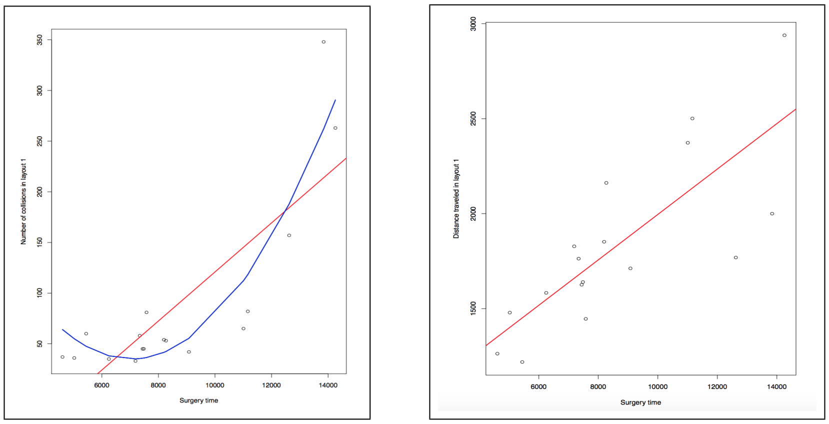

Figure 4: *total distance traveled* and *total number of contacts* significantly increased with surgery time.

Visually speaking, L1 and L3 are different from L2; however, there is no significant difference between L1 and L3 as we just moved the surgery boom in L3 compared to L1. Therefore, L1 and L3 should not be different in terms of *total distance traveled*. But, L2 is different compared to others since the rotated bed directly affects the placement of agents in the OR. In fact, by rotating the bed we rotate the corresponding zones around the bed as well. To see this, the layouts were also compared based on the same sample set. According to Figure 5, L1, L2, and L3 seem to be different in terms of *total distance traveled*.

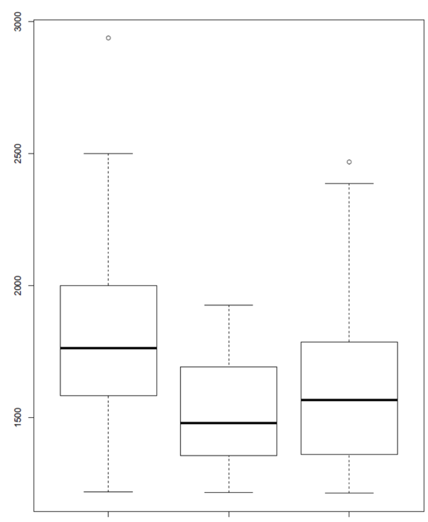

Figure 5: *total distance traveled* in three layouts.

To better investigate our hypothesis, the following two-sided `t-test` was implemented based on the same sample set, where L2 was found to be significantly better than L1 when comparing *total distance traveled* (`p-value` < 0.05), but there was no significant difference between L1 and L3.

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Welch Two Sample t-test data:

Distance traveled in L1 and Distance traveled in L2
t = 2.5989, df = 24.187, p-value = 0.01569
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval: 66.05442 574.65146
```

```
sample estimates: mean of x mean of y 1832.647 1512.294
```

In L1, the bed is perpendicular to the imaginary line between the OR doors. This affects the transition between two doors, because agents may have to change their path in order to go out of the OR. Therefore, we expect to have more distance walked in L1, whereas in L2 we expect to have better flows based on doorways as we have more traffic between the sides of the bed and the doorways.

We conducted the same test based on *total number of contacts*, however, the result was not significant. This is because theses changes (L2 and L3) do not affect the congestion of the OR and thus we do not expect to see a significant difference between layouts in terms of *total number of contacts*.

When used in combination with the ability to statistically test layouts, this simulation could lead to better operating room design and potentially fewer SFDs.

5 CONCLUSIONS

The operating room (OR) represents the most important and expensive hospital resource since a high percentage of the hospital admissions is due to surgical needs of patients. ORs must operate in a way that allows them to provide effective medical services to patient while utilizing the space available in the most efficient way at the lowest possible cost. However, complexity of OR makes it difficult for hospital administration to address these factors when designing the OR. Thus use of simulation models, and quantitative techniques plays a crucial role.

Among operations research techniques, simulation may be the only alternative to provide solutions to complex problems. In this paper, the traffic flow in OR is modeled using the agent-based simulation. The main objective of the model is to understand the impact of applying different layouts in an OR based on some well-defined performance measures. The simulation model is able to collect data and can be used as a managerial decision tool. To show the capability of the model, we improved traffic flow in OR by rotating the bed orientation.

The main limitation of the simulation model is that it performs a surgery playback and locations, activities and number of agents in the OR are all predefined. The next step would be further developing the model to automatically create new surgeries with flexible number of agents in order to generate realistic variability. Additionally, new performance measures are required to shed light on different aspects of the OR.

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