Identifying Influential Factors of Patient Length of Stay in a Surgery Center: a Simulation Modelling Approach

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***Abstract*— Simulation is increasingly being used in the healthcare sector. The dynamic management of resources and patient levels requires a computational and evaluative approach for staff to examine their impacts on the performance of the system. In this paper, a sensitivity analysis via Monte Carlo Simulation is developed to identify influential factors of patient length of stay in a surgery center. The operation of a selected surgery center is re-created by a Discrete-Event Simulation model as a basis for the sensitivity analysis. We compute elasticity measurements for comparing relative influences of identified pertinent on the system output. Results suggest that the patient length of stay is more sensitive to capacity extractions than additions. The capacity of surgery slots is a rewarding option on increased patient level. We suggest healthcare planners are aware of dedicated surgery types and hospital fixtures due to effects on patient length of stay.**

Keywords-discrete-event simulation; monte-carlo simulation; logistics; healthcare

I. Introduction

Performances of surgery centers are determined by complex interactions of agents such as patients, health care staff and infrastructure. According to the Healthcare Financial Management Association, surgery centers are described as the most resource-intensive as well as profitable hospital departments [1], where measurements to gain new efficiencies and reduce costs are vital. To address hospital logistical problems, recent growing utilization of simulation techniques in the healthcare sector encourages its wider adoption by exploring resource options and system control strategies. The operational environment of surgery centers, configured by parameters of different resources, can be defined by healthcare planners and decision makers. In practice, the logistical issues of surgery centers are examined by means of optimizations [2], event-driven simulations or a hybrid model integrating the above techniques [3]. Optimization models could be suitable for engineering systems of low uncertainties. The health system is however a complex and multi-actor system. Simulation models could help project knowledge for networks of high uncertainties. The impacts of configurations on system outputs of surgery centers, important section of the hospital, could be obtained by calculating average length of stay or surgery throughputs.

Routine surgery center simulation models are primary decision-support systems comparing metrics of scenarios with pre-defined values of parameters. However, it is worthwhile to note that this endeavor has a restricted user's capability to understand how the simulated system changes in the entire feasible area, the impacts of capacity uncertainty and demand profiles. Even though simulation models are used in the healthcare-related topics, previous researches on the performance of surgery centers failed to consider variation of resource parameters via sensitivity analyses. Very few studies extended departmental simulation models to a sensitivity analysis, which could hinder a holistic consideration of potential managerial solutions on logistical issues in surgery center operations.

In order to fill this gap, this work presents a simulation framework combining Discrete-Event Simulation (DES) and Monte Carlo Simulation (MCS) for surgery center operations. It is expected that this method will re-create the flow of patient entities and solve the inconvenient endeavor without the ability to discover the most influential pertinent in a numerical way. This complies the positioning of MCS as the major simulation technique [4], pointed out by Mustafee and Taylor in their work with a retrospect of healthcare simulation. Different staffing configurations and demand scenarios are identified as the influencing factors for patient length of stay, together with governing rules and reference to the infrastructure layout. Elasticity measurements are also computed to uncover if additional resources are rewarding towards patient length of stay under increased demand. The method presented in this paper could be generalized to similar surgery centers that are dedicated to specific surgery types. The main contribution of this work is two-fold: 1) it provides a relatively novel method to explore managerial decisions and deal with resource constraints; 2) it aggregates computational results based on a large amount of simulations into the feasible area of the parameter.

The remainder of this article is arranged as follows: a literature review on MCS and sensitivity analysis in healthcare in general and in surgery-related topics in particular is performed in Section 2. Following this, Section 3 presents its application into a real surgery center of a hospital in Jiangsu, China. A simulated environment is constructed for measuring the impact of the managerial decisions on the performance of the system, which is in the form of patient length of stay in this study. A discussion and conclusion on recommendations for continued researches is presented at the end of the paper.

II. LITERATURE REVIEW

The construction of MCS models enables visualization and analysis purposes within various sectors, such as transportation, logistics, energy and healthcare. Banomyong and Sopadang provided a conceptual framework for emergency response logistics in which the MCS presented a range of possible results [5]. MCS has also been applied in healthcare economies and societal cost-benefit evaluations. Barton et al. stated that MCS can achieve the same effect of increasing states of systems to overcome homogeneous assumptions in Markov models [6]. Huang et al. framed a MCS model by simultaneous progression of diseases [7].

Besides above achievements, however, very few previous simulation applications were reported to address logistical related issues in surgery center operation. Logistical related issues in hospital departments revolve around scheduling, patient flow management and staffing configurations. A holistic query of all necessary keywords was used to search in title/abstract/keywords in the Web of Science Core Collection database from the year 1996 until present. Following this, collected publications were obtained after eliminating abstracts book reviews and papers without full access. The data collection was further defined by reading through the main texts and led to 14 reviled surgery-related studies performed either through MCS for various purposes or by a sensitivity analysis by deterministic approaches. To authors' knowledge, these papers have not addressed above mentioned logistical related issues. One previous study of surgery quality and patient output suggested that MCS was promising method for analyzing human factors [8]. Luangkesorn and Eren estimated the surgery duration by combining expert inputs and historical data in a Markov Chain Monte Carlo model [9]. Lymperopoulou et al. used MCS for improved treatment planning for the post-operative state [10]. Huberts et al. studied interval control between surgery and postoperative radiotherapy [11]. Computer-aided clinical practice enhanced by MCS or sensitivity analysis is the main focus in Cerveri et al.'s works [12].

In addition, several feasibility studies have compared MCS with other alternatives. Radioactive seed localization (RSL) was found to reduce health care costs for patients and transferred into increased facility margin [13]. Different beta minus detection strategies were compared by Gigliotti et al. with an emphasize on spatial resolution of medical images [14]. Instead of clinical practices, Stone et al. examined the implementation costs of an Enhanced Recovery after Surgery (ERAS) program with inputs of patient length of stay in the hospital and recommended investments into the ERAS to US hospitals [15].

With the exception of Huberts, previous studies did not consider system-wide performance improvement through logistical activities but rather accounted for variations in clinical practices, human factors or individual health models. There were several limitations in simulation models: 1) none of existing simulation models fully investigates the uncertainty of logistical parameters and its effect on the operational level, leading to trade-offs identified based on a limited set of alternatives; 2) the information gained from studies of MCS or sensitivity analysis rarely consider patient length of stay in the center and potential improvements from managerial controls. Hence, the MCS method can complement this and allows for the evaluation of a wider range of design scenarios and strengthen the managerial insights by establishing connection between the health care planning phase and the operational variations. 3) very scarce examples considered staff workflows in researches on surgical center operations.

This paper utilized MCS to perform the sensitivity analysis for decision supports of managerial controls in the surgery center. Based on the positive results by [16] and a process simulation model of the same hospital [17], this study employs the same method, DES, to re-create flows of entities in a selected surgery center with real data of staffing boundaries, surgery types and movement rules for different participants. On top of this DES model, MCS is conducted by assigning a normal distribution to parameter values. A combined simulation modelling and analysis approach provides the following contributions: visualization of entity flows, convenient interventions to parameter settings, and prediction and comparison of outputs in a numerical manner.

III. THE SIMULATION MODEL

The model proposed in this paper is a hybrid-simulation model of DES and MCS, developed to form the operational logistics. The operational logistics is detailed simulated using DES, whereas the MCS explores system outputs in response of parameter variations. AnyLogic, a dynamic simulation tool, is used for various recourse-related choices and the sensitivity analysis. The surgery types, operational logistics and staffing configurations are modelled in reference to the real physical settings of the department. The layout of the surgery center includes location-to-location information of paths, rooms and facilities. Staffing configurations and primary operation types are allowed to have independent options with the current default values.

The simulation model considers arrival schedules and add-ons, thus enabling the mixed nature of different urgencies, which is an important aspect in the real operation of a surgical center. Patients go through the care pathway and coerce resource sizes so that patient might have excessive waiting times for available rooms, physicians, nurses, beds, or a combination of them. Care provision is event-driven and consists of patient-and material-centric logistics. These two aspects are elaborated in the next sections. Such a simulation model allows the visualization of concrete interactions between the supply-side factors, such as appointment, staff decision making and material supplies, with delays and waiting times at a cross-units level. Since the surgery center consumes approximately 40% of hospital expenditure, decisions upon adding more capacity or altering current control policies need to be wise. This question is to be answered by the sensitivity analysis quantifying the effects of existing resources. Based on this simulation model, a sensitivity analysis accompanied by MCS is conducted to

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investigate the relative uncertainty of chosen parameters and their effects on the outcomes. Interventions are suggested for resources of which the parameters present higher degrees of responses.

A. *Operational Logistics*

Located in the middle of the 5th floor, this surgery center receives requests from upstream diagnoses and emergency drop-ins. As a main hospital in the urban area, the surgery center is dedicated to elective patient types. With a capacity of 8 surgery slots, 14 dedicated beds, 8 surgery physicians and 16 nurses, the surgery center completes 10 missions on the daily basis. The high workload of surgery teams is one of the major problems in the Chinese healthcare sector. Although the center predominately serves elective patients, some dedicated beds and a separate preparation room closer to the entrance of the hospital are provided for non-elective requests. As long as the patient is at the front of the queue, he is able to seize required resources upon availability and start his scheduled session. A non-elective patient seizes the first available bed for preparation and is prioritized available for surgery. Since a surgery center both consumes considerable expenditure and generates a major port of revenue for the hospital, principle instructors might think about if there is any untouched potential of the current configuration to increase patient throughput, average length of stay or even reduce workload of health care staff. Since the main objective is to minimize patient length of stay, improved management for reducing work pressure and maximizing throughput are not discussed in this study.

We have combined patient and staff workflows in the conceptual model, as Fig. 1 shows. This conceptual model is established according to the feasibility study report for expanding the hospital complex and an interview of the project development team designing the units. In order to represent them adequately in the simulation model, empirical data of layouts, default staffing configurations, surgery types and agent movement rules are collected. The clinical pathway consists of functional rooms: Elective surgery arrival area (zone 1), non-elective surgery arrival area (zone 2), preparation area (zone 3), nurse stations (zone 4), surgery slots (zone 5), store supply room (zone 6), cleaning corridor (zone 7) and surgeon offices (zone 8).

A simulation model is then constructed to model the patient flow from arrival to discharge. Elective and non-elective patients arrive from upstream units and are sent to different surgery preparation rooms with bed capacities of 4 and 2. In all cases of decided surgeries, each individual is allocated a surgery bed and gets prepared with the help from nurses. After preparation, the patient waits to be transported to the specific surgery slot for his session processed by the surgery team. The surgery types decide surgery time periods and material supplies.

There are two types of logistical activities carried out by the healthcare staff. These include the assignment of human resources and the provision of necessary materials. The healthcare staff has different levels in the organization and is associated with different movement rules in the center. Surgery physicians and assistants sit in offices and nurse stations during idle times. Upon request, they are obliged to go through several intermediate stages, such as exchanging clothes and a walk through the clean corridor, for contamination purposes. Meanwhile, consumables and facilities have to be ordered from the store and supply room. Demand for these materials is generally greater (with 2 units) for long-duration operations (type I and II) and become less (with 1 unit) for light operations (type III and IV). Each request is fulfilled with the stock and then proceeds to the patient. Approximately 2 times per day, the store room is checked for inventory sufficiency.

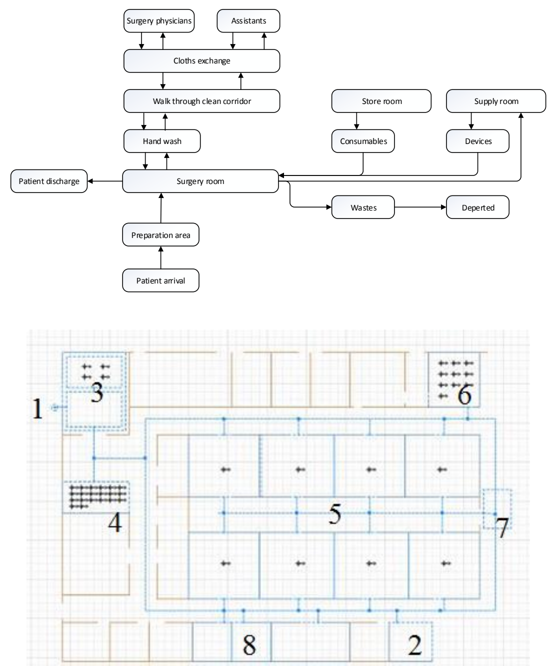

Figure 1. Operational logistics and layout of the surgery center

B. *Simulated Entities*

Patient demand is represented by an arrival rate and types of surgeries according to historical data, the technical setting and function of this hospital in the regional healthcare network. There are 11 categories of patient entities in the model, one representing patients in need of long-duration surgeries and the other ten require relatively short-duration surgeries, as shown in Table 1. The surgery center predominantly addresses eleven kinds of surgeries varying from 30 minutes to 5 hours, including 4 categories of surgical incision. Each incision is fulfilled with a particular type of surgery slot. The surgery slot of special clean has the least pollution parcels in the air and is able to implement all incision categories, whereas the normal clean and clean can handle only forensic surgery, anorectal surgery and similar cases with relatively lower level of requirements of contaminations. Together these capture a majority of the total surgeries executed in this hospital since its dedication to type I and II. Time periods of surgical durations are modelled using uniform distributions.

TABLE I. SURGICAL INCISION CATEGORY, SLOT REQUIREMENTS AND AVERAGE DURATIONS.

Incision Category	Type of Surgery Slot	Notes on Suitable Types of Surgeries (Estimated durations in hours)
I	Special clean	Joint replacement (1-2), transplant (2-3), aural surgery(4-5), cardiac surgery (3-5), glaucoma and dacrocystitis (0.6-2) ;
II	Special clean	Pleural surgery (5), orthopedics(0.5-0.6), urethra (15-25), liver pancreas (3-4), bone surgeries (1), forensic surgery (1)
III	Normal or Special clean	Forensic surgery (excluding Surgical Incision Category Ⅰ),gynecology and obstetrics (1-2);
IV	All slots	Anorectal surgery (1), pollution class (1)

The surgery center is controlled by FIFO policy in the simulation study. Routine elective patients are served on the FIFO basis since they are assigned the surgeries according to the admission date. Although both patient- and material-centric logistics are incorporated, we put more details on simulating the patient flows and fewer efforts on the regulation of inventories. The simulation model calculates performance metrics such as the total length of stay, waiting times, resource utilizations and stock levels. When a mission finishes, the staff leave the surgery slot and returns to offices and nursing stations. We also consider the possibility of no-shows. This occurs before the preparation phase with a given probability of 5%. The cancelled agents are immediately removed from the simulation model.

C. Sensitivity Analysis via MCS

The purpose of sensitivity analysis is to identify influential factors governing patient length of stay. The length of stay in this study did not include the surgical duration since it is already determined by the surgery type of the patient and cannot be changed. In variations of assumptions and policies, it is important to discover parameters that highly affect the key outputs of the system. Although theoretically the supply is already at optimal value to accommodate forecasted health care demand at the feasible study phase, demand might increase or decrease in the operation phase, leading to potential redesign efforts. The feasibility of additional resources enables decision makers updated of the current state of the system. A comprehensive view of potential constraint factors of the system is therefore needed.

A sensitivity analysis through MCS makes up for the disadvantage of using deterministic sensitivity analysis. In the deterministic way, the replications occur with relative lower numbers and might result in analysis biases if the system is inherently stochastic. During a Monte Carlo simulation, values are sampled randomly from the input probability distributions. Each set of samples is operated within a simulation run, and the resulting outcomes from that sample are recorded with a great amount of replications. In this way, Monte Carlo simulation provides more freedom of configurations and is able to realize factors of greater impacts.

The MCS in this study uses the normal distributions with realistic boundaries to detect response to an uncertainty of parameter value by a number of replications. In the surgery center simulation model, the size of each resource along the care pathway is defined as a parameter, where the value can be potentially varied. This variation is useful to quantify magnitude of responses. To this end, a MCS study examines the performance of different managerial alternations with an experimental design consisting of six one-way estimations. 20 replications starting from idle were conducted for each scenario to simulate a 7-day time span. The total running time for the 200 runs is around 4 minutes on a standard PC.

IV. RESULTS AND DISCUSSIONS

Simulation showed that all the function blocks of the model achieved unhindered entity flows with the default staffing setting and historic admission rate. Fig. 2 illustrates the distribution of average length of stay and relative differences of performance metrics with empirical estimation from the interview. For the waiting time, the time period centralized between 50 to 60 minutes with an average of 53.51 minutes, because the surgery team has not fully prepared yet, (e.g., due to the inability to seize the appropriate surgery slot, surgeon or materials) or because of the inability to start pre-surgery tasks (due to unavailable nurses busy on earlier patients). An interview with the project development team produced estimation of the average length of stay and the utilization of different resource types. Overnights did not occur because patients were transferred to downstream units for postoperative activities. The calculated average waiting time of 50 minutes from the simulation model is in line with practices (55 minutes) in real; the consistency also applies to resource utilizations. Above all, the simulation model is considered to be validated for investigating parameter variations in staffing configurations, surgery types and patient levels.

To the author's knowledge, this simulation model of specific procedures is of high accuracy that uses the already defined staffing settings, such as the details of surgery slots, beds and human resources (i.e., sizing and movement rules), and explicitly incorporated 11 surgery types requiring specific slots and surgical case durations. This is of particular importance in sensitivity analysis since the already defined values can be employed as upper or lower boundaries used to detect outputs.

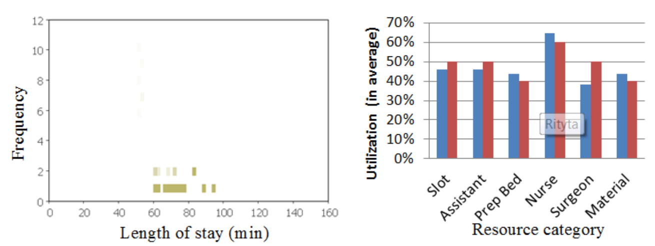

Figure 2. Outputs of simulation: a) scatter diagram of average length of stay; b) resource utilizations per category

Studying the sequential responses of staffing variations can provide more insights on whether the efficiency of the presented patient flow management has potential to be improved, identify by which sources and directions it can be improved and detect lower capacity threshold. To this end, this paper identified parameters related to sizing of beds, nurses, surgery slots and materials by analyzing the average length of stays within each particular feasible interval. We explored potential parameter values by modifying the current setting with resource extractions or additions. The magnitude of extractions and additions are around 4-5 units for all resource types. A uniform distribution was used to assign parameter values the same probability of occurrence.

The simulations demonstrated the benefits and penalties of changeable capacities towards average length of stays. The parameters and corresponding length of stays identified are illustrated in Fig. 3. We implement both increases and decreases on resource sizing, attempting to cover the whole ranges of them. It could be seen that the average length of stay becomes longer with greater deviations as long as the capacities are decreased. Especially for surgery slots and preparation beds, the capacities are not recommended to be lower than 3 and 2 units since the average length of stays will tip up dramatically. The small change implied that the average length of stays is more sensitive to capacity reductions of current levels rather than additions.

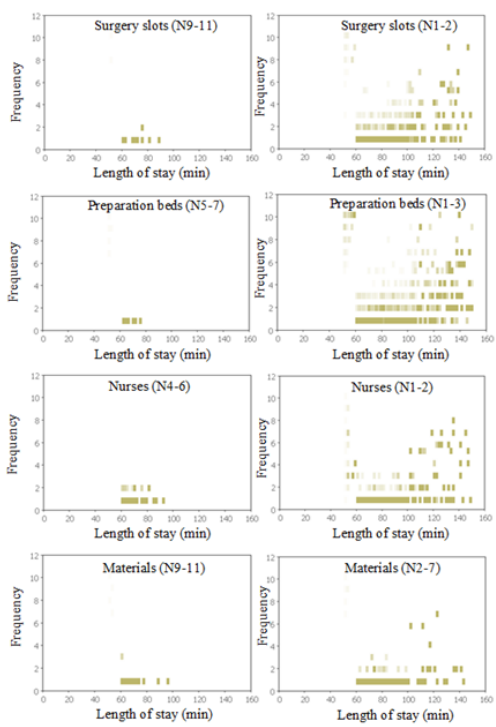

Figure 3. Scatter diagrams of length of stays and frequencies under staffing configurations

While length of stays could be eliminated by a larger-capacity staffing, analyzing focused types of surgeries enable further insights on impacts from demand scenarios. In contrast to previous attempts to implement resource changes, types of surgery also result with variations in average length of stays—as Fig. 4 shows, the noticeable longer length of stays were identified by a 30% demand increase of either of type I. On the other hand, there is a moderate increase from a 30% demand increase of current type III and IV. This means that the stay duration tends to be more acceptable in case of increased type 3 and 4 surgeries. The surgery center or regional health system planners shall be aware of consequences of receiving additional type I and II (special clean) at this hospital.

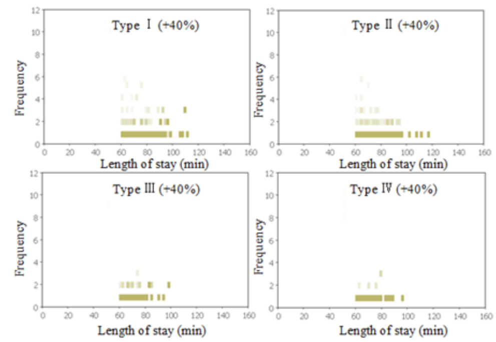

Figure 4. Scatter diagrams of length of stays and frequencies under patient levels

In this study, the sizing of surgery slots and nurses as well as the share of type I cases in the global list are indicated as the most influential factors. Moreover, the corresponding demand profile (+40%) results in surgery slots as the most important source of affecting the patient length of stay with a mean elasticity over 80%. In contrast, nurse sizing is first the most important factor in the baseline scenario but ended in less influential compared to surgery slots. In practice, there is a shortage of nurses to complete pre-surgery tasks under the current demand profile of 75 cases per week. Hence, effects of resources do not necessarily stay the same through all demand profiles as indicated by the proportional output on the total length of stay. Marginal differences presented by such a frontier [Fig. 5] provide valuable information on magnitudes of changes that are not easily captured from the healthcare planners' point of view.

The patient length of stay also depends on configuration of surgery types. This is identified with the current patient level in Fig. 5. As an example, the output is more sensitive to the amount of type I surgery received than type II, although they share surgery slots. However, this influence is smaller from type III and IV. We can conclude that type I affects the waiting time most. The effect of type I is almost 8 times than the one of type IV. The proper combination of surgery types need to consider various factors, amongst others case urgency, resource availability and accountability. In this study, the central point is the impact of category on patient waiting times. It remains as a research question for future studies to identify the exact combination of surgery types associated with different surgical complexities and case durations when the system performance is to be improved.

The influences of candidate factors with the subject change were investigated by MCS. In line with the expectation, there was a correlation between amid resource levels and the performance of the system. Furthermore, there existed a noticeable difference for the average patient length of stay for increased demands of type I and II. The findings implied that the MCS method was able to alleviate the computational efforts than deterministic technique in sensitivity analysis of parameters under the described values. Given the current form, patients spent less waiting times with increased nurse level than they did with increased surgery slot level. However, it did appear that additional surgery slots were a rewarding option under increased demand scenario.

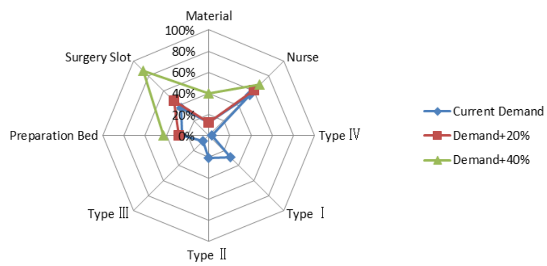

Figure 5. Scatter diagrams of length of stays and frequencies under demand scenarios

V. CONCLUSIONS

In this paper, an event-driven simulation approach for sensitivity analysis was developed to a surgery center of a general hospital. Since implementation of staffing configuration changes and demand management strategies would be difficult in the use case, influential factors on patient length of stay are identified based on sensitivity analysis. This sensitivity analysis is conducted via MCS in which each parameter is assigned the same probability of occurrence. The results of the sensitivity indicate that effects of changing resource capacities might vary in different demand profiles. In addition, the patient length of stay in the surgery center is more vulnerable to capacity reductions rather than additions. The moderate reductions of patient length of stay by increasing capacities of corresponding resources indicate that adding more infrastructures might not be a feasible way of improved system performance.

The following conclusions are subject to the conditions and limitations of this study: 1) the MCS approach is more effective than the deterministic analysis in evaluating the sensitivity of resource- and demand-related parameters; 2) fluctuations with the type III and IV had limited effect on average patient length of stay compared to type I, and; 3) the magnitude of responses by the resource levels subjected to patient levels were not significantly consistent as long as given increased surgery assignments.

The elasticity measures defined in Section 2 are utilized for the purpose of identifying influential factors towards patient length of stays. In particular, three demand profiles are implemented to further recognize important resource candidate for future scenarios. It examines to what extent the patient length of stay respond to influences from different staffing configurations. This sensitivity analysis via a MCS and elasticity measurements enable understanding of the relation between design factors and system outputs and how well the latter can be determined and improved by design efforts especially in the planning phase.

A sensitivity analysis generates clues and references for effectiveness of controllable resources to improve patient length of stay. Follow-up researches shall enable modelling participants as agents, so that both master and decision rules of staffing relocations can be fully deployed to approximate the reality. Besides the lack of agent’s interactions, we admit that detailed scheduling has not been integrated into the current table. Apart from regulations, in what way the surgery scheduling is better engineered with above reinforcements is also worthwhile to tackle based on a simulation approach. In one of the studied patient levels, the amount of surgery slots was found to heavily affect the performance. It is therefore recommended that it may be beneficial for stay duration reductions to increase the provision of slots in case that the hospital is assigned more surgery missions. In what way to better design and distribute dedications considering tolerances of local surgery centers in the regional health care network constitutes another interesting research question in the future.

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