Perioperative Workflow Simulation and Optimization in Orthopedic Surgery

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Abstract. Operating room management aims at the efficient coordination of surgical procedures by maximizing the number of surgical cases while minimizing the required surgery time, with the main goal of improving the patient outcome. Discrete Event Simulation can be utilized to describe, analyze and predict the impact of procedural changes in perioperative processes. The aim of this work is to provide a simulation approach for a holistic perioperative optimization. Therefore, two different process simulation techniques, namely Business Process Simulation and 3D Process Flow Simulation, were utilized. It could be shown that perioperative simulation could lead to the improvement of OR utilization, reduction of process duration and a decrease in personnel workload.

Keywords: Surgical process simulation · Discrete event simulation
Perioperative process opitimization · Operating room management

1 Motivation

The goal of the operating room (OR) management is the effective coordination and execution of surgical procedures in order to create a safe, efficient, and structured environment with the ultimate goal of optimizing the patient outcome. Due to the fact that the surgical department is the most cost-intensive department of the hospital, the OR management aims at maximizing the number of surgical cases while minimizing the required time, resources and related costs. In the last decades, numerous methods and technical approaches have been developed to improve OR scheduling and OR efficiency in order to increase capacity utilization and patient throughput, e.g. formula-based equations [1], statistical methods [2] and process- or discrete-event-simulation (DES) models. DES models aim at describing, analyzing and predicting procedural changes of dynamic systems over the time. Simulation is an essential methodology to (re-)design,

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analyze, execute and evaluate processes in respect of different perspectives, objectives, and stakeholders. DES is in the focus of widespread developments for the improvement of pre- and postoperative processes (e.g. [3,4]). However, only a few efforts have been given to the process optimization of intraoperative processes. Fernández-Gutiérrez et al. analyzed and simulated perioperative (pre-, intra- and postoperative) workflows in order to find the optimal development of new complex procedures in multimodal imaging environments [5] and for the efficient utilization of scarce medical equipment [6]. Currently, there are no simulation studies available, which focus on the streamlining of intraoperative processes and their impact on OR capacity utilization and on the execution of pre- and postoperative processes. The OR is a highly complex environment, all processes are intertwined and have a significant impact on each other. Even small delays can lead to timing problems that affect the entire surgical team and the overall OR performance. This complexity requires the analysis of processes from different perspectives. Most simulation approaches focus on temporal (process duration), behavioral (activities and interactions of personnel) and operational aspects (availability of resources, capacity of facilities) of the pre- and postoperative processes. There is no research available on how the structural perspective (environmental aspects, e.g. layout of the OR and surgical department) is influencing the perioperative processes.

The aim of this work is to provide a DES approach for a holistic perioperative process optimization with a focus on the combination of behavioral, temporal, operational and structural perspective. Two different process simulation techniques, namely Business Process Simulation (BPS) and 3D Process Flow Simulation were utilized. Process re-engineering methods based on the computer simulation are used to improve OR capacity utilization and perioperative process efficiency as well as simultaneously reduce the workload of the OR personnel by minimizing waiting times and overwork time. For this purpose, the DES models were implemented with perioperative data from Total Hip Replacement (THR) and Total Knee Replacement (TKR) surgeries. The optimization objective is to increase the number of surgeries to three cases per day by reducing the intraoperative incision-to-closure-time (ICT) through the optimization of the OR layout. Furthermore, the processes for surgery follow-up and OR preparation (closure-to-incision time (CIT)) should be streamlined in order to reduce vacancies and utilizing the available resources to capacity without overburden. To ensure a persistent high-quality patient treatment, the performance duration of perioperative activities should not be reduced.

2 Materials and Methods

2.1 Data Acquisition

THR is a orthopedic procedure in which the hip joint is replaced by a prosthetic implant to treat arthritis pain or hip fractures. During TKR the knee joint is replaced to relieve debilitating pain or osteoarthritis. For the intraoperative simulation 15 THR and 7 TKR surgeries and for pre- and postoperative simulation

30 (total or partial) knee- and hip replacement surgeries were recorded at the University Hospital Leipzig in 2016. In the pre- and postoperative environment, temporal and procedural process information for every OR staff member as well as CIT (OR turnover times) were acquired. In the intraoperative setting structural data (on-site measurement), surgical process data (surgical activities for THR and TKR), OR layout (number and the arrangement of instrument tables for left- and right side THR and TKR), instrument handover (number, duration and path of handovers between surgeon and scrub nurse), travel paths (number, duration and travel path of the circulator) as well as ICT was recorded. In addition, an ergonomic assessment was performed for every OR team member with the OWAS method (Ovako Working Posture Assessment System), which is used to evaluate the most common work postures for the back, arms, and legs.

2.2 Discrete Event Simulation

DES provides an environment for process design, analysis, re-engineering, and evaluation. It is also used to predict the impact of procedural changes over the time and to quantitatively evaluate different alternative process configurations [3]. Thereby, DES relies on the modeling of activities, which are executed by processing the transitions between a list of events. The events are usually described with instructions and a logic for executing the simulation, which enables the imitation of complex behavior. There are various DES methods and tools for different applications and objectives available. In this paper, BPS has been used for the simulation of the behavioral, temporal and operational perspective. For the assessment of structural dynamic changes and their impact on the underlying processes, 3D Process Flow Simulation has been utilized.

Business Process Simulation

For the modeling, analysis, and evaluation of complex, flexible processes, business process modeling is widely used in academic and industry. Especially, BPMN 2.0 has been proven successful in the modeling of the perioperative process environment [7]. In addition, BPMN is regarded as the most appropriate standard available for BPS. The pre- and postoperative processes in the orthopedic department were modeled with the Signavio Editor [8] in the BPMN 2.0 format. For BPS the free business process simulator BIMP [9] was used.

3D Process Flow Simulation

Following the argumentation and assessment in [5], 3D Process Flow Simulation was utilized for the intraoperative process optimization. Therefore, Delmia by Dassault Systems [10] was used, which provides a 3D Modeling environment and logical process simulation. Delmia was initially designed for manufacturing industry but has also a widespread distribution in healthcare (e.g. [4,5]).

3 Simulation Experiments

3.1 Pre- and Postoperative Simulation

Initially, the pre- and postoperative activities of all OR team members (surgeon, assistant, scrub nurse, circulator, anesthesiologist and nurse anesthetist) were modeled in BPMN format and supplemented with the recorded activity duration (mean duration and standard deviation under normal distribution). The BPMN models were simulated with BIMP in different scenarios for the whole workday with 2 or 3 surgeries. In order to analyze which and how many surgeries are feasible with the currently available OR- and personnel-capacities, different combinations of THR and TKR were simulated. According to the intraoperative data acquisition, the initial mean ICT was set to 64,24 min (std 19,74) for THR and 90,0 min (std 22,67) for TKR. The simulation scenarios were then instantiated 250 times (mean working days per year) and the minimum, average and maximum process duration (Cycle Time (CT)) for one workday were calculated via simulation. The normal working period of the OR staff is scheduled to 8 h, which has been defined as an upper boundary for the CT. In addition, waiting times in the process flow resulting from process bottlenecks or scarce resources were simulated. In order to determine the current personnel utilization, the workload of the staff was also simulated. Thereby, only the pre- and postoperative main tasks were analyzed.

In the first optimization step, the pre- and postoperative processes were streamlined with methods of Business Process Re-engineering by parallelization and summarization of activities, redistribution of responsibilities and temporal alignment of the process. After this optimization step, the BPMN models were adapted to the optimized processes and the simulation scenarios were repeated. In the second step, the intraoperative process optimization was performed. Afterwards, the simulation was repeated with improved ICTs.

3.2 Intraoperative Process Simulation

The aim of the intraoperative process optimization was to shorten the ICT by improving the OR layout, instrument table positions and setups for THR and TKR. For this purpose, the existing table setups were analyzed and simulated considering the duration, number, and paths of instrument handovers. Based on the simulation scenario, new setup suggestions are designed and compared to the initial setups. When creating the new setups, both the ergonomic aspects of the OWAS evaluation method and the average rotational movements necessary for the handovers were included. Further, a possible optimization of the circulators' travel paths was simulated together with the initial and optimized setups.

A 3D simulation environment was created with Delmia and the existing layouts and table positions were modeled and simulated based on the intraoperative recorded data (see Fig. 1). The number and the duration of handovers were included in the simulation in order to obtain the total handover time for THR and TKR. The alternative setups for the left and right side of the operated hip

Fig. 1. 3D simluation scenario of the orthopedic OR modeled in Delmia (left TKR).

respectively the left and right side of the knee were designed, simulated, analyzed and compared with regard to the handover times and travel paths.

4 Results

4.1 Initial Situation

Conventional OR Capacity Planning

OR capacities are optimally utilized if a maximum of surgeries can be performed in the work time. Formula-based equations are the state-of-the-art (e.g. [1]) for capacity calculation and planning. These methods are used to define a baseline for the verification of the perioperative simulation:

$$Current\ Surgeries\ per\ day = \frac{Cases\ per\ year}{Working\ days\ per\ year} = \frac{581}{250} = 2,3 \tag{1}$$

Possible THR and TKR surgeries per working day (8 h-1 h for supportive tasks):

$$PossibleTHR = \frac{Work\ time - 1\,\mathrm{h}}{meanICT(THR) + meanCIT(THR)} = \frac{420}{(64+60)} = 3,4 \tag{2}$$

$$PossibleTKR = \frac{Work\ time - 1\,\mathrm{h}}{meanICT(TKR) + meanCIT(TKR)} = \frac{420}{(90+60)} = 2,8 \tag{3}$$

Possible surgeries per day for a combination of THR and TKR:

$$PossibleTHR/TKR = \frac{420}{(72+60)} = 3,2 \tag{4}$$

According to conventional planning, 3 surgeries per day should be feasible with 3THR and a combination of THR and TKR without overwork time (>8 h).

Analysis of the Initial Situation with Business Process Simulation

Firstly, the CTs of the existing situation for different THR and TKR combinations were simulated (Fig. 2 (light gray)). Two surgeries can be performed without any further process optimization with the disadvantage of an insufficient OR utilization, which results in unused resource capacities. The target of three surgeries per day could be only achieved with 3THR (avg. CT 8,2 h). All combination with one to three TKRs widely exceed the maximum CT of 8 (avg. CT: 3TKR = 9,7 h, 2TKR + 1THR = 9,2 h, 1TKR + 2THR = 8,7 h). The simulation results correspond with the calculation based on the conventional capacity planning method with minor differences for 2THR + 1TKR. In addition, the workload of the OR personnel was simulated and is presented in Fig. 3 (light gray). The upper boundary of 8 h work time per day should not be fully exploited in order to have free capacities for supportive and non-value-added tasks (e.g. supply refill, travel paths etc.). According to the recommendation of [1], the optimal workload is set to 7 h. The maximum workload is set to 4 h per day for the nurse anesthetist, who is responsible for more than one OR and acts as an anesthetist circulator. The simulation results indicate that only 3THR and the combination of 2THR + 1TKR could be performed within one work day. The optimal boundary of 7 h could not be achieved by any surgery combination without further process optimization.

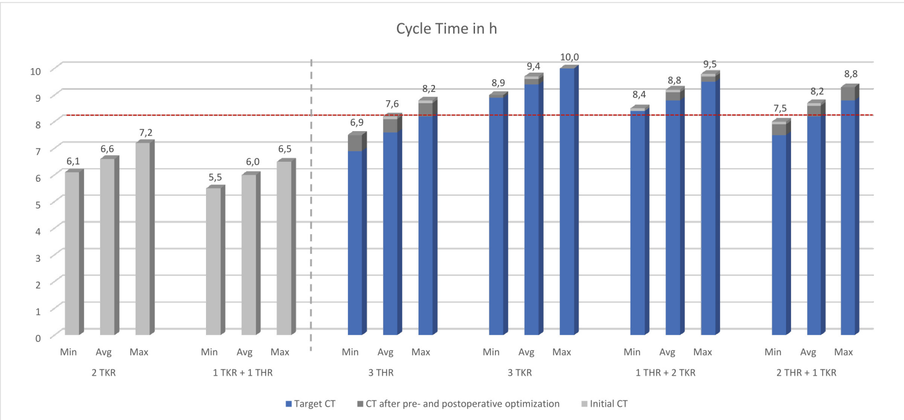

Fig. 2. CT simulation results of THR and TKR combinations: 2 surgeries (left side) and of 3 surgeries (right side). The red line marks the 8 h work time/day boundary. The results after pre-, intra- and postoperative optimization (Target CT) are numbered. (Color figure online)

4.2 Pre- and Postoperative Process Optizimation

For perioperative process optimization several process alignments, such as parallelization and summarization of activities, redistribution of responsibilities and temporal optimization of the process were proposed. Based on these optimizations a decrease of the CTs could be achieved (Fig. 2, dark gray). Still, it is not possible to perform three surgeries with at least one TKR in the time period of 8 h. In Fig. 3 (dark gray) the optimized workload is represented. Through the process optimization, a reduction and a better balancing of workload between the OR team members have been achieved. Especially, the workload of the anesthesiologist has been reduced to less than 8 h while the workload of the nurse anesthetists was slightly increased by 1 h (Fig. 3, dark blue).

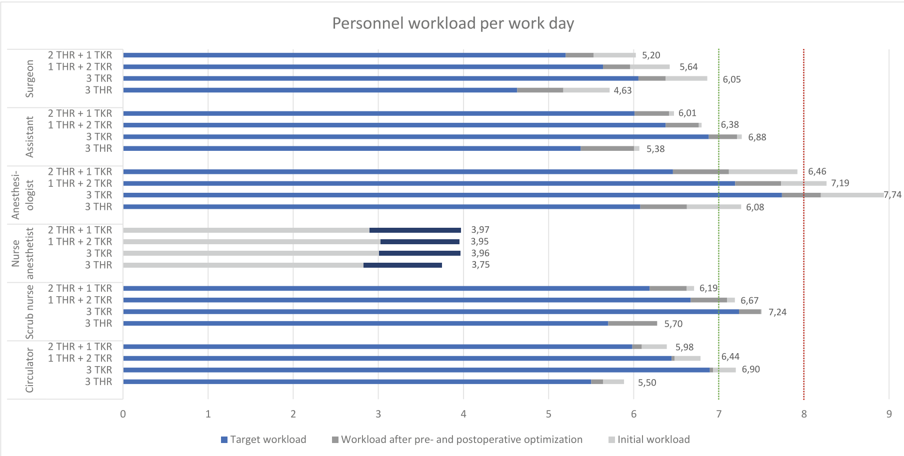

Fig. 3. Personnel workload of THR/TKR with numbered results after perioperative optimization (Target workload). Red line is the 8 h work time/day boundary and the green line is the optimal boundary. Gray: decrease and dark blue: increase of workload. (Color figure online)

4.3 Intraoperative Setup Optimization

Based on 3D Flow Simulation, optimal setups for THR and TKR were defined and evaluated in the real intraoperative OR environment. ICTs were recorded for 8 THR and TKR surgeries, which results in a decrease of 9,45 min for THR (54,75 min (std 15,04)) and 3,25 min for TKR (86,75 min (std 21,91)). The improved ICT were included in the perioperative optimization and the BPS simulation study was repeated (Fig. 2 (blue)). The results of the perioperative optimization indicate that it would be possible to perform 3THR or 2THR + 1TKR in the work time of one day (avg. CT 8,2 h). This result also corresponds with the current case mix of THR and TKR at the University Hospital, which is about 2,3:1 (409 THR, 172 TKR in 2016). Also, the workload of the OR members (Fig. 3 blue) could be decreased to the intended 7 h boundary for 3THR and 2THR + 1TKR.

5 Discussion and Conclusion

It could be shown that perioperative process optimization lead to improvement of OR utilization, reduction of CTs and a decrease in personnel workload. The simulation results of the capacity planning correspond with conventional methods. However, these metrics solely rely on parameters such as ICT and CIT and fail to asses in which way the process need to be changed for improvement. Simulation techniques enable the determination not only that perioperative processes can be improved, but also in which way processes need to be adapted and how the process efficiency is changed due to the impact of different procedural, behavioral, structural, operational or temporal parameters. In this paper different DES methods have been utilized, which were adapted to the underlying optimization problem and objective. Since 3D Flow Simulation is developed for the manufacturing industry, it is suitable for the simulation of operational and structural aspects with a high granularity. On the contrary, it lacks in the representation of complex and intertwined processes with various process actors. Thus, BPS is more suitable and flexible than other modeling methods for procedural and temporal modeling. With the proposed mixed method DES approach, aspects of both domains, could be addressed adequately. An objective time- and resource-saving assessment of different process alternatives and their impact on efficacy and potentials for perioperative process improvement could be achieved.

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