Systematic Evaluation of Operating Room Scheduling Across the Perioperative Process

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ABSTRACT

Given a three-stage perioperative (periop) process with preoperatives in stage 1, operating rooms (ORs) in stage 2, and postoperatives in stage 3, the purpose of this project is to improve the quality of OR scheduling based not only on the efficiency for individual units, such as utilization of ORs, but also on the effectiveness for the whole periop process, such as patient flow time. Maximizing OR utilization does not always lead to minimizing patient flow time, the inconsistency between which generates trade-offs. Consequently, systematic evaluation of OR scheduling is critical to reduce cost in resource allocation and to reduce patient waiting time across the periop process. The main scope is serial processes for service and options in both healthcare and manufacturing. Our methods include the scheduling theory for flow lines to improve the efficiency of OR scheduling and the portfolio theory for marketing to improve the effectiveness. We propose a current and future deviation (CFD) heuristic for balancing trade-offs in serial processes. Our CFD heuristic outperforms the world-leading heuristics in optimizing utilization and flow time. Moreover, our scheduling method can significantly reduce patient flow time without sacrificing OR utilization, based on simulations of historical data from UK HealthCare. The three-stage periop process is better under control using our scheduling schemes in terms of statistical process control (SPC) charts. Our schemes for flow line scheduling and for process evaluation will have fundamental influence on process design and operations management.

Key Words: Flow Shop Scheduling; Operations Management, Portfolio Theory, Statistical Process Control, Trade-off Balancing

PURPOSE

There are two specific aims involved in this project to systematically evaluate OR scheduling across the periop process. Specific aim 1 is to improve the efficiency of OR scheduling, and specific aim 2 is to improve the effectiveness of OR scheduling in three different time phases, with planning in long term, scheduling in the short term, and control in real time.

SCOPE

Serial processes are commonly used in healthcare to provide surgical services and in manufacturing to produce products. Two completion times are fundamental in serial process scheduling. One is maximum completion time (C_{max}), which is the completion time of the last case in the last stage, and the other is average completion time ($\bar{C}$), which is the sum of completion times of all cases in the last stage divided by the total number of cases N, or $\bar{C} = \sum C_j / N$. Minimizations of these two completion times, min(C_{max}) and min($\bar{C}$), drive numerous key performance indicators (KPIs) in healthcare and manufacturing. For example, corresponding to min(C_{max}), we have the following KPIs, such as utilizations of ORs and the periop process, and operational cost of specific units and the whole system; corresponding to min($\bar{C}$), we can evaluate patient flow time and the number of resources in a process; and corresponding to both completion times, customer/patient satisfaction can be modelled by both cost and time.

However, minimizing one completion time does not necessarily lead to minimizing the other, although C_{max} for the last case is included in $\sum C_j$ for all cases as $j = 1,\ldots,N$. In other words, optimizing utilization for a unit or a process might impair patient flow time, and vice versa. The inconsistency between optimization objectives generates trade-offs between relative KPIs, which partially provides the reasons for high cost and long waiting time in healthcare.

Moreover, either min(C_{max}) or min($\bar{C}$) is so complicated that existing scheduling theory cannot guarantee optimal solutions to any of these two optimization problems. Consequently, balancing trade-offs between utilization and flow time is challenging from both theory and application perspectives, especially when a process is under uncertainties, such as in demand arrivals, processing times, resource availabilities, and so on.

METHODS

Three types of difficulties are involved in trade-off balancing for OR scheduling across the periop process. The first type of difficulties is about single-objective and multi-objective optimizations for min(C_{max}) and min($\bar{C}$), respectively; the second type is about trade-offs between the expected returns and the relative risks, especially when objectives are inconsistent with each other; and the third type is about trade-offs of process performance in different time phases.

First, for trade-offs in optimization problems, we innovatively propose the concept of deviations in serial process scheduling. We propose a new scheme to calculate the lower bounds (*LB*s) and upper bounds (*UB*s) of completion times for case $j = 1,\ldots,N$ in stage $i = 1,\ldots,M$. Based on such bounds of completion times, we derive tight lower and upper bounds of necessary KPIs. Deviations are normalized, because KPIs of process performance are not in the same units or scales. Specifically, the normalized deviation is calculated by $d_k = (x_k - LB_k) / (UB_k - LB_k)$, where d_k is normalized deviation for a performance measure $k = 1,\ldots,K$, x_k is the actual process performance for a KPI, and $UB_k - LB_k$ is the variation range of a performance measure. For minimization problems, it is good to have small deviations from the lower bounds. According to such a basic thought, we sequence cases based on the sum of normalized deviations, $D = \sum b_k \cdot d_k$, where b_k is a weight or preference for d_k with $\sum b_k = 1$ for $k = 1,\ldots,K$. Considering deviations for both served and unserved cases at a time, we propose the CFD heuristic for serial process scheduling (Li et al., 2019a). Given a bi-objective optimization problem, to min(C_{max}) and min($\bar{C}$), we set $K = 2$ and change $b_1 = 0.0,0.1,\ldots,1.0$ for min(C_{max}). In this way, we can enumerate all combinations of preferences for deviations of KPIs. This scheme is comprehensive. As patients are not supposed to wait between stages, especially from ORs to the postop stage after the surgery, we also model the periop process as a no-wait flow line, and propose different methods to sequence cases for OR scheduling (Ye et al., 2019, 2017a, 2017b).

Second, for trade-offs between returns and risks, we apply the portfolio theory. Regarding the expected return as the mean or as the first-order effect, and the variance as the risk or as the second-order effect, we model the expected value of deviations over all KPIs as $D = \sum b_k \cdot d_k$, subject to $\sigma^2(D) = B^T \Sigma B$, where $\sigma^2(D)$ is the variance given a portfolio of deviations, $B = \{b_1, b_2, \ldots, b_K\}^T$ is a column vector of weights, T is transpose, and Σ is a $K \times K$ symmetric matrix of variance and covariance among deviations. Effective decisions on OR scheduling should be made based on a portfolio frontier generated by our model, on which given a risk level of $\sigma(D)$, the expected value of deviations D, cannot be further minimized or, given an expected value of D, the risk cannot be further minimized (Li et al., 2019b).

Third, for trade-offs in different time phases, we use the SPC techniques. Specifically, the process performance x of utilization and flow time in real time (e.g., in minute or hour) are taken as averages $\bar{x}$ for short term (e.g., in days or weeks), and then these averages are plotted in *X*-bar charts against a time horizon in long term (e.g., months or years). The *X*-bar charts describe the fluctuation of performance averages over time. Accordingly, the fluctuation of average variations can be captured in *R* charts over time, as $r = \max(x) - \min(x)$. The *R* charts specify the lower and upper limits of variations for performance averages.

Two sets of data are used to verify the effectiveness and efficiency of our schemes to balance trade-offs in OR scheduling. One dataset is Taillard's benchmarks, which are classic to attest the efficiency of scheduling methods for serial processes. The case number in Taillard's benchmarks changes from 20 to 500, the stage number changes from 5 to 20, processing times of each case in each stage change from 1 to 99, and Taillard's benchmarks are available at http://mistic.heig-vd.ch/taillard/problemes.dir/ordonnancement.dir/ordonnancement.html.

Another dataset consists historical records of nearly 30,000 patient cases from 2013-2014 in OR scheduling across the three-stage periop process at University of Kentucky HealthCare (UKHC).

RESULTS

The principal finding through this project is that trade-off balancing is essential for OR scheduling across the three-stage periop process, which is supported by three substantial findings.

First, trade-offs do exist between C_{max} and $\bar{C}$, or process utilization and flow time. Therefore, OR scheduling should focus on multi-objective optimizations instead of on single-objective optimizations. Based on Taillard's benchmarks, our results confirm that our CFD heuristic outperforms world-leading heuristics on min(C_{max}) and min($\bar{C}$), respectively (Li et al., 2019a), and good process performance on min(C_{max}) might generate outliers on min($\bar{C}$), and vice versa, which can drive the process out of control limits for specific KPIs.

Second, trade-off balancing for OR scheduling will keep the three-stage periop process better under control in terms of process performance in real time. Based on simulation results of UKHC's historical dataset, the process performance by our scheduling scheme dominates UKHC's on both utilization and flow time (Li et al., 2019a). Moreover, according to process capacity indices of C_p and C_{pk}, our trade-off balancing scheme not only generates a tight variation range for expected trade-off values but also allows wider variation ranges for C_{max} and for $\bar{C}$, respectively. This means that our scheduling and control scheme allows large variations on utilization and on flow time to keep the process under control. Our scheme provides an excellent tolerance or robustness to disturbances in process control for OR scheduling.

Third, we should eliminate dominated scheduling methods from trade-off balancing, because these dominated methods will generate performance outliers, enlarge performance variance in real time and the short term, blur the portfolio frontier to balance trade-offs in different time phases, and finally lower the quality of OR scheduling (Li et al., 2019b).

The research findings of this project can be used for operations management to allocate resources into each stage across the serial process and to set up performance goals and specification limits in different time phases.

However, three factors affect trade-off balancing for systematic evaluation in OR scheduling. The first one is different capacities of internal processes, such as surgeons' skills, nurses' experience, and the number of available resources; the second one is different properties of external demands, such as the number of cases, types of surgeries, the emergency levels of cases, and case cancellations or no-shows; and the third one is preference variations of OR managers in balancing trade-offs. Taking all these three factors into operations management, modeling a steady state of trade-off balancing is our next research topic.

LIST OF PUBLICATIONS and PRODUCTS

In refereed international journals

Ye, H.H., Li, W., Nault, B.R. 2019. Trade-off balancing between maximum and total completion times for no-wait flow shop production. International Journal of Production Research, (Accepted). DOI: 10.1080/00207543.2019.1630777

Li, W., Nault, B.R., Ye, H.H. 2019a. Trade-off balancing in scheduling for flow shop production and perioperative process. *European Journal of Operational Research*, 273 (3), 817-830. DOI: 10.1016/j.ejor.2018.08.048.

Ye, H.H., Li, W., Abedini, A., Nault, B.R. 2017a. An effective and efficient heuristic for no-wait flow shop production to minimize total completion time. *Computers and Industrial Engineering*, 108, 57-69. DOI: 10.1016/j.cie.2017.04.002.

Ye, H.H., Li, W., Abedini, A. 2017b. An improved heuristic for no-wait flow shop to minimize makespan. *Journal of Manufacturing Systems*, 44, 273-279. DOI: 10.1016/j.jmsy.2017.04.007.

In refereed international conferences

Dang, F.D., Li, W., Ye, H.H. 2018. An efficient constructive heuristic to balance trade-offs between makespan and flowtime in permutation flow shop scheduling. *Procedia Manufacturing*, 26, 40-48. DOI: 10.1016/j.promfg.2018.07.005.

Abedini, A., Li, W., Ye, H.H. 2018. Stochastic bi-level optimization models for efficient operating room planning. *Procedia Manufacturing*, 26, 58-69. DOI: 10.1016/j.promfg.2018.07.008.

Abedini, A., Ye, H.H., Li, W. 2017. An optimization model for operating room scheduling to reduce blocking across the perioperative process. *Procedia Manufacturing*, 10, 60-70. June 4-8, 2017, Los Angeles, CA, USA. DOI: 10.1016/j.promfg.2017.07.022.

Gunna, V.R., Abedini, A., Li, W. 2017. Maximizing operating room performance using portfolio selection. *Procedia Manufacturing*, 10C, 83-91. June 4-8, 2017, Los Angeles, CA, USA. DOI: 10.1016/j.promfg.2017.07.028.

Abedini, A., Ye, H.H., Li, W. 2016. Operating room planning under surgery type and priority constraints. *Procedia Manufacturing*, 5, 15-25. June 27-July 1, 2016, Blacksburg, VA, USA. DOI: 10.1016/j.promfg.2016.08.005.

Under review in refereed international journals

Li, W., Mitchell, V.L., Abedini, A., Freiheit, T.I., and Chang, P.K. 2019b. Balancing trade-off across a perioperative process with variation in processing times. Submitted to *Journal of Health Economics*. (Under review)