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Analysing management policies for operating room planning using simulation

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Abstract In this paper we analyse the operating room planning at a department of orthopaedic surgery in Sweden. We focus on the problem of meeting the uncertainty in demand of patient arrival and surgery duration and at the same time maximizing the utilization of Operating Room (OR) time. With a discrete-event model we simulate how different management polices affect different performance metrics such as patient waiting time, cancellations and the utilization of OR time. The experiments show that the performance of the operating room department can be improved significantly by applying a different policy in reserving OR-capacity for emergency cases together with a policy to increase staff in stand-by. Moreover, the developed simulation model provides estimates for a what-if situation related to the prognosis of an increasing number of hip-joint replacements.

Keywords Simulation · Optimisation · Healthcare · Management · Operating room planning

1 Introduction

Operating room planning is a very challenging task from a number of perspectives. The uncertainty in patient arrival and surgery duration, together with the occurrence of multiple interactions with other departments in the hospital, makes the Operating Room (OR) planning very complex. Also the resources to be planned, i.e. OR with highly skilled personnel, are rather expensive, thus, management efforts to increase performance are needed. The performance of the operating room department concerns various aspects such as costs, patient waiting time, OR utilization, patient throughput, surgery cancellation, surgery delay and staff overtime work, and many of these aspects are more or less interconnected. Considering different metrics of performance, we focus on the problem of how to allocate the available OR time between elective and emergency cases at an orthopaedic department, i.e., how much of the available orthopaedic OR capacity should be reserved for emergency and for elective cases, respectively. The aim is to assign the OR time for elective and emergency cases to maximize the performance of the operating room department.

We use discrete event simulation and optimization modelling to study the impact of the uncertainty in patient arrivals and in surgery durations, subject to different management policies concerning the allocation of OR time. With the developed simulation tool we use probability distributions based on historical data to generate the stochastic patient arrivals and surgical procedure times. Moreover, we provide a method to investigate and analyse relevant what-if situations such as an increase in orthopaedic surgeries. The number of orthopaedic surgeries has in general increased along with technological and medical advances. Today, some orthopaedic surgeries are carried out that would not have been considered for surgery five to ten years ago. For instance, one of the presented scenarios represents a 30% increase of hip-joint surgeries which is one type of surgery that increases substantially [1]. A prediction of how such an increase could influence the performance of the current operating room planning in relation to different management policies is also demonstrated.

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The number of applications using discrete-event simulations in healthcare is rather large and started to increase significantly at the end of 1990s [2]. Simulation techniques provide a range of possibilities for healthcare analysis, for instance: performance analysis (e.g. what is the capacity of current system?) and what-if analysis (e.g. what is the effect of changes to staff planning or of other changes to management policies?). The literature reports on several studies which analyse the performance of medical clinics, i.e. emergency departments, operating room department, geriatric departments and outpatient clinics which use simulation and/or optimization techniques [3–6]. Marshal et al. [7] emphasize the importance of modelling the patient-flow when analysing the complexity of healthcare activities. With patient-flow simulation models, the stochastic behaviour of the system can be taken into account and provide out-comes for different performance metrics [7]. One successful application of a simulation modelling approach is suggested by Harper [8]. His model simulates patient-flows under uncertainty in service times in relation to different proposal schedules in order to reduce patient waiting times in an outpatient department.

Examples of performance metrics in the context of hospital operating room planning are: cost, patient through-put, length of stay, waiting time, cancellations, over-time work, idle operating room time or on-time starts. VanBerkel and Blake [9] present a discrete event simulation model to analyse consequences (patient through-put and waiting times for elective patients) of redistributing beds and OR-time between two sites of a general surgery division. A. Jebali et al. [10] examine different strategies of operating room scheduling with respect to cost minimization. They use performance metrics such as staff overtime, staff under time and patient waiting time which they convert into a cost function.

Additionally, there are several studies exploring the operating room planning and the uncertainty related to surgical procedure time and patient arrival and its effects [11–14]. Denton et al. analyse the surgery sequencing in relation to the stochastic surgery durations [13]. They use waiting times, idle OR-times and tardiness to compute performance of their OR analysis. In [15] a stochastic model for surgery scheduling with respect to emergencies is presented. With an optimization algorithm they show how the cost of waiting time and overtime can be reduced. Van Houdenhoven et al. [11] use discrete event simulation to compare two approaches of how to reserve OR capacity for emergency surgery in order to increase performance of an operating room department. Different to [11], this study focuses on orthopaedic surgeries with a rather different setting. As for example, the emergency waiting time is here of minor concern since orthopaedic surgeries often can wait 24 h before surgery without any medical complications which is not the case for general emergency surgeries. Also the occurrence of a stand-by system (further explained in section 2.1) is of more importance to orthopaedic patients why we let stand-by patients to be one of the main parameters in this research. All of the before mentioned studies overlook the cost of possible surgery cancellation which we argue is one of the main problems when considering operating room planning and cost. In this study we investigate a real problem of how to reserve emergency capacity in an orthopaedic surgery department at a Swedish hospital. We examine how different management policies affect the overall performance. The performance is here defined to measure OR efficiency, cost, medical responsiveness (meeting the demand of different medical priorities in waiting times) and patient ease (a surgery cancellation could be very inconvenient to the patient). Also we emphasise the importance of simultaneously consider all these performance metrics in order to facilitate an accurate and proper analysis of the overall performance. The complex trade-off decisions related to the operating room planning are modelled with an optimization model and incorporated with the simulation model. It is a modification of the model used in previous research used for studying long-time effects of different policies concerning elective waiting list management [16]. In contrast to the model used in [16] this model is developed to analyse the effects of the stochastic influences related to operating room planning, e.g. emergency cases and unexpected disturbances in surgical procedure times.

The rest of the paper is organised as follows. Section 2 introduces the studied problem and we then present our approach in Section 3. This is followed by Section 4 in which the simulation model and results are reviewed. The last section features conclusions and some pointers to future work.

2 Problem description

In this study we investigate the operating room planning in an orthopaedic department at Blekinge Hospital, located in the south of Sweden. The hospital is a medium sized hospital and the orthopaedic department consists of approximately 25 surgeons at different educational levels.

2.1 Emergency vs. elective OR time

Figure 1, demonstrates the problem of how to allocate available OR capacity between elective and emergency surgical cases. If too little time is allocated for elective surgeries, the waiting list may increase; and if too much time is allocated for elective surgeries, cancelations and

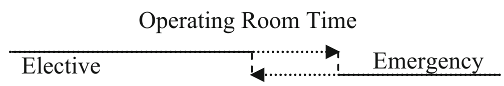

Fig. 1 An illustration of the problem related to balancing the allocation of operating room time between elective and emergency surgical cases

overtime may increase due to requirements of emergency patient operations. In addition to choosing a proper allocation of resources for elective and emergency surgical cases, it is important to achieve a high throughput, or as in this case, to reduce idle time. To reduce idle OR time at the operating room when the number of emergency surgeries temporarily is lower than expected, stand-by patients can be admitted. A stand-by patient is prepared for surgery at home (or at work) and called upon when an opportunity occurs. In advance, the Orthopaedic Department and the stand-by patient have agreed upon dates for which the stand-by patient could be alerted. This is especially suitable for waiting list management at an orthopaedic department due to the characteristics of orthopaedic disease and injuries, and is frequently used at Blekinge Hospital. By accepting the stand-by offer the patient's waiting time could be considerably reduced. However, not every patient or surgery is suitable for the stand-by system. In this study we assume there are a sufficient number of patients that accept the stand-by offer. This means that we do not expect the system to run out of potential stand-by patients.

2.2 The operating room department of orthopaedic surgery at Blekinge Hospital

The department of orthopaedic surgery at Blekinge Hospital is assigned two operating rooms to manage emergency and elective patients, i.e. patients preferably operated within 24 h and the latter within 4–6 weeks. The remaining, long-term elective patients are managed within another setting (all long-term elective patients are managed by a nearby hospital) and are therefore not included in this study.

Presently, the OR time is assigned according to Fig. 2. For Monday to Thursday, all OR time in OR 1 and approximately 1/3 of the OR time in OR 2 are exclusively assigned to elective surgeries and 2/3 of the OR time in OR 2 is reserved for emergency surgeries. On weekends (here Fri–Su) there are no planned surgeries (elective surgeries), i.e., all OR time in OR 2 is reserved for emergency surgeries, and no OR time in OR 1 is allocated to orthopaedic surgery.

The OR-time assigned to the orthopaedic department is based on the total number of orthopaedic surgeries performed during one year and its' mean surgical procedure

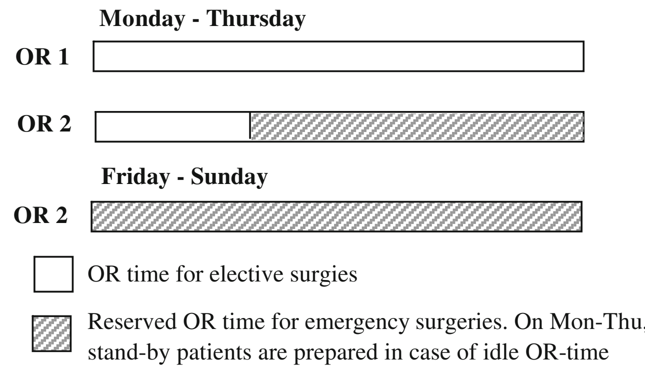

Fig. 2 Current allocation of OR time between elective and emergency surgeries for different days of the week

time. However, the distribution of these hours does not necessarily correspond to the demand on a daily basis due to the uncertainty associated with emergency arrivals and surgical procedure time. Thus, a more exhaustive investigation of the OR need would be suitable.

2.3 System description

The system we study includes the main processes from the point when the patient arrives (either as an emergency patient or elective patient that has decided upon surgery after an appointment) to the point when the patient surgery ends. The three main processes included are: patient arrival, patient queuing and operating room scheduling (see Fig. 3). In *Patient Arrival* patients enter the system and form a queue. *Patient Queuing* represents how the patient queue is designed. After entering the system patients are given a medical priority according to patient need (the medical priority is given by a surgeon either at the emergency department or at the out-patient clinic). Also, the possibility of a stand-by OR-time is considered at this point. A stand-by OR-time is offered to patients who are planned for surgery that is especially suitable for a short-time notice and who also are willing to accept the pre-requirements related to a stand-by surgery (i.e. short-time notice). Dependent on the given priority and the stand-by possibility, a patient queue is formed. Finally, in the *Operating Room Scheduling* process, the schedule is decided based on the patient queue and available resources. The operating room schedule is performed by a coordinator.

3 Simulation model

As a simulation model provides estimates of some properties of system performance under a set of given

Fig. 3 The system we study can be divided into three main processes, patient arrival, patient queuing and operating room scheduling

Patient arrival	Patient Queuing	Operating Room Scheduling
Two different arrival patterns to enter the system: **1.** Patients arrive after an appointment with the surgeon where the decision on surgery is taken. **2.** Patients arrive as emergency patients, in most cases from the Emergency Department	The patient queue is equivalent to the patient waiting list for surgery. A stand-by system is also in use which implies two queues in reality.	Patients are scheduled for elective surgery approximately 3-4 weeks in advance. This means that there exists a working OR schedule that is gradually filled and edited. Step by step, the schedule is updated due to emergency cases and/or cancellations for example.

constrains [17, 18], we propose a discrete-event simulation to analyse the efficiency of the Operating Room Department of orthopaedic surgery with respect to the uncertainty of patient demand and surgery procedure time.

3.1 Queuing system

We compose a queuing system which includes an optimization model as further described below and the three characteristics earlier expressed by E. El-Darzi et al. [3]:

- arrival process—here, patient arrival
- service mechanism—here, operating room scheduling and policies
- queuing discipline—here, patient priority and queuing

3.1.1 Arrival process

The patient arrival is modelled by a Poisson process. We use the intensity parameter λ to represent the mean expected number of patient arrivals per time period for each type of surgery (there are approximately 300 different types of orthopaedic surgeries performed in Blekinge Hospital). The parameter λ is based on the observed daily mean, here calculated from historical data of one year of patient arrivals per type of surgery. The simulated patient arrival describes both the elective patient arrival (i.e. those that are entering the surgery waiting list after an appointment with the surgeon) and the emergency patient arrival. The simulated number of emergency arrivals among the arrivals is also based on historical data.

3.1.2 Service mechanism

Policies related to the operating room management concerns allocation of OR time (for both elective and emergency surgeries), policies for stand-by patients, overtime policies, surgery cancellation policies and surgery delay policies. Due to the multi objective problem associated with the operating room management, we have chosen to model the policies with optimization technique. The decisions taken with respect to current patient queue, current overtime need, and patients allocation to operating rooms (scheduling) and other management issues related to the OR performance are performed by an optimization model, i.e. we incorporate an optimization model to simulate the complexity of the decisions taken related to the operating room planning. In addition, the optimization model also involves the prioritization related to the waiting list management (patient queue) and is further described in the next section on queuing discipline.

The expected surgical durations are based on the particular type of surgery and its mean, calculated from historical data, i.e. all surgeries of a particular type of surgery performed during one year. Different to the expected surgical duration, the actual surgical duration is modelled according to a lognormal probability distribution, also based on the particular type of surgery. The lognormal probability distribution is in previous research commonly used for model surgical procedure times [17, 19, 20]. The discrepancy between the expected and the actual surgical procedure times represents how the uncertainty in surgery durations impacts the performance of operating room planning.

3.1.3 Queuing discipline

Patients included in this study are orthopaedic emergency patients needing surgery within 24 h and orthopaedic elective patients needing surgery within 4–6 weeks. The decisions taken to determine which elective patients to schedule for surgery are modelled by the optimisation model. We argue that the alternative of using a strict First-In-First-Out policy (FIFO) is a too crude policy for modelling patient queuing of elective patients. Our observations indicate that strict FIFO is currently not employed, since other aspects than patient arrival date, such as expected surgery durations, medical priority and costs, are accounted for. Hence, we model the queuing as a bin packing problem (the bin representing the operating room time in a certain day). We use the objective function of minimising the cost of not operating on a patient. We use a patient related cost which increases with waited time (for every simulation step, the patient related cost is increased for those patients that are not scheduled for surgery, i.e. still waiting for surgery in patient queue), and hence, the principle of FIFO is partly accounted for. The increase is non-linearly according to $c(1+\alpha)^{\#week}$, where c is the cost and α is an increase factor and # *week* is the number of weeks the patient has been waiting for surgery. Other cost parameters such as cost for cancelling a surgery and over time cost are also accounted for and included in the model. Stand-by patients deviates from the queuing discipline of FIFO in order to make better use of the resources. The emergency arrivals enter the waiting list under the constraint of getting surgery within 24 h, here, they are scheduled for surgery the next day, i.e. next simulation step.

3.2 Overview of the simulation model

We use discrete event simulation combined with optimisation to model the system of patient arrival, surgery duration and surgery scheduling. The rules related to the planning and scheduling of the surgery operations are represented by constraints in an optimisation model as described above. A detailed account of the optimisation model is attached in Appendix. Each operating room, here one or two rooms depending on the day of week, acts as a server that serves patients with OR-time for surgery. The servers supply a queuing system that exhibits the characteristics of a combination of FIFO, medical priority and a stand-by system, hence the simulation system can be referred to an M/G/2–system [18].

Every simulation step, here representing 24 h in time, starts with the generation of instances of patients (each patient is instantiated with a cost parameter that increases through the simulation as explained above) which are added to a queue. Considering the patient queue with the estimated surgery durations and operating room time available (see Section 2.2), the optimisation model determines the surgery schedule. The schedule has a four week time-frame and is gradually filled with patients and partly re-planned. When performing the scheduling, we let the surgical procedure time be the expected mean (as used for scheduling the four week time-frame) and which typically is different from the actual surgery procedure time. Further on the day of operation a randomly generated surgery procedural time based on a lognormal probability distribution is used. Hence, the optimisation model has to decide upon a surgery schedule for the current day based on constraints related to that particular day (i.e. new emergency arrivals, actual surgical procedure times, cancelations and over-time restrictions) and in addition, continue to fill up the four week time schedule and reschedule, if necessary. In Fig. 4 an illustration of the simulation system is presented.

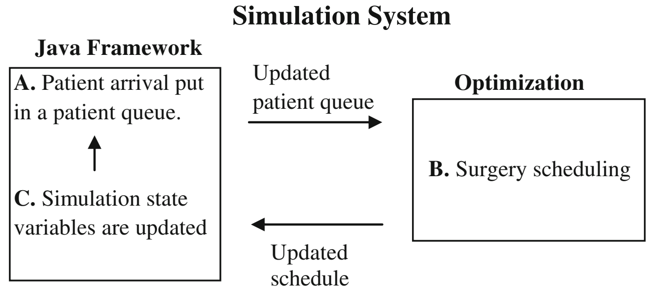

Fig. 4 Description of the simulation model. The simulation starts with A, patient arrival, and further to B, operating room scheduling, and finally to C where the simulation state variables are updated due to the new schedule and the process is re-iterated

3.3 Scenarios

3.3.1 Base scenario

We intruduce a base scenario to represent the current system. By this we also attain an opportunity to validate the model through a comparison with the real system. In a continuous dialogue with the chief surgeon and chief nurse at the department of orthopaedics, validation follow-ups with techniques like *Event Validity* and *Face Validity* have been embedded throughout the work [21].

An initial set of experiment aim at learning how the resources are utilized. After 20 separate simulation runs (using different random seeds) on the base scenario, where one simulation run representing 364 days (one year), the difference in utilisation of the OR-time reserved for emergency surgeries between week-days and week-ends appears significant and is presented in Table 1. Not very surprisingly, the precautions taken in week-ends result in low OR-time utilisation and on the contrary, high OR-time utilisation in week-days as the OR-time seem scarce.

The overutilization in weekdays indicate that the reserved OR-time for emergency patients is insufficient and therefore overtime work and/or elective surgery cancellations are enforced in order to meet the emergency demand. The underutilization in week-ends indicates idle OR-time meaning that expensive resources, already paid for, are not used. In addition to expensive idle OR-time,

Table 1 Utilisation rate of OR-time reserved for emergency surgeries in base scenario. In week-days the utilisation exceeds available OR-time and emergency surgeries can only be performed due to staff overtime work and/or elective surgery cancellations

Utilization of OR-time reserved for emergency surgeries in the base scenario

	Mon–Thu	Fri–Sun
Mean utilization	1.17	0.71

overtime work and surgery cancellations are very expensive actions to take and thus we believe that further analyses in how to reserve OR capacity for emergency patients are needed.

The current decision to reserve longer OR-time for emergency patients in week-ends is taken to ensure emergency capacity in case of unexpected number of emergency surgeries. In the week-days there is always the possibility of using the OR-time assigned to the elective surgeries to emergency surgeries by cancelling elective surgeries or by using overtime work. The overtime work is caused by the uncertainty related to both emergency arrivals and surgery duration. In an effort to increase OR performance (here, minimizing surgery cancellations, idle OR-time, overtime work and elective waiting times) we introduce a proposal scenario to simulate.

3.3.2 Proposal scenario

In the proposal scenario we have tried to compose a policy of OR allocation that better meets the demand of both emergency and elective surgeries on a daily basis with respect to OR performance, i.e. a more efficient OR-time utilization, less surgery cancelations, less overtime work and stable waiting times. The fixed costs (equipments and staff costs excluding overtime costs, etc) in the proposal scenario should preferably not exceed the fixed costs in the base scenario. Thus, by reducing the overtime work a reduction of total cost is expected.

In order to prevent overtime utilisation Monday to Thursday we extend the opening hours in OR 2 by 1 h in week-days. We also expand on the possibility of stand-by patients to keep elective waiting times reasonable but also to reduce idle OR time, see Fig. 5.

The idea is to perform a reasonable amount of surgeries also on days with few emergencies. Similar to the base scenario we assume there is a sufficiently number of patients accepting the stand-by offer. In weekends we introduce a stand-by resource (stand-by system) applied to the staff, meaning that one operating team (i.e. operating nurses, nurse anaesthetist) is scheduled to work but can stay home and being prepared to work if required, i.e. in case of emergency surgeries. If the stand-by staffs are not called upon, the cost is much less than if being on duty at the hospital. Emergency cases of general surgery and gynaecological surgeries are often recognized to have a higher urgency level compared to orthopaedic emergency surgeries. Therefore, the OR-time reserved for general and gynaecological emergency surgeries is sufficiently allocated, i.e. the opening hours of in Blekinge Hospital 24-hours a day (Figs. 2 and 5 only shows the OR-time allocation for the Orthopaedic Department). This means that this OR could also be used by some shorter orthopaedic emergency surgeries when it is not in use by any of the other operating departments (general surgery and gynaecological surgery). Hence, we believe that a stand-by system applied to the staff (OR-staff working with orthopaedic surgery) can be justified.

3.3.3 Main differences between base scenario and proposal scenario

Base scenario:	Proposal scenario:
- Patient stand-by system	- Extended time for patient stand-by system
- No stand-by system for staff	- Extended opening hours in OR 2 in week-days (i.e. extended OR time reserved for emergency patients)
	- A stand-by system for staff is introduced

The extended opening hours in OR 2 in the proposal scenario implies a higher accumulated cost for staff but this cost is compensated for by the stand-by system for staff that is introduced in week-ends. Accordingly, the cost for a

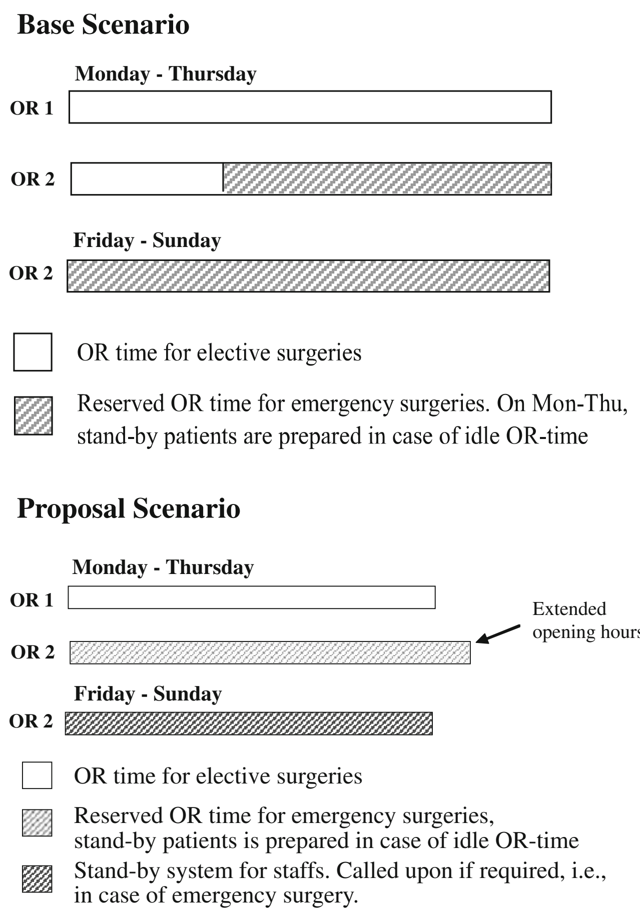

Fig. 5 In proposal scenario, the opening hours in OR 2 is extended and no elective patients are scheduled in OR 2. In week-end a stand-by system for the staff is introduced

stand-by system for staff in week-ends is lower than having staff on duty in a regular way in week-ends. Hence, the requirement of retaining the fixed cost intact (or reducing the fixed cost) when introducing a proposal scenario is fulfilled. All costs are calculated and based on present union agreements and salaries at the Blekinge Hospital.

4 Results

In Table 2, a summary of the simulation output is displayed and grouped according to scenario type. In the proposal scenario the results indicate a significantly decreased number of surgery cancellations and overtime work compared to the base scenario. However, the elective waiting time is more than twice as long as in the base scenario, but still, the timeframe of 4–6 weeks in which the elective surgeries preferably should be operated, is fulfilled and the longer waiting times are therefore of no major concern. The patient through-put is almost the same as in the base scenario.

A paired t-test validation technique is used to see if there is a significant decrease in overtime work and the number of cancellations in proposal scenario compared to base scenario. The overtime work, the cancellations and the average waiting times from the compared scenarios were found to be significantly different, $p<0.01$. When emergency resources are insufficient, as the case in the base scenario, elective surgeries are cancelled and/or overtime work increases in order to manage the effects of unexpected events (i.e., emergency patients, surgery complications indicating longer surgery durations than expected). However, the average time spent in queue (weeks) were increased but remained within the limit of 4–6 weeks. In total, 10 % of the patients did not meet the requirement of meeting the time limit (of 6 weeks) but none had to wait more than 10 weeks. In reality, there are always a number of surgeries that are postponed or cancelled on patient initiative (patients get better, they get ill and inoperable or they might even die). This factor is not accounted for in this study which might indicate an over estimate of the time waited.

Table 2 Results from 20 separate simulation runs from each scenario considering 364 days, i.e. base scenario and proposal scenario

	Number of surgeries	Number of surgery cancellations	Avg. time spent in queue (weeks)	Overtime hours
Base scenario				
Mean	1,916	15	2.1	132
St.Dev.	32	5.4	0.56	18
Proposal scenario				
Mean	1,914	2.15	4.4	62
St.Dev.	29	1.8	0.53	15

4.1 Costs

As discussed above, the fixed costs related to the proposal scenario turned out to be approximately the same as in the base scenario. This means that the cost for equipment and staff (excluding overtime work) was not increased, even though a stand-by system for staff was introduced. The overtime work was significantly reduced and hence, the variable cost (here, cost for overtime work) was decreased. Besides a total cost reduction, a reduction in surgery cancellations also occurred.

4.2 Steady-state

In order to validate that the warm-up period (of one year) is enough and that the system has reach steady state (i.e. waiting times and patient queues are stable) 12 simulation runs (6 for each scenario) were studied more carefully. In these set of experiments, 20 years (including the warm-up period) were simulated for both scenarios. The results are presented in Figs. 6 and 7.

These graphs (Figs. 6 and 7) indicate that the simulations are stable and that a reasonable steady state is reached after 1 year in both scenarios.

4.3 A potential future scenario

A potential future scenario in which there is a 30% increase in hip-joint surgeries added to the patient arrival has been studied (a general opinion is that the hip-joint surgeries will increase the coming years). The results are presented in Table 3, based on the previous scenarios (base scenario and proposal scenario). The results indicate even greater stress to the emergency resources which promotes more cancellations and increased overtime work. Furthermore, in these simulation runs the mean waiting time firmly increases and indicates an unstable situation if no additional resources are added to the system.

5 Conclusion and future work

This paper presents estimates on the performance of an operating room department related to two different management policies for operating room planning with the use of a discrete-event simulation. We analyse the performance of the operating room department, focusing on the problem of meeting uncertainty in demands, i.e. the focus is on uncertainty related to patient arrival and surgical procedure

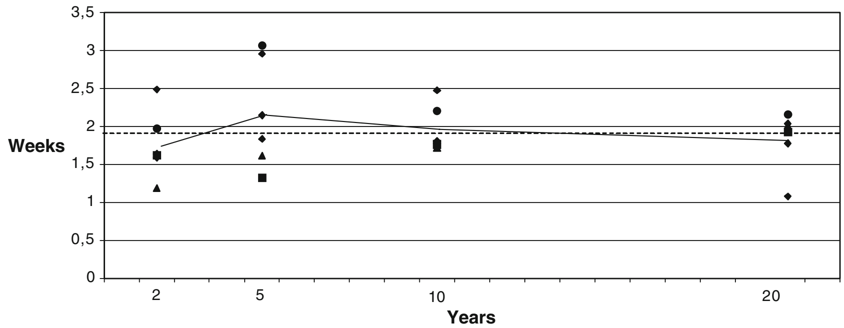

Fig. 6 The mean waiting times in weeks for 6 randomly chosen runs from *base scenario* taken at 4 separate occasions in time, i.e. during year 2, 5, 10 and 20. The dashed line represents the mean of all the plotted waiting times and the continuous line represents how the mean changes throughout the simulation

time. Two scenarios, representing two different management policies for operating room planning, are demonstrated and simulated for which one, i.e. base scenario, expresses current practice at the department of orthopaedics that we have studied.

The simulation of one year using the base scenario demonstrates insufficiency in meeting the demand of emergency cases. Here, the negative effects of disturbances increase, i.e., surgery cancellation and overtime work. A proposal scenario is suggested, representing a management policy that better meets the demand of uncertainty to approximately the same fixed cost as in the base scenario (cost of overtime work is excluded from the fixed cost). The management policy in proposal scenario showed to better meet the patient demand as a significant decrease in surgery cancellation and overtime work was achieved. As based on the results from the simulation experiment we conclude that the simulated performance of the operating room department was improved, except for a smaller increase in mean waiting time, when applying the proposal scenario.

Moreover, we simulate a plausible scenario specifying a 30% increase in hip-joint surgeries. We study how the different management policies given current available resources would manage with such an increase. The difference in cancellations, overtime and queue time between the base scenario and proposal scenario are further accentuated compared to the situation without the increase in hip-joint surgeries.

With the developed simulation approach we have demonstrated how different management policies can be analysed and assist in decision-makings related to the performance of the operating theatre. The policies are modelled by using an optimization technique that is re-iterated every 24th hour in the simulation model in order to represent decisions taken on a daily level. We emphasize the benefits of using optimization techniques to simulate the complexity related to operating room planning. Additional scenarios representing different management policies are of interest to study, in particular with respect to resource allocation of different resources, i.e., operating rooms, operating teams (nurses, anaesthetist etc.) and surgeons. For instance, a flexible number of operating teams in relation to operating rooms and surgeons seems to be a promising approach for increasing the resource utilisation and one point of future research could be to investigate how to achieve the potential of such flexibility.

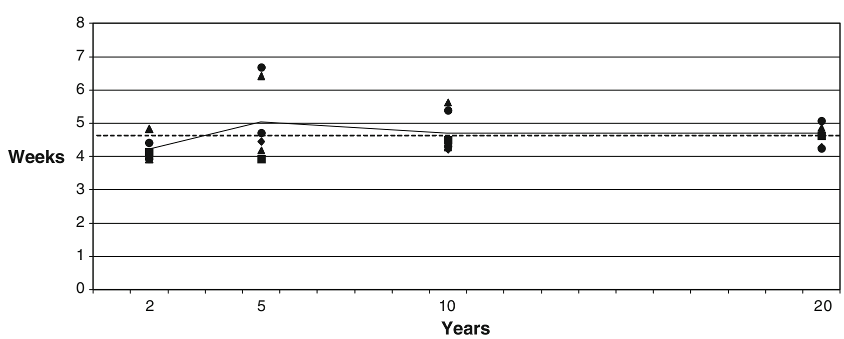

Fig. 7 The mean waiting times in weeks for 6 randomly chosen runs from *proposal scenario* taken at 4 separate occasions in time, i.e. during year 2, 5, 10 and 20. The dashed line represents the mean of all the plotted waiting times and the continuous line represents how the mean changes throughout the simulation

Table 3 Results from base scenario and proposal scenario with a 30% increase in hip-joint surgeries added to the patient arrival. 20 separate simulations runs from each scenario were performed

	Number of surgeries	Number of surgery cancellations	Avg. time spent in queue (weeks)	Overtime hours
Base scenario 30% increase hip-joint surgeries				
Mean	1,976	19.4	3.0	170
St.Dev.	28.3	6.5	0.81	24
Proposal scenario 30% increase hip-joint surgeries				
Mean	1,967	2.15	5.02	83
St.Dev.	31	1.76	0.97	24

Appendix

Optimisation model

This model is similar to the model presented in [16].

- J Index for patient set J
- M Index for operating room set M
- P Index for time periods (weeks) in the scheduling set P = $\{1,..,\overline{p}\}$, where $\overline{p}$ is the number of time periods in P.
- T Index for time slot (days) set T, where T= $\{1,..,|T|\} = \{1,..,|\overline{p}|*\overline{t}\}$, where $\overline{t}$ represents the number of time periods in T (days) per time periods in P (weeks).

Parameters, where some of the values have been included within parentheses:

- a_{mt} Number of opening hours at operating room m in time slot t.
- b_j 1 if patient j has been scheduled before, 0 otherwise.
- c_{jp}^{prio} Cost related to an estimation of patient need and suffering.
- c^{overt_1} Cost of 1 h single over-time (3600 SEK).
- c^{overt_2} Cost of 1 h double over-time (7200 SEK).
- c^{overt_3} Cost of exceeding the limitation of the weekly overtime work. (10000 SEK).
- c^{cancel} Cost of cancel an operation on operating day (15000 SEK).
- c^{cancel_2} Cost of cancel an operation on other days (2000 SEK).
- d^{week} Limitation of the weekly overtime work.
- e_j^{sched} Estimated surgical procedure time for patient j.
- e_j^{oper} Surgical procedure time for patient j.
- f^{restr_1} Available single overtime (2 h).
- f^{restr_2} Available double overtime (2 h).
- f^{restr_3} Available maximum overtime (8 h).
- h_{jmt} 1 if patient j is scheduled for operation in operating room m at time slot t, 0 otherwise.

Variables:

- g Overtime exceeding maximum per week. Could correspond to extra personnel.
- s_j 1 if patient j is not operated during period, 0 otherwise.
- v_{mt} Number of single overtime hours in room m at time slot t.
- w_{mt} Number of double overtime hours in room m at time slot t.
- ww_{mt} Number of overtime hours exceeding 4 in room m at time slot t.
- y_{jmt} 1 if patient j is operated/scheduled in operating room m in time slot t, 0 otherwise.
- $z_j^{current}$ 1 if patient j is cancelled current operating day from schedule, 0 otherwise.
- z_j^{other} 1 if patient j is cancelled other day than current operating day from schedule, 0 otherwise.

minimise z =

$$c_{j(\overline{p}+4)}^{prio}\sum_{j\in J} s_j + \sum_{j\in J}\sum_{m\in M}\sum_{t\in T:} c_{j\lceil t/\overline{t}\rceil}^{prio} y_{jmt} + c^{cancel}\sum_{j\in J} z_j^{current} + c^{cancel\_2}\sum_{j\in J} z_j^{other} + c^{overt\_1}\sum_{m\in M}\sum_{t\in T} v_{mt} + c^{overt\_2}\sum_{m\in M}\sum_{t\in T} w_{mt} + c^{overt\_3}\sum_{m\in M}\sum_{t\in T} ww_{mt} + c^{overt\_\exp} g$$

subject to:

$$\sum_{m\in M}\sum_{t\in T} y_{jmt} = 1 - s_j \qquad \forall j \qquad (1)$$

$$\sum_{j\in J} y_{jmt} e_j^{sched} \le a_{mt} \qquad \forall m, t > 1 \qquad (2)$$

$$\sum_{j\in J} y_{jmt} e_j^{oper} \le a_{mt} + v_{mt} + w_{mt} + ww_{mt} \qquad \forall m, t = 1 \qquad (3)$$

$$\sum_{m\in M} h_{jmt} \le \sum_{m\in M} y_{jmt} + z_j^{other} \qquad \forall j, t > 1 \qquad (4)$$

$$\sum_{m\in M} h_{jmt} \le \sum_{m\in M} y_{jmt} + z_j^{current} \qquad \forall j, t = 1 \qquad (5)$$

$$\sum_{m\in M} v_{mt} \le f^{restr\_1} \qquad \forall t \qquad (6)$$

$$\sum_{m \in M} w_{mt} \leq f^{restr\_2} \qquad \forall t \qquad (7)$$

$$ww_{mt} + w_{mt} + v_{mt} \leq d^{week} \qquad \forall m, t \qquad (8)$$

$$d^{week} \leq f^{restr\_3} + g \qquad (9)$$

$$b_j + z_j^{current} \leq 1 \qquad \forall j \qquad (10)$$

The objective function minimises different costs related to operating room planning. First we have costs related to not scheduling a patient for surgery. If a patient is *not* selected for surgery within the four-week schedule, we assume the patient to be scheduled for operation in four weeks after the considered time horizon, and hence, a penalty corresponding to that the patient waits 8 weeks in the queue is included. Also we have a cost related to *when* to operate on a patient (naturally this cost requires that the patient has been selected for surgery). This controls in which week patients should be scheduled in the four-week operation schedule. Less cost is incurred in the beginning of the schedule and more later. Further we have costs related to surgery cancellations and overtime. All costs are set up in order to achieve a behaviour which corresponds to the real system behaviour.

Constraint (1) specifies that patients can only be scheduled for surgery once and forces the variable s_j to become one if patient is not operated on. Constraint (2) and (3) balances the estimated/actual time for surgeries scheduled with opening hours at the operating theatre included overtime in constraint (3). Constraint (4) and (5) connects patients scheduled for surgery from one simulation step to the next simulation step and keeps track of possible cancellations. Constraints (6–9) define restrictions related to overtime and constraint (10) delimits the cancellations to a maximum of one per patient. Further the variable g and parameter h_{jmt} are transferred into next simulation step in order to keep track of the weekly overtime and the operating room schedule.

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