Increasing Utilization in a Hospital Operating Department Using Simulation Modeling

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This article focuses on the planning and scheduling of operating rooms (ORs) in a regional hospital in Sweden. A simulation study was carried out to find new ideas and new planning and scheduling techniques to improve the overall process of surgery, including pre- and post-operating activities. This study mainly addresses the problem of low utilization of the ORs, and also takes into consideration problems with variation in workload, both in ORs and in post-anesthesia care units. The final simulation model includes pre-operative care carried out in the operating department and all ORs, as well as post-operative care units. It was driven by a number of input parameters, such as the volume and specific characteristics of actual cases, opening hours and number of ORs, and the number of beds for pre- and post-operative care. The model also includes logic for prioritizing and allocating cases to available ORs, planning operating schedules and the utilization of medical equipment limited in quantity. Output performance measures from simulation experiments include the utilization of allocated OR times, waiting time for patients, queue dynamics, number of cancellations, and variation of finishing times, as well as occupancy statistics in the post-operative care unit. Four different change alternatives were evaluated using the simulation model. Simulation experiments showed that with the implementation of the proposed changes it is possible to achieve slightly better and more even resource utilization, as well as provide greater flexibility in scheduling operations.

Keywords: healthcare, operating department, operating rooms, utilization, discrete-event simulation, planning, scheduling

1. Introduction

Planning and scheduling is part of the everyday work in any industrial system. Techniques and methods for planning and scheduling have been developed and refined since the beginning of the industrial revolution. In the latter half of the 20th century, simulation became a well-known and utilized tool to investigate planning and scheduling activities in industry and in other applications

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as well. Healthcare is one application that has been under huge pressure to become more efficient and effective and in that perspective, the simulation of planning and scheduling activities in healthcare is gaining much interest in both academia and from hospitals.

This article focuses on the planning and scheduling of operating rooms (ORs) in a hospital in Sweden. A simulation study was carried out to find new ideas and new planning and scheduling techniques to improve the overall process of surgery, including pre- and post-operating activities. There are some circumstances that make this work valuable for other researchers and practitioners in the same field. First, ORs incur high costs [1] both when utilized, due to the cost of the workforce, and when idle, due to the cost of expensive machinery. Second, the aging population implies that there will be an increasing number of elderly patients that will result in an increasing load on the OR resources [2]. Given these two facts, the solution to the increasing load of patients can be to simply create more OR resources, i.e. build more facilities. Another approach is to simply learn to better utilize the facilities that are already present by applying planning and scheduling techniques to the planning of ORs with the goal of increasing utilization and increasing the throughput of the whole system. There is a third circumstance that makes the planning and scheduling activity challenging, which is the fact that OR times differ greatly for the same procedure in different hospitals [2, 3]. The planning and scheduling environment is thus very complex. There are many actors involved that need to cooperate and merge their efforts in order to carry out operating activities. Each planned activity is also dependant on the other activities that are scheduled for the same resources. This gives a problem, both complex and dependant, that is hard to analyze without help from analysis tools, such as simulation. It is hard to see which changes will lead to better performance without the help of simulation. This study mainly addresses the problem of low utilization of the ORs, and also takes into consideration problems with variation in workload, both in ORs and in post-anesthesia care units (PACUs).

The purpose of this paper is to verify the bottleneck in post-operative care and find solutions to lift this constraint in order to get a more even utilization of the operating department. At the same time, the purpose of the simulation project is to show the benefits of using simulation modeling in this kind of environment.

Simulation has been applied in healthcare for many decades and in many different areas. Jun and Jacobson [4] give a comprehensive overview based on an extensive literature survey of applications of discrete-event simulation in healthcare clinics and identified several areas where simulation is used to affect patient flow and resource allocation, such as patient scheduling and routing, resource scheduling, and the sizing and planning of beds, rooms, and staff. Most of the simulation work is done on the department or clinic level, and it is very difficult to find simulation applications in complex integrated systems [4]. Most of the published simulation studies, however, fail to report adequately on the implementation of the results, which makes it difficult to assess the value of simulation in healthcare management [5]. Brailsford [6] mentions several possible reasons for the poor implementation record – the organizational culture in healthcare, high cost of performing simulation studies, problems with data, few incentives for academics to wait for and assess potential implementation before publishing, and the perceived need for site-specific models.

A number of simulation studies have also been carried out concerning operating departments, including pre-operative assessment and PACUs. Below is a short review of previous work that is most closely related to our research. Edward et al. [7] determined the required capacity necessary in pre-operative assessment clinics in order to decrease patient access time to surgery. They also used simulation to determine scheduled consultation lengths in order to decrease waiting time for the patients. Marcon et al. [8] used a simulation model to determine the minimum number of PACU beds, and investigate how factors such as length-of-stay (LOS) and number of porters influence the hourly occupancy of the PACU. Marcon and Dexter [9] use simulation to find out which sequencing rules, based on the predicted length of procedures, lead to the smooth flow of patients through the PACU. VanBerkel and Blake [10] built a site-specific model of a general surgery system that included both elective and emergency patients and included both OR time and beds as resources in the model. Lowery and Davis [11] describe a model that is built and used for OR capacity estimation in terms of the number of OR rooms before reorganization of the OR facilities in the hospital. Tyler et al. [12] use a simplified OR model in order to determine the optimal utilization of the OR, keeping the utilization rate as high as possible and at the same time minimizing risk for cancellations and overtime. Both Dexter et al. [13] and Dexter and Traub [14] use simulation to investigate different surgical procedure-scheduling strategies in order to maximize the utilization of OR resources. Bowers and Mould [15] describe a simulation experiment that shows that a substantial increase in throughput can be achieved by scheduling elective patients within the emergency sessions. They also show that in their case a much simpler model would yield the same results as a detailed simulation model. Stahl et al. [16] use a simulation model to determine if it is cost effective to introduce a kind of parallel processing, having two anesthesiologists instead of one taking care of a patient in the OR. McAleer et al. [17] give a very detailed account of OR suite simulation model development, including descriptions of employee involvement. The model was used to find out bottleneck resources and how the system would cope with an extremely high load. One of very few cases where a generic model of an OR has been developed is described by Everett [18]. This model can be used for decision support for capacity planning for elective surgery services, although no actual use is reported.

Table 1. Example data on three surgical cases

ID	96503	96511	96520
Operation code	MCA10	DJD20	GAA31
Room	8	12	14
Date	2005-01-10	2005-01-10	2005-01-10
Operating team meets the patient	08:30:00	07:50:00	07:52:00
Anesthesia start	09:03:00	08:05:00	08:16:00
Ready for operation	09:10:00	08:20:00	08:50:00
Operation start	09:15:00	08:43:00	09:00:00
Operation finished	09:55:00	09:03:00	09:22:00
Arrival to post-operative unit	10:15:00	09:30:00	09:25:00
Patient signed over to post-operative unit	10:15:00	09:35:00	09:30:00

From the literature review it seems that simulation results stand a much stronger chance of being implemented if a specific model is developed for a particular hospital OR. This correlates with one of the barriers to implementation in [6] mentioned above. Even though researchers try to uncover general truths regarding OR management, it can be concluded that great care needs to be taken when applying them in practice, since local circumstances can be very different and vary from country to country and hospital to hospital.

The paper is outlined as follows. First, after the introduction and positioning of the research, an overview of the Department of Operations and Intensive Care is given. Then, the overall methodology of the research is presented in Section 3. In Section 4, the pilot study is presented that led to the main study, presented in Section 5. Finally, Section 6 contains conclusions and an outlook for future research.

2. Overview: Department of Operations and Intensive Care

The Department of Operations and Intensive Care at County Hospital Ryhov consists of several units. The operations central (OPC) is responsible for organizing hospital's elective and emergency surgery operations. The department also includes an intensive care unit (ICU), outpatient surgery unit, pain unit, sterile central, anesthesiology reception, and a secretariat. This study will mainly deal with OPC, ICU, and the outpatient surgery unit. In OPC there are on average approximately 12,000 operations carried out each year.

The system under study consists of 18 ORs, numbered 1–17 and 19, pre- and post-operative care units for outpatients (DUVA), inpatients (UVA) and children (BARN), as well as an ICU. The ORs are open for booking eight hours each day on weekdays except Friday, when most of the rooms are only available until lunch.

There are two dedicated emergency rooms, number 11 and number 17, where most of the inpatient emergency operations are carried out. Emergency rooms are available 24 hours a day, seven days a week.

Rooms 8–19 are for inpatient surgery and are connected to the post-operative care unit for inpatients (UVA). The UVA has 12 staffed beds between 08:00–21:00 on weekdays, and a smaller number of staffed beds available during nights. For inpatients, the majority of the pre-operative care is carried out in the ward.

For outpatients there are three dedicated ORs (5–7) and patients come in and out the same way through the DUVA. When patients arrive at the outpatient unit they are assigned a bed in the DUVA where they receive pre-operative care. When the OR becomes available (according to the schedule), the patient is moved to that room and after the operation is completed the patient is moved back to the same bed in the DUVA for post-operative care. The DUVA also takes patients from other parts of the hospital, not only those that have operations at the OPC.

There are three rooms for eye surgeries (rooms 2–4), which have a separate entry point. The ophthalmology department does 50–60% of the work themselves, which means that they do not use OPC services (apart from the physical room) for most of their operations. Finally, there is one room for oral surgery – room 1.

There is a computerized registration system called FENIX, which, among other things, is used to measure patient time during operations, and also time spent for pre-operative and post-operative care. Patient time is defined as the time from the moment when the operation team meets the patient until the patient is signed over to the next unit. Within this time several other measurements are made, such as anesthesiology time and operation time. Table 1 contains example data for three surgical cases.

This table depicts the process surrounding the OR very well. The team meets the patient (the first measurement point), who then arrives in the OR and anesthesia induction is started (the next measurement point). When the patient is anesthetized and the operation nurses have prepared the patient and the room for the operation, the next measurement is made (ready for the operation). The operation start time is when the surgeon actually starts op-

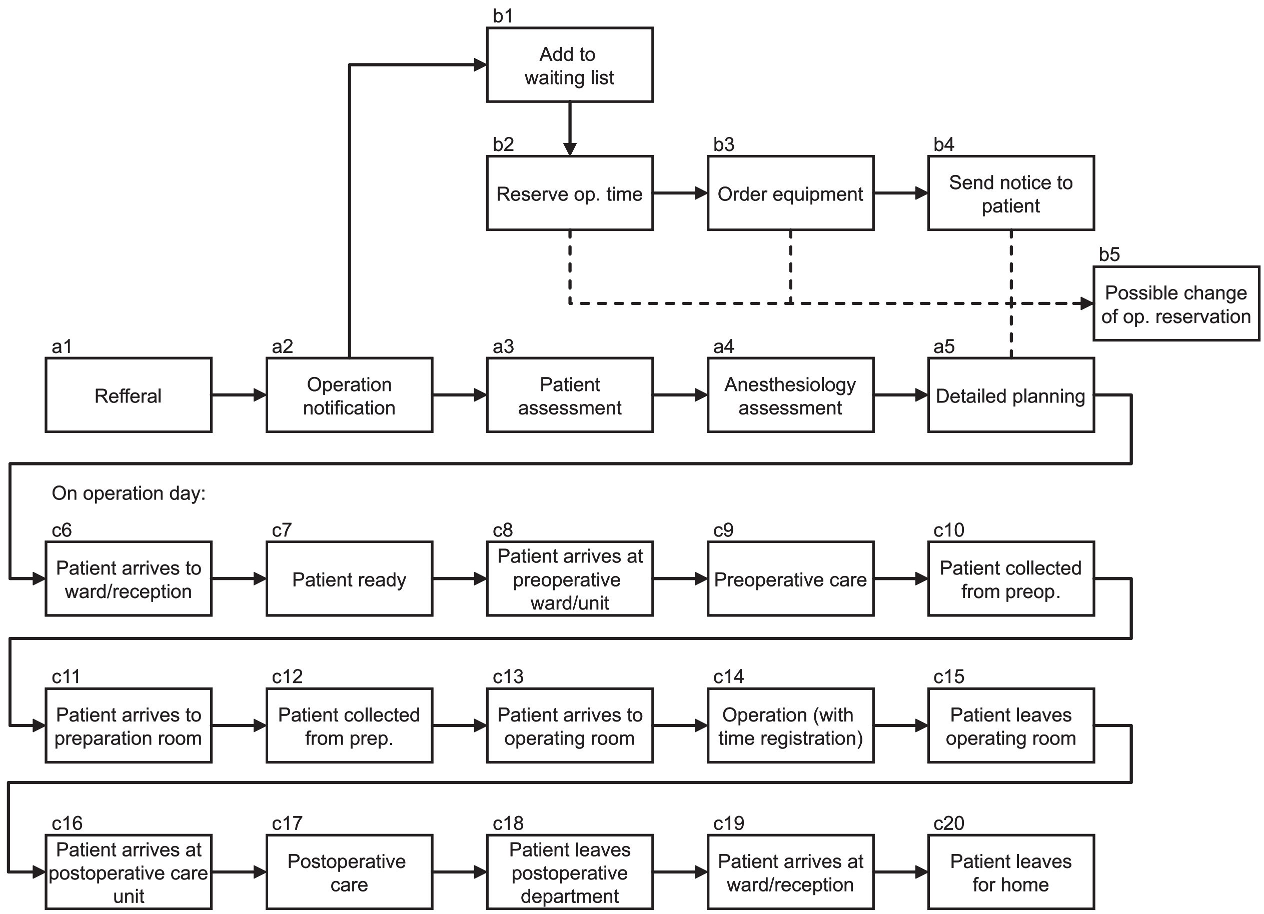

Figure 1. Operation activity flowchart

erating on the patient, and the next measurement is made when the operation is finished. When patient arrives in the post-operative unit another measurement is made, and finally, the last measurement is made when the anesthesiology/operation staff signs over the patient. The whole time interval from the moment the team meets the patient until signing over to PACU is called patient-time in this paper.

Figure 1 illustrates the whole activity flow concerning an operation. The timestamps in Table 1 are mainly related to step c14 in the flowchart, i.e. there is no direct association between the timestamps registered in the FENIX system and the activities in Figure 1.

The flow starts with a referral to the hospital and the decision to operate is made in the next step. A rough plan of the operations for a given day is available in the computer system several days in advance as it is filled by staff reserving operation time in the available time slots for each department. Detailed planning of operations is carried out the day before the actual operations during an operation conference meeting at 15:30.

The starting time for the first patient is set depending on which department is responsible for the operation. Starting times for all other patients are set by the operator and operation team during the actual operation day. The rough planning works well and there are at most 2% cancellations due to planning mistakes or rescheduling in the rough plan.

OPC provides ORs and the operation team, operator excluded. It can be seen as a service department to other functions, operating specialties, or departments. It is mainly the other departments that are responsible for filling the operation schedule so that utilization of OPC's resources (rooms and staff) is as high as possible. OPC cannot influence what is being done and how well the schedule is filled, since it is the operating specialties that act as clients who order the services from OPC. The main clients of OPC are:

- Ear, Nose and Throat department (ENT)
- Neurosurgery department;

- Obstetrics and Gynecology department;
- Ophthalmology department;
- Oral surgery department;
- Orthopedics department;
- General surgery department.

Operation planning is first done by client departments and then adjusted at the planning conference the day before the actual operations (step a5 in the activity flowchart, Figure 1), when the plan is finalized in terms of which operations will be carried out in which rooms the following day. There are several factors that affect the planning, such as the availability of operating surgeons and special equipment. In addition, some operations must be carried out in a specific room, and some operations require that patients stay overnight at the post-operative care unit and those beds are limited in number.

During the actual operation day, the schedule often needs to be readjusted, as not all operations take exactly as long as planned and sometimes emergency operations need to be carried out at the expense of elective ones. This can result in operations changing rooms or even result in cancellations.

During an earlier internal study, a number of problem areas and improvement possibilities in OPC were identified. These included the following:

- large variations in the operation schedules, which means unnecessary variation in workload at OPC;
- patients are poorly prepared for operations (missing information);
- the first operation starts very late (85–95 minutes after the operation team starts its shift);
- operations are delayed;
- long changeover times (the time between the finish and start of two consecutive operations);
- low utilization of ORs (the average utilization is as low as 34% when measured as the time between 'operation start' and 'operation finished' versus the total available time).

It is mainly elective surgery that has the most problems as mentioned above, emergency surgeries work well as they have dedicated rooms and operation teams. Another problem area is the post-operative care unit, which by some staff members was reported as overloaded from time to time.

3. Methodology

The purpose of this work is twofold as previously stated. The first and also overall goal of the study is to explore the usability of simulation as a tool to analyze complex healthcare environments, since the use of simulation in Swedish healthcare is not widespread and not well documented. Second, the simulation modeling was used to get answers to specific questions regarding proposed changes in the operating department:

- investigating an experienced bottleneck at post-operative care, which had not been confirmed by data analysis;
- evaluating a couple of simple, proposed solutions to the post-operative bottleneck problem – will changing the LOS or having an earlier start for some operations alleviate the problem?
- how does the optimal allocation of OR resources to the OPC client departments look like?

Discrete-event simulation was chosen as the method for this analysis. The choice of simulation was primarily based on the fact that OPC can be seen as a queuing system where patients queue in order to utilize the operating resources. There exists also a certain degree of stochastic behavior in the system, since the operating times are unpredictable. Simulation also offers the possibility to visualize new planning scenarios, which in this case is most important. Simulation also allows the dynamics of a system to be analyzed. In this case, the patient load varies from day to day, creating a dynamic system.

During the work, several models were built with an increased level of complexity. The first model in the pilot study represented only the flow through the post-operative care unit, the second model also included the patient flow through the operating theatres, and the final model in the main study also included the logic for planning the operations, thus adding much complexity to the model. The preliminary results of this work have been reported in [19].

To get the model and its results accepted in the organization, representatives of all operating specialties were involved in the model building process, which helped in validating the model and also increased the model's credibility. Earlier research shows that this is important if the changes that, according to the simulation, result in good patient flow and resource utilization are to be implemented in the real world [20, 21]. Another factor that increases the credibility of the model is that one of the co-authors possesses an extensive amount of knowledge about the modeled system and the theoretical framework that governs it.

4. Pilot Study

Since simulation as a method was unfamiliar to the operating department, it was decided to start out with a pilot

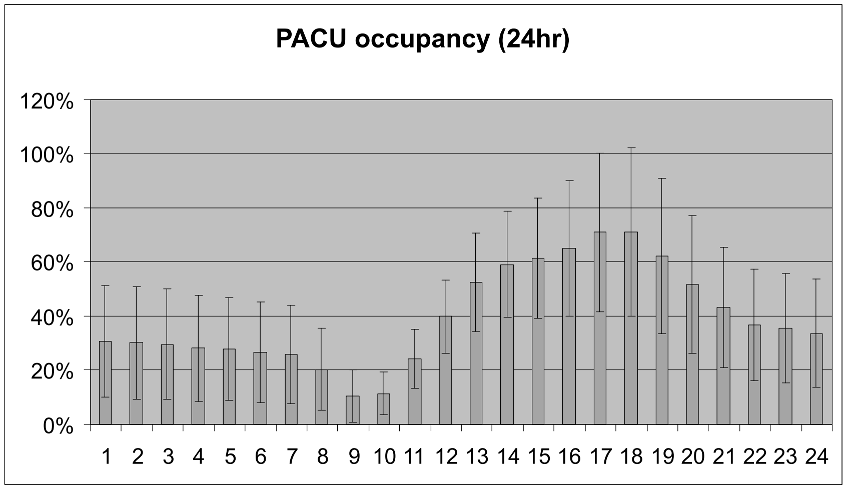

Figure 2. Hourly PACU occupancy, pilot study (average and standard deviation)

study, building a simple model around the problem with the post-operative care unit. The first version of the model was a trace-driven simulation based on historical data patient records. The goal was to validate the model results against the data, confirm the experienced problem at the post-operative care unit, and also do a first evaluation of simulation as an analysis method, as this was the first time simulation modeling has been used in this particular department.

The simulation model was built using the commercial simulation software ARENA [22] and included patient flows through pre-operative, perioperative, and immediate post-operative care episodes. Since the model did not include logic for operation planning and scheduling, the model was run with actual schedules for the year 2005. Outputs from the model included the utilization of post-operative care units, including counting the number of occasions when the care unit was full. For the PACU, both overall utilization and hourly utilization was recorded. It was necessary to look into hourly utilization in order to determine when during the day the PACU was most occupied and thus when there was a bottleneck to the whole flow.

During the validation of this model it was discovered that there was a discrepancy in what was considered to be the maximum capacity of the PACU. Originally it was set to 15 beds, but as it turned out later, only 12 beds were fully staffed, and 3 additional beds were used as temporary holding beds in case there were more than 12 patients coming into PACU. Therefore we used 12 beds as 100% capacity during normal the opening hours of 08:00–21:00.

Overall utilization turned out to be quite low – around 50%, even if looking at the utilization during weekdays between 08:00 and 21:00 only. Looking at the hourly utilizations (see Figure 2), there are peak loads during afternoons, and this phenomena during some weekdays (see Figure 3) creates the feeling among the employees that there is a capacity problem at the PACU.

The simulation model confirmed the bottleneck at the post-operative department. The graph in Figure 4 shows the number of busy beds during a 10-month period.

The limit of 12 busy beds was reached 308 times during the simulated 10 months. After the bottleneck was confirmed, a couple of simple solutions were tried to see if there was anything that could be done to alleviate the problem. For instance, shortening the LOS in the post-operative department to see how much shorter it has to be to make the problem disappear. So for every 5% decrease in LOS, a simulation run was carried out and the results showed the number of times the capacity limit was reached. The results of those experiments are displayed in the Figure 5. It was concluded that for capacity problems to disappear it was necessary to shorten the LOS by around 50%, which was not realistic.

When investigating the utilization of post-operative beds, it was noticed that most of these capacity problems occur on afternoons around 4–5 pm. So another, quite reasonably sounding, idea was to see what happens if starting times for operations in two rooms were changed so that they started one hour earlier. It was expected that this simple change could shift the peak load somewhat and the post-operative unit would not experience the same capacity problems any more. The results from the simulations showed that not much would change. Bed occupancy showed approximately the same pattern as before and the limit of 12 beds was reached about the same number of times. Both time and money was saved here since the post-operative department did not have to implement a change that would not give the expected results.

It was clear at this point that none of the proposed solutions above would solve the post-operative bottleneck problem. The solution to it was probably to be found in the

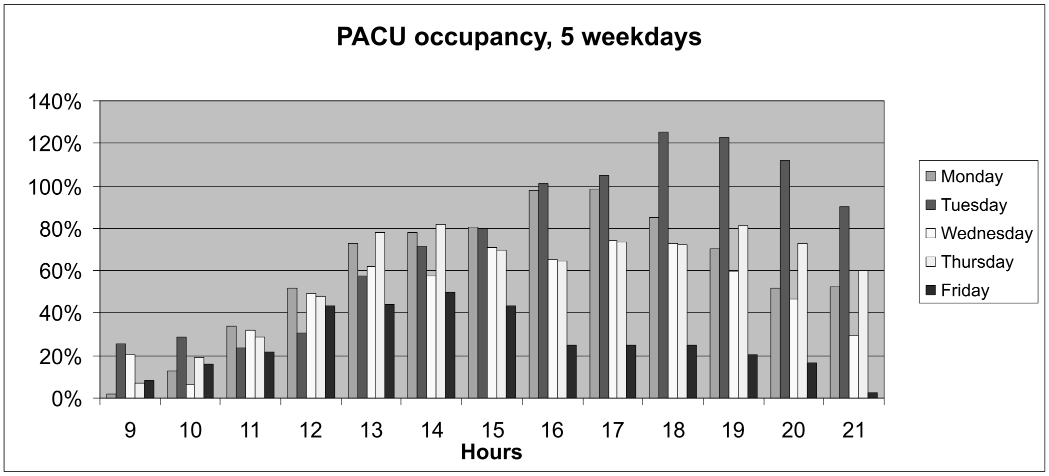

Figure 3. PACU occupancy variation during weekdays

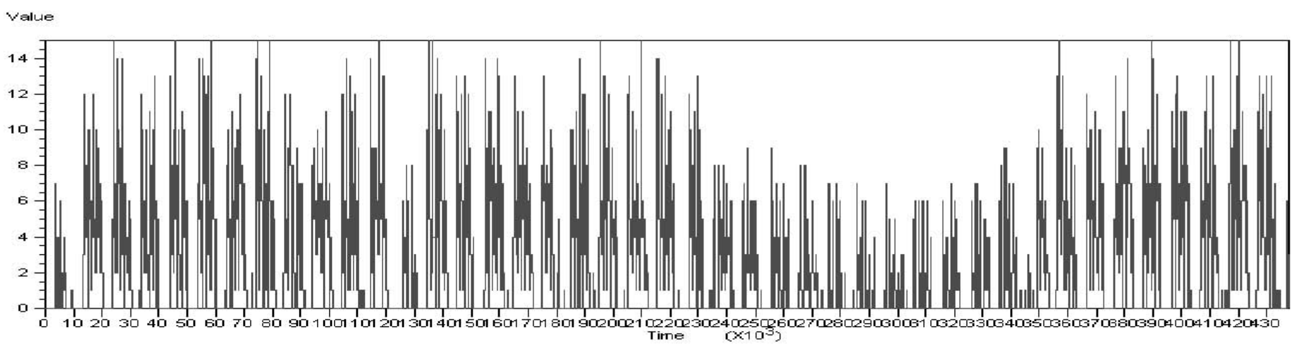

Figure 4. Number of busy beds in PACU during a 10-month period

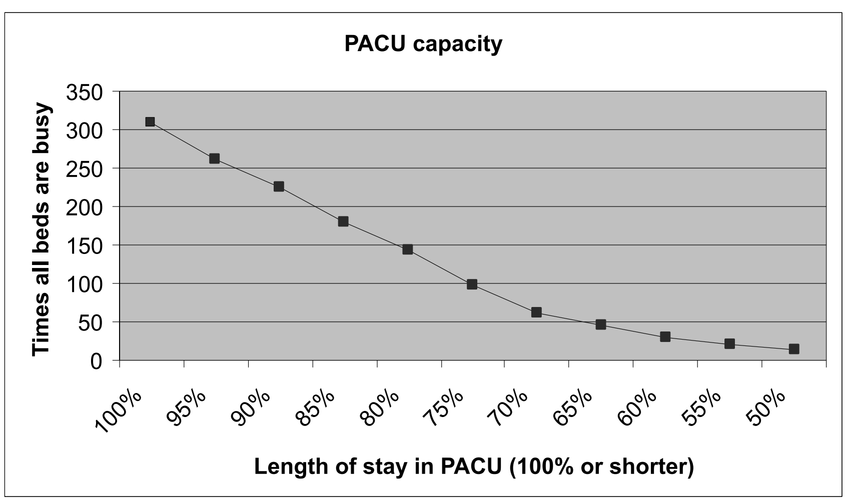

Figure 5. Capacity limit and LOS decrease factor (100% = original LOS)

Table 2. Selected versus total procedure codes

	Elective inpatient	Elective outpatient	Emergency inpatient	Emergency outpatient	Total
Total number of analyzed procedure codes	384	283	362	114	1,143
Number of selected procedure codes	36	47	24	4	111
Ratio of selected codes (number of)	9%	17%	7%	4%	10%
Total patient time	541,405	404,654	301,142	37,469	1,284,670
Patient time for selected codes	296,509	315,791	121,473	8,439	742,212
Ratio of selected codes (time)	55%	78%	40%	23%	58%

way procedures are sequenced in the OR on a given day, as indicated also by Marcon and Dexter [9]. The model was then extended to include the logic for planning and sequencing the procedures, thus allowing testing of several ways to solve the post-operative bottleneck problem.

5. Main Study

In order to be able to test even more alternatives in a realistic way, a flexible logic for planning of the operation schedules needed to be included in the model (the pilot study model was running with the actual schedule from 2005). This new model would also allow the number of available ORs to be changed and the reallocation of operation time to operating specialties in order to achieve better utilization and better fit to the actual demand.

5.1 Data Collection and Input Analysis

Data about time durations on surgical procedures and LOS in the PACU was collected from the registration system FENIX using data from the year 2005. The procedure codes that represented most common procedures were selected for the analysis covering 95% of all procedures, thus eliminating procedures that were very short and very seldom done. Nevertheless, many procedures in the selected data were performed less than five times per year. In total, 1,143 surgical procedure types were analyzed, divided into seven operating specialties (main clients of OPC) and further divided into four types of care (inpatient elective, outpatient elective, inpatient emergency, and outpatient emergency). Each procedure type thus has a main procedure code associated with it as well as a type of care code (1–4). The total amount of procedures done in 2005 was 12,955, and the selected 1,143 procedure codes represented 12,147 procedures.

For each of the 1,143 procedure codes the following characteristics were analyzed and were used to drive the model logic:

- Number of procedures to be performed per year.
- Type of care.
- LOS (patient-time), generated from probability distribution.
- What is the latest time at which the operation can be performed?
- In which ORs can the procedure be performed (priority)?
- Need for special equipment or instruments.
- Are there specific weekdays upon which this procedure has to be performed?
- Does the patient need pre-operative care at the department?
- Does the patient need post-operative care at the department? Will the patient need to stay overnight?
- LOS in pre- and post-operative care, generated from a probability distribution.

Due to the large number of infrequent procedures, the codes were grouped together only leaving out certain, selected large volume codes and grouping the rest by specialty and type of care. This grouping was done after the individual characteristics of the separate codes listed above were specified, so that the group had an accurate representation of those characteristics. Table 2 shows the number of selected codes per type of care and illustrates clearly that a small number of procedures (10%) contribute to a large volume of patient-time (58%).

A lognormal distribution was found to be the best fit for most of the procedure codes for both patient-time in the OR and also the LOS at the PACU. Each of the selected codes, as well as the aggregated groups, were assigned specific probability distributions for the generation of OR patient-time and post-anesthesia time.

Other input parameters not directly related to procedure codes include the following.

- For each of the 18 ORs:
  - opening hours, lunch breaks, changeover times (including a special schedule for emergency rooms);

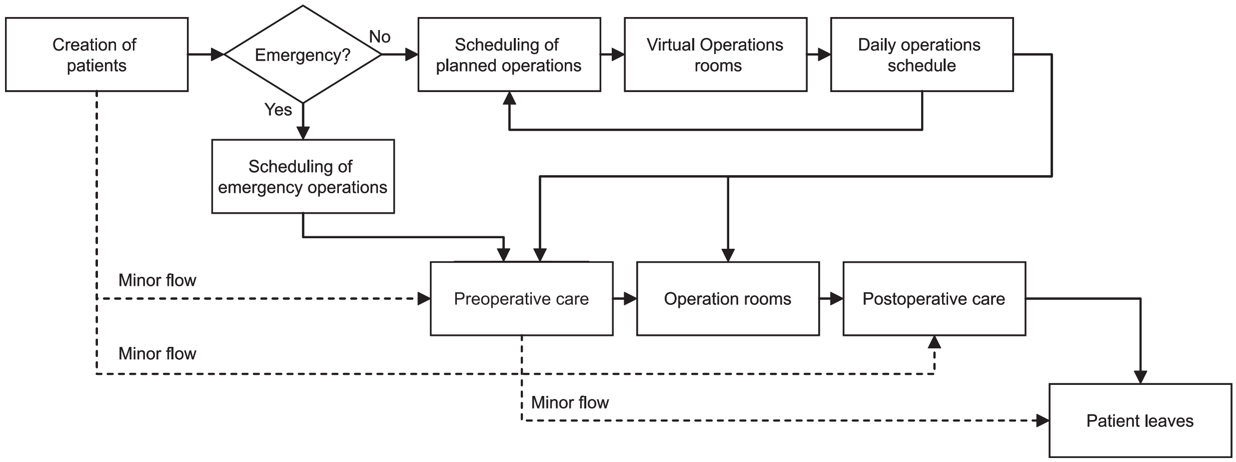

Figure 6. Simplified conceptual model

- allocation of block time to operating specialties.

- For each of the PACUs:
  - opening hours, number of staffed beds, number of temporary holding beds.

Later, the same analysis was carried out for data from the year 2007, and the inputs were adjusted accordingly for the latest set of experiments described below.

5.2 Model Design and Validation

Figure 6 shows the simplified conceptual model used in the main study. Below is a brief description of model logic.

The model starts out by defining a demand of different surgical procedures, which is derived from actual patient data and then randomly generated in the simulation model. Generated patients, when admitted to surgery, are scheduled for operation by the operation planning algorithm, which tries to minimize waiting time while at the same time trying to put together as efficient a schedule as possible given certain constraints.

Planning the operation schedule is the most complicated part of this model. We use a kind of a meta-model inside the simulation model. The next day's list of planned operations for each room is generated by simulating the next day during the current day in the 'virtual OR', using the same constraints that would apply the next day, only without a stochastic element.

Scheduling is done by selecting the first best OR for the case that is first in queue, using the list of priorities for the ORs. If the first case in the queue cannot be performed, then the next case is chosen from the queue for evaluation. The queue is sorted with the most urgent cases first. The urgency, or deadline for performing the procedure, is determined by the time the case was generated in the model (arrival time) and a time interval, specific to this case, that is generated from a probability distribution specified for each case. For instance, most planned cases can be performed at the earliest a couple of weeks from the time the decision about the operation is made (arrival time) and no later than three months after it, which is the limit of 'maximum waiting-time guarantee' in Swedish healthcare.

The constraints that are taken into account when scheduling planned procedures are:

1. is the particular OR allocated to the specialty performing the operation?
2. is there enough time left to perform the operation?
3. if special equipment is needed, is it available?
4. can this procedure be performed during this particular weekday?
5. in case the patient will need to stay in the PACU during the night, is there a bed available?

Thus, the model assumes that staff will be available to perform this operation on a given weekday. The determination whether there is enough time left to perform the case is based on the predicted length of the procedure. We use historical data to determine the median time for this particular case type and add 10% in order to calculate the predicted time in the model. Most operation theatre management information systems use a similar approach, based on mean or median time when suggesting a predicted time for a particular case in planning an OR schedule.

One could argue that perhaps a more advanced algorithm should be used when making the OR schedule, but we wanted to mimic real-life planning as closely as possible. There is also evidence that simple online bin-packing

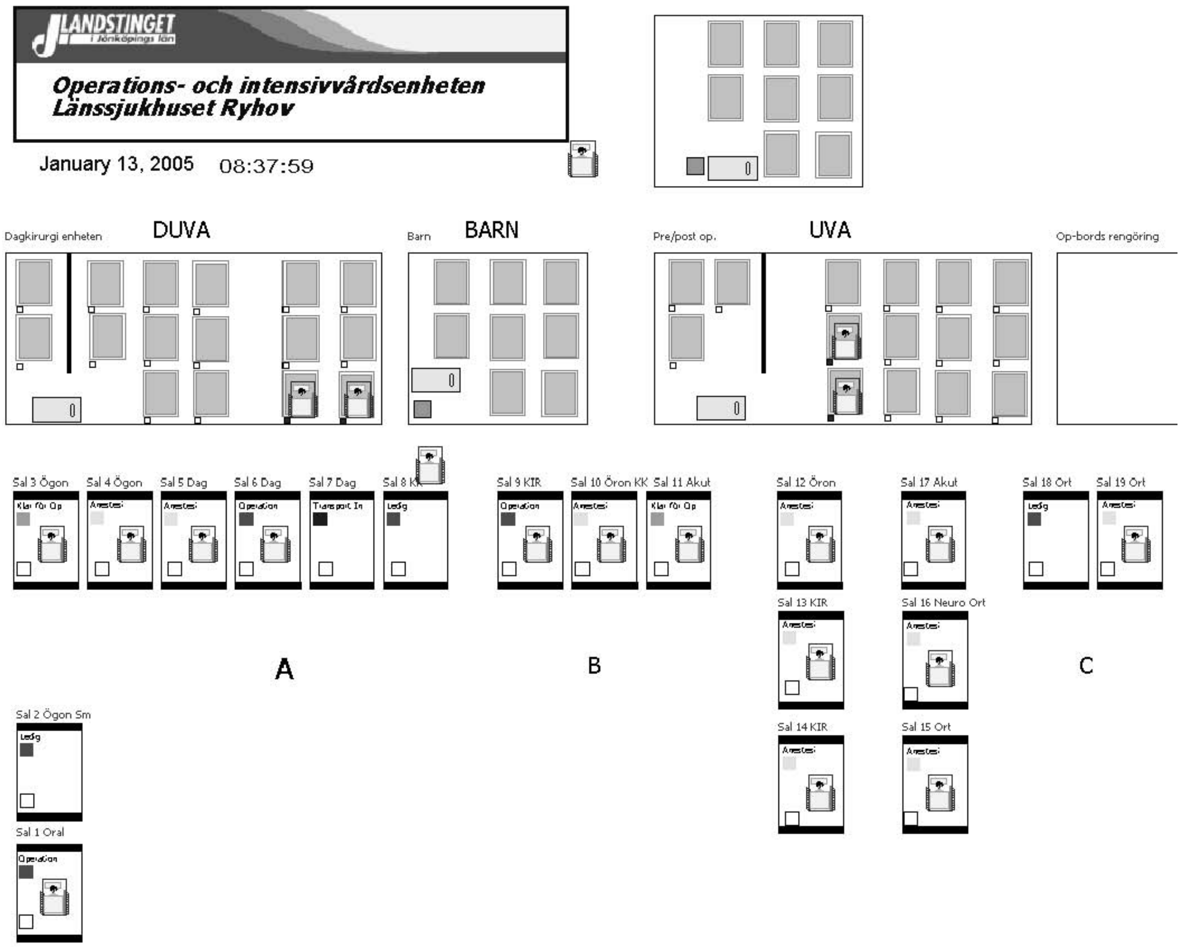

Figure 7. Visual layout of the simulation model

algorithms like this perform just as well in terms of the resulting utilization [13].

For emergency operation scheduling, the model logic is slightly different. Emergency cases are also assigned a randomized deadline, which is of course much shorter than for planned cases, and ranges from 0 to several hours, depending on a case type. Then the case is evaluated against available emergency rooms and staff. There are always two emergency rooms available, but they are not always staffed. For instance, during the night only procedures that cannot wait until morning are performed by an emergency team that is on call. During the day both emergency rooms are staffed, and in cases where all emergency resources are already busy, and we have a case that cannot wait until they become available, the emergency case is performed in one of the elective ORs, delaying the originally planned cases in that room.

After the case is scheduled, patients can then go through pre-operative care, the actual operation and thereafter post-operative care, which is the most common flow, but there are also minor flows that take other paths through the system that are also accounted for in the model. Whether a patient for a particular case requires pre- and post-operative care in OPC is determined by a probability distribution derived for each case type.

The PACU operates very much the same as in the pilot model. For the inpatient PACU (UVA) there is enough staff to take care of 12 patients, but in total there are 15 beds, which means that there are three extra beds, so-called holding beds. If a new patient arrives and there is no room among the 12 staffed beds, one of the recovering patients is moved to a holding bed and the model results show how often this happens, as well as how long a patient stays in the holding bed.

The model was implemented in ARENA software, and had a visual presentation that was easy to recognize for all involved parties (see Figure 7). The layout represents all of the ORs, and also the pre- and post-operative units. This visual aspect of the model is important because it also helps to build credibility and increases the acceptance of the results, when one can actually see what is going on in the department day by day, hour by hour. If needed, the model can be stopped and one can examine the characteristics of the particular patient, which can further help in developing an understanding of the patient flow.

Outputs from the model include the following:

Grouped by speciality and type of care:

- Total number of patients admitted to surgery,
- Number of the patients on the waiting list,
- Number of patients not cared for in time
- Average delay for patients not cared for in time (hours)
- Number of case cancellations
- OR utilization (grouped by speciality and by room)
- Number of PACU staffed bed shortages (inpatient and outpatient PACU)
- Number of times all PACU beds are full (inpatient and outpatient PACU)

The number of patients on the waiting list was monitored at the end of each simulated week, enabled in order to assess the patient queue development during the simulated time.

The ARENA simulation model was validated using several validation techniques. First of all, the conceptual model was thoroughly discussed during the meetings with OPC staff and representatives from the operating specialties. This ensured that the right scope and level of detail was chosen for the purpose of simulation. The model was also validated against historical data. A number of performance measures were compared from the model and the historical data extracted from the FENIX system. These performance measures included the number of procedures performed for each procedure type in the model, the utilization of ORs and post-operative care units, the number of cancelled cases, etc.

In order to validate the most complicated part of the model – the scheduling of operations – the number of real performed operations in each OR, separated into operating specialty (clinic) and different types of care was compared with the model data. Table 3 shows the complete table that was used for this comparison. For each OR, there are two columns, one with data from the model (M) and one from the FENIX system (F). The rows in the table represent operating specialties (from General Surgery down to Ophthalmology), further subdivided in the type of care (1 – planned inpatient, 2 – planned outpatient, 3 – emergency inpatient, and 4 – emergency outpatient).

For the most of the cases, the model follows the real allocation pattern quite well, for instance, room 8, Obstetrics and Gynecology, type 1, is a quite good fit. One major difference is that the model is little less flexible, which is illustrated by many cells where the FENIX data has a few cases but the model has none, e.g. room 11, Orthopedics, type 3. While most of the Orthopedics emergency cases are performed in room 17, a small number of them were also done in room 11, while the model logic was stricter in following the priority list and placing all cases in room 17. Compared with the total number of operations in the Orthopedics cases, this deviation is quite small, 17 cases in room 11 compared to 675 in total.

The same applies for General Surgery, type 3, where the model has placed all emergency operations in room 11, while in the real world some of these emergency operations have been performed in elective rooms (8–10, 13, 14), probably due to urgency and unavailability of emergency rooms at that particular time. In short we can conclude that the model has incorporated much more strict rules to OR allocations than are followed in the real planning. This is of course a conscious choice of making the model follow the rules. The new allocation procedure should not need to bend the allocation rules in order to create a feasible plan.

Some of the output performance measures are difficult to compare with historic data. For instance, the number of times a holding bed has to be used in a PACU (i.e. a new patient arrives and all 12 ordinary beds are full) should be higher in the model, since its logic does not include the extra effort that is made in reality to free one bed in advance, and therefore historic data does not always show occupancy that exceeds 12 when in fact it should have. The number of cancellations is another figure with quite large discrepancies against actual data from the real system. In reality, cancellations depend not only on the fact that actual time in the OR turns out to be much longer than predicted, but also on the patient and other circumstances that are not included in the model. Planning-related cancellations were estimated to be around 2–3% in reality. The model in fact produces a much higher rate of cancellations, and this is mainly because the planning logic uses a strict median (median + 10%) as the planning time. This was a deliberate decision. We know from other research that, apart from procedure type, at least two other factors influence the procedure time significantly – the surgeon carrying out the operation and type of anesthesia [23].

5.3 Experimental Design

Experimental design aims at creating a plan for experiments that minimizes the cost of experiments (the number of simulation runs and computer time), while maximizing the usefulness of the results. In total, four different experiments were executed, testing four different ideas to find the optimal allocation of OR resources and increase the utilization of the OR.

In experiment 1 a new allocation of OR resources was tested in order to find an allocation that would better fit the

Table 3. Operation planning logic validation results (all seven operating specialties and all ORs)

Number of operations		Operation room																																					
Clinic	Type of care	1M	1F	2M	2F	3M	3F	4M	4F	5M	5F	6M	6F	7M	7F	8M	8F	9M	9F	10M	10F	11M	11F	12M	12F	13M	13F	14M	14F	15M	15F	16M	16F	17M	17F	19M	19F	Total M	Total F
General Surgery	1	0		0		0		0		0	7	0		0		2	13	68	30	276	295	0	35	0		349	357	262	235	3		0		0		0		960	972
	2	0	1	0		0	1	0		300	331	0	1	16	50	0	2	40	20	39	24	0	7	0		17	24	33	14	0		0		0		0		445	475
	3	0	1	0	1	0		0		0		0		0		0	4	0	4	0	9	504	446	0	1	0	32	0	21	0		0	1	0	4	0	1	504	525
	4	0		0		0		0		0		0		0		0		0		0		18	9	0		0	1	0		0	1	0		0	2	0		18	13
Obstetrics and Gyn.	1	0		0		0		0		0	3	0	2	0		224	215	34	54	0		0	10	1		0	3	0		0		1		0		0		260	287
	2	0		0		0		0		55	75	46	45	0		277	319	95	34	0	1	0	6	0		5	1	0		0		0		0		0		478	481
	3	0		0		0		0		0		0		0		0	33	0	6	0	2	215	170	0		0	3	0	3	0	1	0		0	7	0		215	225
	4	0		0		0		0		0		0		0		0	3	0		0	1	29	22	0		0		0		0		0		0		0		29	26
Orthopedics	1	0	1	0		0		0		0		0	2	0		0		0		0		0	1	0		1		0		263	227	132	157	0	33	322	309	718	730
	2	0		0		0		0		121	129	678	791	1	10	0		0		0		0		0		0		0		82	12	28	1	0	42	82	6	992	991
	3	0		0		0		0	1	0		0		0		0	1	0		0		0	17	0		0		0	3	0	26	0	38	667	544	3	45	670	675
	4	0		0		0		0		0		0	3	0		0		0		0		0	7	0		0		0	1	0	5	0	2	212	220	0	3	212	241
Neurosurgery	1	0		0		0		0		0		0		0		0		0		0		0		0		0		0		0	1	100	90	0	1	1	1	101	93
	2	0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0	0
	3	0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		5	14	9		0		14	14
	4	0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0	0
Oral Surgery	1	47	45	0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		0		47	45
	2	328	335	0		0		0		0	3	0		0		0		0		0		0		0		0		0		0		0		0		0		328	338
	3	5	17	0		0		0		0		0		0		0		0		0		14		0		0		0		0		0		0		0		19	17
	4	0		0		0		0		0		0		0		0		0		0		0	1	0		0		0		0		0		0		0		0	1
ENT	1	0		0		0	1	0		0		0		68	112	0	1	78	74	0		0	4	334	260	1		0	1	0		0		0		0		481	453
	2	6		0	1	0		0		149	46	13	1	411	399	4		78	141	0	2	0	2	158	239	5		0	4	0		0		0		0		824	835
	3	0		0		0		0		0		0		0		0	1	0	2	0	1	48	43	13	20	0	2	0	1	0		0		0	2	0		61	72
	4	0	1	0		0		0		0		0		0		0		0	8	0	1	23	18	0	4	0		0		0		0		0	3	0		23	35
Ophthalmo-logy	1	0		3	4	4	20	166	155	0		0		0		0		0		0		0		0		0		0		0		0		0		0		173	179
	2	0	2	716	578	772	895	700	655	0		0		0		0		0		0		0		0		0	1	0		0		0		0		0		2,188	2,131
	3	0		0		0	3	13	10	0		0		0		0		0		0		0		0		0		0		0		0		0		0		13	13
	4	0		0		0	1	4	3	0		0		0		0		0		0		0		0		0		0		0		0		0		0		4	4
Total		386	403	719	584	776	921	883	824	625	594	737	845	496	571	507	592	393	373	315	336	851	798	506	524	378	424	295	283	348	273	266	303	888	858	408	365	9,777	9,871

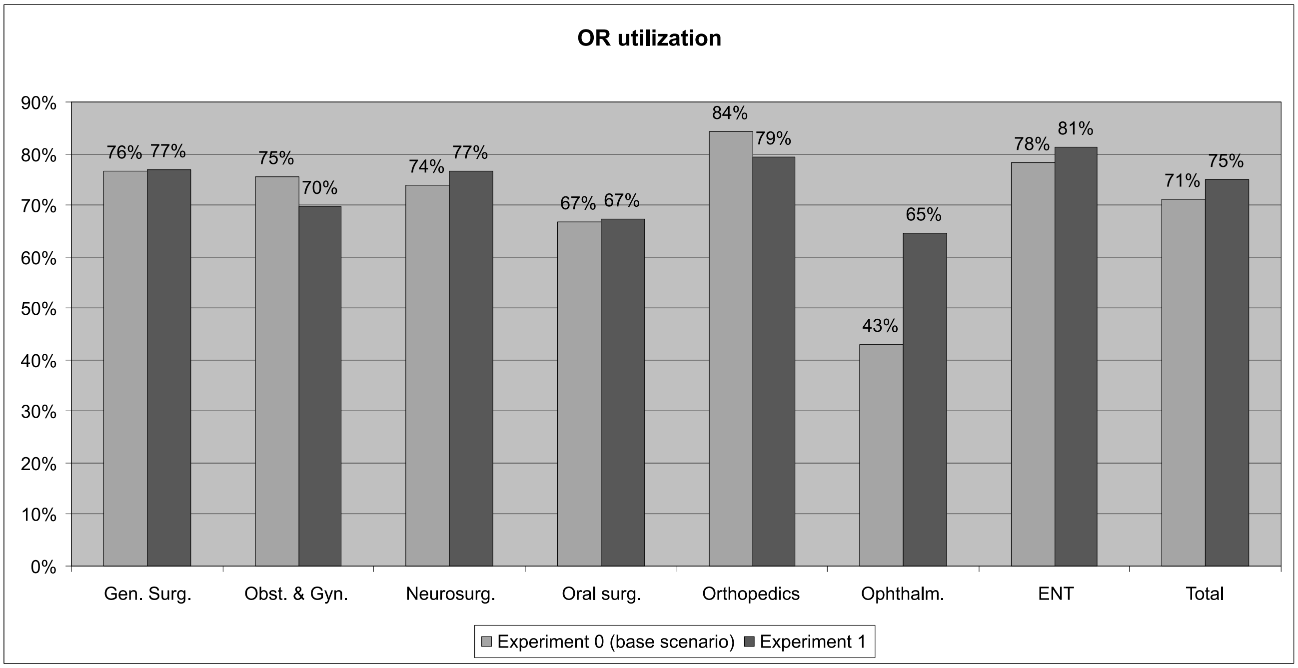

Figure 8. Utilization of OR resources

actual demand and result in an evenly distributed utilization of OR rooms among operating specialties. This meant no other changes than taking some of the OR time away from specialties with low utilization and giving more to those specialties that have higher demand and high utilizations.

Experiment 2 was a simulation of a prospective scenario where ophthalmology would move out most of its procedures from OPC and use OPC resources only for patients that are under general anesthesia. This means that two of the ORs could be closed and two others (9 and 10) rebuilt as one large room, thus enabling additional types of procedures to be carried out in that room.

As described above, inpatient and outpatient flows are currently separated in OPC, and all outpatient operations are carried out in three dedicated ORs. Experiment 3 was a test of whether allowing a mixture of inpatient and outpatient surgery in all rooms would lead to better utilization of resources. The idea behind this is that outpatient procedures are in general shorter, and mixing longer and shorter procedures would allow the daily schedule in all rooms to be filled better than in the current situation.

Experiment 4 proposes a more radical change to the organization of the ORs. Instead of operating in 18 rooms, each being open from 07:45 to 16:30 with a lunch break, the experiment tested the set up of two six hour shifts without a lunch break to create a full work day between 07:00 and 19:00. The idea behind this was that it is easier to schedule for 12 hours instead of for four (before or after lunch break).

These experimental ideas were discussed and selected at the operating council with all operating specialties present. The current situation or the base scenario was simulated first and will be referred to as experiment 0.

5.4 Results

The main study involved a considerable development of the model, which then included logic for scheduling operations and detailed input data regarding surgical procedures. This version of the model allowed for the testing of larger changes in the operating department and now the focus shifted from solving the bottleneck problem in the post-operative department to allocating operating department resources to better fit actual demand and test several other reorganization alternatives. The model was run for 20 replications for each of the experiments and a large number of output statistics were collected. Each run started with the generation of a queue of patients waiting for operations that corresponded to a two-month volume of patients for each of the operating specialties. The most important results of the experiments are presented below.

The goal of experiment 1 was reallocation of OR resources to achieve a better fit to actual demand. The results in terms of utilization of allocated resources can be seen in Figure 8. The biggest change is for the ophthalmology department, which is using only two ORs instead of three. The orthopedics department got more block time allocated, since utilization levels approaching 85% and

Table 4. Results from the experiments

	Experiment 0	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Results					
Total number of patients admitted to surgery	9,224	9,327	7,930	9,330	9,358
... among those elective patients	7,339	7,451	6,059	7,459	7,487
Patients on the waitinglist (% of total number)	4.1%	2.0%	2.5%	2.1%	1.2%
Patients on the waitinglist	303	152	151	154	89
Elective patients not cared for in time	995	1,072	945	1,081	872
... with an average delay (hours)	66.87	88.38	80.97	111.86	76.54
Emergency patients not cared for in time	396	102	366	383	113
... with an average delay (hours)	6.81	6.63	6.01	5.60	3.58
Resource utilization					
Allocated time (hours per week, elective)	566.00	546.00	485.00	543.75	546.00
Utilization (%)	**71%**	**75%**	**77%**	**76%**	**76%**
Number of cancellations (bad planning)	679	664	546	607	488
Cancellations (%)	**9.2%**	**8.9%**	**9.0%**	**8.1%**	**6.5%**
Allocatied emergency time (hours per week)	196.3	196.3	196.3	196.3	207.0
Utilization emergency resources (%)	**65%**	**65%**	**65%**	**64%**	**61%**
Postop					
Number of staffed bed shortages (inpatient PACU)	129	175	139	147	115
All beds full (inpatient PACU)	0	1	0	1	0
Number of staffed bed shortages (outpatient PACU)	1	2	0	0	0
All beds full (outpatient PACU)	0	0	0	0	0

higher in our case can generate an increase in overtime usage (or an increase in queues for operations). The result is higher and more even utilization of resources among the operating specialties.

The summary results of all four experiments can be seen in Table 4. It can be concluded that all four experiments improved the throughput slightly (except experiment 2, where a large group of patients was moved from OPC altogether) and decreased the number of patients on a waiting list at the end of the simulation.

Waiting list dynamics for each of the operating specialties are shown in Figures 9 (for experiment 0) and 10 (for experiment 4). The model was run for 33 weeks where OPC was operating at 100% capacity, as is the case in reality during a normal year. During the remaining 19 weeks OPC's capacity is lower, due to vacations and holidays, which means that operating at 100% capacity OPC should be able to decrease the queues in all specialties. It can be concluded from Figures 9 and 10 that the OR setup in experiment 4 is capable of decreasing waiting lists at a much higher rate than the current setup, particularly for general surgery and orthopedics. Experiment 4 was also better than the rest of the alternatives in terms of taking care of patients within the time limits that were set for each of the procedures. The overall utilization of OR resources increases in all four experiments and the number of cancellations is significantly lower in experiment 4.

It can also be concluded that none of the tested alternatives significantly improve the situation at the inpatient PACU. The hourly PACU occupancy pattern is slightly improved, leveling out the peak load in the afternoon. This can be explained by the fact that the model is selecting the first patient of the day regardless of the predicted procedure time and not the most difficult or longest case as was often the case in reality. Figure 11 displays the hourly occupancy in experiment 1, which can be compared to Figure 2 in the pilot study.

6. Conclusions and Discussion

The simulation experiments show that with implementation of the proposed changes it is possible to achieve better resource utilization. Experiments 3 and 4 show that the proposed changes result in a greater flexibility in scheduling operations (e.g. fewer cancellations).

One of the major contributions of this paper is the set up for OR utilization planning that is built into the simulation model. This has the characteristics of a meta-model, where the planning activity is in fact a simulation model inside the model that creates a valid plan for the next day's operations. This is a novel and innovative approach that could inspire other researchers in the field to also try this simple but efficient set up.

If the goal of the simulation project is to evaluate alternatives for implementing change (changing the real system), the model and its results must be convincing to all involved parties. The model results have to become more objective grounds for discussion than just intuition

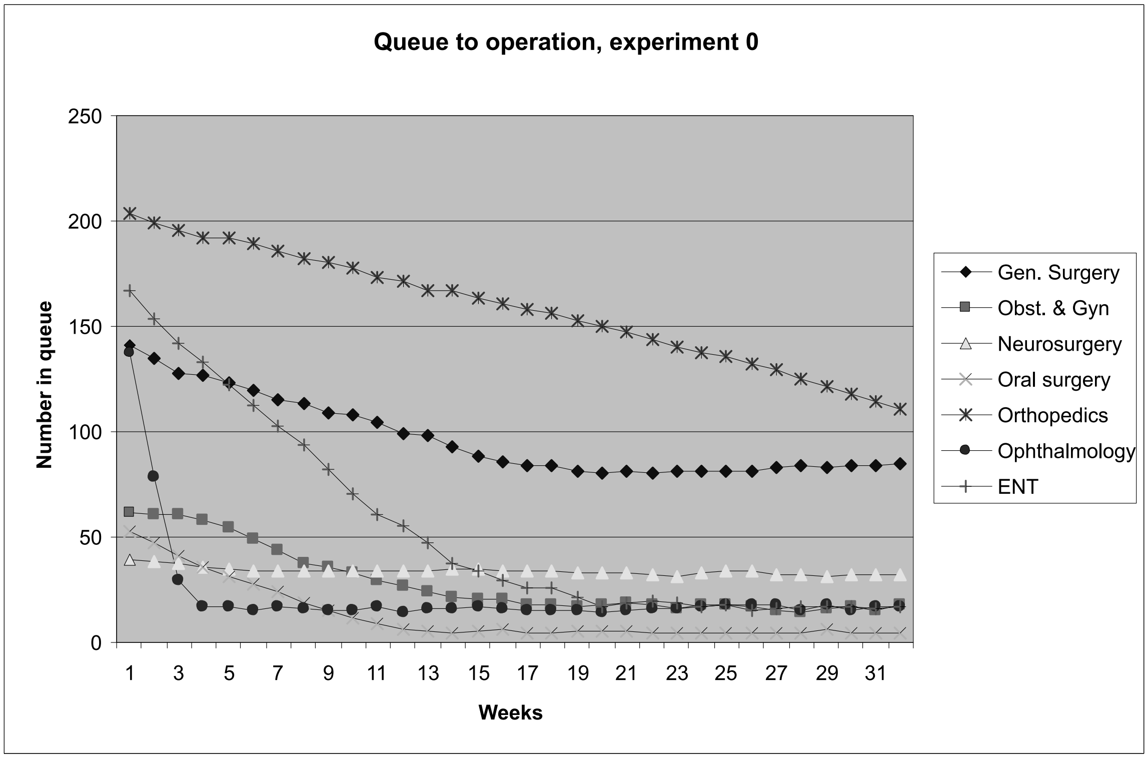

Figure 9. Waiting-list dynamics, experiment 0

and loose thoughts. This means that the model must have high credibility, even in situations when the results show 'unpleasant' things. High credibility is achieved through model validation, client involvement, and the good reputation of the method and analyst, but it is not a guarantee that the results will be accepted and implemented. In this project we spent quite a lot of time on validation and client involvement, thus helping increase the credibility of the results.

During the experimentation phase, the modeling group met a number of challenges, for instance, how do we know when the optimal result is reached in terms of operation planning? What is the optimal utilization of ORs? What output data should be chosen from the simulation model? Finally, the following criteria were chosen as the most important for a 'good solution':

- all operations performed (no patient queue build-up);
- all operations performed within given time limits;
- high (80–85%) utilization of resources (ORs);
- few cancellations
- post-operative care unit not overloaded.

All four experimental ideas tested in the model have a potential for implementation. At the time of writing this paper, actual plans are made to go further with testing re-allocation of OR resources similar to experiment 1. The goal is to find an allocation scheme that fits the current demand, taking into account actual patient queues in different operating specialties. Implementation of the ideas tested in experiment 2 was postponed partly due to financial reasons. Experiment 3 is part of a larger investigation about outpatient surgery and it is too early to say what impact the simulation results will have on the final outcome. What can be said is that simulation results alone did not convince the members of the operating council to go ahead with implementation of the proposed change in experiment 3. The results of experiment 4 have been presented to hospital management, since such substantial change would not only affect the operating department but also other departments in the hospital. This is also the reason why further investigation is required before implementation of this particular alternative. On the issue of implementation it can also be mentioned that the pilot study indicated that shortening the LOS alone will not solve the capacity problem at the PACU. This was taken into account by the staff working on the problem in the sense that several different measures should be taken in order to lessen the load in the afternoons. PACU occupancy is therefore no longer a problem at the department.

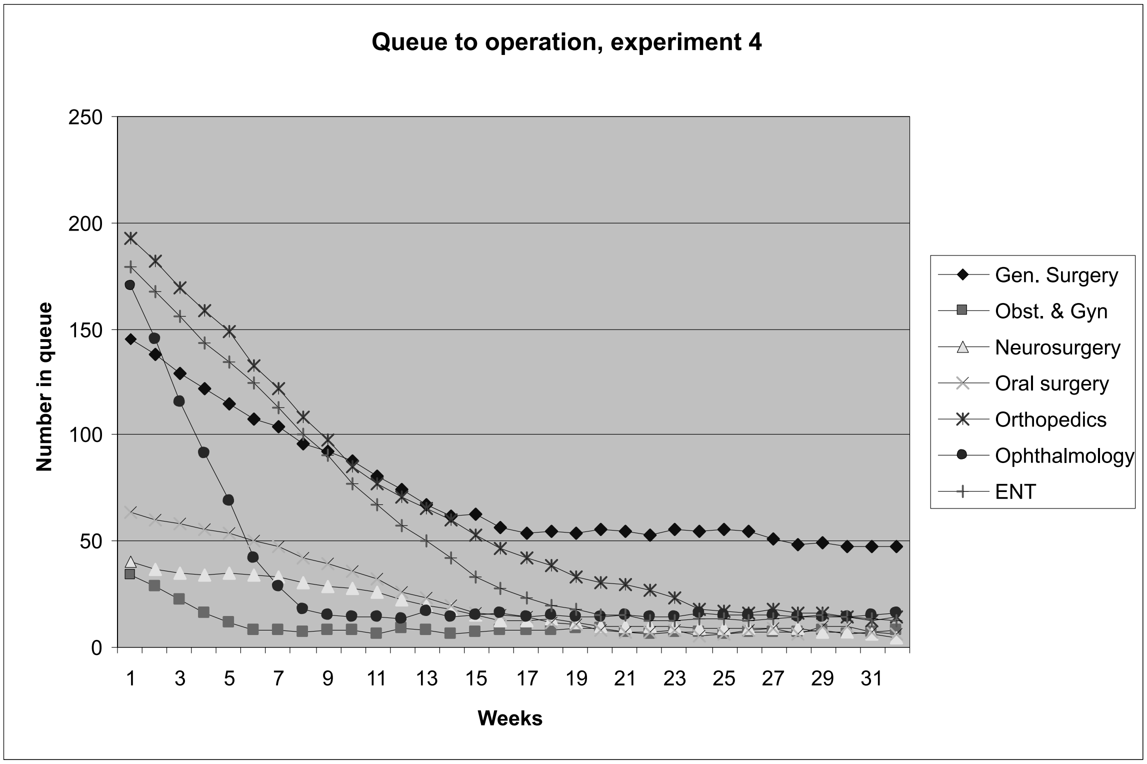

Figure 10. Waiting-list dynamics, experiment 4

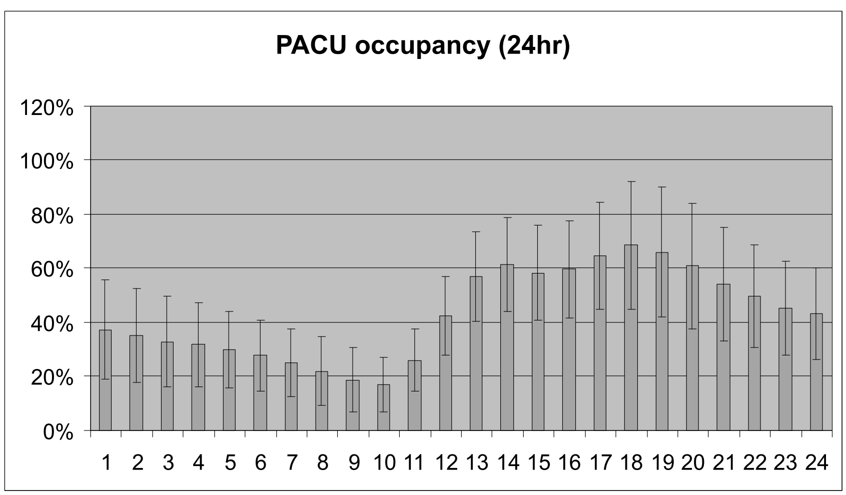

Figure 11. Hourly PACU occupancy, experiment 1 (average and standard deviation)

One of the goals of the study has been to evaluate simulation as a tool for the analysis of operating departments. The experiences using simulation can be summarized as follows. It takes a lot of time for the staff involved in the modeling process to learn and understand both simulation and their own processes. The model will never behave exactly like reality, and the modeling team needs to find the balance between a high level of detail and ease of handling the model. All important simplifications made in the model were discussed with OPC staff and operating specialties. One important simplification that raised a lot of questions was that the staff is not included in the model explicitly. This was done deliberately in order to keep the model as simple as possible. This can be considered as a limitation of the model, since all experimental alternatives should also be evaluated in terms of staffing possibilities. In the process of modeling the operating department, it was decided that the simulation model would first of all test different allocations of resources, such as ORs, instruments, and equipment. The staff is included implicitly, for instance, in requirements that certain procedures can only be performed on certain weekdays. In addition, certain equipment requires a certain competence, so when the model allows for five simultaneous radiology-supported procedures it also means that it is possible to staff accordingly. For more radical changes, like in experiment 4, if the simulation model results suggest that the experimental alternative should be implemented then further investigation will be carried out on possibilities to staff the allocation scheme tested in the model. Modeling work like this also requires large amounts of good quality data. Fortunately, the data available in the FENIX system did not contain too many errors. Nevertheless, some information that would improve the quality of the analysis was missing at this point. For instance, we did not have accurate data on current waiting lists for each of the operating specialties, and thus tested the model with a two-month queue for all specialties.

Even though this was the first simulation project at OPC, after gaining some experience it was easy to understand the methodology and the model, which enabled the testing of different solutions with simulation. Another advantage of simulation was that it was easy to visualize and gain acceptance and understanding for what is being done or should be done in order to improve the current situation. Simulation has the potential to save money, as we did not need to test solutions in reality that would not work. As one of the usual ‘side effects’ in simulation, in this project the modeling also forced us to go through the patient flow step by step and thus ‘discover’ possibilities for improvement. Working on this simulation model also helped everyone involved to get the same view of the process.

Currently, simulation modeling is seldom used in Swedish healthcare organizations. We have seen that there is a great potential in using simulation in studying patient flows and managing capacities. Is it going to be easier and more accepted to use simulation in the future? Is simulation going to be built into future IT-support systems, such as operation planning systems? For it to happen we still have a lot to do in order to show the real value of using simulation for analyzing patient flows in healthcare. This is also one of our goals for future work with this model; we want to see if the solutions that we find with the help of simulation can be implemented in reality and what the outcome is.

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