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MODELING AND SIMULATION OF CATARACT SURGERY PROCESSES

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ABSTRACT

In this paper, we present results of a simulation study that is related to cataract surgeries in an eye hospital in Germany. Cataract extraction is one of the most common and cost effective surgical procedures. We describe the process flow of the cataract surgeries in detail. We are interested in reducing waiting time of the patients and increase utilization of the operating rooms (OR). The data collection and input modeling effort using real-world data is described. The proposed simulation model using the SLX simulation package is presented. We discuss some suggestions for improvements based on the conducted simulation study. Possible extensions of the present research are also suggested.

1 INTRODUCTION

The costs of health care are rising in Germany. In 2006, these costs are more than three times the cost that appeared in 1980. There are major concerns regarding these cost which are caused by a changing demographic situation and by increasing expenditures for medical equipment, improved medical care, and more advanced pharmaceuticals. There is a certain pressure for managers of hospitals to improve their business processes. Hospital treatments are expensive. On average, about 300 Euros are spent for a patient per day to stay in a German hospital. The competition between the hospitals forces the management of hospitals to reduce the costs and to increase at the same time the patient satisfaction.

In this paper, we model cataract operations in an eye hospital. Cataract extraction is one of the most common and cost effective surgical procedures. There is an increasing pressure on eye hospitals because the threshold for a cataract surgery has reduced and the number of elderly patients who could benefit from surgery has increased (Tuft and Gallivan 2001). The cataract surgery is one of the standard operations of ophthalmology. An anesthetic is given to the patient to numb the eye. Then a small incision is made on the end of the cornea. The lens is crushed into pieces by specific sound waves. The pieces are removed from the eye. The new lens implantation is placed in the same area as the original lens. Because of the very small incision normally no stitches are needed to close it.

Over 650.000 cataract operations are conducted each year in Germany. In order to increase the overall productivity of eye hospitals, it is therefore highly desirable to improve the efficiency of the patient flows related to cataract surgeries.

Computer simulation of patient flows has been used as a tool to assess the effects of changes in the organization and management of hospitals (cf. Jun et al. 1999 and Ballard and Kuhl 2006 amongst others). In contrast to discrete simulation in manufacturing, simulation in hospital management involves more personal resources and also a larger level of variability (cf. Jun 1999 and Baumgart 2007). On the other hand, there are various similarities between simulation in these two domains. However, it seems that simulation models are more often used for operative decision-making in manufacturing.

To our best knowledge there is no detailed simulation model for cataract surgeries in an eye hospital. In two studies by Tuft and Gallivan (2001) and Comas et. al (2008), the authors discuss the more strategic question how to organize waiting list for cataract surgeries. However, because of shorter waiting times for cataract surgeries in Germany these questions are not so important in the German context. Therefore, in this paper, we will describe major steps to create a simulation model that can be used to answer operative questions for cataract surgeries in an eye hospital.

The paper is organized as follows. In the next section, we describe the process flow in the cataract surgery area including all the necessary resources in detail. In Section 3, we formulate the problem and discuss related literature. The proposed simulation model is discussed in Section 4. We present our design of experiments, discuss the obtained results of simulation runs, and present our major findings in Section 5.

2 PROCESS DESCRIPTION

Many hospitals contains surgical suites that are the backbone of the profitability of the hospital. Generally, several physical and personal resources are involved in a cataract surgery process. The process itself can be decomposed in the following five sub processes:

1. entrance and intake of the patient and eventually preparation of the patient in the preparation room and in the examination room,
2. preparation of the patient in the surgery preparation room,
3. conduction of the surgery,
4. transportation of the patient to the recovery room or to the preparation room,
5. transportation of the inpatient to its wards or discharge of outpatients.

We describe the five sub processes in more detail in the remainder of this sub section. The different sub processes are performed within the following physical resources:

- preparation room with a corresponding waiting room,
- examination room with a corresponding waiting room,
- surgery preparation room,
- ORs,
- recovery room.

The physical layout of the cataract surgery area is shown in Figure 1. Note that typically different ORs are used in parallel where the other resources are shared by all the patients and are unique. In Figure 1, we also try to indicate the patient flow by arrows. We have to differentiate between the treatment of outpatients and inpatients. However, the details of the flow are described later in this sub section when we discuss the different sub processes.

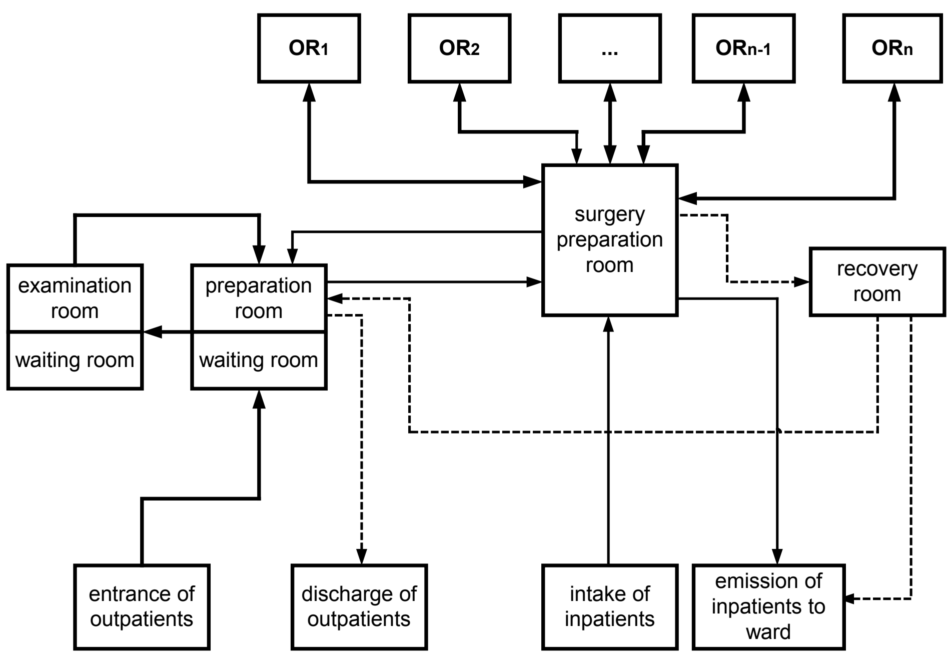

Figure 1: Basic Layout of the Cataract Surgery Area in an Eye Hospital

Different personal resources are a prerequisite to conduct cataract surgeries. These resources are the following ones:

- surgeons (SDs),
- operating nurses (OPNs),
- anesthesia doctors (ADs),

- anesthesia nurses (ANs),
- doctors of operation preparation (DOPs),
- nurses for preparation of the operations (NOPs),
- non-medical staff (NMS),
- floaters (FLs) are specific OPNs for the support of SDs and OPNs.

In contrast to OPNs, FLs are not sterile. FLs serve in several ORs at the same time. One SD is assigned to each OR. There is only one AD and AN that have to serve in different ORs. In the present situation, only one DOP is used. There are several nurses and also NMS. The different cardinalities of the personal resources for the basic scenario found in the cataract surgery of an eye hospital are summarized in Table 1.

Table 1: Cardinality of the Different Personal Resources in the Cataract Surgery Area for the Basic Setting

Resource type	Count
SD	2-3
AD	1
DOP	1
OPN	4
AN	1
FL	1
NMS	2
NOP	1

After the discussion of the different resources, we are able to describe the patient flow within the eye hospital where the study is conducted. Here, we basically assign the personal resources to physical ones. The patient flow is formed by the following steps:

1. a) Outpatients enter the hospital at the registration. They will be immediately sent to the preparation room where paper work has to be done by a single NOP. The NOP can treat only one patient at a specific point of time. Before the patient can enter the preparation room he has to wait in a waiting room when the NOP is busy. After finishing the paper work the patient is sent directly to a second waiting room. A DOP checks the laboratory values and runs some additional examinations in an examination room to prepare the surgery. After this examination the patient is waiting for the NOP in a waiting room in front of the preparation room. His clothes are changed and he enters the surgery preparation area. We call all the activities until the entry into the surgery preparation room pre-examination.
   b) Inpatient are sent directly to the surgery preparation room.
2. The patient is prepared in the surgery preparation room. This includes a disinfection of his eye and also a control of his pulse. A control of the eye of interest by the SD follows. Now the differentiation between local anesthesia and general anesthesia is important. After a peripheral venous aditus is prepared, the local or general anesthesia is performed by a SD or AD respectively.
3. Then the surgery of the patient is conducted by a SD. In case of a general anesthesia, an AD is also necessary as an additional resource.
4. After the surgery, an antibiotic is injected in the surged eye of the patient by the SD. He is supported by a FL. Furthermore, devices are detached. The patient is transported into the recovery room by the AN when a general anesthesia was conducted before. Otherwise, an outpatient is sent directly to the preparation room. The set of activities immediately after the surgery is called post-operative treatment.
5. An inpatient returns to his ward while an outpatient will be discharged when no difficulties occur. In case of any problems, the patient will be examined by the DOP.

The different process steps for outpatients are summarized in the UML activity diagram in Figure 2. Note that a second activity diagram for inpatients is very similar.

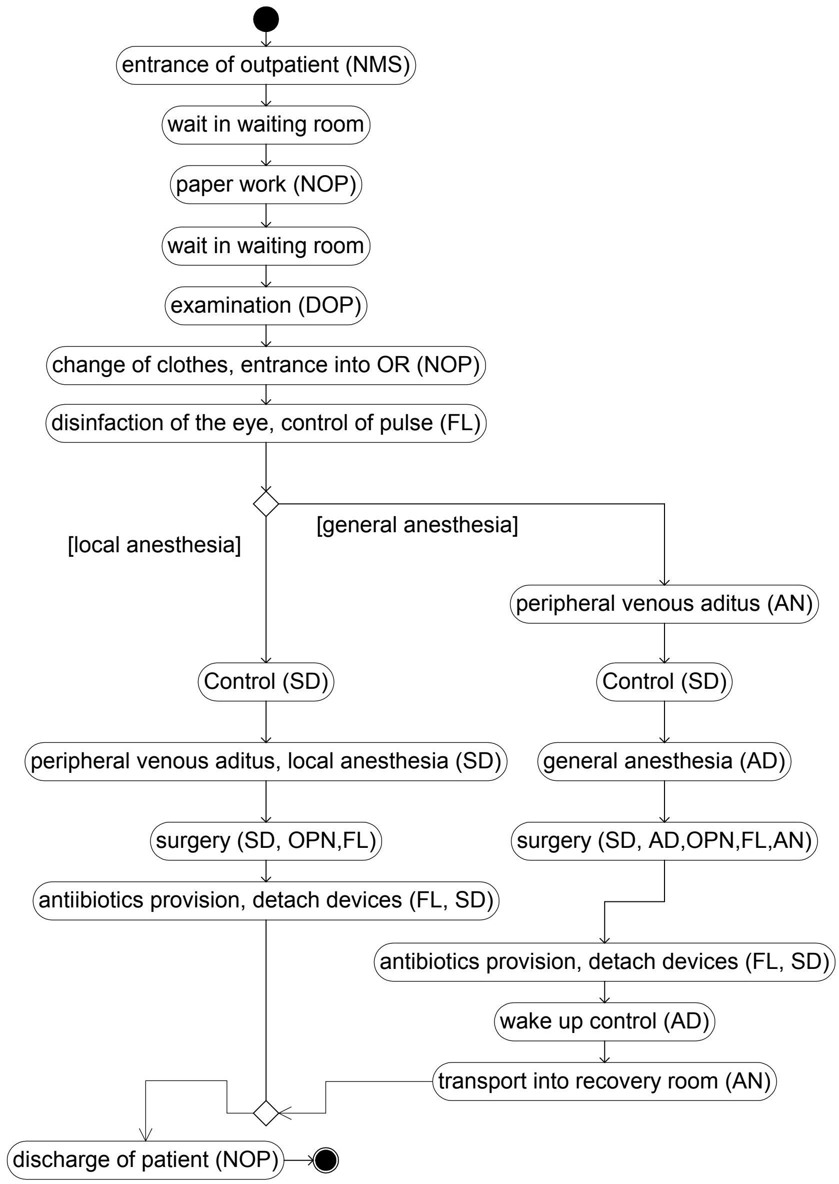

Figure 2: UML Activity Diagram for Patient Flow in the Cataract Surgery Area of an Eye Hospital

3 PROBLEM STATEMENT

We describe the goals of the simulation study. Furthermore, we also discuss related work that can be found in the literature.

3.1 Objectives of the Study

We are interested in building a simulation model that mimics the behavior of the cataract surgery area in an eye hospital. Input modeling issues based on real-world data are quite important because of the huge variability of the patient flow process.

An examination of the utilization of the different personal resources is one of the main objectives. Different staffing decisions can be made using the suggested simulation model. We will change the number of OPNs. At the same time, we will study the impact of the availability of the DOP. One the other hand, we are also interested in assessing the benefit of increasing capacity, i.e., considering more ORs as currently in use. These questions are more strategic questions.

We are also interested in looking for different strategies to manage the outpatient arrivals. Here, we have certain degrees of freedom but we have to take the patient satisfaction with respect to waiting time into account. These questions are more operational by nature.

Our ultimate goal of future research is to come up with different schedules for the surgeries taking different objectives like minimizing waiting times of the patients and maximizing utilization of the ORs into account. Because of the variability of the patient flow process it seems appropriate to use simulation-based optimization to solve this kind of problems. However, an detailed simulation model is a necessary prerequisite for this approach.

3.1 Related Research

Discrete event simulation is a well-established method to model and analyze health care operations. A survey related to the the usage of discrete event simulation for health care operations is provided by Jun et al. (1999). Baumgart et al. (2007) discuss the possible role of computer simulation in operating room management from a business process point of view.

White (2005) discusses the question which data sources are appropriate to build simulation models in the health care domain. Several simulation studies for answering different operative and strategic questions are presented in the literature (cf. Ballard and Kuhl 2006, Takakuwa and Shiozaki 2004, Sinreich and Marmor 2004, Wijewickrama and Takakuwa 2006, Denton et al. 2006 amongst others). Sobolev et al. (2007) use statecharts to build simulation models for patient flow to get a larger modeling flexibility.

Tuft and Gallivan (2001) and Comas et al. (2008) use simulation to determine appropriate waiting list strategies for cataract surgeries in UK and Spain. However, the level of detail in their models is low because they have to answer a more strategic question.

Vasilakis et al. (2007) combine scheduling and simulation to determine clinic appointments. Gupta and Denton (2008) provide a survey related to appointment scheduling in health care. They point out that simulation is important to ensure that all the constraints of the schedules are taken into account.

To our best knowledge there is no study that is especially dedicated to cataract surgeries. Therefore, it is highly desirable to come up with a detailed simulation model to answer different strategic and operational questions and to prepare future scheduling activities.

4 SIMULATION MODEL

In this section, we discuss first our data collection and input modeling effort. Then we describe the identified model elements in some detail.

4.1 Data Collection and Input Modeling

The study is based on nine weeks of historical patient data from the hospital. The data consists of the following main elements for each patient:

- planned arrival time of the patient,
- identifier for the OR,
- start time for surgery preparation,
- start time for the surgery,
- start time of stitching,
- completion time of the post-operative treatment,
- name of the SD,
- name if the OPN,
- name of the FL,
- type of anesthesia.

This data is enough to create a representative model. Among all the surgeries there are 58 percent cataract surgeries, eight percent of the surgeries were canceled, and the remaining 34 percent are other type of surgeries that take place in the ORs of the hospital. Among the cataract surgeries 80 percent were related to outpatients and the remaining 20 percent to inpatients. Almost 80 percent of the cataract surgeries are with local anesthesia, the remaining surgeries are related to general anesthesia.

We use this data to estimate random distributions for the duration of the preparation of the patients in the preparation room and the examination room including waiting times, i.e., the duration of the pre-examination time, the duration of the preparation of the patient in the surgery preparation room including waiting times to enter an OR, the anesthesia duration, the duration of the surgery, and finally the duration of the post-operative treatment. The arrival times of the outpatients are planned. Therefore, in a preprocessing step we correct those arrival times that are after the start of the surgery preparation. Because no arrival data for the inpatients is available, we determine synthetic arrival data based on a preprocessing of the start times of the surgery preparation and the arrival times of the outpatients. The inter arrival times of the patients with non-cataract surgeries are exponentially distributed, while the inter arrival time of the patients with cataract surgeries is Weibull distributed. We use the software XLSTAT and the chi-square test to perform the statistical analysis. The fitted random distributions for surgery preparation and the surgery are shown in Table 2.

Table 2: Random Distributions Based on Historical Patient Data

Duration	Random Distribution
surgery preparation	Gamma
general anesthesia	Gamma
surgery (cataract)	Pearson Type V
surgery (non-cataract)	Gamma

For the pre-examination time and the post-operative treatment we assume based on information of the hospital staff uniform distributions when the DOP is available. We assume that the DOP is unavailable for 25 minutes every 20 minutes.

4.2 Model Elements

We build the simulation model using the simulation engine SLX. The tool SLX differentiates between active and passive objects. Active objects have own action methods while passive objects have not this property. Patients and ORs are modeled as active objects. There is a one to one correspondence between ORs and SDs. Furthermore, the non-cataract surgeries and unavailability periods of the DOP are also active objects. Non-cataract surgeries are not modeled in detail, however the consume capacity of the ORs. The different type of nurses and the anesthesia types are modeled as passive objects. They do not own any actions and will be used by the patient objects. The DOP and the AD are modeled as facilities with queue. Only one patient can use them at the same time. Sets are used to control the availability of the different nurses and the ORs.

The model was verified by comparing the model results with the collected data. For example, we checked the inter arrival times of the patients or the random distribution of the surgery preparation. The model was validated by comparing the flow of the patients in the model with flows obtained from the collected data.

5 RESULTS OF SIMULATION EXPERIMENTS

We start with describing the design of experiments. In the second sub section, we present computational results from simulation runs. Finally, we present our findings.

5.1 Design of Experiments

We simulate 182 independent days and take the average values of the performance measures. The cardinalities of the different personal resources are summarized in Table 1. The number of OPNs and FLs, the patient arrival scheme, and the duration of unavailability of the DOP are the factors of the design. The arrival scheme provides the frequency measured in minutes for a patient appointment. The different levels are shown in Table 3.

Table 3: Design of Experiments

Factor	Level
# OPNs and FLs	$\{3,4,5,6,7\}$
Patient arrival scheme	$\{1,10,20,30,40,60\}$
duration of unavailability periods of the DOP	$\{5,15,25,40,60\}$

In the experimentation for this paper, we always change only the values of one factor and fix the levels of the remaining factors. The reference scenario contains four OPN, one FL (as shown in Table 1) and two ORs. The outpatients are appointed every 30 minutes. Note that we simply use such an appointment scheme for all kind of surgeries. A certain number of surgeries are non-cataract. The average duration of the period of unavailability of the DOP is 25 minutes. Throughout the experiments, we assume one FL as in the reference scenario.

5.2 Computational Results and Findings

In Table 4, we show the results of the first scenario. We assume a fixed working day of 7.5 hours for the ORs. The maximum appointment time is chosen in such a manner that the maximum time to run the ORs is not exceeded.

Table 4: Computational Results for the First Scenario

Performance Measure	# OPN + FL				
	3	4	5	6	7
# patients per day	11.60	13.60	14.0	14.40	14.4
# cataract operations	6.60	7.60	7.90	8.10	8.10
total # of operations	18.20	21.20	21.80	22.4	22.40
lead time of the patients (in hour)	3.17	2.36	2.09	2.02	2.00
total waiting time of the patient per day (in hours)	1.89	1.07	0.81	0.74	0.72
duration of service of AD per day (in hours)	2.29	2.67	2.76	2.85	2.84
occupancy of ORs (in hours)	5.42	4.47	4.00	3.96	3.92
pure surgery time per OR (in hours)	3.00	3.48	3.58	3.68	3.68
waiting time of the patients in OR	2.42	1.00	0.42	0.28	0.24
maximum appointments of patients (in hours)	4.67	5.50	5.67	5.83	5.83

It turns out that more than five nurses increases slightly the number of patient per day. The pure surgery time in an OR is increased. At the same time, the occupancy of ORs by cataract surgeries is decreased.

In Figure 3, we see the computational results for the second scenario. It turns out that more clustered patient arrivals lead to a better OR utilization. However, the waiting time of the patients is increased significantly. It seems that an appointment interval of 20 minutes is a trade-off between patient satisfaction and OR utilization.

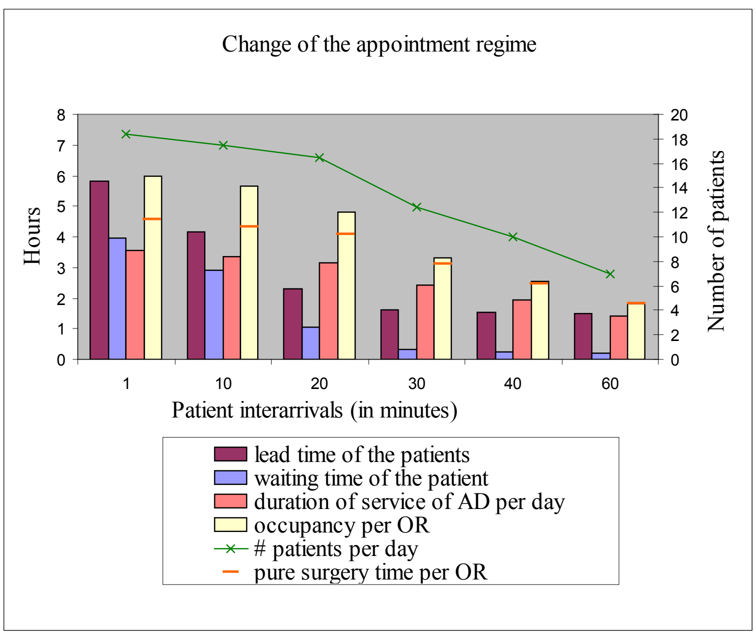

Figure 3: Simulation Results for the Second Scenario

In Table 5, we see the computational results for the third scenario. An unavailability period with duration smaller than 25 minutes as in the reference scenario reduces the waiting times of the patients to a large degree.

Table 5: Computational Results for the Third Scenario

Performance Measure	**Duration of the unavailability periods of the DOP**				
	5	**15**	**25**	**40**	**60**
# patients	14.70	14.70	14.00	13.20	12.0
# non-cataract surgeries	8.30	8.30	7.90	7.40	6.90
total # of operations	23.00	23.00	21.80	20.60	18.9
lead time of the patients (in hour)	1.65	1.80	2.09	2.69	3.44
waiting time for examination per patient (in hours)	0.04	0.19	0.47	1.08	1.76
examination time per patient (in hours)	0.16	0.31	0.59	1.19	1.88
total waiting time of the patient per day (in hours)	0.37	0.52	0.81	1.41	2.16
duration of service of AD per day (in hours)	2.94	2.91	2.76	2.64	2.40
occupancy of ORs (in hours)	4.22	4.22	4.00	3.81	3.57
pure surgery time per OR (in hours)	3.78	3.77	3.58	3.39	3.11
waiting time of the patients in OR	0.44	0.44	0.42	0.42	0.46
maximum appointments of patients (in hours)	360	350	340	320	290

6 CONCLUSIONS AND FUTURE RESEARCH

In this paper, we suggested a simulation model for cataract operations in an eye hospital in Germany. Therefore, we identified the main building blocks of such a model. Based on real-world data, we estimated random distributions of the various input quantities. We build an appropriate simulation model using the SLX tool. It turned out that important performance measures in the eye hospital like patient waiting time or number of completed patients per day strongly depend on the number of nurses and also on the used appointment policy.

There are certain areas for future research. First of all, it seems necessary to conduct more simulation experiments to understand the interaction of the different factors that influence the values of the performance measures. Furthermore, we are interested in customize and extend the suggested simulation model to the situation of eye hospitals that only perform cataract surgeries.

So far, we assumed a fixed patient appointment schedule. However, it makes sense to determine improved schedules that take more constraints like, for example, the availability of the ADs into account. It seems possible to determine these schedules using scheduling methods for parallel machines from the manufacturing domain. However, carry out the necessary details is part of future research.

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