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Adrian Schmutzler

Entwicklung eines Simulationsprogrammes zur Evaluation und Optimierung der OP-Personaleinsatzplanung in einem deutschen Krankenhaus

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Authors:

Adrian Schmutzler (University of Bayreuth)

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Edited by:

Prof. Dr. Torsten Eymann

Managing Assistant and Contact:

Universität Bayreuth
Lehrstuhl für Wirtschaftsinformatik (BWL VII)
Prof. Dr. Torsten Eymann
Universitätsstrasse 30
95447 Bayreuth
Germany

Email: wi@uni-bayreuth.de

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Lehrstuhl für Wirtschaftsinformatik (BWL VII)
Prof. Dr. Torsten Eymann

Bachelor thesis

Development of a simulation program to evaluate and optimize surgical workforce planning in a German hospital

Vorgelegt von:
Adrian Schmutzler
Zur Weinleite 7
95364 Ludwigschorgast
Tel: 0151/566 1111 2
uni@adrianschmutzler.de
8. Fachsemester BWL
Mat.-Nr.: 1171666

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Betreuer:
Gaurang Phadke

Abstract

The surgical unit typically is the biggest cost and revenue center in full-service hospitals, but also a facility with outstanding complexity. This has led to particular interest in the topic at the executive offices and in academic research. While most publications deal with the scheduling and stringing together of operating theaters, this work investigates the planning process in advance of those actions. The thesis presents a multi-agent simulation tool, which describes surgical workforce planning based on a model process from a particular German hospital. It combines both key performance indicators and staff satisfaction to study the effect of parameter changes as comprehensively as possible. For evaluation of the program and to draw first conclusions on the planning process a general analysis of influence factors is performed, supplemented by a case study based on a particular model scenario. The simulations yield that effective and satisfying compensation for sickness induced staff shortages is only available by increasing the available workforce in the first place, while other influence factors do not exhibit solely positive impact. As payment for required additional staff exceeds accessible savings in planning cost by one order of magnitude, though, the applicability of direct results is limited. The simulation tool itself however represents a powerful planning environment for hospital managers, so they can tune parameters with their particular priorities in mind.

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List of abbreviations and acronyms

ASCII	American Standard Code for Information Interchange
BPMN	Business Process Model and Notation
IDE	integrated development environment
GUI	graphical user interface
KPI	key performance indicator
OOP	object-oriented programming
OP	surgical operation

List of symbols

A	number of planners (agents)
c_a	cost of planner a per time unit
c_{ext}	cost of externals per time unit
D	set of departments
d_{diff}	difference between maximum and minimum d_{vac}
d_i	amount of work done by externals within period i
$d_{lost,q}$	presence time lost due to insufficient planning
DOY	current position in simulation time relative to a year
d_{vac}	sum of days of additional vacation
d_{year}	working days per year
$e_{all,q}$	sum of default and shortage events for department q and global events

$e_{day,q}$	counter for daily shortage events handled inside department q
e_{def}	counter for actual defaults of OPs
e_{ext}	counter for shortage events handled by the OP manager
$e_{week,q}$	counter for weekly shortage events handled inside department q
f_x	prefactor for satisfaction contribution x
H	number of halls according to plan
H_{act}	actual number of planned halls
H_{init}	initial number of planned halls
i_{qual}	input value for *qualification-accounting workforce assignment*
N	number of days elapsed
OP_{act}	actual number of planned OPs
OP_{hall}	operations per hall and day
OP_{init}	initial number of possible OPs
p_{ext}	average number of externals per OP
$p_{lost,q}$	percentage of time lost due to insufficient planning
$Sat_{k,q}$	saturation contribution of category k for department q
s_q	total number of employees in department q
$t_{a,i}$	time required by planner a within period i
$t_{day,i}$	time required for daily planning within period i
$t_{initial}$	time required for initial (annual and semiannual) planning
t_{total}	summed time required for planning by all planners
$t_{week,i}$	time required for weekly planning with period i

1 Introduction

During recent years, German hospitals have increasingly suffered from a situation where they have to treat a rising number of patients [Stüb14, 1; PPBK10, 419–422; Welt13], while monetary support frequently is insufficient [Telg14]. Especially ageing population is responsible for both past and future increases in patient numbers. [PPBK10, 425] In addition, progress in medicine and surgical capabilities has created additional demand. [Brau14, 95; KBA13, XVII]

At the same time, the pressure on nursing personnel has severely increased. [Brau14, 93] From 1996 to 2011 the number of patients cared for by a single nurse in full-time employment has risen by 27 %. [Stat13] In addition, the profession shows a considerably increased sickness absence rate. [Nann14, 24]

One of the most costly and workforce-intensive units in hospitals is the surgical division. [CDB10, 921] Despite that fact, it also introduces a high level of complexity as surgeries generally involve a high volatility in time. Additional uncertainty arises from emergencies, which cannot be planned, but just be allowed for stochastically. According to that, planning and scheduling of surgical operations (OPs) offer high potentials for cost saving. [EDC+10, 1; Stüb14, 2]

While this topic had not been of much interest to operations research in the past [HaNi07, 25], more recent works show an increased attention to the topic in the last 15 years. [CDB10, 922] Since meanwhile computing power has become cheap and easily scalable, computational methods and simulations have emerged as a standard tool to support and evaluate processes in the surgical unit.

Up to now, an enormous number of programs has evolved, which aim at problems of all sizes from assisting in basic planning up to integrated organization and data management for a whole clinic. Similarly to the broad range of subjects, modelling techniques also cover all possibilities of mathematical and programming methods [CDB10, 927]. However, most of this research is limited to an optimization of operating room scheduling and assignment. Since a big share of cost is caused by the high salaries of specialized staff members [CDB10, 923], e.g. surgeons, an important step of surgical operations management is already represented by the staff planning process.

The surgical workforce planning represents the steps done before any surgeries are performed, from fixing quotas by the executive board to assigning duty rosters by the heads of individual departments. Due to the increased workload of employees discussed earlier, this is of particular importance for dealing with personnel shortages and sickness replacements. However, simulations on this subject are usually limited to economic parameters, while impacts on workforce satisfaction level are discussed qualitatively or even not dealt with at all.

In this thesis, the aim is to link a quantified staff satisfaction to the classical key performance indicators (KPIs) quality, productivity and cost, to give a more comprehensive image of how changes affect the planning process. To achieve this, a simulation program for surgical workforce planning is developed, which returns KPIs and satisfaction partitioned by profession and displays their evolvement during the year.

Based on a business process model from a German full-service hospital, a multi-agent simulation is derived and reasonable values for durations and the influence of intermediate results on satisfaction are estimated. The tool is designed as a *learning cockpit* which is easy to use for managers not familiar with programming or simulation design. Once a small set of parameters is required to define the situation in the hospital of interest, results are displayed during the simulation run, so the user gets the ability to immediately see the effects of any changes made.

After the effect of available parameters on simulation results is presented and analyzed in general, a case study is provided by introduction of a model scenario with variables set to typical values. The model is used to rate influence factors by their effect both qualitatively and quantitatively, so best case and worst case configurations can be retrieved. Based on both analyses, it is checked whether the simulation yields reasonable results. Beyond that, conclusions are drawn how improvements are possible both by changes in variables and in the process itself.

2 Surgical workforce planning

2.1 Aim

In contrast to many examples in literature which deal with sequencing and allocation of surgeries and operating theaters [CDB10], this thesis treats the planning process itself. Since surgical operations (OPs) require an interaction of several stakeholders, this process is not limited to simply setting up a duty roster: Surgeons are a very expensive resource and therefore motivate managers to assign them as efficiently as possible. In contrast, a timetable which is too efficient is quite unstable, as it is not possible to absorb even small disturbances. For a perfect plan with 100 % utilization, for example, a single incident will suffice to result in a reduction of output. [CDB10, 923] While it is generally easy to optimize a predefined process, one central objective of this simulation is lowering the negative impacts of uncertainty.

For further investigation, the process can be divided into levels in different manners: From a hierarchical point of view, it is convenient to distinguish between the planners, i.e. those individuals doing the planning, and the workforce, which refers to the doctors and nurses *being* planned in the process. While the former are implemented as interacting agents, the latter are just the object of the planning process. The far-reaching consequences of this concept are discussed in more detail in chapter 3.2.

Another mode of classification is possible in terms of organizational control: Staff planning is divided into strategic, tactical and operational level, so there is an annual, semiannual, weekly and daily procedure. At each of those levels, decisions are dependent on the levels below and above.

As the program presented in this thesis aims at visualizing results of the planning process to the users in order to improve their strategic capabilities, it is not sensible to merge all perspectives into the simulation. Instead, the program implements the operational level of surgical staff planning in a way that decision makers are able to adjust strategic and tactical decisions based on what results they obtain.

This is particularly reasonable as surgical workforce planning obviously is no topic which can be analyzed without considering related processes and the influence on them. It may, for example, be efficient to hire more people when taking into account just the efficiency of staff planning, but later someone will have to pay them. While, for an independent problem, it is often suitable to build a model and then perform a computational optimization, surgical workforce planning needs to be interpreted more individually.

2.2 Indicators

In correspondence to shifting the scope from performing surgeries to planning them, performance indicators also need to be reconsidered. While quality is obviously dependent on the drop-rate of surgeries, productivity and cost need to incorporate the variables of the planning process itself. For the *output*, it is convenient to simply evaluate the number of planned surgical operations rather than those performed when the plan is executed. The more significant figure is, however, the *input* of the process, as it represents the efforts required to *establish the workforce plan*. The productivity of the more commonly discussed operating room planning and scheduling, however, naturally uses the cost of the input factors for the surgeries themselves.

This is of vital importance, as a high productivity of the planning process not necessarily implies a high productivity of the executed plan. A highly efficient plan may for example include a significant overemployment of doctors, as this buffer will effectively eliminate staff shortages due to incidents like sickness or training. Although this does only slightly affect productivity and cost of planning, the additional salaries may severely lower the productivity of the whole surgical unit in the end.

This bipolar perspective is even more complicated for cost. Depending on how restrictive cost is defined, the evaluation of a scenario may change completely. In the following analysis, I will distinguish between a strict interpretation, that includes only those cost resulting from the planners' consumed time, and a more comprehensive point of view, which also includes expenditures *caused* by the planning process (see also paragraph 3.4.3).

This latter approach is tightly linked to the example given for productivity: Although planning may save cost for the planners' time, a bad plan may have costly consequences, such as fees for additional external workforce to contain shortages. According to that, regardless of what mode of calculation is chosen, an evaluation of performance indicators is only reasonable in the context of their effect during execution.

In addition to this performance-focused point of view, rostering and vacation scheduling is one of the most important topics concerning satisfaction. [WSL14, 9–20] Highly efficient workforce planning is not necessarily good in terms of workforce happiness: A lower number of employees will reduce cost, but it is also more likely to cause reschedules in vacation plans and therefore reduces the efficiency of the *planning process*.

In contrast, cost savings due to an improved planning model can create an amplified benefit: As pointed out in [CDB10, 924], saved money can be spent to investments making the improved model or process possible. If applied to the simulation presented here, which incorporates satisfaction, this may be accompanied by a no-cost rise in staff satisfaction, i.e. a double gain as illustrated in figure 1.

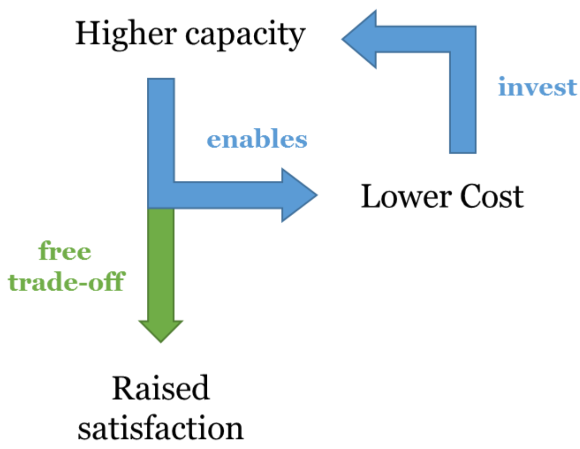

Figure 1: Investment opportunity due to improved planning may yield risen satisfaction as a no-cost trade-off.

2.3 Process

For the design of the staff planning process, it is convenient to refer to a process which is implemented and running at a real facility. In case of this project, I reproduce a model process which has been created in collaboration with a full-service hospital in southern Germany. It consists of four different levels, i.e. timescales, which are summarized in figure 2. The processes for annual, semiannual, weekly and daily procedures have been translated into diagrams according to the *Business Process Model and Notation (BPMN)*. [Obje11]

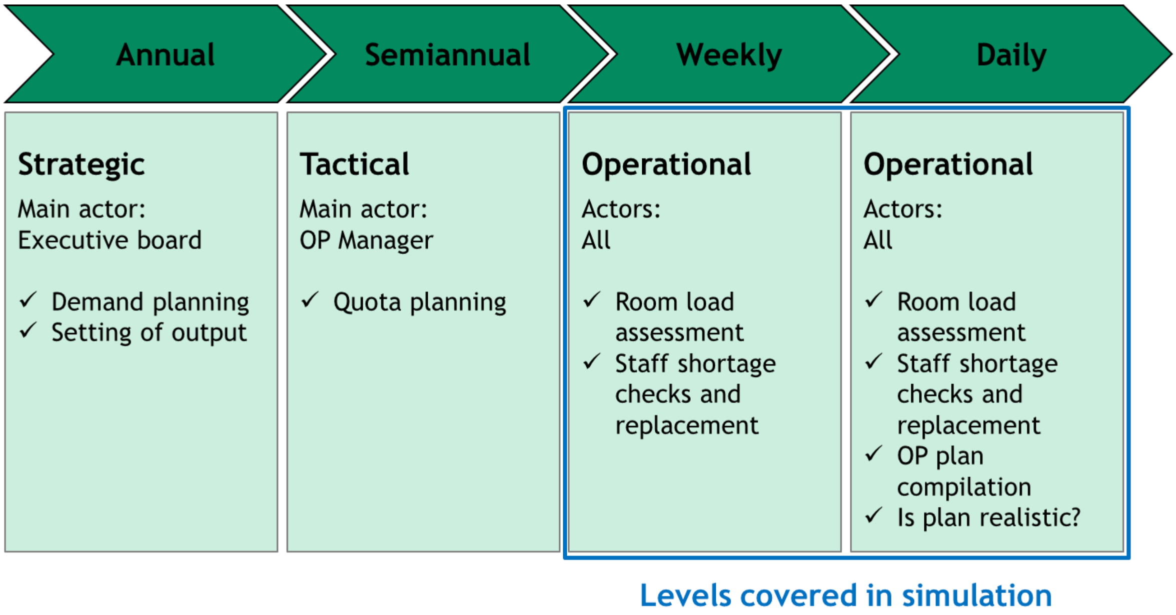

Figure 2: Schematic overview of different levels in the model process.

Resembling the organization structure in the named hospital, the model process involves two groups of interacting agents: On the one hand, there are the departments participating in surgical operations, which are equal to four professions (surgeons, anesthetists, OP care and anesthesia care) required during surgeries. On the other hand, there are individuals at management level which are not assigned to a specific segment. In particular, the latter consist of the *executive board*, which is the main actor at strategic level, the *OP manager*, who is the chief responsible for managing surgical operating planning and scheduling, and finally the *OP coordinator*, who assists the OP manager at operational level. A detailed distinction and more comprehensive description of particular tasks is found frequently in literature, e.g. [BHK10, 70] or [Welk06, 143–145].

Dealing with the given model process, it is rather obvious that allocation of responsibilities is led by the levels of organizational control: While the executive board is the authority in strategic planning, the OP manager solely handles tactical level. Only at operational level, both OP coordinator and departments have relevant roles. For the program design, this is another reason to restrict simulation to this ultimate layer: Here is the place where interactions between multiple agents occur, while the higher levels essentially represent sequential task lists of single managers.

3 Simulation program

3.1 Concept

The simulation is designed to enable users to provide a particular set of variables contingent on the process and then obtain performance indicators and satisfaction based on this input. It therefore acts as a *learning cockpit* for the healthcare managers, where they can study how parameter changes affect the output of the process, without requiring knowledge about computer science.

For both programming and execution, the proprietary software AnyLogic, version 7.1.2 [Anyl14] is used, which is a modelling environment and Java IDE suitable due to its wide range of functionality concerning process design [DjGe13, 250] and easy to use graphical editor.

The simulation is intended to fulfill a particular set of aims:

Easy to use

The program is designed to provide a graphical user interface (GUI), where users just have to set parameters according to their wishes. If the meaning of a parameter is unclear, a default value provided by the program can be used. While the simulation is running, results are displayed immediately, so the effect of all changes becomes obvious.

Platform independent

The use of a virtual machine-based programming language like Java enables executing the program on various operating systems, as long as a Java runtime environment is available. AnyLogic is currently available on Windows, Linux and Mac operating systems.

Close to reality

As AnyLogic allows a direct modelling of the process by agent-based statecharts, the model process can be reproduced one-to-one inside the simulation. The programmer only has to implement the actions for a particular step reasonably.

Easy to modify

As the program mirrors the model process, changes to the latter can be incorporated directly in the statecharts. As this is a high level interface, it is also easily done by people not familiar with coding.

Extendable

Although particular features might not be implemented, the design of the program is built to facilitate easy extension. For some effects, the respective line of code has just to be commented in. In many other cases, a small additional method will easily fit into the logic of the process.

Powerful

Any desired change or modification is still possible by simply changing the code. As the program uses the well-developed and widespread Java programming language, adjustments or even revisions should not be a problem for a trained programmer.

In addition, the same is valid for data analysis. While users may stick to the cockpit itself, the simulation also creates tab-separated ASCII output files for both intermediate and final variables. Those files are accessible for extensive analysis by virtually any program.

3.2 Design

In contrast to a simulation on scheduling and stringing together surgeries, the tool presented here evaluates the *planning* process. Therefore, it is important to understand that a different point of view is taken: In this case, the agents, i.e. the active players are represented by the planners, not the surgeons or nurses. Although the latter are the main *object* of the process, they do not actively participate, but effectively remain figures on a planning sheet.

The former are the managers introduced in chapter 2.3, namely the heads of departments, the OP coordinator and the OP manager. Their actions are given by the process diagrams for one day or week, which are just reproduced by employing a multi-agent simulation approach. At each transition of the resulting statechart, a duration for the corresponding process is defined and a function representing the concrete action is called. As the time required for this is just counted though, the program is limited to one agent of each kind. For an increased number the required time would effectively be split. An analysis of mutual interference is not treated here, though.

However, in contrast to the simulation of a continuous sequence, the implementation has to incorporate different levels in time, according to the daily and weekly processes. Therefore, simulation time is separated into a discrete chain of days, within each of those the corresponding daily process with all relevant agents is taking place. As illustrated in figure 3, this means the same process is conducted day by day. The variables, however, will be subject to change during that procedure.

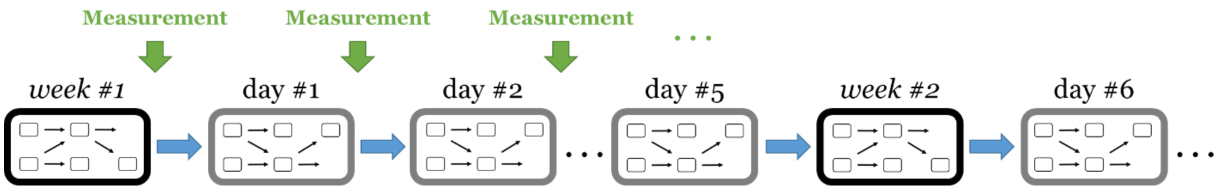

Figure 3: Simulation time as a mix of discrete steps and a weekly/daily process.

Following this logic, the weekly process is included by just putting it in front of the first daily process of a week. Since in simulation one week consists of five working days (no regularly planned surgeries during the weekend), the next weekly slot takes place between the fifth and the sixth day. The evaluation of output parameters is performed only after a complete step has finished. As strategic and tactical aspect are not modelled, annual and semiannual steps are included solely as an additional amount of planning time at the beginning of the simulation (referred to as *initial planning* in the following).

While the planning agents are the active part in the program, the *planned workforce* is simply treated as a given amount of staff members which is then just increased or decreased depending on the parameters set. An overview of the whole treatment through the simulation is given in figure 4:

The initial numbers are determined by demand, meaning that the number of halls is multiplied by a (user-provided) factor to yield the number of employees required per profession or department, respectively. This value is then multiplied by another factor to account for the vacation granted to the staff. The total staff is then reduced again by a similar factor to gain the available personnel, however in this case one has to include additional vacation caused by sickness days. After that, further reductions in staff take place at weekly and daily level, which are compensated by weekly and daily internal replacements. At daily level, replacement capacity is limited, so external replacements are the next step of settlement. Finally, if external resources are also insufficient, surgeries have to be cancelled. While the black values in figure 4 are evaluated only once, of course the numbers of available staff will deviate from day to day.

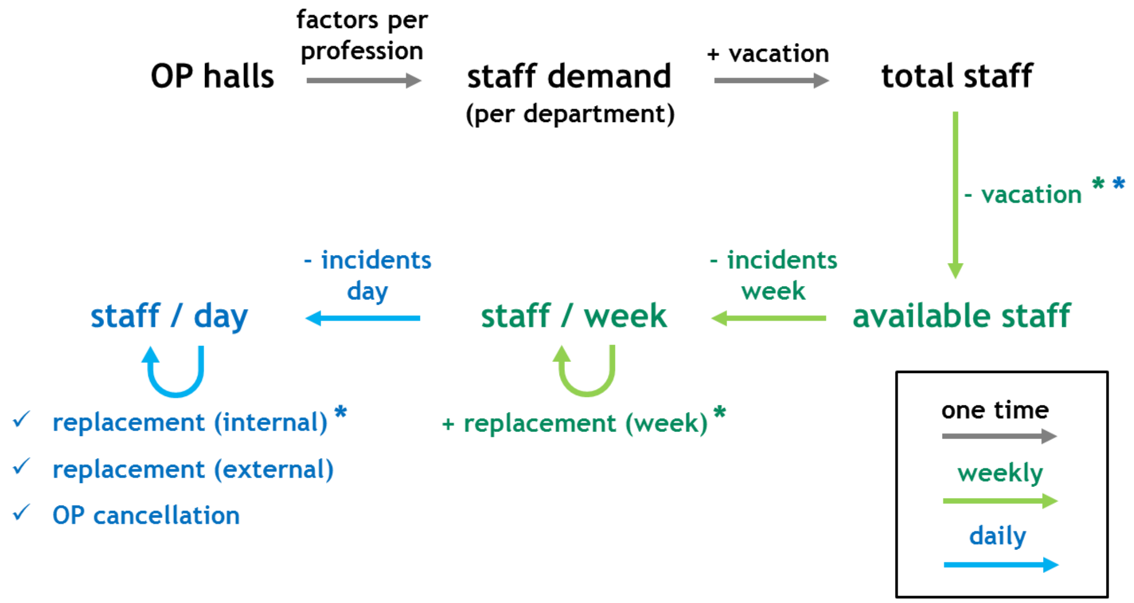

Figure 4: Simulation of workforce through different levels in simulation time.

One particular problem arises from the implementation of vacation: Replacing sick people by calling in other employees will cause the latter to take their holiday at some later point in time. Effectively, this may be seen as additional vacation days created by sickness. However, when the available staff is calculated according to figure 4, these days will cause non-integer numbers for the workforce.

One way to deal with this would be to have decision criteria for each individual employee, so a judgment takes place whether he is included at one particular day or not. However, a corresponding treatment could introduce huge rounding effect for the output indicator. Therefore, this simulation treats all variables representing workforce numbers or day counts as floating-point numbers.

While this describes the simulation in a time dependent fashion, the processes also involves different levels of organizational control: Corresponding to the main agents in figure 2 on page 6, starting from the annual regime, the responsibility is continuously shifted to lower authorities. At daily level, however, the chain of responsibility is passed through in opposite direction. While internal replacements can be performed by the departments themselves, mobilizing external staff and cancelling surgeries is the job of the OP manager. A very simplified overview of those two different dimensions is given in figure 5.

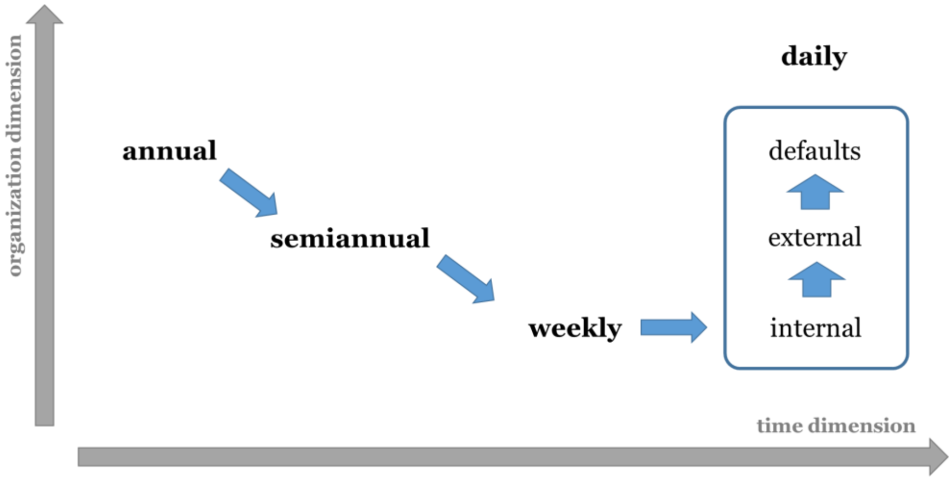

Figure 5: Two-fold classification of the planning process.

3.3 Input parameters

In the learning cockpit, a number of parameters can be set to define the simulation environment. For a convenient user experience, this is implemented by a set of sliders (figures 6 and 7), which provide both value restrictions and standard values. In particular, the latter enable a quick first try without setting anything in the first place. An overview including explanations, standard values and value ranges is given in table 1.

Table 1: Overview of input parameters

Parameter	Description	Default value	Value range
Number of halls	The total number of operating theaters.	100	1 to 200
Planned halls	The amount halls included in planning. This is just a scaling factor to *number of halls*.	100 %	0 to 100 %
Staff members per halls (for each profession)	Number of doctors, anesthetist, OP care nurses and anesthesia care nurses *per hall*.	1	1 to 3
Vacation per year	Number of vacation days granted *per year*.	30	20 to 35

Parameter	Description	Default value	Value range
Workforce buffer	Relative increase/decrease of initial workforce based on the values calculated by the *number of halls*.[1]	± 0 %	-50 % to +100 %
Weekly incidents	Average number of incidents per week and department (sickness, training, etc.)	0	0 to 20
Weekly variation	Range for incidents per week and department in both positive and negative direction, i.e. ± x	0	0 to 20
Daily incidents	See *weekly incidents*	0	0 to 20
Daily variation	See *weekly variation*	0	0 to 20
Internal replacement limit	Replacements due to incidents within a department are only possible up to the number of people per day given here	1	0 to 5
External replacement limit	Replacement of workforce by externals is only possible up to the number of people per day (in total) given here	10	0 to 100

The value range in the simulation is not necessarily limited to the values given there. Instead, the numbers just represent the limits defined for the user interface.

In addition, input for particular satisfaction contributions is required. A more comprehensive discussion of those parameters is given in paragraph 3.5.6.

[1] In figure 4, this means an effect immediately after calculating staff demand.

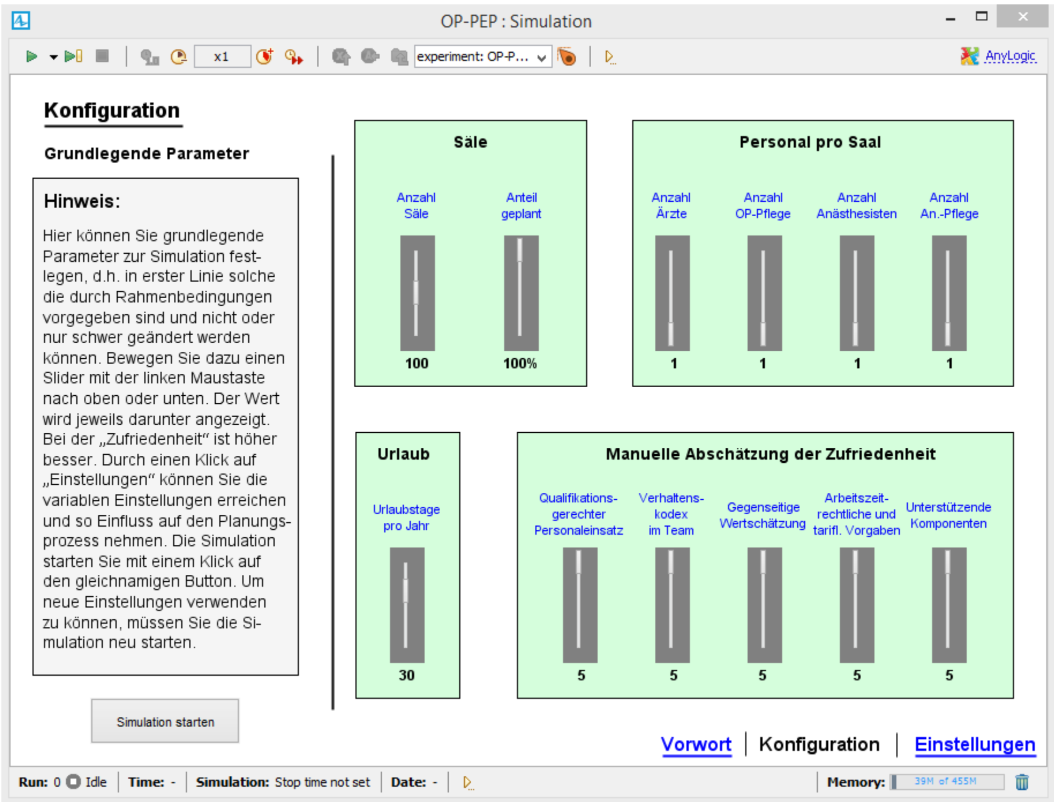

Figure 6: Interface for specifying the site-dependent input parameters.

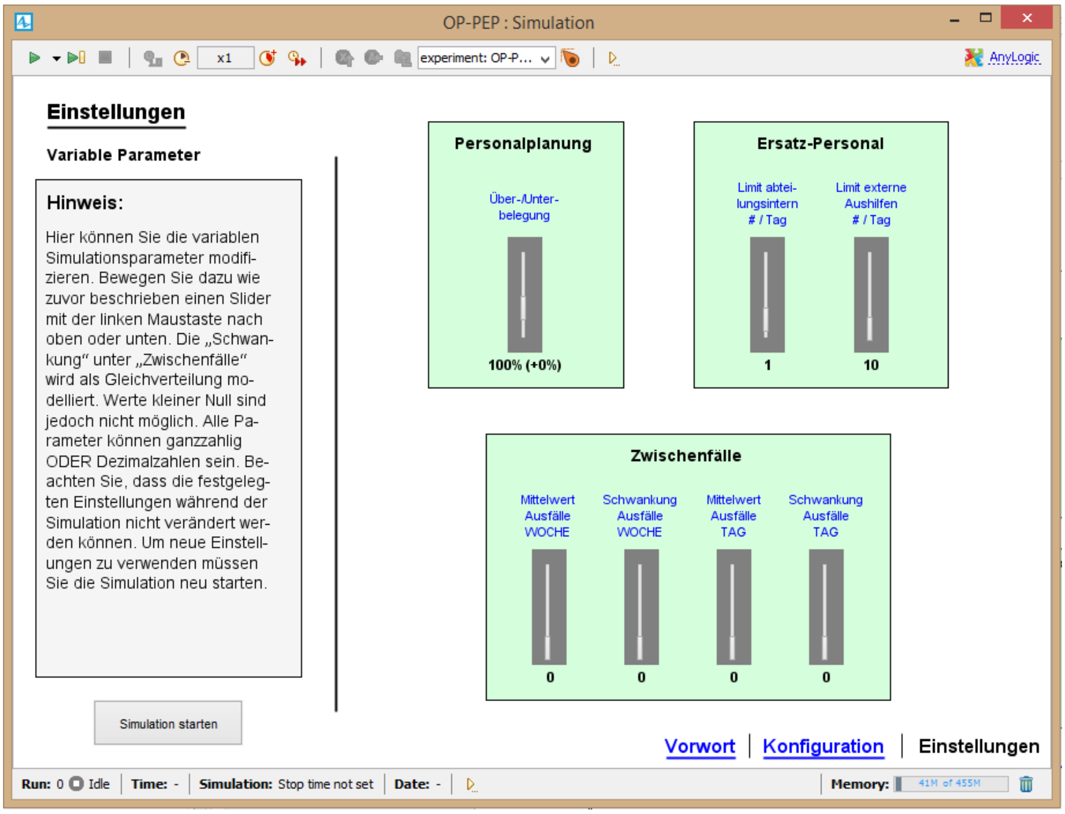

Figure 7: Interface for specifying the variable input parameters.

3.4 Key performance indicators

The simulation output consists of the three key performance indicators (KPIs) quality, productivity and cost on the one hand and of the satisfaction values for all four groups of employees (surgeons, anesthetists, OP care and anesthesia care) on the other hand. As a substantial understanding of those is vital to the analyses made later, the output parameters are discussed to the very detail here. While this chapter focusses only on the KPIs, a very comprehensive view on satisfaction is given subsequently.

3.4.1 Quality

The quality of the planning process is determined by the successful planning of operations. Consequently, the share of dropped OPs is the quantity evaluated for this KPI.

Since the simulation does not deal with the execution, but with the planning of operations, *dropped* in this context means surgeries which had been scheduled initially, but are not included in the final plan. The value OP_{init} therefore represents the initial number of possible operations within the restrictions given by the user, while OP_{act} is the remainder after some of the former may have had to be dropped:

$$quality = \frac{OP_{act}}{OP_{init}} \tag{1}$$

Albeit, the program does not simulate individual surgeries, but uses the surrogate of available OP halls. For those a global, constant number of operations per hall and day OP_{hall} is assumed. Accordingly, the number of halls initially (H_{init}) and actually (H_{act}) planned is evaluated:

$$quality = \frac{H_{act} \cdot OP_{hall}}{H_{init} \cdot OP_{hall}} = \frac{H_{act}}{H_{init}} \tag{2}$$

As those may fluctuate from day to day, the share is averaged over the simulation timespan:

$$quality = \frac{1}{N} \sum_{i}^{N} \frac{H_{act,i}}{H_{init,i}} \tag{3}$$

where i represents a single day and N the number of days elapsed.

The parameter consequently yields values between 0 and 1 or 0 % and 100 %, respectively, since $H_{act,i} \leq H_{init,i} \quad \forall i \in \{1, \dots, N\}$.

3.4.2 Productivity

For productivity, the number of successfully planned operations with respect to the time required for planning (t_{total}) is used. The denominator is calculated by the time consumed for all tasks of all planners. The numerator is equal to OP_{act} introduced in the previous section, which is again replaced by the number of halls actually planned (H_{act}):

$$productivity = \frac{OP_{act}}{t_{total}} = \frac{H_{act} \cdot OP_{hall}}{t_{total}} \qquad [4]$$

Since productivity is defined as surgical operations per time unit, the factor OP_{hall} is required here. Like for quality, the value of halls planned may change daily, so both time and halls have to be added up:

$$productivity = \frac{\sum_i^N H_{act,i}}{\sum_i^N t_{total,i}} \cdot OP_{hall} \qquad [5]$$

OP_{hall} is left constant and set to 10 operations per hall and day. Productivity results are returned as *the number of operations per minute of planning* and are not limited to a specific range.

3.4.3 Cost

For cost, it is reasonable to use the time required for planning $t_{a,i}$ by an agent a multiplied by a cost factor c_a dependent on the planners' salary. This is summed for both agents A and days N:

$$cost = \sum_a^A \sum_i^N t_{a,i} \cdot c_a \qquad [6]$$

Depending on the setup of the planning, it may happen that external personnel has to be deployed. Although the payment of these additional staff members is no intrinsic part of the planning cost, it is nevertheless *caused* by the planning arrangement and should therefore be taken into consideration.

The payment for external personnel may follow different principles, usually reduced to a service-level agreement (SLA) [DFG98]: Some hospitals have agreements with other clinics or third party companies so they can request a given amount of people for a flatrate. As there is no dependency on the simulation results in this case, but just a constant added to the cost, this case will not be dealt with in detail here. Another possibilities is to account for the additional staff with a specific cost factor c_{ext}, and add their contribution to the cost from equation 6:

$$cost = \sum_{a}^{A}\sum_{i}^{N} t_{a,i} \cdot c_a + \sum_{i}^{N} d_i \cdot c_{ext} \qquad [7]$$

The value d_i represents the amount of work done by externals.

Depending on the information which is to be retrieved, both cost with and without contribution of externals may provide more valuable insights. In the analysis section of this thesis, both versions are used depending on their applicability.

For a better interpretation, the program normalizes those cost values either to the number of surgical operations planned OP_{act} (equation 8) or to the number of days simulated (equation 9). As for the productivity in the previous section, the assigned halls H_{act} act as a surrogate for individual surgeries and are added up during simulation.

$$cost\ per\ operation = \frac{cost}{\sum_i^N H_{act,i} \cdot OP_{hall}} \qquad [8]$$

$$cost\ per\ day = \frac{cost}{N} \qquad [9]$$

In case of a well-planned process, i.e. a quality of 100 %, both values remain proportional to each other during simulation, because the number of operations per day remains constant.

3.5 Satisfaction

Satisfaction represents the, usually negative, effect of the planning process on the staff. If, for example, vacation has to be cancelled because an ill doctor has to be substituted, satisfaction of the fill-in guy will go down. According to this logic, satisfaction is fixed to a range between 0 and 1 (or 100 %), where maximum satisfaction represents the "normal" situation, i.e. when everything just works as planned.

3.5.1 Composition

To be able to measure satisfaction, it is convenient to define certain categories which are treated individually, but finally are combined into a single indicator. During a benchmark in five hospitals, a set of categories and questions had been created. [WSL14, 2–8] Based on the answers of the staff, proportional contributions to the overall satisfaction had been retrieved. [WSL14, 11, 17-18] An overview is given in table 2. The four categories with highest proportion for each department are highlighted in bold print.

Table 2: Contribution to satisfaction by department

Category	doctors	anesthetists	nursing personnel
Responsiveness of duty roster	**16.1 %**	**20.0 %**	**20.8 %**
Information and communication of OP plan	**26.2 %**	**17.3 %**	**16.8 %**
Code of conduct in team	9.8 %	5.5 %	11.4 %
Mutual appreciation	**19.9 %**	10.0 %	**11.7 %**
Qualification-accounting staff assignment	**21.0 %**	**13.4 %**	**16.2 %**
Standards in working time regulations and tariffs	1.8 %	**19.1 %**	10.1 %
Timely announcement of workforce management	0.5 %	5.5 %	3.7 %
Supporting components for workforce management	4.8 %	9.3 %	9.3 %

Although values deviate quite significantly between departments, the three categories *responsiveness of duty roster*, *information and communication of OP plan* and *qualification-accounting staff assignment* are amongst the top four for each of them.[2] Consequently, the three named contributors to satisfaction are simulated in detail based on the modelled process. The remaining ones, in contrast, have to be provided by the user as an integer between one and five, corresponding to how he rates the situation in the hospital of concern. The value set (not the share) is treated globally for all professions.

[2] Henceforth, the three categories will be abbreviated *responsiveness*, *information* and *qualification*, respectively.

Despite that, for the category *timely announcement of workforce management*, which by itself has very low contribution, the topical overlap with *information* is quite strong, so it is convenient to merge both with summed proportions.

So, to obtain the final satisfaction, for each department the seven resulting satisfaction contributors are first calculated with the respective data, and then summed with their proportions as weighting factors. As a result, one obtains four satisfaction values, one for each department (surgeons, anesthetists, OP care and anesthesia care).[3]

3.5.2 General remarks

As with overall satisfaction, each contributor is fixed to range of zero to one. All variables calculated during simulation have a negative effect on the satisfaction, so for each category the final value is obtained by subtracting the specific indicators from 1. Dependent on the topic dealt with, the indicators are corrected by specific prefactors.

The *responsiveness* category, for example, uses the number of additional days at work per staff member as input variable. It is assumed that satisfaction is 1 for zero days and 0 for ten or more days added per year. Consequently, the number of days has to be multiplied with 0.1 and then subtracted from 1 to obtain the correct result. If the value for a category is negative, zero is used. Note that for distinction between calculation results and corrected, non-negative values the same symbols are used, which only differ from each other by using upper and lower case for the first letter, respectively (e.g. $Sat_{qual,q}$ and $sat_{qual,q}$). The choice of constraints and factors is described in detail in the corresponding section of each contributor.

As for the KPIs introduced in the previous chapter, the base variables for satisfaction may change at each day in simulation time. Satisfaction itself is recalculated after each timestep based on the updated accumulated variables. If not only the final outcome is to be investigated, but also the development of the variables during simulation, it is necessary to adjust the results by an additional factor. For the number of additional days at work already used in the previous example, the worst situation after 6 months in simulation time would be five rather than ten. Correspondingly, a scaling factor *days*

[3] In the study, there was no distinction between nurses for surgical and anesthesia care. In the program, however, those two are treated as independent departments, so different satisfaction values may arise according to the process, but they are weighted by the same proportions.

of year (DOY) is introduced, whose inverse value 1/DOY is multiplied to each indicator evaluated on a daily basis:

$$DOY = \frac{N}{d_{year}} \quad [10]$$

where N is the number of days elapsed and d_{year} the number of working days per year.

3.5.3 Responsiveness of duty roster

The *responsiveness* is derived from two internal variables:

When staff is reduced due to an event (sickness, training, etc.), the first measure to recover this shortage is to reschedule vacation for the remaining personnel. This means, a staff member's holidays have to be cancelled. As a result, the cancelled amount of time has to be regarded as *additional vacation* in the future. A variable d_{vac} sums up all the latter for the respective department. For evaluation, d_{vac} has to be set in relation to the total number s_q of people employed in the corresponding department q.

Since d_{vac} is evaluated department-wise, different constraints within the latter may result in a high number of rescheduled days for one department and a low number for another. This is also considered to reduce the satisfaction. To account for this effect, a value d_{diff} is created which is the difference between the maximum and minimum d_{vac} at a certain point in simulation time:

$$d_{diff} = \max_{q \in D} \frac{d_{vac,q}}{s_q} - \min_{r \in D} \frac{d_{vac,r}}{s_r} \quad [11]$$

where D is the set of departments. Note that d_{diff} is a global variable, so there is only one result for all departments. This is reasonable, as the cause for differences is not the actions taken by the heads of departments (which all stick to the same process), but the general amount of fluctuations in shortage events.

The satisfaction for *responsiveness* $sat_{resp,q}$ of a department q consequently is as follows:

$$sat_{resp,q} = 1 - \frac{1}{DOY} \cdot f_{vac} \cdot \frac{d_{vac,q}}{s_q} - \frac{1}{DOY} \cdot f_{diff} \cdot d_{diff} \quad [12]$$

where f_{vac} and f_{diff} are the prefactors to normalize the effects on satisfaction. Based on a year with 250 working days, it is assumed that for both d_{vac} and d_{diff} a value of 10 or more days per person results in zero satisfaction. Consequently, both f_{vac} and f_{diff} equal 0.1. It should be noted that the condition is valid for either of both variables, so a value of five for each them is also sufficient.

If the result for $sat_{resp,q}$ is negative, zero is used to obtain the final contribution $Sat_{resp,q}$:

$$Sat_{resp,q} = \begin{cases} sat_{resp,q} & if\ sat_{resp,q} > 0; \\ 0 & otherwise. \end{cases} \quad [13]$$

3.5.4 Information and communication of OP plan

For the *information* part of the satisfaction, there are also two constituents:

While in the previous section the amount of additional vacation due to e.g. sickness was measured, valuable insights are also accessible through the frequency of those events. For this purpose, the simulation includes counters for all kinds of situations with negative impact: actual default of OPs (denoted e_{def}), shortage events which are handled by the OP manager (denoted e_{ext}) and shortage events which are handled inside the departments. The latter are evaluated per department q and split between weekly $e_{week,q}$ and daily $e_{day,q}$ routine. These four are then added up to the total number of change events $e_{all,q}$:

$$e_{all,q} = e_{def} + e_{ext} + e_{week,q} + e_{day,q} \quad [14]$$

An *event* in this context means a function call to add personnel or to resolve a conflict, regardless of the number of people rescheduled, i.e. the variable is a simple counter. As those events are raised based on a comparison of required and available workforce, they are not dependent on the number of people and thus do not need to be normalized.

The second contribution is based on an adverse situation: If surgeries have to be cancelled because one department does not provide sufficient personnel, but the other departments planned sufficiently, there will be people at work that are present, but not required. This is evaluated by a variable $d_{lost,q}$, which represents the time lost due to overcapacity. Since the lost work is essentially caused by bad planning, an assignment into the *information* category is logical. The value is normalized to the number of employees s_q and the number of days elapsed N:

$$p_{lost,q} = \frac{d_{lost,q}}{s_q \cdot N} \quad [15]$$

As a result, one yields the percentage of working time which is wasted. (Note that a further scaling with 1/DOY is not required in this case.) To convert this information into satisfaction, it has to be kept in mind that spare time at work it not *per se* a bad thing. Correspondingly, for evaluation a lower limit of 10 % is assumed, which has no effect on satisfaction. For higher values, the impact increases linearly until it reaches 30 % (and above), which results in zero satisfaction:

$$sat_{lost,q} = \begin{cases} 0 & if\ p_{lost,q} < 10\%; \\ 5 \cdot (p_{lost,q} - 0.1) & if\ 10\ \% \leq p_{lost,q} \leq 30\%; \\ 1 & otherwise. \end{cases} \quad [16]$$

For the total *information* satisfaction value, the following equation is used:

$$sat_{info,q} = 1 - \frac{1}{DOY} \cdot f_{event} \cdot e_{all,q} - sat_{lost,q} \quad [17]$$

The f_{event} prefactor is set to 0.05, so satisfaction reaches zero for 20 or more events per year. In accordance to the previous section, the final satisfaction $Sat_{info,q}$ cannot have a negative value:

$$Sat_{info,q} = \begin{cases} sat_{info,q} & if\ sat_{info,q} > 0; \\ 0 & otherwise. \end{cases} \quad [18]$$

3.5.5 Qualification-accounting workforce assignment

For this category, a calculation only based on simulation variables did not seem sufficiently suitable. Regarding qualification, there is always a general, process-independent environment which cannot be *calculated*. For example, the distribution and allocation of experienced surgeons and trainees, as well as their total shares in staff composition, are management decisions not linked to the planning process.

As a consequence, the *qualification* contribution to satisfaction is a combined value based on manual input i_{qual} and calculated data $Sat_{calc,q}$ as well:

$$Sat_{qual,q} = 0.5 \cdot i_{qual} + 0.5 \cdot Sat_{calc,q} \quad [19]$$

The simulation-based part accounts for two impact factors: First, it is assumed that the presence of external personnel and the resulting change in surgical group assembly lowers satisfaction. Therefore, the amount of work done by externals d_i is added up and set in relation to the days elapsed N and the number of halls available H, yielding the average *number* of externals per hall and day:

$$p_{ext} = \frac{\sum_i^N d_i}{H \cdot N} \qquad [20]$$

The second contributing value is the effect of spare time or lost working time, respectively. Since most of the staff is highly qualified, a non-negligible amount of useless presence time can be conceived as a kind of disrespect towards personnel. For implementation, the same scheme and constraints as in the previous paragraph are used. The simulation-based part of the *qualification* satisfaction contribution therefore evaluates to:

$$sat_{calc,q} = 1 - f_{ext} \cdot p_{ext} - sat_{lost,q} \qquad [21]$$

The factor f_{ext} is chosen to result in zero satisfaction for at least one external in each hall in average and consequently set to 1. As before, there has to be a check for negative values. Note that in this case not the final quantity $Sat_{qual,q}$ is checked, but simulation-based contribution $Sat_{calc,q}$:

$$Sat_{calc,q} = \begin{cases} sat_{calc,q} & if\ sat_{calc,q} > 0; \\ 0 & otherwise. \end{cases} \qquad [22]$$

3.5.6 Remaining satisfaction contributors

For the four other satisfaction contributors, i.e. *code of conduct in team*, *mutual appreciation*, *standards in working time regulations and tariffs* and *supporting components for workforce management*, reasonable links to simulation parameters could not be established. As they have comparatively small shares to total satisfaction anyway (see table 2 and corresponding discussion on page 17), they have to be set manually before starting the simulation by choosing an integer value from 1 (worst) to 5 (best). The evaluation is done globally, i.e. there is no distinction between departments, except by the different weighting factors.

4 Simulation results and implications

In this section, a set of simulation results for different configurations and scenarios is presented. The purpose of this presentation is three-fold:

First, the data obtained verifies the correct performance of the simulation tool, as all results are reasonable and can be fully explained. Second, the effects of various parameters and the more in-depth simulation coherences are visualized, so the reader has a chance to understand them to a higher extent. And finally, the results found can be used to draw conclusions on the process itself, so improvement potentials may be derived.

The discussion is split into two chapters: Initially, a *factor analysis* investigates the effect of all influence factors on the output. Therefore, they are mostly treated independently from each other. Later on, a model scenario is defined, so a *scenario analysis* can be performed. At that point, the influence factors introduced before are combined and applied to a particular model situation.

Although the planning process itself is given, there is no information included about the time required for the various steps. The values used in this thesis therefore had to be estimated. Even though relevant variables are included, like time for planning workforce has to be proportional to the number of employees, it has to be clearly stated that this fact is a major obstacle for quantitative interpretation. According to that, most of the results discussed in this whole section refer to qualitative aspects.

All plots shown in this section where build based on the ASCII output from the simulation, using MATLAB 2014b [Math14] for plotting and arrangement.

4.1 Factor analysis

4.1.1 Reference scenario

To have a standard for all results discussed below, it is reasonable to define a particular setup which serves as reference for further analyses. For the process at hand, the natural reference is a configuration without any disturbances and an amount of staff which is exactly sufficient. It is worth mentioning that this setup is not necessarily a recommended one, as the latter constraint makes it sensitive to perturbation (see chapter 2.1).

The number of halls is set to 100, which roughly matches the reference hospital. It is assumed that one person of each relevant profession, i.e. one doctor, one anesthetist and two nurses (one from OP care and one from anesthesia care), are employed per hall. The number of incidents is set to zero and vacation to 25 days a year. All contributions to satisfaction which have to be provided manually are at maximum level.

For this configuration, it is obvious that without incidents both quality and satisfaction constantly equal 100 %. Productivity and cost show plots with adverse behavior compared to each other (see figure 8), reaching values of 0.33 planned OPs per minute planning for the former and 2.2 € per planned OP for the latter. To make the following analysis more easily readable, further results will be given in units of OP/min or €/OP, respectively.

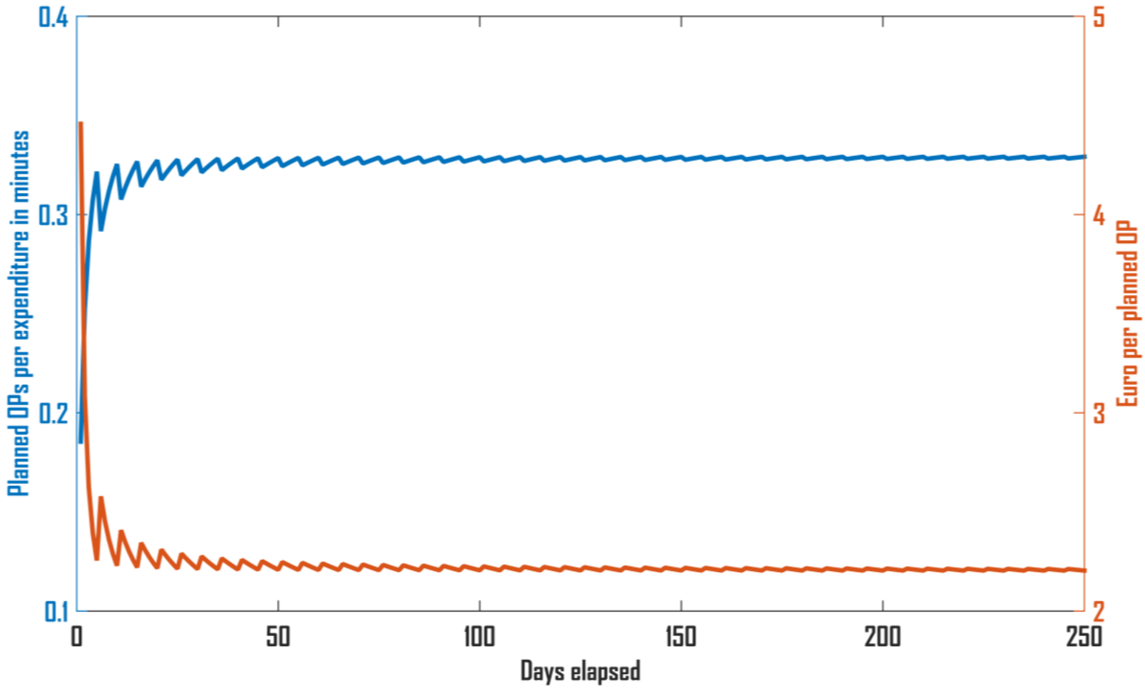

Figure 8: Productivity and cost of the reference scenario.

4.1.2 Simulation time

In the simulation, one has to distinguish between two different types of time: The time consumed by planners for completing their tasks in the process (called *planning time*) and the days which are planned, so surgical operation can take place (called *simulation time*). While the latter is obviously measured in days, the unit for the former is minutes.

In chapter 3.2, the simulation flow was introduced as a chain of initial (annual/semi-annual), weekly and daily step. This is of particular importance for the interpretation of productivity and cost, which both incorporate the planning time. Accordingly, as simulation time elapses, the effect of initial planning is distributed over an increasing number of days and thus reduced in relative units. The same occurs during the week, when efforts for weekly planning are distributed amongst one to five days. The whole effect can be observed quite nicely in figure 8: The saw tooth shape reflects the weekly changes, which can be easily smoothed by choosing every fifth point (the end of each week), like in figure 9.

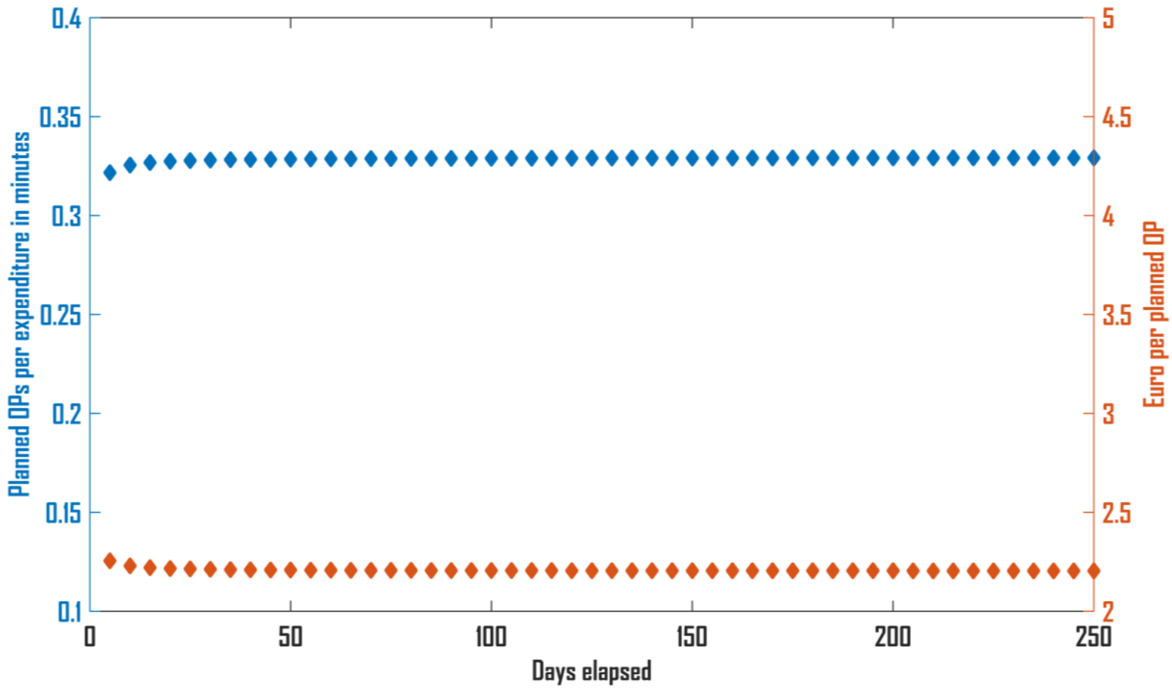

Figure 9: Productivity and cost of the reference scenario evaluated at the end of each week.

The remaining curvature at the left is observed due to the initial planning time. If the latter was zero, the reference scenario would yield straight lines with a slope of zero for the weekly plot. From a mathematical point of view, this can also be derived from productivity as in equation 5:

$$productivity \sim \frac{\sum_i^N H_{act,i}}{\sum_i^N t_{total,i}} \qquad [23]$$

Since for the reference case no surgeries are cancelled, the number of surgical operations (and halls) is proportional to the time elapsed N. Despite that, total time can be split in initial, weekly and daily portions:

$$productivity \sim \frac{N}{\sum_i^N t_{day,i} + \sum_i^N t_{week,i} + t_{initial}} \qquad [24]$$

The same is possible for cost (see equations 7 to 9):

$$cost\ per\ agent \sim \frac{\sum_i^N t_{day,i} + \sum_i^N t_{week,i} + t_{initial}}{N} \qquad [25]$$

For equal cost factors of all agents, productivity and cost are inversely proportional.

Although the aspects discussed here are mostly trivial, it is worth mentioning them as their influence may become particularly relevant when constraints are more demanding.

4.1.3 Incidents and default

The main task of surgical workforce planning is to deal with incidents, i.e. unexpected defaults of personnel. Thus, a first step of analysis investigates the effect of incidents of different extent. In this context, vital parameters are the limits for available replacement at both department and management level. For the following discussion, the former is set to one person per department and day and the latter to one person per day at all. For weekly incidents, it is assumed that personnel available due to rescheduling is unlimited, as there is sufficient time for reacting.

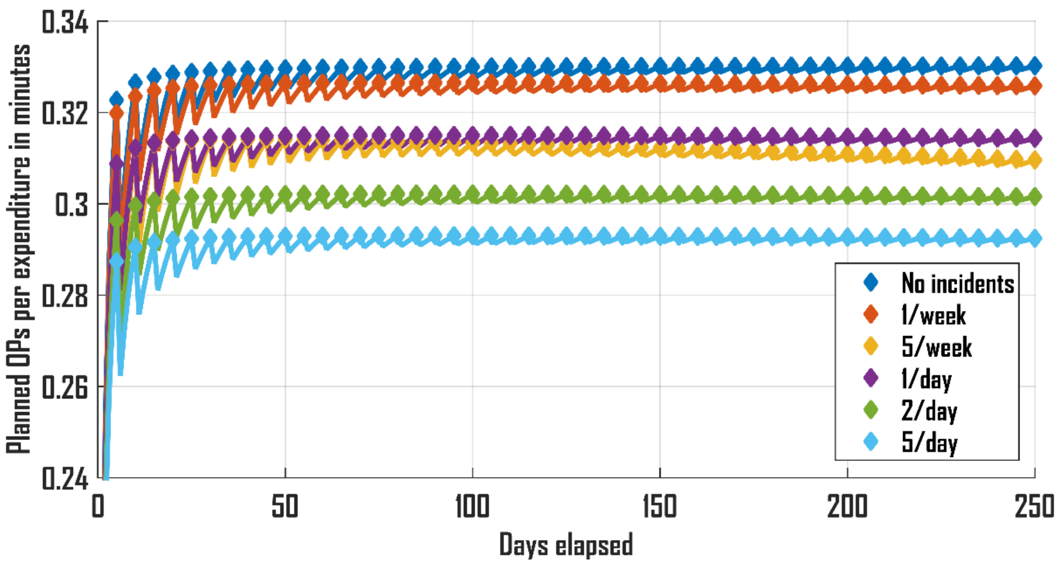

Figure 10: Productivity in dependence of the number of incidents.

In figures 10 to 12, both cost and productivity are compared for a different number of incidents. As expected, productivity is always lower and cost always higher compared to the reference scenario. However, in both cases the effect of weekly incidents is much smaller compared to daily defaults, although the effective loss of workforce is the same.

This can be explained since an incident count of 1/week means that the person is not available for five days, but the default has to be handled only once. For an incident count of 1/day, the amount of work lost is also five days per week. But since the event itself has to be dealt with every day, the cost of planning is increased. Therefore, the simulation yields about the same cost for one incident per day and five incidents per week, the latter representing a five times higher default volume. Already for two events per day, productivity is considerably lower than for five incidents a week.

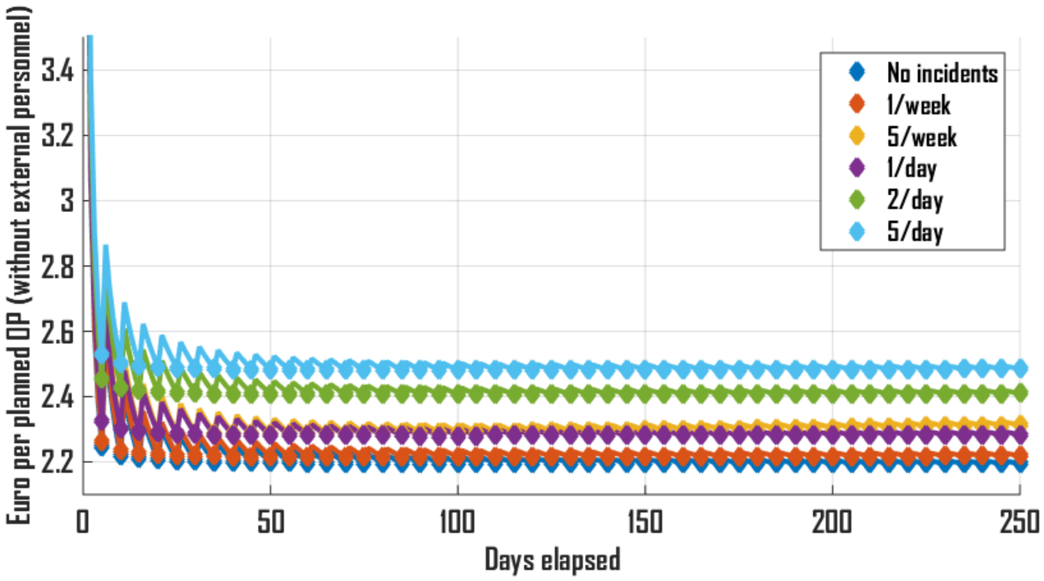

Figure 11: Cost in dependence of the number of incidents.

A comparison of figures 11 and 12 shows a significant deviation for two and more events per day, while for lower values and weekly incidents plots are similar. This can be explained by the external workforce required for those cases, since the daily internal replacement capability is limited to one person per day and department. As external resources are limited, too, further increases in daily incidents only affect productivity and cost due to OP defaults. If cost is plotted with respect to the days elapsed, for instance, the plots for two or five events per day cannot be distinguished at all.

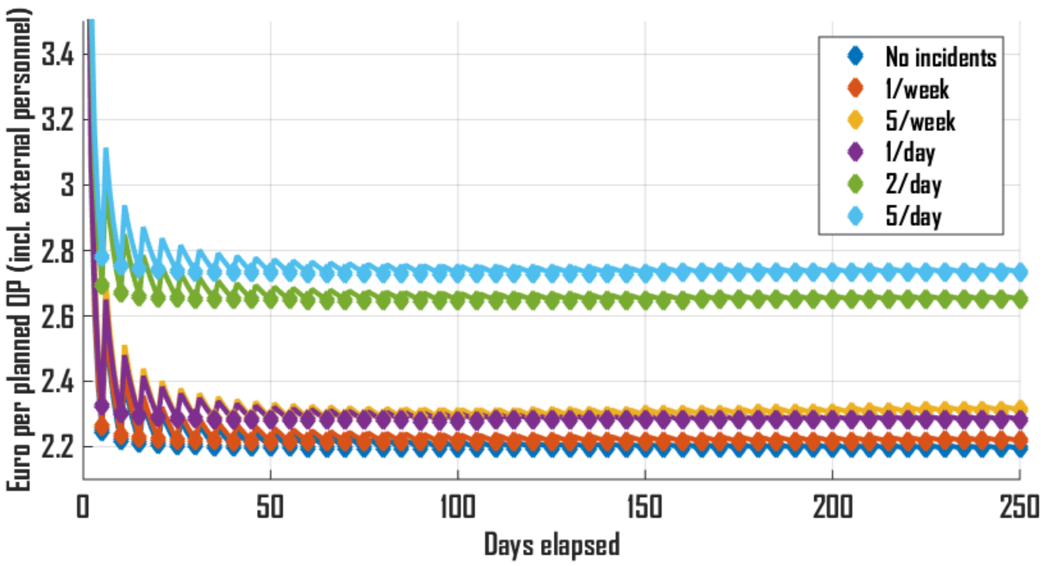

Figure 12: Cost in dependence of the number of incidents, including additional cost raised by external workforce.

One final remarkable effect is observed for five incidents per week, most pronounced in figure 10: In this case, (weekly) productivity first rises until it reaches a maximum at 40 days in simulation time, and then declines again. The reason for this behavior is the additional vacation which is granted when staff members are called in to compensate incidents. These vacation days accumulate during the year and consequently continuously lower the amount of available personnel. A reduced number of people available then again worsens the effect of incidents, so it slightly amplifies the impact of default events.

This *postponed vacation effect* is present for any example given here except the reference. However, in most cases the magnitude is quite small, so it is not visible in the figures given in this paragraph. Especially for daily incidents, where internal compensation is limited to one person a day anyway, the effect can essentially be neglected. For scenarios with a high default rate, in accordance, one should nevertheless keep in mind that a personnel buffer or other preventive action in the beginning can provide extra benefits in the long range in addition to the immediate effect.

The effects on *quality* are rather simple compared to the facts discussed above: Quality is only affected if incidents can neither be handled internally nor by the management. In addition, as there are no random variables included, the values are constant throughout the simulation. Consequently, quality is only different from 100 % for two runs: For two incidents per day, it equals 99.25 %, and for five event per day, it drops to 96.25 %.

Satisfaction, in contrast, shows effects for all simulation runs except the reference (100 %): In figure 13, the results for surgical care is displayed as an example; the plots for other staff groups exhibit the same general behavior, while only the range of effects (and values) is changed due to the proportion of certain satisfaction contributions.

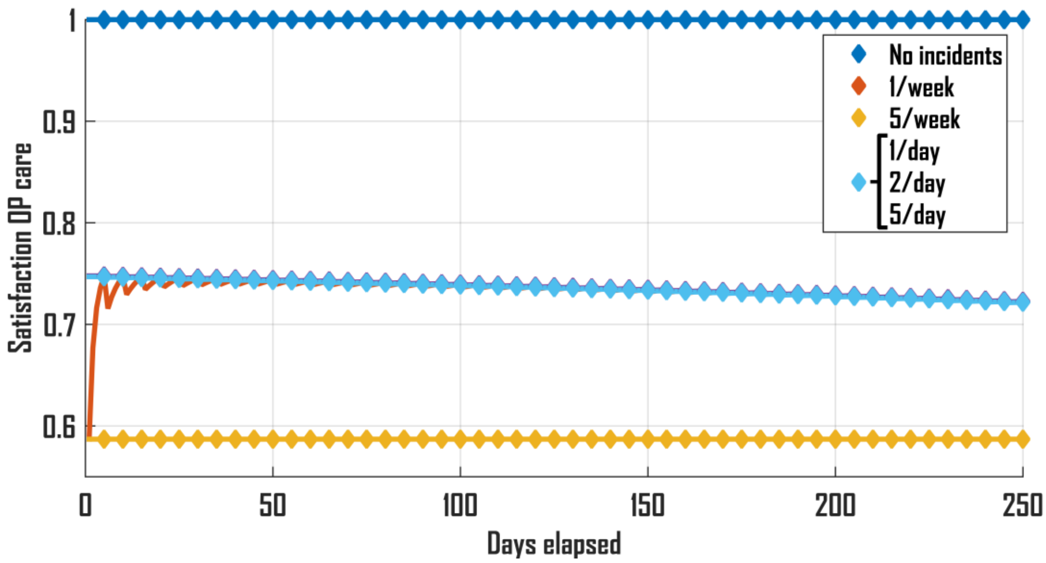

Figure 13: Satisfaction of OP care personnel in dependence of the number of incidents.

The most important observation is that for satisfaction, in contrast to the KPIs discussed above, the worst results are produced for high incident numbers on a weekly basis, which is rather counter-intuitive. To better comprehend this phenomenon, it is necessary to split the satisfaction into its simulation-dependent contributors:

The special thing about the five days per week scenario, in accordance to the facts discussed above, is that all shortages are handled inside the department. In terms of KPIs, this means both no additional planning and no dropped surgeries due to shortages. In terms of satisfaction, this means that for every single incident one person has its vacation cancelled. For the five people per day scenario, however, only one person is replaced internally, representing just 20 % compared to the situation before. The remaining efforts for replacing personnel or even dropping surgeries may be worse in terms of KPIs, but are far less relevant concerning satisfaction. For the former, increasing the number of externals available shows at least a slight spread, as illustrated in figure 14.

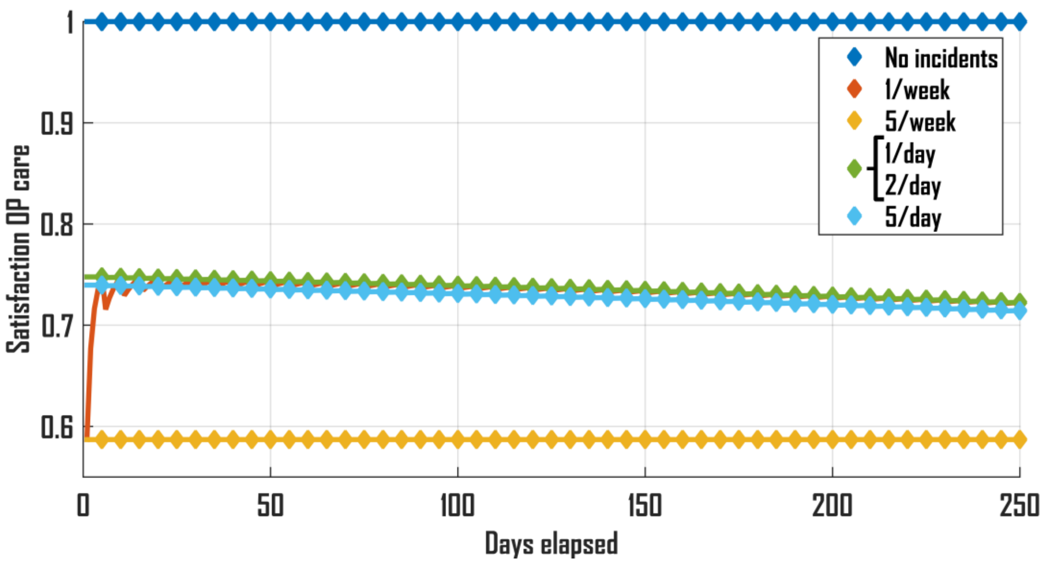

Figure 14: Satisfaction of OP care personnel in dependence of the number of incidents. Compared to figure 13, the number of externals available is increased from 1 to 10.

The slow decline of satisfaction for mediocre event numbers (see figure 13), is again due to accumulation of additional vacation during simulation. In case of five incidents per week, this effect is suppressed as satisfaction is already at its lowest level for the contribution of interest.

4.1.4 Chance

So far, all variables and parameters have been set before starting the simulation and remained constant throughout. However, for a simulation to deal with personnel shortages and fluctuations, this would be a rather limited approach. The constant values could be simply included in strategic planning, and no further measures were necessary.

In reality, of course, defaults of workforce happen unexpectedly. In the simulation, the events are therefore calculated as combination of an average and a variation range. For the latter, random numbers are calculated with uniform distribution, using the average as mean value. If both average and variation are set to five (denoted 5±5), for example, the resulting values range from zero to ten, including non-integer numbers. This is performed by independent parameters and values for weekly and daily events. In both cases, negative results are replaced by zero.

Obviously, those random parameters cause fluctuations in all output variables, corresponding to the magnitude of the randomness parameters set. The subject of this paragraph, though, is to explain the effects of chance with respect to the ultimate results.

While for weekly incidents the effect of random events is negligibly small, the plots of variable daily incidents in figures 15 and 16 are rather surprising at first look: Especially for five events per day, the plots with a deviation of five show considerably better (higher for productivity, lower for cost) values than those with no or low degree of chance. The same effect is observed for two incidents a day, but much less pronounced than in the first case. For cost including external personnel, the effect is greatly increased.

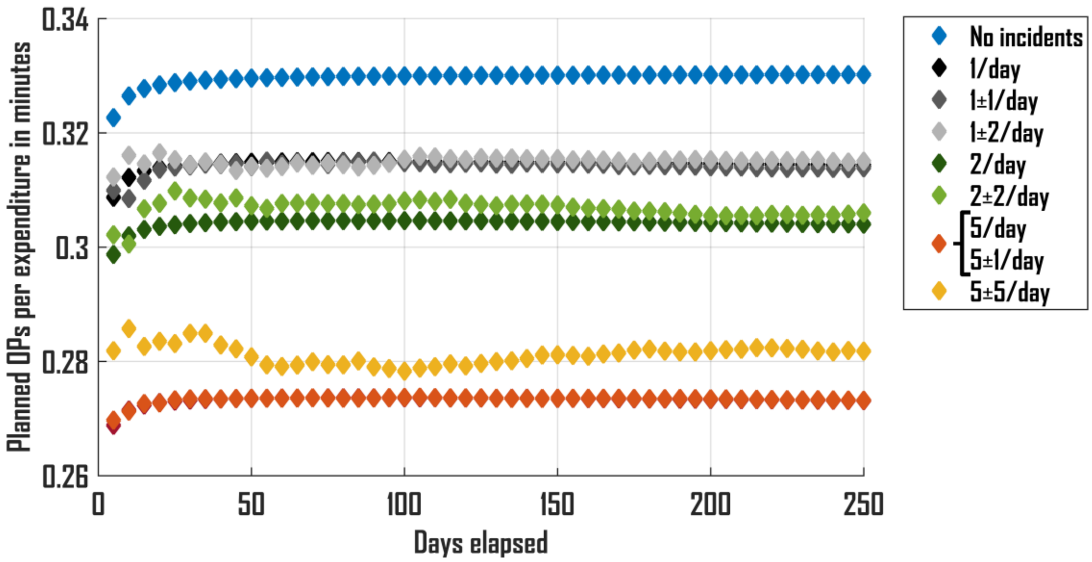

Figure 15: Productivity in dependence of the number of incidents, where the latter is partially random.

The reason for this behavior is again related to the limited number of externals and the efforts for dealing with shortages: If the number of incidents is constantly at five per day, the maximum amount of replacements is used, and the remainder is dealt with by cancelling surgeries. The same happens for a variation of ± 1 (i.e. 4 to 6 incidents), as the resulting minimum of four events still is above the limits.

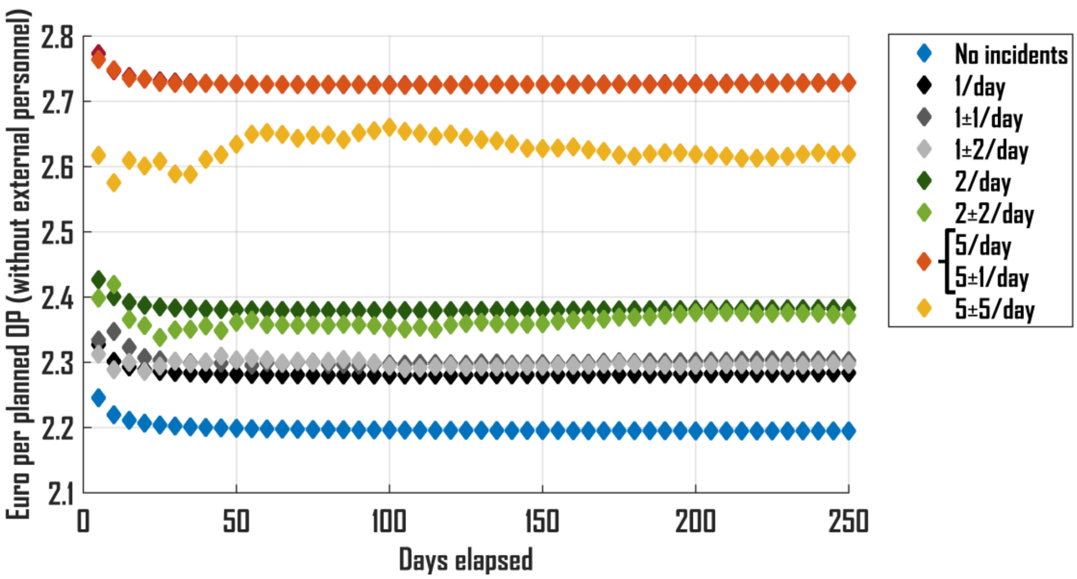

Figure 16: Cost in dependence of the number of incidents, where the latter is partially random.

For a deviation of 5±5 (0 to 10 incidents), however, there will be days requiring less externals or even without the necessity to rely on externals at all. Of course, in return there will be days with higher shortages. But the effects on cost and productivity due to the additionally cancelled operations are less high than the savings discussed before. This explanation is supported in figure 17, where the quality is displayed.

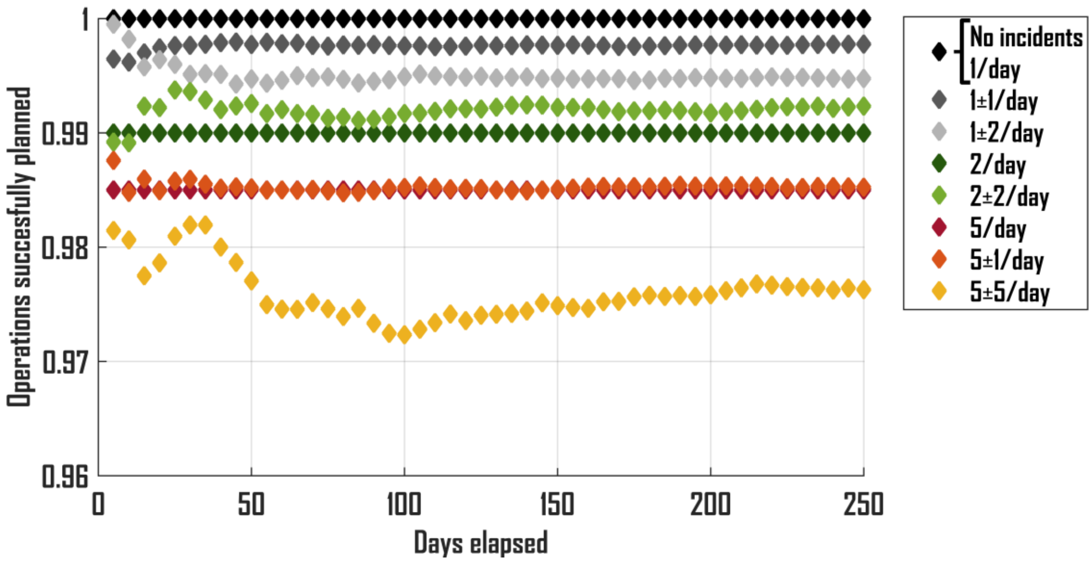

Figure 17: Quality in dependence of the number of incidents, where the latter is partially random.

Here, the data shows the exact opposite of the situation for quality and productivity: As cancelled surgeries only appear when both internal and external replacements are exhausted, the high incident number caused by deviations has an exaggerated effect on quality, so here 5±5 per day is the worst case. However, the absolute value is still considerably high for all scenarios. For an average of 2 incidents per day, in contrast, the variable calculation yields better values than the constant one.

For satisfaction, results depend mostly on internal replacements, and therefore are tightly linked to the facts discussed for productivity and quality (see figure 18). It is worth noting that 5±5 incidents almost reaches the plot for two (and, therefore, one) incident per day, while satisfaction for 2±2 events is already better than for one day fixed.

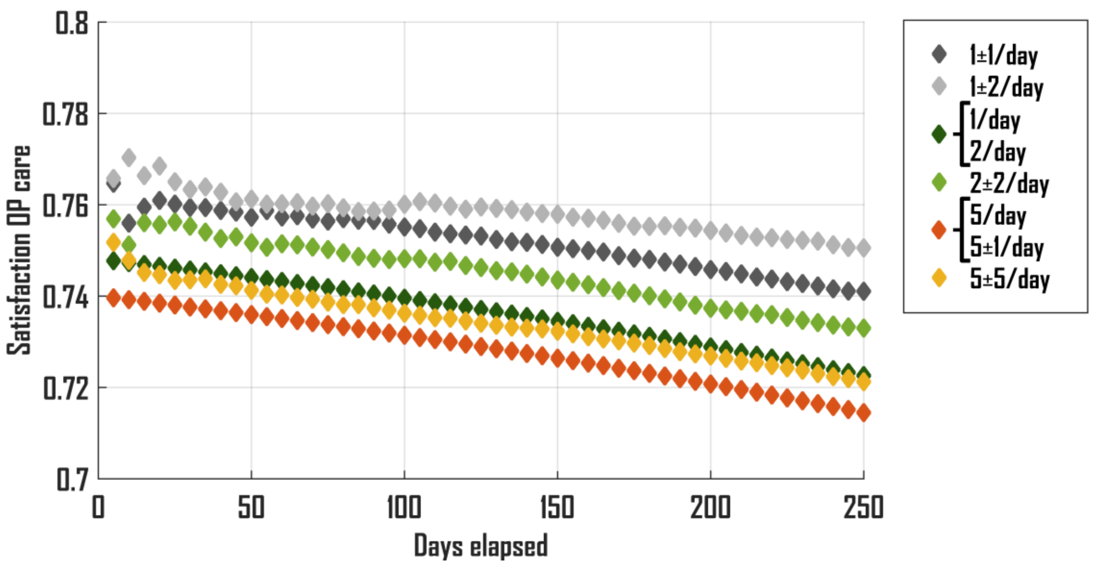

Figure 18: Satisfaction of OP care personnel in dependence of the number of incidents, where the latter is partially random. The plot for *no incidents* is not visible, as it has a constant value of 1.

To conclude, introducing a random component to incidents is likely to considerably improve results compared to a constant number of events with the same average. Only for quality, some configurations may have worse results, but only for particular configurations.

4.1.5 Workforce buffer

A powerful parameter, and the most obvious instrument to deal with shortages, is the workforce buffer. It represents the possibility to increase (or decrease) the *initially* available personnel by a certain percentage, while the planned personnel still depends on the number of halls. Accordingly, increasing the buffer causes higher cost and lowers productivity due to additional planning required, whereas decreasing the buffer below 100 % is a theoretical option equivalent to introducing weekly incidents.[4]

As an immediate consequence, quality will be 100 % for all values. For satisfaction, both reduced and additional workforce will have negative effects: For the former, rescheduling within departments will occur, which severely lowers satisfaction. For the latter, a smaller negative effect will be observed to due personnel being present without an occupation (see *lost work* in paragraph 3.5.4). This effect will of course be less prominent when buffer and incidents are combined in later analyses.

The plots for productivity and cost are given in figures 19 and 20, respectively. Despite the fact that the reference represents the best scenario in both cases, it is remarkable that adding and removing a given percentage of workforce have about the same effect.

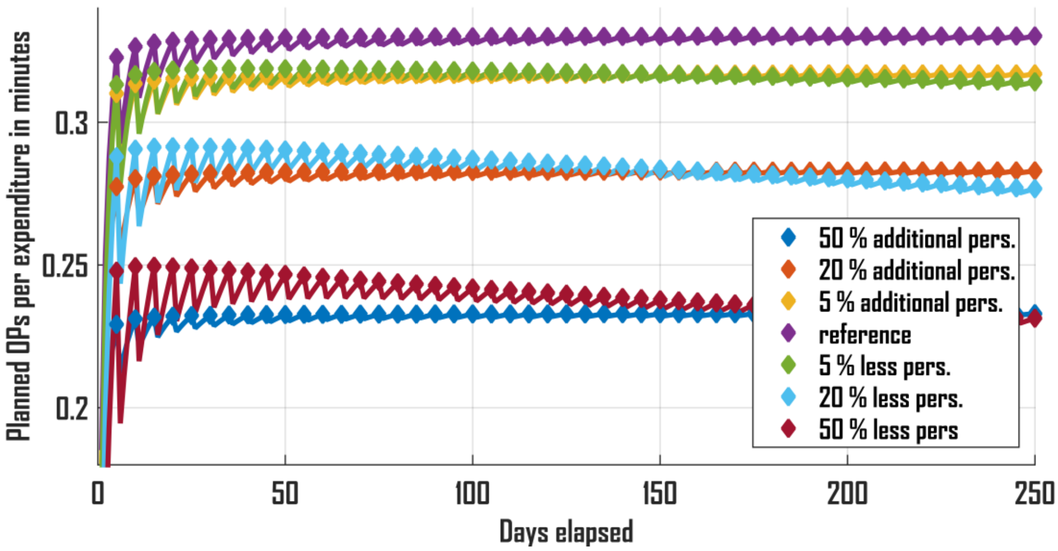

Figure 19: Productivity in dependence of the workforce buffer.

The shape of the plots for reduced numbers of personnel, i.e. for productivity a maximum followed by a decline, can be explained by postponed vacation, as introduced for incidents in paragraph 4.1.3. It has to be kept in mind, however, that a staff reduction using the buffer is only a theoretical possibility, so in this case data from the simulation has to be interpreted carefully.

[4] For the given setup with 100 halls, a workforce reduction by 5 % is roughly the same as introducing 5 incident per week. Although results are similar, differences in internal calculations will yield slightly different values.

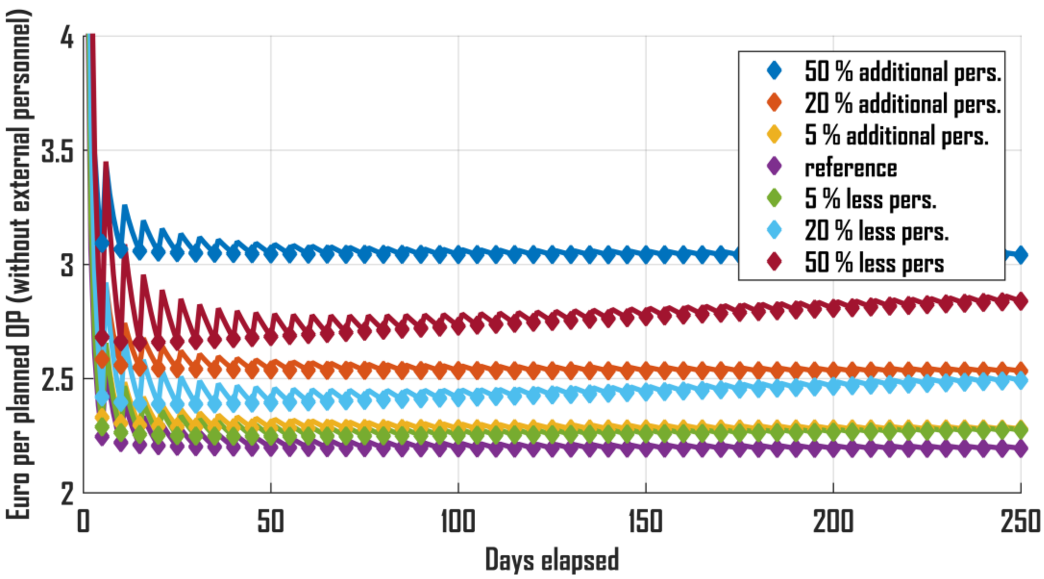

Figure 20: Cost in dependence of the workforce buffer.

4.2 Scenario analysis

4.2.1 Model

As introduced in previous chapters, the program presented herein models the process in a particular German hospital. Accordingly, the variables for calculation, especially those for the durations, were chosen to reflect the situation in the model facility where possible. Additional parameters, which have not been available directly, where retrieved from literature by bearing in mind geographical and branch-specific deviations.

As for the reference scenario in paragraph 4.1.1, the number of halls is set to 100 and one person of each profession (doctor, anesthetist, OP case nurse and anesthesia care nurse) is required per operating theater. The number of vacation days per year is set to 30, the amount granted to employees of civil service in Germany. All manually provided satisfaction contributions are at maximum.

Despite that, the most relevant variables are the incidents and their variations. As introduced above, those are essentially caused by sickness and training courses. For sickness, and with respect to the working days defined here, typical values are 6 to 8 per cent of the available working days. [Dreb14; Bors14; Barm13] With a workforce of 100 employees per department, this equals 6 to 8 people ill per department and day. As there is no reasonable data on days required for training, the model uses a value 8 from 100 employees for sickness and courses altogether.

It is further assumed that those defaults are split evenly between weekly and daily incidents. In both cases, the variation is set to four, so the model incorporates 4±4 events a week and the same number per day. To have a clear distinction from the reference scenario in paragraph 4.1.1, the setup introduced here will be referred to as the *model scenario*.

4.2.2 Parameters

Obviously, and in accordance to paragraph 4.1.3, the incidents introduced to the model scenario have a negative effect of both satisfaction and the KPIs. The aim of this whole chapter is to describe how a combined modification of variables in the simulation helps to improve the outcome again.

Within the learning cockpit, there are three parameters which can be modified, assuming that all model variables are fixed.[5] The first one is the workforce buffer, which has already been discussed generally in paragraph 4.1.5. In contrast to the analysis given there, where no incidents were set, the parameter is now used to compensate those events.

The second and third variable, the limits for replacement within departments (*internal limit*) and for replacement by externals (*external limit*), have only been discussed briefly so far. As their names suggest, setting them affects the way how shortages are resolved. In accordance to chapter 3.2, the program moves through multiple levels: In the beginning, workforce is increased by the buffer and reduced again by the weekly incidents. Then, the daily process consists of three consecutive steps: First the (try for) replacement in departments, which is limited by the internal limit, second the mobilization of external personnel, restricted by the external limit, and finally the cancellation of surgeries, if preceding steps were not sufficient.

The choice and combination of parameter values therefore determines both which fraction of the incidents is dealt with at which step and whether later steps have to be entered at all. The resultant effect on KPIs and satisfaction may vary from stage to stage in both direction and magnitude. If, for example, a very high value for the internal buffer is chosen, external personnel will be required less often and defaults will happen less frequent, too.

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5 A discussion on how modification of the latter will act on results is given later in this chapter.

4.2.3 Workforce buffer

The most obvious – and most powerful – lever is the workforce buffer: If the available number of employees is reduced due to incidents, this can be compensated by hiring more in the first place. In terms of planning simulation, this strategy also has almost no drawbacks: Quality is raised, as additional personnel compensates shortages. Satisfaction is increased, since no internal replacement takes place and no externals are involved in surgeries. Cost is lower, as the expensive, i.e. time-consuming, steps required for replacing staff members can be spared out, while planning additional staff members in advance only slightly increases time consumption. For productivity, the same is valid with opposite direction, additionally amplified by the raised number of planned OPs.

While for quality and satisfaction values are increased until they reach the maximum 100 %, productivity and cost exhibit optimum results for a particular configuration (see figure 21). If lower or higher parameter values are chosen, results for the latter become worse again. In figure 22, this minimum is observed for a buffer of 12 %, while a value of 25 % is already nearly as expensive as setting only five per cent. Despite that, note that fitting a second order polynomial to the data yields poor agreement, whilst the points for buffers greater than 12 % appear almost linear.

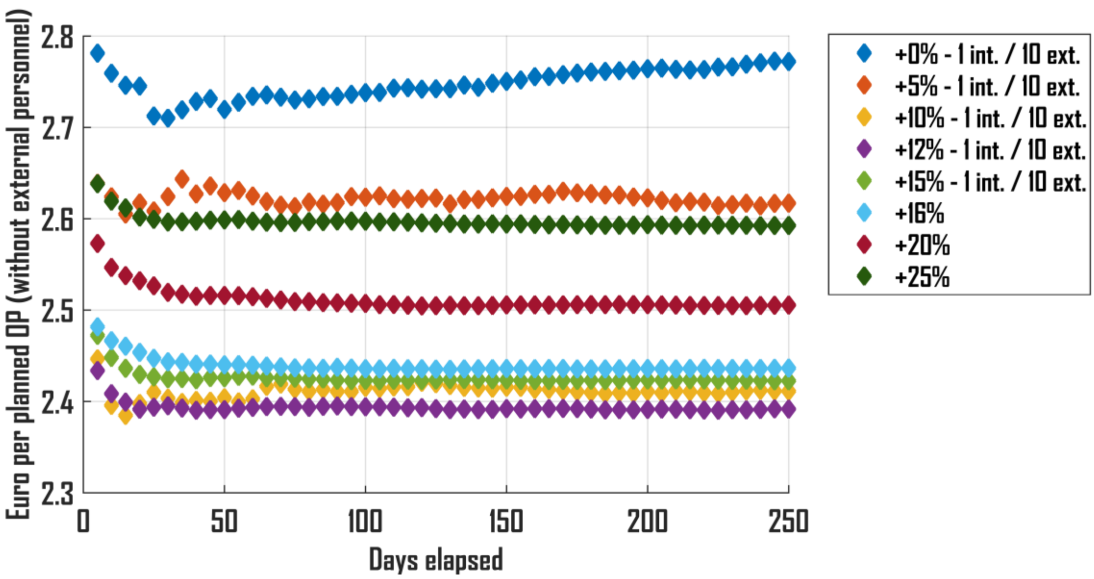

Figure 21: Cost in the model scenario in dependence of the workforce buffer. The internal limit is denoted *int*, the external limit *ext*.

When interpreting plots like in figures 21 and 22, the significance of quantitative data in this simulation has to be kept in mind. As durations for the process were only estimated, a distinction between close plots is pointless. Therefore, the minimum can be anywhere between 9 and 16 %. A similar result is obtained for productivity.

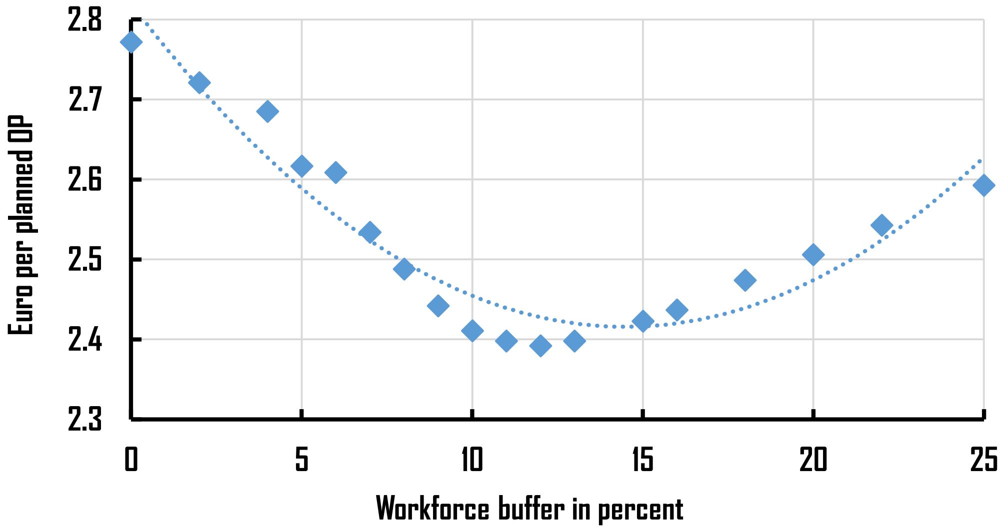

Figure 22: Cost in the model scenario after one year in dependence of the workforce buffer. The dashed line represents a fitted second order polynomial.

While quality is easily maximized, it is quite demanding to reach 100 % for satisfaction. In figure 23, maximum satisfaction of anesthetists (others behave similarly) is reached not until 16 % buffer, whereas a value of 12 % is already one quarter lower. In addition, it is worth noting that the satisfaction is reduced again at a buffer of 25 %, as too much presence time without occupation has a negative impact on satisfaction, too.

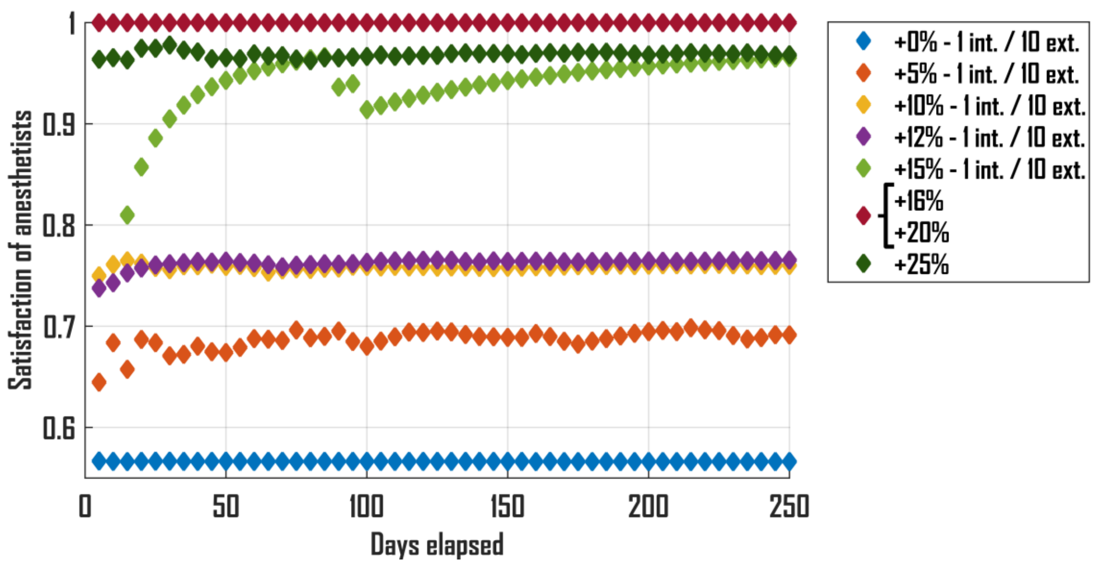

Figure 23: Satisfaction of anesthetists in the model scenario in dependence of the workforce buffer.

It is remarkable that, given the fact that incidents only equal 8 % in average, even a buffer of 10 % is not even near the optimum of satisfaction. Every single replacement or default is counted and affects satisfaction. However, since the latter is calculated based on historically cumulated data, no event is forgotten, it is just diluted by more elapsing days. In figure 23, this can be observed quite nicely at the plot for 15 %, where a drop occurs due to an incident (e.g. between 95 and 100 days), followed by a regeneration of satisfaction afterwards. While absolute replacement activities and default numbers are quite moderate, most of the satisfaction drop is caused due to the contribution of the *information and communication of OP plan*.

According to the situation described in this chapter, the optimum solution for the model scenario would therefore be to employ roughly an additional 20 % of workforce to overcome the shortage incidents. Of course, this is only a good strategy as long as the view is restricted to the planning process. In reality, there will be a time where all those additional employees want to be paid. Then, someone will have to answer the question whether improving staff satisfaction and saving 300 Euros a day is an adequate reason for paying salaries to 80 new staff members, which equals about 20 000 Euros a day. Since this simulation is limited to workforce planning, the answer has to be given by the user of the learning cockpit in a real environment.

4.2.4 Limits

If using the workforce buffer is no option, or if its range is limited, the alternatives are internal and external replacement. In this paragraph, the effect of increasing and reducing both is investigated in detail. Although it is quite easy to change those numbers in a computer, one has to keep in mind that, for example, an increase of internal limits to gain some percentages in a particular KPI may be a severe and challenging objective in a real work environment.

Where the workforce buffer had positive effect on all output factors, changing internal or external limits means buying improvement in one indicator by worsening another. If, for example, the aim is to reduce surgery defaults by using an increased number of externals, the result will be raised cost due to planning and payment of the additional staff, and a reduction of satisfaction, as surgical teams include more foreigners.

In addition, both limits depend on each other as well as on the buffer set. Table 3 gives a short impression on the effects observed through a set of simulations. Figures 24 to 26 provide a quantified image with a moderate buffer set to 5 %.

Table 3: Effect of workforce buffer and replacement limits on KPIs and satisfaction

	productivity	cost without externals	cost incl. externals	quality	satisfaction
workforce buffer	strong increase until 10 %	strong decrease until 10 %	strong decrease until 10 %	strong increase	strong increase
internal limit	stable or slight decrease	stable or slight decrease	moderate decrease	moderate increase	moderate decrease
external limit	slight decrease	slight increase	slight increase	strong increase	slight to moderate decrease[6]

It is remarkable that increasing internal and external limits has mostly negative effects on KPIs and satisfaction. On the other hand, setting both to zero results in a quality of slightly above 94 %, so only six per cent of surgeries are cancelled (with a buffer of 5 %). With zero buffer, quality still equals 93.6 %!

External personnel therefore is a component which is better reduced, despite the situation when internal replacement is zero, where it shows adverse behavior. Most astonishing in table 3, however, is the contradictory behavior of productivity and cost for modification of the internal limit.

One could argue dealing with replacement within departments requires more time, as it is done independently four times, so more spent time means lower productivity. For cost, however, time is multiplied, i.e. weighted, with the cost factor of the responsible planner. As externals are handled by the OP manager, which is paid considerably more than the heads of the departments, the time saved for him is worth more and inverts the result for cost. Whether this effect is real or just a result of the durations implemented is, however, beyond the scope of this thesis.

[6] Slight increase for internal limit = 0.

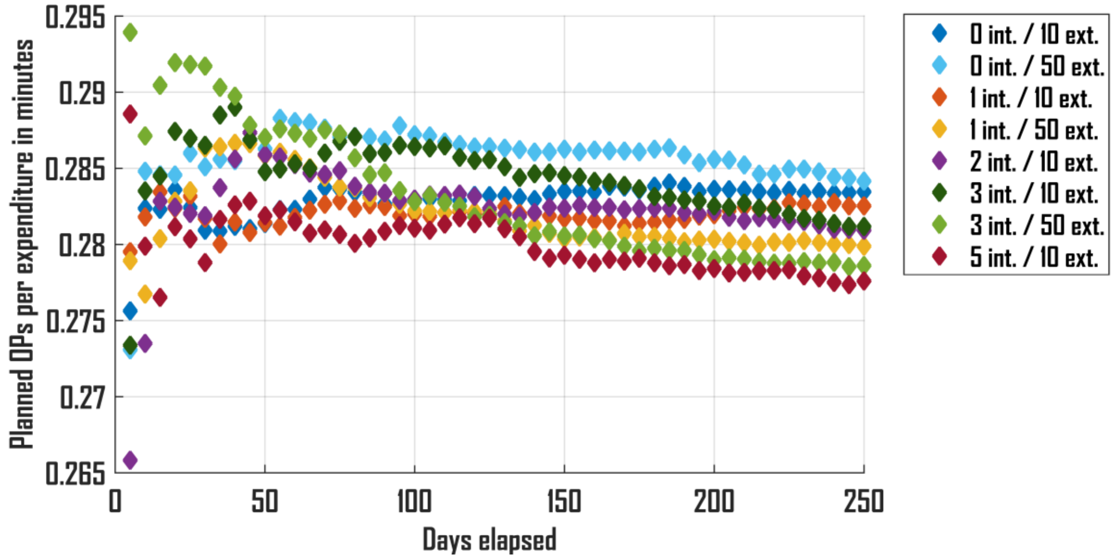

Figure 24: Productivity in the model scenario in dependence of internal and external limit with a workforce buffer of 5 %.

The productivity in figure 24 also shows how subtle the impact of changing limits actually is: An increase of the internal limit from zero to five changes productivity only by 2 %. For the external limit, the huge jump from 10 to 50 even yields a change below one per cent. For cost of planning, which is not depicted here, the situation is similar. If payment of external personnel is included (see figure 25), the effects of both internal and external limits become more pronounced.

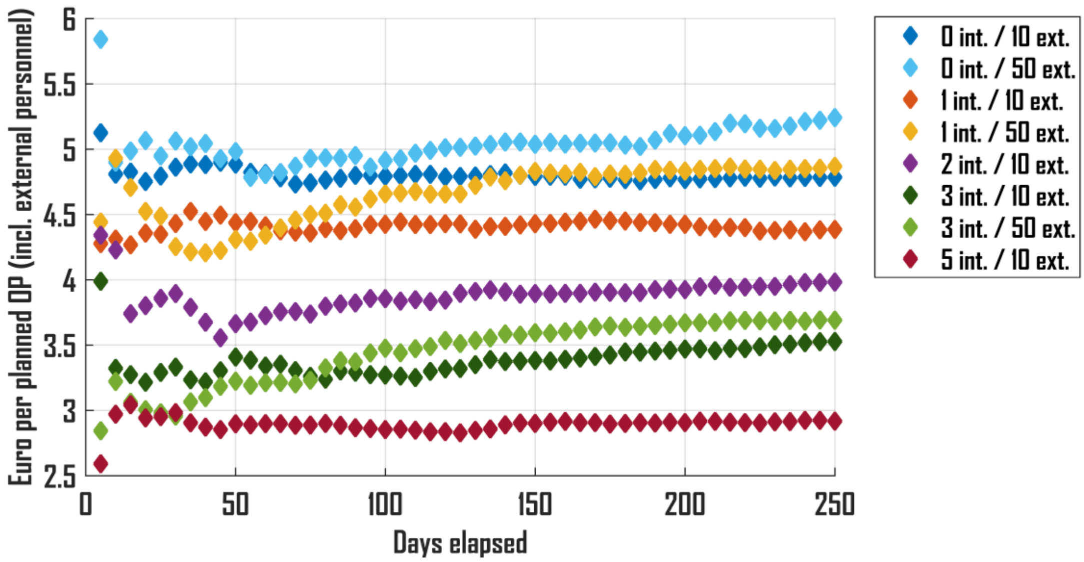

Figure 25: Cost for planning and external personnel in the model scenario in dependence of internal and external limit with a workforce buffer of 5 %.

Concerning satisfaction, as displayed in figure 26, it once again becomes clear that internal and external limits may be handy in tuning the outcome to a certain degree, but are no replacement for an adequate compensation by the workforce buffer. If the goal is to reach values above 75 %, the only way for the given model is to increase staff through the buffer.

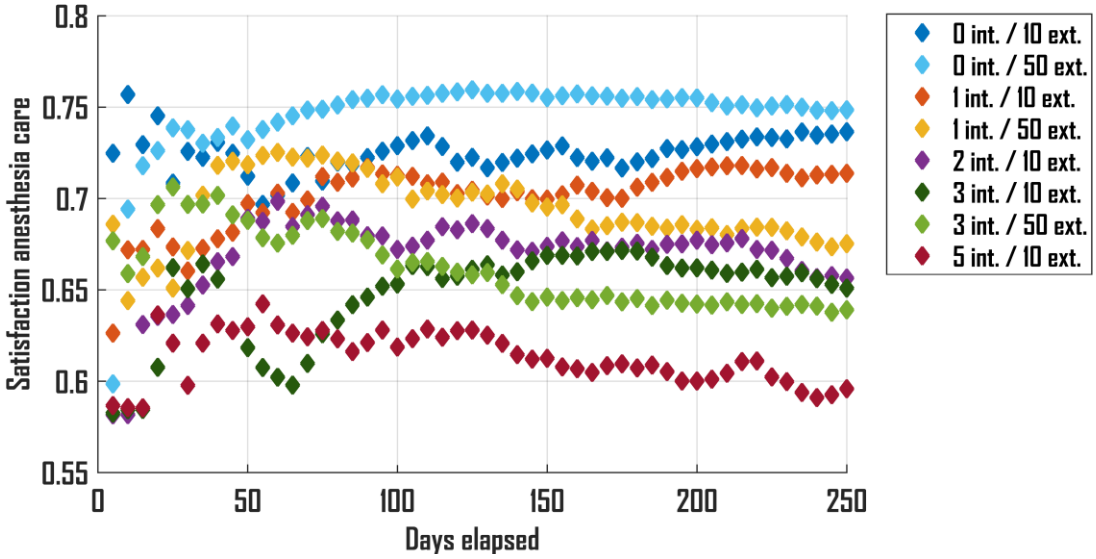

Figure 26: Satisfaction of anesthetists in the model scenario in dependence of internal and external limit with a workforce buffer of 5 %.

For the argument made here, the value of 5 % was chosen quite arbitrarily. Using lower values, one will see similar effects, but with a small amplification. Accordingly, if set to higher percentages, a reduction of magnitudes will occur. At a buffer value of sixteen per cent, both limits will become irrelevant for this model.

4.2.5 Extremes

Given the number of indicators, it is hard to ultimately define a single best or worst case, as an extreme of one might not occur for the others. In addition, if the scope is *not* limited to workforce planning, additional influence factors like the cost of additional employees discussed earlier in this chapter will change the entire argumentation.

In this paragraph, best case and worst scenarios for the model given in paragraph 4.2.1 are derived. In accordance to the problem description just made, I distinguish between a best case in terms of KPIs, particularly cost and productivity, and another best case led by satisfaction. In some cases, where particular scenarios have already been introduced and analyzed in earlier discussions, this paragraph gives a comprehensive overview of extremes.

Later on, an investigation of worst situations focusses on quality at the one hand and productivity/cost at the other hand. Satisfaction is not relevant in this case, as the limits introduced in the simulation (see chapter 3.5) yield about the same minimum satisfaction in all relevant cases.

Most of the discussion relevant for finding the best case has already been made in paragraph 4.2.3, when the workforce buffer was discussed. When satisfaction is the ultimate goal, the best case clearly is just increasing staff by 16 %, yielding 100 % quality and satisfaction and rather good productivity and quality. Note that internal and external limits are not relevant in this case.

If the tiny differences in productivity and quality, as depicted in figure 21 on page 37, are considered to be accurate, a best case with respect to them would be a workforce buffer of 12 %. Applying the same criterion to the limits yields an internal limit of 5, as illustrated in figure 27. This is rather unexpected, as the buffer in combination with a limit of four should be sufficient to cover the maximum possible staff shortage of 16 %.[7]

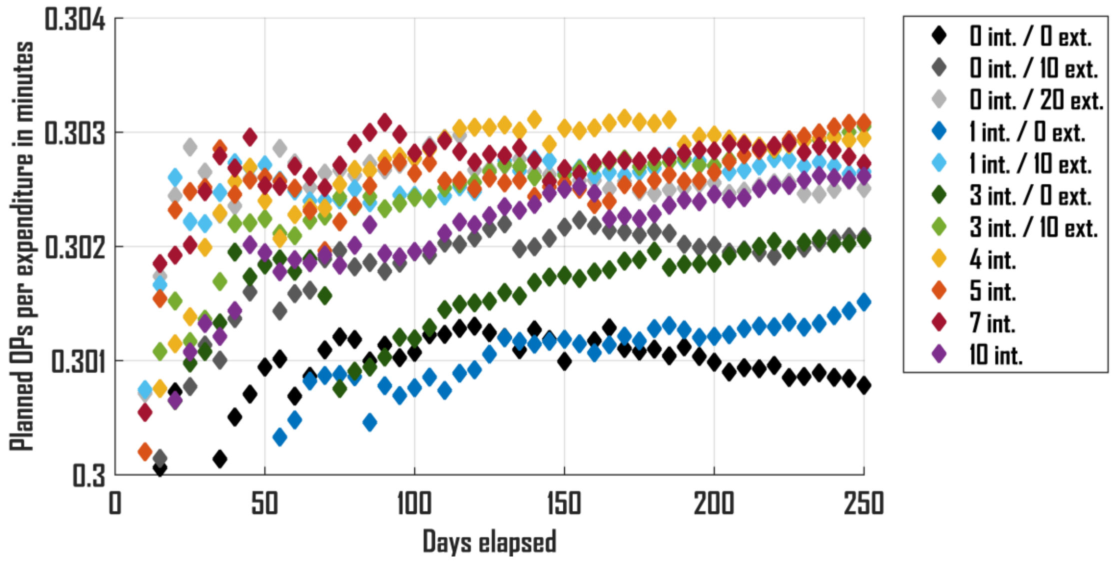

Figure 27: Productivity in dependence of internal and external limit with a workforce buffer of 12 %.

[7] Multiple simulation runs were performed to exclude random numbers as a reason.

Since variations are below 1 % for both productivity and cost, one could also make a contribution to satisfaction and choose limits of zero to boost satisfaction by some percent.

In contrast, identifying a worst case is quite easy. If quality is the leading criterion, the resulting configuration is simply doing nothing, i.e. no buffer and no replacements take place (limits equal zero). For all other indicators (including satisfaction to a very small extent) the worst thing to happen is a high number of externals, while all other parameters still equal zero. While a comparison of cost for different buffer values is given in figure 21 on page 37, figure 28 shows how the limits affect this indicator.

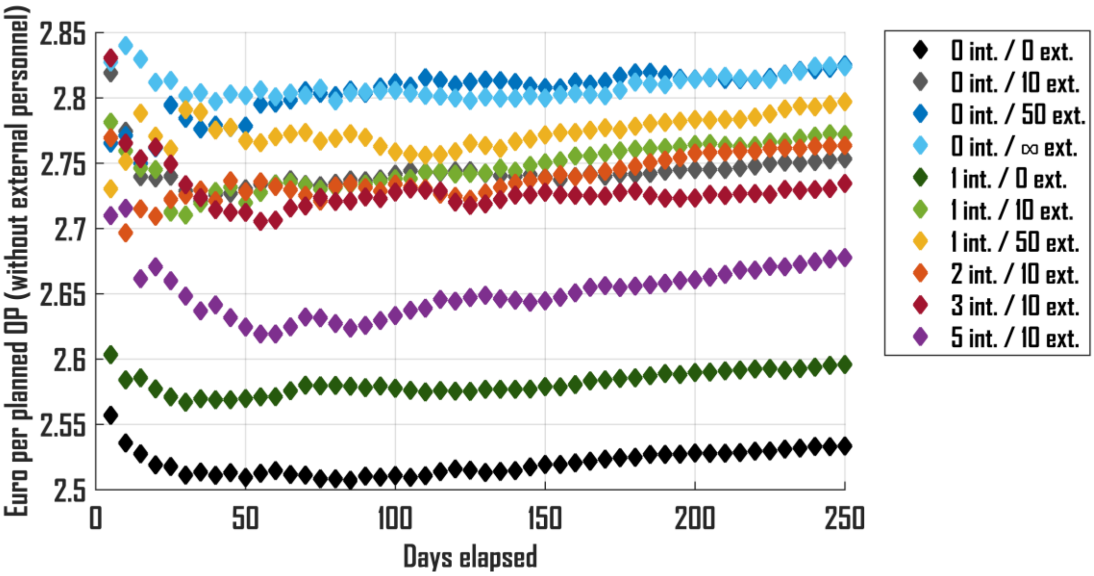

Figure 28: Planning cost in dependence of internal and external limit without a workforce buffer.

A short summary of all scenarios is given in table 4:

Table 4: Effect of workforce buffer and replacement limits on KPIs and satisfaction

	cost/productivity	quality	satisfaction
Best case	buffer: 12 % internal limit: 5 external limit: –	n. a.	buffer: 16 % internal limit: – external limit: –
Worst case	buffer: 0 % internal limit: 0 external limit: ∞	buffer: 0 % internal limit: 0 external limit: 0	n. a.

4.2.6 Beyond the model

Everything discussed in this chapter so far is limited to the model defined by its parameters in the beginning. This paragraph aims at giving a brief overview of additional levers to obtain a view beyond the model and the simulation constraints. Consequently, the analyses on those topics only aim at giving a first idea on the subject and are therefore rather short and less comprehensive compared to earlier discussions.

The most obvious and rather trivial lever is, of course, reducing the number of incidents, i.e. sickness days. Since this is effectively comparable to a raise of the workforce buffer and in accordance to the general analysis in paragraph 4.1.3, decreasing the frequency of events will equivalently yield improvements in all indicators.

A second very potent influence factor which has not been discussed at all so far is the stochastic function used. Throughout all former analyses, incidents where calculated based on a uniform distribution. Consequently, for 4 ± 4 incidents, every value from zero to eight has the same probability. In figure 23 on page 38, one can easily see how this leads to several drops even for a buffer of 15 %. If, for example, a Gaussian distribution was chosen instead, a sufficient satisfaction possibly could be reached with lower buffer values, since extreme incident numbers become rare.

Another important influence factor illustrated in figure 23 is not the frequency, but the depth of satisfaction drops for a buffer of 15 %. In this case, a single contributor, namely *information and communication of OP plan*, leads to a severe reduction of total satisfaction. This is possible as in this case all events to handle shortages are counted, regardless of the actual amount of staff replaced or surgeries cancelled. Especially in the latter case, it is important to note that cancelling an operation includes four calls: weekly and daily internal replacement, using externals and finally default of OPs. If those counters lead to drops in satisfaction, a long period of time is required to dilute the effect. However, as the limits and impact factors of all satisfaction contributors are defined on very basic assumptions, a modification of those constraints might yield different results.

In general, the method of measuring satisfaction is not as predefined as the calculation of the KPIs. In this simulation, satisfaction is treated in a way that employees have a good memory, i.e. every incident is counted and then averaged over the whole simulation timespan. In contrast, if staff is very forgiving, any statement regarding satisfaction made here is subject to change. However, describing the problem this way will render most comparisons useless, as the outcome will depend more on which section in time is selected than on the simulation variables themselves.

Like there are satisfaction contributions weighted by estimations, all durations of the individual processes are set by approximations, too. Consequently, the same argument holds in this case: If values are set differently, it is easy to introduce penalties for whatever decision one wants to suppress. Although this affects only cost and productivity, a future revision of the simulation should evaluate and, if necessary, refine those timings.

4.3 Conclusions and implications

4.3.1 Model

The unique and rather obvious consequence of the previous chapter clearly is: The silver bullet for compensating short-term workforce shortages is employing additional personnel. However, with the view restricted to planning, the analysis of extremes has shown that this means a requirement of 1.5 (12 % buffer) to 2 (16 % buffer) times the number of those sick or on training (8 % in the model).

As this implies an extraordinary raise in cost during operation, in reality managers will have to make concessions. Thus lowering sickness days is most likely no option or has already been done, the alternative is choosing a lower personnel buffer and then tune with internal and external limit. Since there is no solely good way for those, the result will be strongly dependent on the individual preferences and objectives of the management in this case. However, a considerable rise in satisfaction may also have a positive effect on sickness days in the end.

With respect to the individual indicators, the analysis has shown that quality is quite high in any case and also quite easy to maximize. For cost and productivity, at least with the durations provided, effects are notable, however the absolute value is comparatively small. Without considering cost of externals, the accessible range of cost is approximately between 2 200 and 2 800 Euros per day. This corresponds to an improvement potential of just 12 000 Euros per month, so about two additional employees or a buffer value of 0.5 %.

Accordingly, planning *efficiency* is not the benchmark in this case, at least as long as it is treated independently of connected processes like executing surgeries. In contrast, the most flexible and adjustable parameter is satisfaction. Here, the whole range of values is accessible, and every adjustment can have a considerable effect. Nevertheless, while shifting values is rather easy, it is quite hard to reach the optimum. In this case, again the manager in charge has to ask himself whether it is really necessary to put all efforts into reaching 100 %, or if it is more reasonable to get just a nice boost with reduced efforts.

As already stated in paragraph 4.2.6, most results obtained here depend on certain variables which have been estimated. Consequently, an important future objective will be first obtaining more accurate process step durations from a live process. Secondly, an evaluation of the simulation in comparison to a model case should be performed to tune both durations and also the satisfaction contributions.

4.3.2 Process

The core constituent of the simulation as it is presented here is the model process representing the actual planning procedure in a particular hospital. Despite optimizing variables within the constraints of these guidelines, it is of viable interest to draw conclusions from simulation results to optimize the plan itself.

One particular problem in the process might arise from the fact that, although both halls and workforce are registered and checked several times, this is mostly performed independently of each other. A link between those is however performed only unidirectional, so planned personal depends on the number of halls. Only at the end of the daily procedure, the number of operating rooms is compared with the available workforce.

Accordingly, although personnel planning may react on mid-term or short-term changes of available halls (which is not modelled in simulation), the reverse link is not possible at an early stage. However, an earlier adjustment could gain benefits in multiple ways, though possibly with slightly increased cost. On the one hand, knowing about cancelled operations earlier will allow to shift the appointments for elective patients. Though the information is available in advance then, from the perspective of a patient this will be more like a shift than a default/cancellation.

At the other hand, an earlier link of workforce and infrastructure can also prevent useless efforts for replacements. If, for example, one department has severe staff shortages which eventually will cause defaults, other departments would still try to fulfill their quota. In the end, surgeries are cancelled anyway, and the workforce called in is redundant. However, the cost and lowered satisfaction remain.

Completely independent from this argument, valuable insights are also accessible by including additional organizational levels into the simulation. Though the program presented here is limited to operational level, an extension implementing tactical or even strategic decisions based on the results of the operational performance might add another perspective to the problem. In a future version, hospital managers might be able to determine good and bad reactions to particular configurations this way.

5 Conclusion

In this thesis, a benchmarked surgical workforce planning process from a German full-service hospital has successfully been translated into a multi-agent simulation tool. The resulting program has proven to be capable of giving a handy and easy-to-use interface which allows hospital managers and other stakeholder of the planning process to link accessible input parameters to output indicators.

Although several limitations had to be included during modelling, an analysis based on changing the input factors yielded reasonable results to prove the functioning of the program and the basic suitability of the assumptions and estimations made, also showing good discrimination between methods. Later investigations made based on a particular model scenario yielded particular insights in the planning process: While the clearly most striking improvements are possible by raising available personnel in the beginning, this strategy induces additional cost which far exceed the measurable benefits on planning.

In the end, the problem thus has to be solved by hospital managers employing their specific priorities and their expertise on related and linked processes. For that, the learning cockpit developed herein will be an excellent companion.

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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und ohne Benutzung anderer als der angegebenen Quellen und Hilfsmittel angefertigt habe.

Die Arbeit hat in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen.

Bayreuth, den 30.03.2015

Adrian Schmutzler

The surgical unit typically is the biggest cost and revenue center in full-service hospitals, but also a facility with outstanding complexity. This has led to particular interest in the topic at the executive offices and in academic research. While most publications deal with the scheduling and stringing together of operating theaters, this work investigates the planning process in advance of those actions. The thesis presents a multi-agent simulation tool, which describes surgical workforce planning based on a model process from a particular German hostpital. It combines both key performance indicators and staff satisfaction to study the effect of parameter changes as comprehensively as possible. For evaluation of the program and to draw first conclusions on the planning process a general analysis of influence factors is performed, supplemented by a case study based on a particular model scenario. The simulations yield that effective and satisfying compensation for sickness induced staff shortages is only available by increasing the available workforce in the first place, while other influence factors do not exhibit solely positive impact. As payment for required additional staff exceeds accessible savings in planning cost by one order of magnitude, though, the applicability planning environment for hospital maangers, so they can tune parameters with their particular priorities in mind.

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