MASTER

Development of a decision support system for operating room scheduling

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Development of a Decision Support System for Operating Room Scheduling

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Abstract

A number of novel techniques during surgery, that will soon take place in the Radboud University Nijmegen Medical Centre (RUNMC), result in new surgery processes leading to (1) an increase in surgery duration uncertainty, (2) an increase in the amount and diversity of required resources during surgery, (3) an increase or decrease in average surgery duration, and (4) a possible relocation of a patient under anaesthetics from one operating room (OR) to another. To deal with these changes, a decision support system (DSS) has been developed, presenting which personnel and equipment should be available at what times and in which ORs. The objective is to create an optimal surgery schedule. Whether the schedule is considered optimal has been determined by the following performance measures: (1) patient waiting time during surgery, (2) patient surgery rate, (3) personnel overtime, (4) personnel waiting time, and (5) OR utilization. A number of scenarios have been developed and the effects of different schedules on the performance measures are discussed.

Executive Summary

BACKGROUND
A significant reduction in patient throughput time from a couple of weeks to one day might be possible due to a number of novel and faster techniques to treat cancer. This involves the throughput time from the moment a patient arrives in the operating room (OR) until a patient has received his first external therapy (such as radio-, hormone-, or chemotherapy). The new treatment methods will be applied in the Radboud University Nijmegen Medical Centre (RUNMC) in three so called Medical Innovation & Technology expert Centre (MITeC) ORs: one intra-operative radiotherapy (IORT) OR, one hybrid (HYB) OR, and one magnetic resonance imaging (MRI) OR. Patients are included with three different tumour positions: (1) oral cavity squamous (OCS), (2) ovarian, and (3) prostate. In addition to the tumour treatments, diagnostic MRIs can be added to the MRI OR schedule. The new treatments will influence surgery scheduling due to: (1) an increase in surgery duration uncertainty, (2) an increase in the amount and diversity of required resources during surgery, (3) an increase or decrease in average surgery duration, and (4) a possible replacement of a patient under anaesthetics from one OR to another.

RESEARCH QUESTION AND SUB QUESTIONS
In order to handle the aforementioned changes, the RUNMC management would like to get insight in which personnel and what equipment should be available at what times and in which ORs to utilize the MITeC ORs and its accompanying personnel and equipment in an optimal manner. Whether the ORs are utilized optimally is determined by the following performance measures:

- (minimize) patient waiting time during surgery,
- (maximize) patient surgery rate,
- (minimize) personnel overtime,
- (minimize) personnel waiting time consisting of:
  - Time personnel has to wait due to the absence of equipment (avoidable)
  - Time personnel has to wait between consecutive surgeries (avoidable)
  - Time personnel has to wait during a surgery as part of the process (unavoidable)
- (maximize) OR utilization.

These performance measures might be conflicting and therefore an appropriate balance should be found. The exact performance measure definitions can be found in: List of Definitions and in the remainder of this document. The research question is formulated as follows:

Which personnel and what equipment should be available in which ORs and at what times to utilize the MITeC ORs and its accompanying personnel and equipment in an optimal manner?

In order to answer the research question, three sub questions have been formulated. Before a surgery schedule could be developed, we had to determine which personnel and equipment should be available at which locations at what times during each particular surgery.

Sub question 1:
Which personnel and equipment should be available in which MITeC ORs at what times during each particular surgery?

When it was clear which resources should be available at what times during a certain surgery, we could start to identify how surgeries should be scheduled to optimize the utilization of the MITeC ORs and its accompanying personnel and equipment. It was decided to allocate the surgeries used to treat a tumour first. These surgeries are executed by the surgical groups (SGs) head/neck, gynaecology, and urology. In the remainder of this thesis, this particular group of surgeries is called: “tumour surgeries”.

Sub question 2:
How to optimize the utilization of the MITeC ORs and their accompanying personnel and equipment for the three tumour surgeries under study?

As anticipated, when the tumour surgeries were scheduled, it appeared some spare time was available in all MITeC ORs. This resulted in the allocation of additional treatments to the surgery schedule. It was decided diagnostic MRIs under general anaesthesia would be included in the schedule in addition to the tumour surgeries. These diagnostic MRIs take place in the MRI OR.

Sub question 3:
How to improve the utilization of the MRI OR and its accompanying personnel and equipment by scheduling patients that will receive a diagnostic MRI in the spare time of this OR?

LITERATURE REVIEW

Although quite some authors have written about the topics at hand, to our best knowledge none of the articles are directly applicable to this research. This is caused by a number of properties that should be included in this model to answer the research question and have not been described in literature thus far: (1) some resources are only required during a certain surgery period, (2) a possibility exists to relocate a patient from one OR to another during surgery, (3) patient waiting time during surgery might occur, and (4) personnel waiting time during surgery might take place. Therefore, the recommendations and guidelines that are found in the literature have been used instead of an existing model. From these guidelines it appeared that developing a multi-objective simulation model combined with other solution techniques, such as heuristics, linear programming (LP), or integer programming (IP) would be an appropriate approach to build a model for the development of a CSS.

METHOD

For each surgery type a process flow chart has been developed. Each process step in these charts consists of the (1) OR in which the step takes place, (2) required resources or resource teams to execute the step, (3) (stochastic) duration of the step, and (4) source used to retrieve the (stochastic) duration of the step.

A simulation model has been developed based on these process flow charts. With this model overviews have been created for each surgery type revealing the probability that rooms, personnel, and equipment might be required. By using these overviews, different CSSs have been proposed to allocate time blocks to the SGs: head/neck, gynaecology, urology, and/or radiology. In the first scenarios (1 to 7b) only tumour surgeries were scheduled to provide an answer to sub question 2. In the latter scenarios (8 to 11) both tumour surgeries and diagnostic MRIs were allocated.

RESULTS

From the different overviews revealing which personnel, equipment and rooms are required during a certain surgery, we can provide a number of results: (1) ORs might get crowded due to the large amount of personnel and equipment required at the same time, (2) all considered surgeries will finish before 15:00 in at least 95 % of the cases, and (3) gathered information during surgery can be helpful to revise and improve the estimation of the surgery end time.

In Figure 1 to Figure 3 the following performance measures are given for each proposed schedule: (1) surgery rate, (2) personnel overtime, and (3) avoidable personnel waiting time. These were the performance measures that appeared to be conflicting in the proposed scenarios. None of the scenarios resulted in significant patient waiting time during surgery or avoidable personnel waiting time during surgery. It is impossible to schedule all tumour surgeries without creating patient waiting time, avoidable personnel waiting time or personnel overtime without adjusting the current OR days or resource availability.

In scenarios 1 to 4 and 8 to 9 not all expected malignant tumour surgeries are scheduled as can be seen in Figure 1. In scenarios 8 to 11 all patients receiving a diagnostic MRI were scheduled. Scenario 11 was the only scenario in which all expected treatments, including both tumour surgeries and diagnostic MRIs, were allocated.

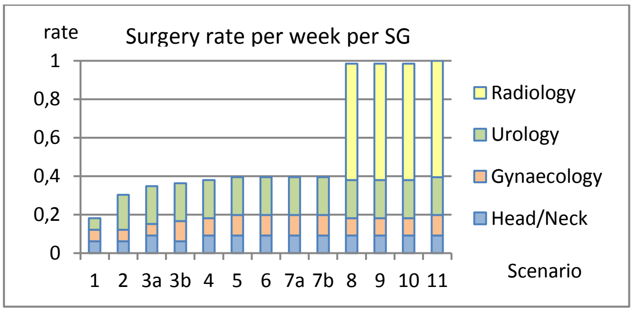

Figure 1: Surgery rate of all treatments under study per SG for each scenario

In scenarios 6, 7a, and 7b, two surgeries took place in parallel. One surgery would start at 08:00 and one would start at 12:00 or 12:30. This late start avoids a long patient waiting time during surgery and personnel waiting time during surgery. This waiting time was caused by one piece of equipment, i.e. an in vivo microscope, which was required for both surgeries. Delaying the start time of one surgery resulted in a significant amount of overtime as illustrated in Figure 2.

In scenarios 8 and 9, the personnel overtime was a result of diagnostic MRIs taking place in the afternoon. These MRIs were performed in time blocks with an estimated time of four hours. However, the real execution of these MRIs took longer than four hours in some cases. Currently this amount of overtime is common for the radiology department.

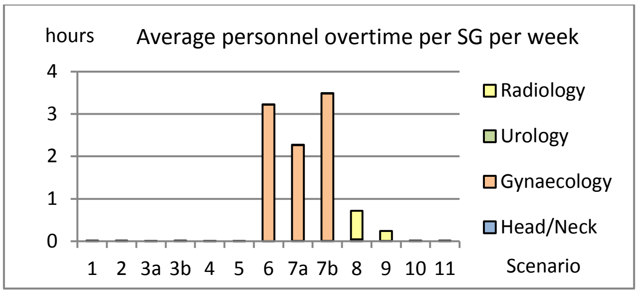

Figure 2: Average personnel overtime per SG per week for each scenario

In scenarios 2, 3b, 5, 6, 7a, 7b, 9, 10, and 11 two subsequent surgeries were performed on the same day by the urology SG every week. This resulted in avoidable personnel waiting time between those surgeries as illustrated in Figure 3. In scenarios 4 and 8, the same surgeries were performed subsequently but only once every two weeks. Since these surgeries were executed by the same SG, this waiting time could be reduced by starting the second surgery immediately after the clean-up of the first surgery instead of waiting until the scheduled starting time.

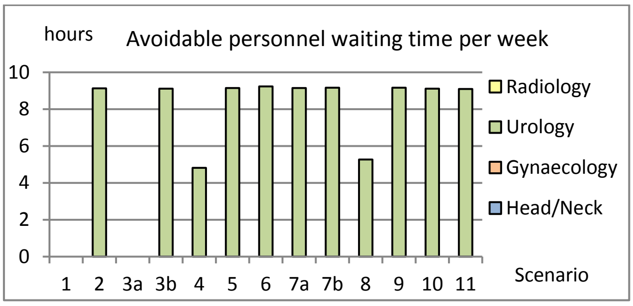

Figure 3: Average avoidable personnel waiting time per SG per week for each scenario

OVERALL CONCLUSION

This research provides a unique model not presented in the literature thus far to our best knowledge. It includes the following elements: (1) duration uncertainty, (2) multiple possible sequences per surgery, (3) resources that are only required during a part of the surgery, (4) relocations of patients from one OR to another, and (5) five previously described performance measures. Since many elements are covered in this model, it could become a useful tool for other hospitals to develop an OR schedule (cyclic or non-cyclic). Not only surgeries can be scheduled with this model but other production processes as well.

From the results it appeared approximately ten expected patients cannot receive treatment according to the new surgery processes if no adjustments are made to the current situation. In case the RUNMC management would like to treat all their expected patients receiving cancer treatment according to the new surgery processes in an optimal manner two solutions exist.

This first solution is to treat either head/neck or gynaecology patients on Tuesday or Thursday once every two weeks. This solution has several advantages compared to the second solution: (1) no additional equipment is required, and therefore no costs are involved to buy this equipment, (2) the flexibility to schedule patients increases because more options to allocate time blocks to SGs are available, and (3) the HYB OR is unoccupied during the entire year, hence it can be used for other SGs. The disadvantages of this solution are: (1) a change in current OR days might meet some resistance from the personnel and (2) the planning of prior and subsequent processes of these surgeries have to be adjusted, which requires effort.

The second solution is to purchase two in vivo microscopes instead of one and conduct one surgery every two weeks in the HYB OR. The advantages of this solution are: (1) the SGs do not have to change their current OR days, which results in less planning effort in the prior and subsequent departments and is in line with the current practice and (2) the in vivo microscope results in an increased flexibility of scheduling to surgeries in parallel (one in the IORT OR and one in the HYB OR). The disadvantage of this solution are: (1) purchasing an additional in vivo microscope leads to an additional expense and (2) the HYB OR is partly occupied, resulting in less patients that can be allocated to this OR compared to the first solution.

By introducing the patients receiving a diagnostic MRI to the schedule it appeared that, equal to the previous situation, approximately ten expected patients cannot receive treatment according to the new surgery processes in case no adjustments are made in the current OR days or available equipment. In addition, personnel overtime will occur if no table-top micro MRI will be purchased. The acquisition of a table-top micro MRI has a number of advantages: (1) the scheduling flexibility of the MRI OR increases because the interruptions, generally taking place between 09:00 and 13:00, will be eliminated and (2) all patients can be treated without generating patient waiting time, personnel overtime, or personnel waiting time given that either the current OR days change or an additional in vivo microscope will be purchased.

RECOMMENDATIONS

We would recommend to start with the surgery schedule as proposed in scenario 2, in which five surgeries are scheduled per week. This does not require the acquisition of any additional equipment. In this scenario, both the head/neck and gynaecology SG can execute one surgery per week and the urology SG can perform surgery on two different days during this week. The non-allocated OR days can be used for different purposes, such as research, additional surgeries from the regular OR program or diagnostic MRIs. If the surgeries are executed well, which can be evaluated by monitoring and controlling the surgery processes, additional surgeries can be added to the surgery schedule in the next scheduling phase.

Before a new surgery schedule can be implemented in reality, a number of steps have to be executed: (1) crowded OR moments, which require the presence of numerous personnel members and equipment at the same time, should be tested physically in order to make sure these surgeries can be performed in reality, (2) the developed schedule should be discussed with a number of involved personnel members to make sure it is applicable in reality, and (3) Time should be made available to train personnel or acquire new equipment to ensure that required resources are available and of sufficient quality.

Some future actions can help improve the developed simulation model: (1) streamlines processes by includig process steps that take place before or after surgery, (2) include costs in the analysis to make a more informed choice, and (3) register every occasion when the combination of required resources during a surgery changes, possibly with a swipe card in the OR doors, to improve the estimated durations in which personnel and equipment should be available during a surgery.

Preface and acknowledgements

This master thesis report is the result of the last phase in the master Operations Management and Logistics at Eindhoven, University of Technology. This project has been carried out in the Radboud University Nijmegen Medical Centre and lasted from October 2012 till August 2013. In this hospital a very challenging and unique project is taking place with the objective to provide a one-day surgery for patients diagnosed with cancer. When I heard about this project I was enthusiastic immediately and working in this team was a very nice experience with a steep learning curve. I could not have executed this project without the help of several people, which I would like to thank gratefully.

First, I would like to thank prof. M. Rovers and ass. Prof. J. Grutters, who have made much time available to discuss the project and give critical feedback. They reminded me that logistics and healthcare are not the same language and thought me (hopefully) how to blend the healthcare and logistics field into an understandable language for both. Furthermore, they thought me how to stay focussed on the essentials instead of getting lost into details and chaos. This has truly been a great learning experience which I will try to keep in mind for future projects. In addition to my supervisors in the RUNMC, I would like to thank all surgeons, radiologists, and anaesthesia employees for their input. Without them, this research could not have been executed. I even had the unique opportunity to be present at two surgeries, an experience I will not quickly forget! A number of MITeC project team members should not be forgotten in this word of gratitude. They gave me a great insight in the future surgery processes and responded quickly to all my questions.

Second, I would like to thank dr. ir. N. Dellaert and dr. ir. S. Flapper for their insights in the logistics field and very useful feedback. I enjoyed the both critical and joyful conversations we had and every time I walked from their offices my motivation was given a boost.

Finally, I would like to thank my family and friends. My parents have always thought me to do the right thing and work hard and my friends have made my time as a student fun and worthwhile! I would like to thank my fellow students of Industrial Engineering for Healthcare, since they motivated me and gave critical and useful feedback on some parts of this thesis and my poster. I would like to thank my boyfriend especially, who understood I didn't have all the time in the world during the execution of my thesis and cooked very nice meals whenever I was really busy ☺.

Loes Clephas

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List of Abbreviations

CSS	Cyclic Surgery Schedule
CTG	College Tarieven Gezondheidszorg
DSS	Decision Support System
HYB	Hybrid
IOBT	Intra-Operative Brachy Therapy
IORT	Intra-Operative Radio Therapy
MDP	Markov Decision Process
MITeC	Medical Innovation & Technology expert Centre
MRI	Magnetic Resonance Imaging
MSS	Master Surgery Schedule
OR	Operating Room
PDM	Product Data Model
PET	Positron emission tomography
RUCO	Radboud University Centre for Oncology
RUNMC	Radboud University Nijmegen Medical Centre
SG	Surgical Group
SIM DET	Simulation model with Deterministic durations
SIM STOCH	Simulation model with Stochastic durations
SLN	Sentinel lymph node
TB	Time Block

List of Definitions

95 % interval	With 95% confidence we can assure that all patients can be treated within the interval ranging from x to y.
Avoidable waiting time	Waiting time that occurs due to choices made in the planning. This waiting time could have been avoided by scheduling fewer patients, or scheduling patients on different days or hours for example.
Busy	In operation.
Decision space	In each state in the decision space a number of decisions can be made. For the execution of a Product Data Model these decisions are described by the set of process steps that are executable in the current state of execution (i.e. those process steps of which the input elements are available and that have not yet been executed).
Early end	Actual start time of the surgery is earlier than scheduled start time of a surgery.
Flowchart	Type of diagram that represents a process, showing the steps as boxes of various kinds, and their order by connecting them with arrows.
Idle	Not in operation.
Late start	Actual start time of the surgery is later than scheduled start time of a surgery.
Occupation	Time in which the ORs are occupied within the regular working time divided by the regular working time.
Occupied time	Time in which the ORs are occupied within the regular working time.
Overtime	The number of hours that a resource is working on top of his regular schedule, usually from 08:00 to 16:00.
Patient waiting time before surgery	Duration from the moment a patient is placed on the surgery waiting list until the surgery takes place.
Patient waiting time during surgery	Duration of intervals between the first surgery process step and the last surgery process step during which no activities take place that require the patient.
Personnel member	A person working at the RUNMC who is a member of a staff of workers, i.e. of the personnel.
Personnel team	Team with a certain function consisting of one or multiple personnel types.
Personnel type	A personnel member with a specific function.
Personnel waiting time during surgery	Duration of intervals between the start of the first surgery activity and the end of the last surgery activity performed by a certain personnel member during which this member is not required.
Personnel waiting time between surgeries	Duration of intervals between the end of the first surgery in which the personnel member is required and the start of the last surgery in which this member is required.
Planned slack	Time allocated on top of the time allocated for surgeries to make a schedule more robust against overtime.
Portfolio effect	The effect of distributing investments into various different projects instead of investing in a single project on risk and profitability.

Portfolio management	Used to reduce risk (minimize variance) or increase the profitability by distributing investments into various different projects instead of investing in a single project.
Process	Collection of related, structured activities in order to treat a patient, often visualized with a flowchart as a sequence of activities with interleaving decision points.
Process step	One of a series of activities taken to executed to treat a patient.
Process time	Time period during which work is performed on the patient.
Product Data Model	The product of a workflow process is usually an informational product, e.g. the decision on an insurance claim or the allocation of a subsidy. The structure of a workflow product can be described by a tree-like structure similar to a bill-of-material from manufacturing. Such a description of a workflow product is called a Product Data Model.
Required time	Time required for executing a process or process step, including waiting time.
Resource type	A resource with a specific function.
Resource team	Team with a certain function consisting of one or multiple resource types.
Robustness	The ability of a system to resist change without adapting its initial stable configuration.
Shift end time	Time at which a shift ends (in this case 16:00). This is the time from which overtime starts.
State space	State space (S) describes the states the process can be in. The states can be described by the operations that have been executed (together with the data elements for which a value is available).
Surgery	An activity taking place under general anaesthesia to investigate and/or treat a patient to deal with a pathological condition or improve bodily functions. A surgery starts when a patient enters either an OR or MRI OR and ends when the patient leaves this OR.
Surgery rate	Amount of patients that are scheduled in a CSS divided by the amount of patients expected to arrive.
Surgery type	A collection of properties, shared by a group of similar surgeries. Within such a category, surgeries share both medical as well as logistical characteristics.
Surgical group	Group consisting of surgeons of the same surgical specialty.
Transition probabilities	Transition probabilities are given by a matrix P that describes the probabilities that the system moves from the current state to any of the other states in the system. These transition probabilities are dependent on the process step that will be executed.
Treatment	**T**he application of medicines, surgery, therapy, etc., in handling a disease or disorder.
Throughput time	The period required to undergo a part of the treatment process from the moment a patient arrives in the OR until a patient has undergone his first external therapy (such as radio-, hormone-, or chemotherapy).
Tumour surgeries	Surgeries to treat a tumour. In this report the surgeries to treat OCS-, ovarian-, and prostate cancer are included in the tumour surgeries.

Unavoidable waiting time	Waiting time that occurs because a resource simply has to wait as part of the process. For example, a surgeon might have to wait 30 minutes for the result of a certain analysis before he can continue operating.
Utilization	Time that activities are carried out within the regular working time divided by the regular working time.
Utilized time	Time that activities are carried out within the regular working time.
Validation	Determining whether the conceptual simulation model is an accurate representation of the system under study **.**
Verification	Determining that a simulation computer program performs as intended, i.e., debugging the computer program.
Workflow	Collection of related, structured activities in order to treat a patient, often visualized with a flowchart as a sequence of activities with interleaving decision points.

1 Introduction

A number of novel and faster techniques that will be used during a tumour surgery have been developed recently. These new techniques will be used in a research setting in the Radboud University Medical Center Nijmegen (RUNMC). Three newly equipped operating rooms (ORs), so called Medical Innovation & Technology expert Centre (MITeC) ORs will be used for this purpose. The focus in this research lies on the planning of these MITeC ORs, since ORs are the hospital's "heart" and have a major impact on the performance of the hospital as a whole [1]. Planning of ORs is a complex task, due to high number of constraints, preferences and objectives that planners need to take into account. In this chapter the research area will be described (1.1) followed by the challenges that are generated by the innovative surgery processes (1.2).

1.1 Radboud University Nijmegen Medical Centre

This research is executed in the Radboud University Nijmegen Medical Centre (RUNMC), a centre advancing human knowledge by conducting biomedical, translational and clinical research in order to improve patient's wellbeing. The medical centre's key strengths are medical life-sciences and clinical practice, with an impressive infrastructure comprising state-of-the-art technology platforms and (translational) research facilities. The RUNMC established a partnership, called "Medical Innovation & Technology expert Centre" (MITeC) together with the Eindhoven, University of Technology, the University of Twente, and several industrial partners. The partnership strives for efficient care accompanied by an improvement in both short and long term outcomes for the patient, such as quality of life, satisfaction and recovery time. Many interesting research opportunities were created by convincing the Executive Board to transform three existing ORs into the three following ORs: one new full-hybrid OR, one OR containing a Magnetic Resonance Imaging (MRI) device, and one intra-operative radiation therapy (IORT) OR. The combination of these ORs and their equipment will form an eminent threesome to initiate different unique one-day surgery processes for patients diagnosed with cancer. In these ORs state-of-the-art equipment will be placed to facilitate different innovative healthcare technology developments, which will become part of the surgery processes.

1.2 Innovative Surgery Processes Lead to OR Planning Challenges

To accomplish a one-day surgery several newly developed healthcare technologies will become part of the surgery processes in the RUNMC. These new technologies (extensively described in Appendix I: Recent Healthcare Technology Developments) have several planning implications: (1) surgery durations become less predictable because a part of the course of the surgery will become clear during surgery instead of before or after surgery, (2) the amount and diversity of required resources during surgery increases, which will be time-consuming due to an increase in exchange of information, wait times, and error possibility, (3) average surgery durations change, due to additional or possibly removed process steps, which might have an effect on the amount of patients that can be treated during a certain period, overall utilization of resources, and patient waiting time until they can undergo surgery, (4) patients might have to be transported from OR to MRI OR and vice versa.

1.3 Report Outline

A method to develop a CSS in a systematic way will be described in the remaining part of this thesis. In Chapter 2 the research design is described, including the research question and its sub questions, the deliverables, and we elaborate on the context by providing the scope of this research. A literature review is included in Chapter 3, reviewing the contributions of several authors to the field of planning and scheduling of ORs. In Chapter 4 the research method is provided, describing the way in which the decision support system has been developed. Chapter 5 includes the verification and validation of the developed simulation model. Hereafter, in Chapter 6 different scenarios are included that were designed together with employees of the RUNMC to show what possible CSSs could be implemented and to which performance measures this would lead. Chapter 7 is used to describe the implementation of the process. Chapter 8 provides a general conclusion and answers the research question and its sub questions and Chapter 9 provides recommendations that can be used to implement the decision support system in an optimal manner.

1.4 Chapter Summary

Introducing new healthcare technologies to the surgery processes for patients receiving cancer treatment at the RUNMC to be able to provide a one-day surgery per se have a large effect on different aspects of planning ORs. A combination of these developments results in an even more complex planning problem, due to an increase in surgery duration uncertainty, an increase in the amount and diversity of required resources, a change in average surgery duration, and a possible transportation from one OR to another and vice versa when the patient is still under general anaesthesia. In the remainder of this report, we will try to find a way to deal with these changes and provide a CSS.

2 Research Design

As explained in the previous chapter, the management of the RUNMC will initiate several entirely new surgery processes. These processes require planning to make sure the right personnel and the right equipment are at the right place at the right time and this planning does not exist yet. In this chapter, the problem will be analysed in more detail. First, the research question will described (2.1), followed by the research sub questions and deliverables used to answer the research question (2.2). After the objectives, questions, and deliverables are clear, the scope of the research is provided (2.3), followed by the formulas to calculate the required performance measures (2.4).

2.1 Research Question

The management of the RUNMC would like to have a CSS developed at the tactical level which can be used to allocate their resources. This CSS will include surgeries, which are defined as activities that take place under general anaesthesia to investigate and/or treat a patient to deal with a pathological condition or improve bodily functions. A surgery starts when a patient enters either an OR and ends when the patient leaves this OR. The priority of surgeries scheduled are the surgeries to treat cancer. Hereafter other surgeries can be scheduled that require the MITeC ORs. In order to decide whether a CSS is optimal, the following performance measures will be included in this research: (1) patient waiting time during surgery, (2) patient surgery rate, (3) personnel overtime, (4) personnel waiting time, and (5) OR utilization. In this section the reason behind these performance measures is provided, combined with a definition of each measure.

Patient waiting time during surgery

Furthermore, patient waiting times will be considered that might occur during surgery, due to a scarcity of specific resources. This objective is important because researchers found that for patients of all ages the risk of complications, ranging from fever to pneumonia and heart attack, increases between 18 % and 36 % for each hour under anaesthesia, with the average anaesthesia time just under four hours [2]. Although there is not enough evidence to prove that the risk is not a result of the complexity of lengthy surgery itself, this is clearly a case of: “better safe than sorry”.

Patient waiting time during surgery

- Duration of intervals between the first surgery process step and the last surgery process step during which no activities take place that require the patient.

Surgery rate

The surgery rate, i.e. the number of patients that are allocated in a CSS compared to the expected number of patients to arrive, will be provided as well. The patients that cannot be treated according to schedule will influence the planning of other ORs in the RUNMC because these patients will be treated according to the current processes in other ORs.

Surgery rate

- The amount of patients scheduled in a certain period divided by the amount of patients expected to arrive in this period

Personnel overtime

A lot of authors included personnel overtime in their model as well, when developing a CSS. Overtime pay rates are usually higher than pay rates during regular working time, so minimizing personnel overtime will have a positive effect on the finances. In addition, avoiding overtime is important because in a study of workplace accidents it was found that accident risk increased exponentially after the 9th hour at work [3]. The authors concluded that shifts that last longer than 8 hours might lead to more worker fatigue and higher risk of accidents. On the other hand workers were studied at a power plant and no difference in sleepiness or performance between those who worked 8-hour shifts and those who worked 12-hour shifts was found [4]. However, this difference in findings might be explained by another article which proposed that work that requires complex cognitive tasks may be ill suited for longer shifts, whereas work with limited cognitive demands may be well suited for longer shifts [5]. Obviously, performing surgical surgeries is a job that does require complex cognitive tasks and therefore overtime should be avoided as much as possible to prevent accidents which might impair both patient-, and personnel safety.

Personnel overtime

- Number of time units a personnel member is working on top of his regular schedule

Personnel waiting time

Personnel waiting time is an important performance measure since waiting can be annoying, frustrating and therefore it might reduce personnel satisfaction levels. In addition, personnel waiting time is costly if these resources cannot perform other required activities during their waiting time.Three types of personnel waiting time exist:

- Time personnel has to wait during surgery due to the absence of equipment (avoidable)
- Time personnel has to wait between consecutive surgeries (avoidable)
- Time personnel has to wait during a surgery as part of the process (unavoidable)

All three types of personnel waiting time have not been used as a performance measures in the literature. In all literature the surgery process is a process requiring the same resources during the whole surgery.

The first type of personnel waiting time is the waiting time during surgery due to the absence of equipment. In reality, this absence of equipment might have different causes but in this case this is always due to another surgery taking place at the same time requiring the same piece of equipment. This is avoidable waiting time because the two parallel surgeries requiring the same piece of equipment could have been scheduled on two different days or one of them could not have been scheduled at all.

The second type of personnel waiting time is the time personnel has to wait between two consecutive surgeries. This might have two causes: (1) the OR has to be cleaned and setup for the next surgery and in the meantime the personnel has to wait, (2) the first surgery ends earlier than expected, and the second surgery, requiring the same personnel, starts at its scheduled time.

The third type of personnel waiting time is unavoidable waiting time. Some personnel types are only required during one or more surgery intervals, which might lead to unavoidable personnel waiting time. This waiting time is often caused by diagnostic steps during surgery and is simply part of the process. This waiting time is included in the personnel waiting time during surgery.

Personnel waiting time during surgery

- Duration of intervals between the start of the first surgery activity and the end of the last surgery activity performed by a certain personnel member during which this member is not required

Personnel waiting time between surgeries

- Duration of intervals between the end of the first surgery in which the personnel member is required and the start of the last surgery in which this member is required.

OR utilization

Many authors who developed CSSs at a tactical level tried to maximize OR utilization, which seems an obvious choice since maximizing OR utilization has a positive effect on financial costs, which become more and more important these days due to the crisis. Furthermore, high usage rates in a surgical suite are extremely important in meeting the increasing demand for healthcare services [6].

OR utilization

- Time that activities are carried out in an OR within the regular working time divided by the regular working time

Section summary

In summary, the RUNMC management would like to identify which personnel and what equipment should be available in which of the MITeC ORs at what times to utilize these ORs in an optimal manner. Optimality is determined by the following performance measures: (1) patient waiting time during surgery, (2) surgery rate, (3) personnel overtime, (4) personnel waiting time, and (5) OR utilization.

RESEARCH QUESTION

Which personnel and what equipment should be available in which ORs and at what times to utilize the MITeC ORs in an optimal manner?

In order to answer the research question, three different sub questions will be answered. For the hospital management it is important to know which resources should be available at which locations at what times during each particular surgery, which leads to sub question 1.

Sub question 1:
Which personnel and equipment should be available at which locations at what times during each particular surgery?

Deliverable 1:
An overview of every surgery type showing at what times during each particular surgery the resources or resource groups should be available.

When it is clear which personnel and what equipment should be available at which locations and at what times, we can start looking at surgery types which can take place during a surgery schedule length in the MITeC ORs. The objective is to utilized the MITeC ORs in an optimal manner. Optimality is determined by the following performance measures: (1) patient waiting time during surgery, (2) patient surgery rate, (3) personnel overtime, (4) personnel waiting time, and (5) OR utilization. First, tumour surgeries will be allocated to the different ORs, since they have priority over other patients.

Sub question 2:
How to optimize the utilization of the MITeC ORs and their accompanying personnel and equipment for the three tumour surgeries under study?

Deliverable 2:
An overview of tumour surgery types during a certain scheduling period, that lead an optimal utilization of the MITeC ORs.

When the tumour surgeries have been scheduled and not all MRI OR capacity is utilized, other patients will be scheduled in the MRI OR as well. Patients receiving a diagnostic MRIs will be included for this purpose, leading to sub question 3.

Sub question 3:
How to improve the utilization of the MRI OR and its accompanying personnel and equipment by scheduling patients that will receive a diagnostic MRI in the spare time of this OR?

Deliverable 3:
An overview of both tumour surgeries and diagnostic MRIs that lead to an improved utilization of the MRI OR.

2.2 Research Scope

In this section the research scope is described regarding the patients, surgery types, resources, and available data.

2.2.1 Surgery Types

Patients with three different tumour positions will be included, namely patients with a tumour in the (1) oral cavity squamous (OCS), (2) ovarian, and (3) prostate. It is expected approximately 60, 70, and 130 patients per year will be eligible to be treated in the MITeC ORs, respectively. These patients have priority over other patients that will be scheduled. In addition to the tumour surgeries, we will consider patients that have to be under general anaesthesia to undergo an MRI (for example children and patients with the Down Syndrome). These MRI's are currently taking place approximately 9 to 10 times per week during 50 working weeks per year. In Table 1 an overview is provided of all the different surgery types, their expected numbers of arrival assuming 40 weeks per year, and the percentage of patients per surgery type per surgical group (SG). A surgical group is a group consisting of surgeons of the same surgical specialty. The surgeries within a surgery type share both medical as well as logistical characteristics:

- SG — Surgical group required for the surgery type
- Personnel — Required personnel belonging to a SG for the surgery type
- OR — OR in which the surgery type is conducted
- Equipment — Required equipment for the surgery type
- Process flow chart — Steps and their order that represent the process flow of a surgery type

Note: It is assumed radiology continues its diagnostic MRIs in 10 extra weeks but this is not considered in this research, because we can argue that the ORs will be less occupied than usual in these weeks so this won't result in any scheduling problems.

2.2.2 Resource Types

Three kinds of resources are included in this research: ORs, equipment, and personnel, which are all provided in Table 2. The resource types, i.e. a resource with a specific function, are provided per OR, equipment, and personnel. Of all included ORs and equipment only one will be available. Personnel members are assumed to be available and therefore are no constraint. If more personnel is required than currently available new personnel members will be hired for this project. The personnel often exist of a personnel team with a certain function including one or multiple personnel types. For example, the personnel team called "surgery team" consists of one personnel member with the function "surgeon", and two personnel members with the function "OR assistant".

Table 1: Expected number of patients per surgery type

Surgery types per SG	# Expected patients	% surgery type within SG
HEAD/NECK	**60**	
- Oral cavity squamous (OCS) tumour	60	100%
GYNAECOLOGY	**70**	
- Expected malignant overian tumour	21	30%
- Proven malignant overian tumour	49	70%
UROLOGY	**130**	
- Open prostatectomy to treat prostate tumour	30	23%
- Robot prostatectomy to treat prostate tumour	30	23%
- Laser to treat prostate tumour	20	15%
- HIFU to treat prostate tumour	10	8%
- CRYO to treat recurrent prostate tumour	40	31%
RADIOLOGY	**400**	
- Diagnostic MRI	400	100%

ORs

The three MITeC ORs included in this research are shown in Figure 4, available 24/7: (1) An intra-operative radiotherapy OR (IORT OR) that can be used for different types of intra-operative radiotherapy, such as intra-operative brachy therapy (IOBT). This OR consists of very thick walls to keep the radiation inside. (2) An MRI OR including an MRI, with thick walls in which IORT can be applied as well. Surgeries that need materials including ferrous metals are not possible in this OR, because the MRI contains a strong magnet functioning 24/7 and ferrous metals will be attracted by the MRI. (3) A full hybrid OR (HYB OR) is an OR that is equipped with advanced medical imaging devices that enable minimally-invasive surgery, which is less traumatic for the patient. Though imaging has been a standard part of the OR for a long time, these new minimally-invasive procedures require imaging techniques that can visualize smaller body parts such as really thin vessels in the heart muscle and can be facilitated through intra-operative 3D imaging. These visualization techniques are more useful to other surgery types than the included surgery types in this research. Therefore, this OR should be kept unoccupied as much as possible.

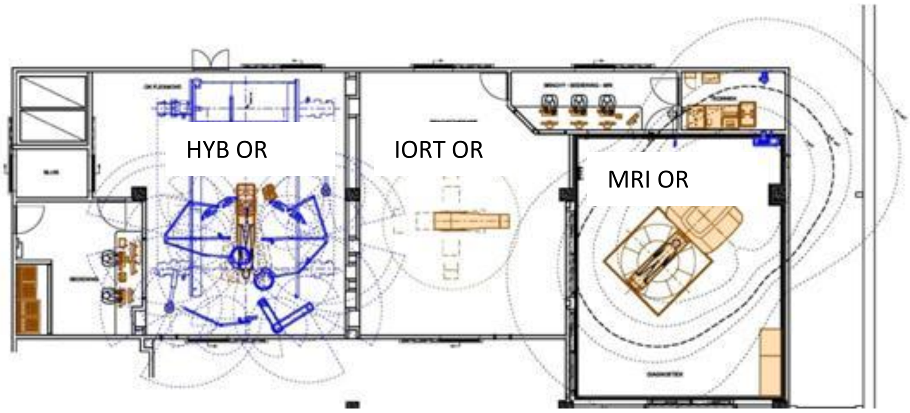


Figure 4: Map of the three MITeC ORs: HYB OR, IORT OR, and MRI OR

Table 2: Resource Types

	#	Capacity
ORS		
IORT OR		**1**
MRI OR		**1**
HYB OR		**1**
EQUIPMENT		
MRI		**1**
IV microscope		**1**
PET probe		**1**
Da Vinci Robot		**1**
HDR device		**1**
Echo MRI fusion device		**1**
Laser device		**1**
HIFU device		**1**
Cryo device		**1**
Micro MRI		**1**
PERSONNEL		
Surgery team	**3**	
- Surgeon	1	No constraint
- OR assistant	2	No constraint
Anaesthesia team	**3**	
- Anaesthesiologist	1	No constraint
- Anaesthetist	2	No constraint
Pathology team	**2**	
- Pathologist	1	No constraint
- Analyst	1	No constraint
Radiology team	**2**	
- Radiologist	1	No constraint
- Analyst or technician	1	No constraint
Cell biologist	**1**	
- Cell biologist	1	No constraint
Nuclear medicine physician	**1**	
- Nuclear medicine physician	1	No constraint
MRI team	**2**	
- Laboratory Technician	2	No constraint
Radiologist	**1**	
- Radiologist	1	No constraint
OR assistant	**1**	
- OR assistant	1	No constraint
Anaesthesia team2	**2**	
- Anaesthesiologist	1	No constraint
- Anaesthetist	1	No constraint

Personnel
Many different personnel types will be required during the new surgery processes. In the previous situation most of the time only a surgery team and anaesthesia team were required during surgery, a total of six to seven people. In the new situation more personnel will be required simultaneously during some surgery periods not per se in the OR itself.

Equipment
The only equipment considered is the equipment which can cause waiting times due to their scarcity (often only one piece available). All equipment is assumed to be available 24/7, so maintenance or equipment breakdowns are not included.

2.3 Performance Measures Formulas

In the research objective, described in 2.1 Research Question, different performance measures have been provided that are important to the management of the RUNMC, namely: (1) patient waiting time during surgery, (2) patient surgery rate, (3) personnel overtime, (4) personnel waiting time, and (5) OR utilization. Before providing the formulas to calculate these performance measures some assumptions are made:

- The OR hours should be allocated as fairly as possible between different SGs
- A working day starts at 08:00 and ends at 16:00.
- Working days are from Monday till Friday
- 40 working weeks in a year
- For each personnel member overtime starts at 16:00
- The head/neck department can conduct surgery on Monday, Wednesday, and/or Friday with a preference for Monday
- The gynaecology department can conduct surgery on Monday and Wednesday
- The urology department can conduct surgery every day of the week
- The radiology department can conduct diagnostic MRI's every day of the week
- The diagnostic MRI's are preferably allocated in blocks of four hours on different days of the week
- A surgery starts as soon as possible on a certain day
- A cycle length is either one or two weeks

In order to explain how all performance measures are calculated, Figure 5 is provided. All values in hexagons are registered in Arena:

- start time per process step,
- end time per process step,
- process time per process step,
- shift end time, which is the starting point of overtime generation, in this case 16:00.

Patient waiting time during surgery

The first performance measure that will be explained is patient waiting time during surgery. The idea is to boil down every performance measure to values that are presented in the rectangles in, since these values are registered in Arena. As shown in Figure 5, process step 2 cannot start immediately but waiting time occurs for some reason (for example because of scarce equipment that is not available yet) before it can be executed. The waiting time of a process step can be calculated by extracting the process time (the time period during which work is performed on the patient) from the required time (the time required for executing a process or process step including waiting time):

> **Patient waiting time during surgery**
> - Duration of intervals between the first surgery process step and the last surgery process step during which no activities take place that require the patient.

$$Waiting\ time_{ps_x} = Requiredtime_{ps_x} - ProcessTime_{ps_x} \quad (2.01)$$

Where:

ps_x is a process step with number x where 1 is the first process step and X is the last process step
$Requiredtime_{ps_x} = end_{ps_x} - start_{ps_x}$

Rewriting Formula 2.01 leads to:

$$Waiting\ time_{ps_x} = end_{ps_x} - start_{ps_x} - ProcessTime_{ps_x} \quad (2.01)$$

Because patients are involved in every process step, the patient waiting time during surgery can be calculated with Formula 2.02.

$$Waiting\ time_{patient} = \sum_{x=1}^{X} Waiting\ time_{ps_x} \quad (2.02)$$

Where:

X is the total number of process steps for one surgery type with a certain followed scenario.

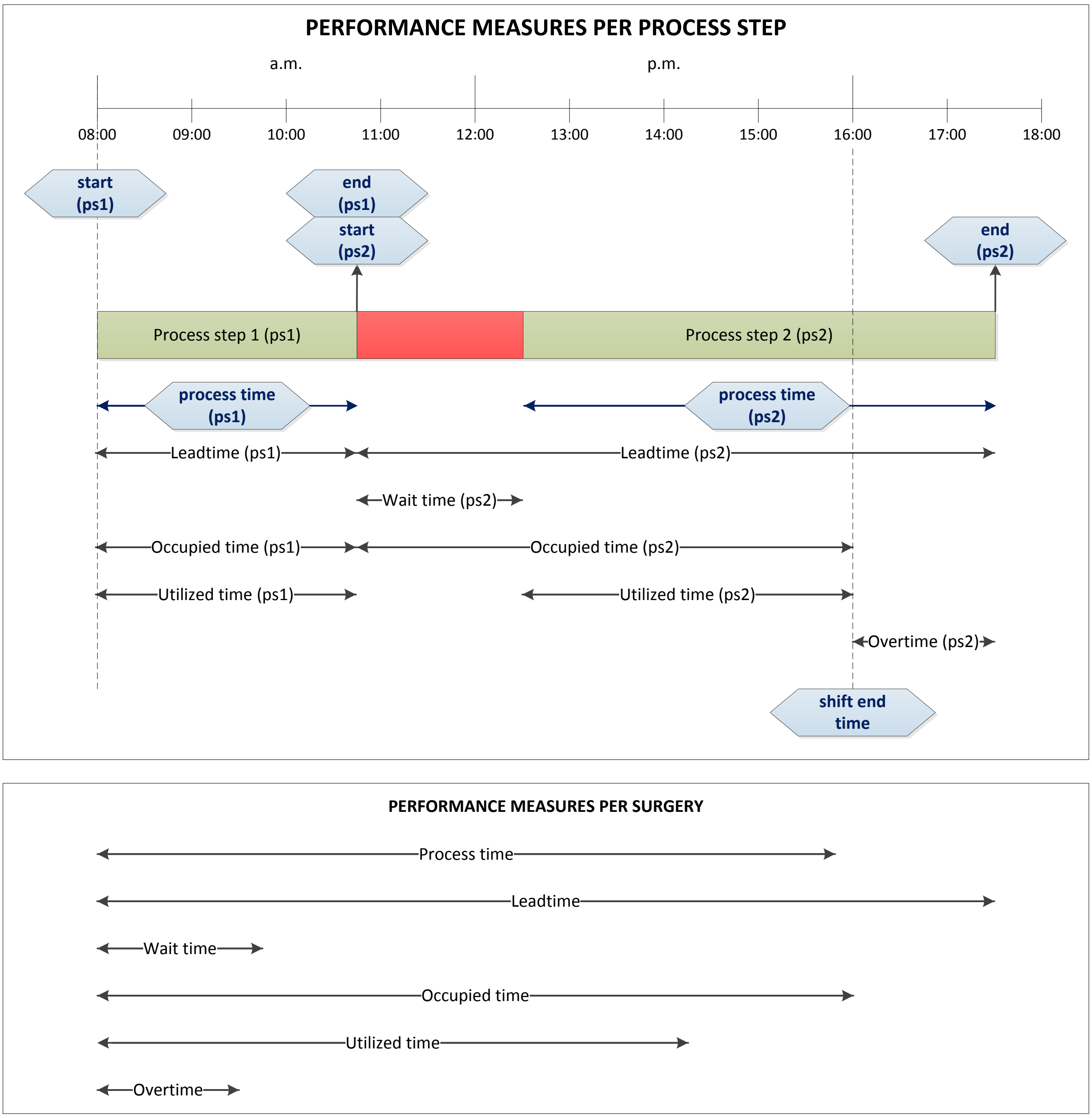


Figure 5: Performance measures

Personnel waiting time

Unlike patients, not all personnel types are included in every process step. The waiting time per process step is calculated with Formula 2.01. Since we know which personnel with what function has been involved in each process step, the waiting time for each personnel type is calculated by simply adding up the waiting time of all process step numbers in which the personnel member with the appropriate function was involved.

Personnel waiting time during surgery

- Duration of intervals between the start of the first surgery activity and the end of the last surgery activity performed by a certain personnel member during which this member is not required

$$Waiting\ time_{pmember} = {}_{pmember \in ptype}\quad {}_{ptype \in pteam}\quad {}_{pteam \in x} Waiting\ time_{ps_x} \qquad (2.03)$$

Where:
$pmember$ is personnel member
$ptype$ is personnel type
$pteam$ is personnel team

Calculating the waiting time for each personnel team can be done by multiplying the number of team members times the waiting time for each team. The number of team members per team can be found in Table 2. The waiting time for a personnel team can be calculated as follows:

$$Waiting\ time_{pteam} = {}_{pteam \in x} Waiting\ time_{ps_x} \cdot number\ of\ members\ in\ pteam \qquad (2.04)$$

The simulation model does not include a formula to make a distinction between unavoidable or avoidable personnel waiting time during surgery. However, by comparing surgeries in which equipment is necessary for only one surgery or for two or more surgeries, the avoidable and unavoidable personnel waiting time can be calculated.

The waiting time between surgeries can be calculated by determining the waiting time before a surgery starts:

Personnel waiting time between surgeries

- Duration of intervals between the end of the first surgery in which the personnel member is required and the start of the last surgery in which this member is required.

$$Waiting\ time\ between\ (s_y)_{pmember} = start_{pmember \in ps_1\ \cap\ ps_1 \in s_y} - end_{pmember \in ps_X\ \cap\ ps_X \in s_{y-1}} \qquad (2.05)$$

Where:

s_y is a surgery with number y, where $y = 1$ is the first surgery of the day, $y = 2$, the second surgery, etc.
$Waiting\ time\ (s_1)_{pmember} = 0$
ps_x is a process step with number x where 1 is the first process step and X is the last process step

$$Waiting\ time\ between_{pmember} = {}_{y=1}^{Y} Waiting\ time\ between\ (s_y)_{pmember} \qquad (2.06)$$

Where:
Y is the total number of surgeries in a day

The waiting time for a whole team is determined with the following formula:

$$Waiting\ time\ between_{pteam} = {}_{pmember \in pteam} Waiting\ time\ between_{pmember} \cdot number\ of\ members\ in\ pteam \qquad (2.07)$$

OR utilization

The third performance measure is the utilization of different ORs. Utilization is defined as the time that activities are carried out in the involved ORs within the regular working time, which is from 08:00 to 16:00. The occupied time is the time in which the ORs are occupied within the regular working time. Waiting time, caused by missing equipment for example, is not considered time in which activities are carried out and should therefore be subtracted from the occupied time to arrive at the utilized time. This leads us to the following formula to calculate utilized time:

> **OR utilization**
> - Time that activities are carried out in an OR within the regular working time divided by the regular working time

$$Utilized\ time_{ps_x} = Occupied\ time_{ps_x} - WaitingTime_{ps_x} \quad (2.08)$$

Where:

$$Occupied\ time_{ps_x} = \min\ ShiftEndTime, end_{ps_x}\ \ - start_{ps_x}$$

So we can rewrite formula 2.05 as follows:

$$Utilized\ time_{ps_x} \quad (2.08)$$
$$= \min\ ShiftEndTime, end_{ps_x}\ \ - start_{ps_x} - \ \ end_{ps_x} - start_{ps_x} - ProcessTime_{ps_x}$$
$$= \min\ ShiftEndTime, end_{ps_x}\ \ - end_{ps_x} + ProcessTime_{ps_x}$$

As you can see, the final formula only includes values that are registered in Arena. We can now calculate the utilized time for each OR as follows:

$$Utilized\ time_{room} = \ {}_{room\in x} Utilized\ time_{ps_x} \quad (2.09)$$

Finally, the utilization of a OR is calculated using Formula 2.07

$$Utilization_{room} = \frac{{}_{room\in x} Utilized\ time_{ps_x}}{working\ hours\ per\ day} = \frac{{}_{room\in x} Utilized\ time_{ps_x}}{8} \quad (2.10)$$

Personnel overtime

The last performance measure is the personnel overtime. From 16:00 onwards the time is considered as overtime. In Figure 5 one can see that this can be calculated by extracting the occupied time from the required time, thus:

> **Personnel overtime**
> - Number of time units a personnel member is working on top of his regular schedule

$$Overtime_{ps_x} \quad (2.11)$$
$$= Requiredtime_{ps_x} - Occupiedtime_{ps_x}$$
$$= end_{ps_x} - start_{ps_x} - \ \ min\ \ ShiftEndTime, end_{ps_x}\ \ - start_{ps_x}$$
$$= end_{ps_x} - min\ \ ShiftEndTime, end_{ps_x}$$

The overtime for each personnel type can be calculated using Formula 2.09

$$Overtime_{pmember} = \ {}_{pmember\in ptype}\ \ {}_{ptype\in pteam}\ \ {}_{pteam\in x} Overtime_{ps_x} \quad (2.12)$$

Where:
pm is personnel member
$ptype$ is personnel type
$pteam$ is personnel team

Calculating the overtime for each personnel team can be done by multiplying the number of team member's times the waiting time for each team. The number of team members per team can be found in Table 2. The overtime for personnel team can be calculated as follows:

$$Overtime_{pteam} = \ {}_{pteam\in x} Overime_{ps_x} \cdot number\ of\ team\ members\ in\ pteam \quad (2.13)$$

Surgery rate

The last performance measures considered is the surgery rate. This rate can be calculated by using Formula 2.11 and is determined by dividing the amount of patients scheduled in a certain scheduling period t by the amount of patients expected for this same period t.

Surgery rate

- The amount of patients scheduled in a certain period divided by the amount of patients expected to arrive in this period

$$surgery\ rate(t) = \frac{amount\ of\ patients\ scheduled(t)}{amount\ of\ patients\ expected(t)} \tag{2.14}$$

Where

t Scheduling period t

With formulas 2.01 to 2.14 all required performance measures are now covered.

2.4 Chapter Summary

In this chapter the problem was analysed in more detail. The research question and associated sub questions have been provided. The objective is to utilize the MITeC ORs in an optimal manner, which will be determined by using five performance measures. Formulas to calculate these performance measures are given in this chapter. The different surgery types and resource types involved in this research are described as well.

3 Literature Review

In this chapter literature will be described that can be helpful to answer the research question and its sub questions. Literature was sought in the following four databases: (1) PubMed, (2) ScienceDirect, (3) ABI/Inform, and (4) TU/e library. The search words were scheduling of operating ORs and all their synonyms as provided in Table 2. Since the literature addressing scheduling of operating ORs is very extensive, only papers published in English were included. This search led to 1 924 publications which were trimmed and filled, resulting in a final list of twenty-two articles. In addition to this search articles about the concepts explained in this chapter have been explored. These concepts were extracted from the twenty-two included articles.

Table 2: Search words

AND

Domain	Result
1	2
OR	Allocating
ORs	Allocation
Operating suite	Planning
Operating suites	Programing
Operating theater	Programming
Operating theaters	Schedule
Operating theatre	Schedules
Operating theatres	Scheduling
Surgery room	
Surgery rooms	
Surgical suite	
Surgical suites	

In the first part of this chapter, the difference between open-, block-, or modified block scheduling is described (3.1) followed by the concept of a master surgery schedule (MSS) (3.2). Hereafter, the existing uncertainty in both surgery durations (3.3) and surgery sequences (3.4) is explained. The difference between single-and multi-objective models (3.5) is briefly mentioned, followed by the different solution techniques that can be used to include the different concepts (3.6). Finally an explanation is provided on how this literature can be applied in this research (3.7).

3.1 Open-, Block-, or Modified Block Scheduling

It appeared that most of the authors developed a model for either an open scheduling method or a block scheduling method, as extensively described by Guerriero and Guido in their survey about operational management of the operating theatre [7].

An open scheduling method allows assigning surgical cases to an available OR, at the convenience of surgeons. An empty schedule is filled up with surgical cases, at two levels, by following the order of arrival time First Come First Serve. The first level concerns the construction of a surgical case schedule at medium term, whereas the second level concerns a detailed OR scheduling at short-term. The surgeons can submit cases up until the day of surgery and hereafter a schedule is defined by allocating individual surgeries to ORs. The main aim of the scheduling phase is to accommodate all surgical interventions.

In case of a block scheduling method, a set of time blocks (TBs) is assigned to specific surgeons or SGs (consisting of surgeons of the same surgical specialty), generally for some weeks or months. Surgical cases are arranged in TBs and they cannot be released. This strategy requires the solution of two different problems: the first one concerns the construction of a “cyclic timetable that defines the number and type of available ORs, the hours that ORs will be open, and the SGs or surgeons available for each OR block” [8]. Such a cyclic timetable is called either “OR block allocation table” or “master surgery schedule”. The second problem to be solved consists of filling-up the TBs with surgical cases, which are then booked into the assigned time in such a way that the average duration fits the scheduled time period. If this is not the case, an overbooking allowance must be requested by the surgeon. The length of the block can both affect the patient waiting time before surgery, OR utilization, and surgery rate. Dexter et al. used computer simulation to address several variables that can be considered when attempting to optimize surgical scheduling, including the number of hours in each block [9]. They found little difference in OR use for each of the four possible scheduling algorithms. Generally, full-day blocks (seven or eight hours) produce greater OR use than half-day blocks. No significant improvement in OR use can be obtained by changing from a seven-hour to an eight hour block duration. If the wait time is one week and average case length was more than two hours, then two four-hour blocks were used more efficiently than one eight-hour block. If the wait time is two weeks, however, there is little advantage of two half-day blocks over full-day blocks.

A third approach, not often used is a modified block schedule. This modified block schedule requires a modification of the block-scheduling strategy to increase its flexibility, which can be done in two ways: (1) some TBs are booked and others are left open, or (2) unused TBs are released at some time before surgery. Like the block-scheduling policy, a CSS is constructed but some flexible TBs are not assigned to any surgeon or SG [10].

Although open scheduling is more flexible than block scheduling, open scheduling is rarely adopted in practice, because it is not practical with regards to surgery schedules and increases competition for operating time capacity [7] [11] [12] [13].

3.2 Cyclic Surgery Schedule

It is well known that most elective surgeries do not differ much over time. During several weeks, more or less the same pattern of patients arises, which means a repeating or cyclic schedule can be developed for these patients. The tactical level concerns developing this cyclically constructed schedule, often referred to as a CSS throughout the literature [7]. Although the term turns up in different articles, definitions vary. We will use the definition presented by Blake et al. (2002): “a cyclic timetable that defines the number and type of ORs available at a facility, the hours that the ORs will be open and the SGs or surgeons who are to be given priority for the OR time” (p. 144). A CSS both offers autonomy of medical decision making to surgeons (who may assign patients to slots), while at the same time it yields a high OR utilization, robustness of schedules, a low degree of required organizational effort at operational level, and offers financial control [7]. In addition, a cyclic schedule is recommended throughout the literature Furthermore, advantages of both centralized and decentralized approaches are combined [14]. On the other hand a CSS is less flexible, more costly (due to staffing costs), and increases patient access time compared to a non-cyclic schedule [15].

This schedule usually is constructed in a given planning period of one month, three months or a year. It determines the daily number of patients flowing through the OR, thereby influencing the surgery rate. Historical data and actual demand or forecasts of demand are primarily used as input. A CSS defines number and type of available ORs, the hours that ORs will be open, and the surgeons or the SGs to whom the OR time is assigned.

Before this scheduling will take place, the patients have to be divided in clusters guaranteeing a sufficient allocation of the TBs, especially if set up times are involved. These clusters can for example be divided by the surgeon performing the surgery or the resource usage of the patients. Patients that do not fit the profile can be put in so called “dummy surgeries”. According to van Oostrum et al. [16] the goal is to construct a set of surgery types with a low volume of dummy surgeries as well as a low variability in their demand usage. Surgery types will need to make sense from both a medical as well as a logistical point of view. Characteristics of an operation type, such as expected operation duration or required instrument sets, should be accurate predictors of the characteristics of actual patients that belong to this type.

The assignment of entire TBs to SGs is not easy for two main reasons: (1) the target allocation to an SG may not be represented as a multiple of whole TBs and it is not possible to divide a TB, and (2) a supply of staffed ORs and/or specialty equipment may restrict the actual number of hours that can be assigned to an SG [8].The task of allocating the target number of hours of OR time to each surgeon (or SG) can be tackled by adopting several criteria and by taking into account different constraints (e.g., two sites hospital organization and personnel restrictions, even if the number of published papers dealing with this specific issue is limited [17]). Obviously, the number of ORs, as well as the available operating time and the capacity of succeeding departments (e.g., the number of available beds) affect the CSS construction.

3.3 Uncertain Surgery Durations

Due to significant uncertainty in surgery durations, it can be very challenging to provide a CSS that closely represents reality. Longer than average surgery durations might result in late starts not only for the next surgery in the schedule, but possibly for the rest of the surgeries in the day as well [18]. Late starts also result in direct costs associated with personnel overtime when the last surgery of the day finishes later than the scheduled shift end time [18]. They might even lead to surgery cancellations. Early endings result in lower OR utilization, which might be a waste of available OR time if other patients could have been scheduled as well.

Although perfect prediction of surgery durations is impossible, improved estimates can have a positive impact on OR utilization. Hans et al. studied bin-packing heuristics with a portfolio effect to consider the uncertainty in surgery durations [19]. Portfolio management is used to reduce the risk (minimize variance) or increase the profitability (maximize expected return) by distributing the investments into various different projects instead of investing in a single project. They found that, as a result of the portfolio effect, surgeries with similar duration variability are often scheduled on the same day for each SG. Denton et al. found that sequencing surgeries in a daily schedule in order of increasing variance of surgery duration is typically optimal or near-optimal [18]. Intuitively, this is because delaying highly uncertain surgeries to the end of the day limits their impact on other surgeries in the schedule. The current literature suggests that considering the stochastic aspects of the surgical environment can be an improvement to realistic problem solving.

3.4 Uncertain Surgery Sequences

None of the 1 924 included articles resulting from the literature search included uncertainty in surgery sequences,. All authors assumed a surgery would last a certain amount of time and would require the same personnel during this entire period. In this research a resource can be required only during certain surgery periods, which might result in personnel waiting time during surgery. The fact that the subsequent surgery steps might become apparent during surgery can highly influence the course of the day for the involved resources. In addition, the estimation of the remaining surgery duration will be improved, which might be useful to increase the number of patients treated, thereby increasing the surgery rate and OR utilization, in the remaining surgery day planning.

3.5 Single Objective versus Multi Objective Models

Although single-objective models perform better on the extremes than multi-objective models, they often are not very useful in practice since they do not account for any other objectives [20]. Competing performance criteria, such as (1) OR utilization, (2) overtime, (3) surgery rate, (4) patient waiting time and (5) personnel waiting time should be balanced by using a multiple-objective model, since this will lead to a model that is closer to reality [20].

3.6 Solution Techniques

Many authors writing about operating OR planning and scheduling provide extensive mathematical models in terms of heuristics, integer programming (IP), linear programming (LP), or integer linear programming (ILP). For solving these models, several techniques are used. Belien (2006), Guinet and Chabaane (2003), Ogulata (2003), Jebali (2006) and Adan and Vissers (2002) all present some exact solving methods, but none of the methods used yield satisfying results because of excessive computation times.

In the field of operations research we have searched for workflow or process scheduling problems including both parallel and sequential planning and resource constraints, since these are the main characteristics of our research. Research on workflow scheduling has largely concentrated on temporal and causality constraints, specifying existence and order dependencies among tasks. This allows for both sequential and parallel planning. For example, task 1 must be executed before task 2 or if task 1 will be executed, task 2 should be executed as well.

Among the methods used for workflow scheduling, job-shop scheduling is most relevant, which can be described as an optimization problem in which ideal jobs are assigned to resources at particular times. In this research the jobs would be the patients that would be assigned to the different ORs. Many alternative problems exist within a job-scheduling problem such as: related machines, machine set up times, sequence dependent setups, job constraints, etcetera. All these aspects seem relevant for this research. However, a workflow can be much more complex than a job-shop. For example, iterative blocks of workflows do not exist in job-shop problems but they do exist in this research (see Appendix II: Process Flow Charts).

One promising article that can include multiple relations between process steps and includes resource allocation has been written by Senkul and Toroslu [21]. They present an architecture to model and schedule workflows with resource allocation constraints as well as with the traditional temporal/causality constraints. They use a constraint programming language called Oz. However, they do not include process step durations in their model and even though it can be adjusted in order to include deterministic durations it can't be used when including stochastic durations. In addition, Ozkarahan (2000) states: "considering that the OR scheduling personnel are not operations research analysts, the mathematical model needs to be integrated with an expert system…" (p. 377) [6]. This applies to all techniques presented above and since the model developed in this research will be used by the planners of the RUNMC, it will require a solution with a system that doesn't require a development or purchase of an additional expert system, so any solution requiring the development or purchase of additional expert systems would be infeasible.

Simulation, regularly in combination with another solution technique, is often used and by all means an appropriate technique to develop a mathematical model and solution technique to tackle the complexity of OR session planning and scheduling including stochastic durations. The RUNMC owns a license to use the Rockwell Arena Simulation package, so no additional purchase or development of software is required. Besides, simulation can be used to include probabilistic constraints, multiple objectives, many different situations, and it is accurate. On the other hand, simulation often results in a long computation time, especially when many different constraints are included.

3.7 Literature Applicability

Due to the fact that this research includes a combination of elements that none of the articles fully covered, it is not possible to directly use one of the articles for this research. Most articles did not consider uncertainty in surgery duration, and none considered resources that were required only during a specific part of the surgery, replacement of patients from one OR to another during surgery, or different surgery scenarios for a single surgery type. Therefore it was decided to follow the general recommendations applicable to OR scheduling which were provided throughout the literature. With a high OR utilization as a main objective of this research and the notion that the project is entirely new, which asks for a low degree of required organizational effort, it is decided to develop a cyclic surgery schedule (CSS) because it yields a high utilization, robustness of schedules, and a low degree of required organizational effort at operational level. This automatically implies that a block scheduling method will be used. Furthermore, stochastic durations will be incorporated to enable and demonstrate the exploitation of the portfolio effect and to develop a model closer to reality. In the research design described in Chapter 2 we have already discussed several performance measures that should be included, indicating that a multi-objective model has to be developed. The appropriate method to include all aforementioned different elements seems to be simulation combined with one or multiple other solution techniques, such as heuristics, LP, IP, or ILP.

3.8 Chapter Summary

Literature can be helpful to answer the research questions and although quite some authors have written about the topics at hand, none of the articles are directly applicable to this research. Therefore, the recommendations and guidelines that are found throughout the literature will be used. Concluding from the literature study it would seem that developing a multi-objective simulation model combined with heuristics, LP, IP, or ILP would be an appropriate solution technique to build a CSS using a block scheduling method, including resource constraints, and including stochastic durations.

4 Simulation Model Development

In the previous chapter, the literature about planning and scheduling of operating ORs has been described. It has been concluded that developing a multi-objective simulation model combined with heuristics, LP, IP, or ILP seems to be an appropriate solution technique to build a CSS using a block scheduling method, including resource constraints, and including stochastic durations. In this chapter the method to develop such a multi-objective simulation model in order to answer the research question will be described. First, the process flow per surgery type will be developed using different pragmatic guidelines (4.1), followed by the description of the development of a multi-objective simulation model with stochastic process step durations (4.2).

4.1 Process Flow per Surgery Type

Before any schedule can be developed, for every surgery type a structured overview of different steps undertaken is developed. Both pragmatic and operational guidelines have been used to build process flow charts that are easy to comprehend and are not ambiguous [22] [23] [24] [25] [26]. A surgery step is considered different from its previous step if the required resources differ. Every overview of a surgery type will start at the beginning of a surgery or surgery and will end at the end of this surgery or surgery. The absence of stored event logs to discover the process flow, led to the need to collect the data manually from the personnel involved in the process.

In Figure 6 a process of gynaecology is provided to develop a general idea on how these models might look like. In Appendix II: Process Flow Charts for each surgery type the modeling symbols are explained and the process flow charts of all the included surgery types are illustrated. Per process step the following elements have been described: (1) OR in which process step takes place, i.e. the IORT OR, HYB OR, or MRI OR. (2) Required resource teams, which are different resource types clustered in a team. Since their team composition is always the same, so will be their performance measures. (3) Duration source, describing the source from which data was retrieved. (4) Duration, which has been filtered from the OKsimed database, described in Appendix VIII: Database Description, whenever possible.

Data has been checked for outliers and unrealistic data (such as zero or extremely high durations for certain steps). In some cases an initiate-, or preparation duration of zero minutes was found but in consultation with the experts it was decided to add these times up to get one combined initiation and preparation duration, because this could be seen as one process step. The total duration of both processes should be correct even if the duration of one of the processes was equal to zero. All other durations have been verified by an expert as well and all were close to their estimations (a largest deviation of 22 %).

4.2 Clean-up and set-up times between surgeries

If two subsequent surgeries take place in the same OR, clean-up and set-up times are included in the model. These set up and clean up times might vary per combination of a prior and subsequent surgery. Including these set up and clean up times will lead to a better estimation of the duration intervals in which resources are required and to a better estimation of personnel overtime and personnel waiting time.

4.3 Development of a Simulation Model with Stochastic Process Step Durations

In order to determine which personnel and what equipment should be available at which locations and at what times during surgery we have developed a simulation model with stochastic durations. Therefore, for all process step durations that had a certain level of uncertainty, either estimated by personnel members or extracted from the OKsimed database see Appendix VIII: Database Description), an empirical uniform distribution was developed to use in the Arena model assuming each duration could occur with the same probability. In Figure 6 the interval has been shown of the different durations of each process step.

The simulation model keeps track of the enter and leave time per process step as illustrated in Figure 6. A process step includes potential waiting time caused by the unavailability of a scarce resource. Subtracting the enter time from the leave time results in the required time to execute a process step. This required time is not the same for every patient because the durations vary. For the process flow in this example, 34 patients have undergone the same treatment, according to the OKsimed database. So for each process step in this example 34 durations have been found that can be used to represent the duration of each process step.

This number of data points leads us to $34 \cdot 34 \cdot 34 + 34 \cdot 34 = 40\ 460$ different scenarios that could exist for a patient that will flow through the Arena simulation model. Every patient can follow one of these scenarios. For example, let us assume a patient follows the process steps called “preparing surgery and laparoscopy”, “stage and debulk”, and “wake patient” sequentially and would enter and leave these steps at 08:00 and 09:00, 09:00 and 13:00, and 13:00 and 13:30, respectively. If we would like to know who (which personnel), and what (which equipment) should be available when (at what times) and where (in which OR), we have to figure out when the required resources are idle, i.e. not operational, and when they are busy, i.e. operational.

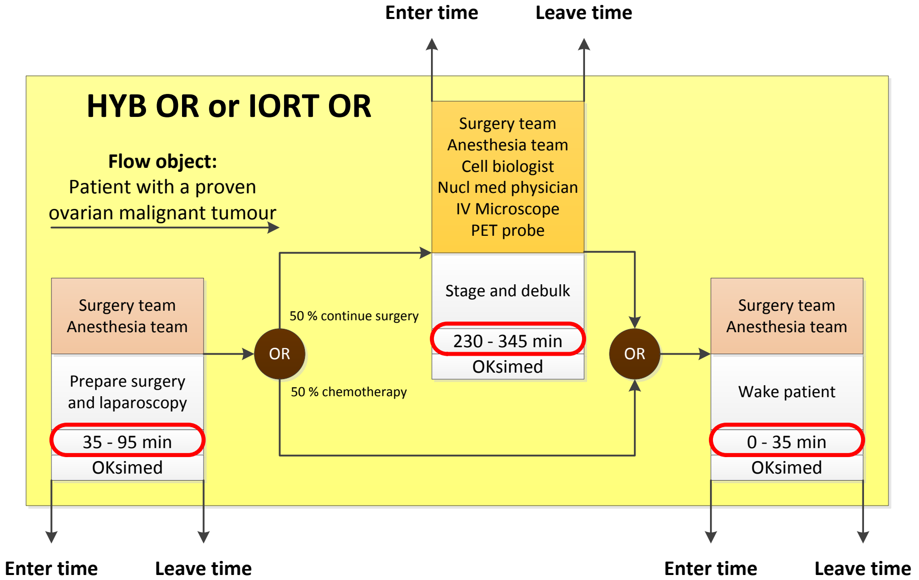


Figure 6: Example to illustrate Arena registration with stochastic durations

If we analyse the example provided above and if we assume the proven malignant overian tumour surgery takes place in the IORT OR, we can see that the resource types: (1) IORT OR, (2) surgery team, and (3) anaesthesia team are required during all three process steps. This would lead to the following sequence of idle and busy:

- 08:00 – 09:00 busy (prepare surgery and laparoscopy)
- 09:00 – 13:00 busy (stage and debulk)
- 13:00 – 13:30 busy (wake patient)
- 13:30 – 18:00 idle

If we look at the resource types: (1) cell biologist, (2) nuclear medicine physician, (3), in vivo microscope, and (4) PET probe, we can see that they are only required during the process step called: “stage and debulk”. For these resource types the idle/busy sequence would look like:

- 08:00 – 09:00 idle (prepare surgery and laparoscopy)
- 09:00 – 13:00 busy (stage and debulk)
- 13:00 – 13:30 idle (wake patient)
- 13:30 – 18:00 idle

These idle and busy sequences are automatically generated with the simulation model by letting 3000 patients flow through the system. The probabilities that resources are busy or idle are given in Appendix III: Arena Model, for each patient that enters the system. An example is given in Figure 7. As you can see the IORT OR is busy from 08:00 to 11:15 in at least 80 % of the cases. In at least 95 % of the cases the IORT OR is idle from 15:00 onwards, meaning with 95% confidence we can assure that all patients can be treated before 15:00 if the surgery started at 08:00.The MRI room is idle in 95 % of the cases between 08:00 and 09:15 and from 11:15 onwards.

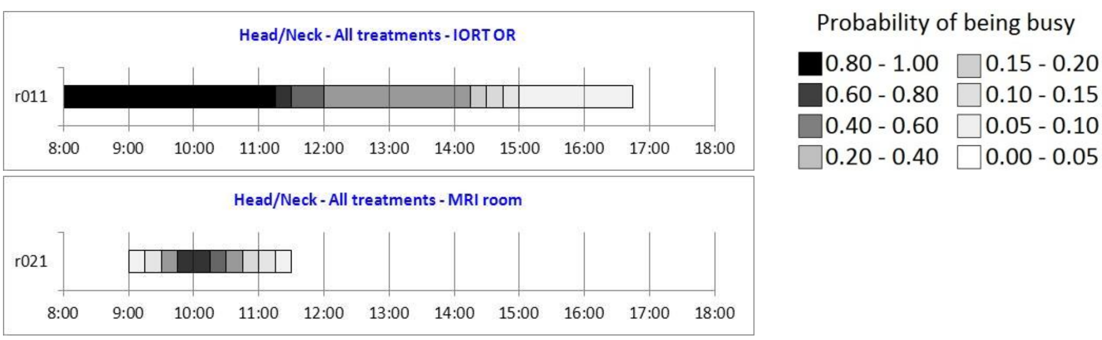


Figure 7: Probability of the IORT OR and MRI OR to be busy or idle during surgeries from the head/neck SG

In compliance with the MITeC project team, the duration intervals in which a resource type is busy in zero to five percent of the cases are not considered in the CSSs. The 95 % interval, i.e. with 95% confidence we can assure that all patients can be treated in the interval from x to y. The duration from x to y is used to develop different scenarios for a CSS to allocate TBs to SGs.

4.4 Development of Scenarios for Cyclic Surgery Schedules Including Only Tumour surgeries

In this section the different scenarios to treat patients with cancer are described. These scenarios have been developed in discussion with the members of the MITeC project team. Only the development of the first scenario is described in detail. The latter scenarios are described more generally.

Scenario 1 (one surgery per surgical group per week)
The starting point is to allocate one surgery per SG per week in the IORT OR. This seems an obvious starting point because the surgeries should be allocated equally amongst all SGs. Furthermore, it gives an indication how much OR will still be left and how much patients can be treated if every SG can conduct one surgery per week. From this scenario the ORs will be filled until all patients are allocated somehow.

Since an SG can conduct multiple surgery types we combined these surgery types to create three groups according to their SG, i.e. a head/neck group, a gynaecology group, and a urology group as illustrated in Figure 8. The percentage that a certain surgery type would occur within one SG is given as well. These percentages have been extracted from the expected amount of patients to arrive for each surgery type, provided in Table 1.

For example, within the gynaecology group, two different surgeries might occur in one week, namely an expected malignant tumour surgery or a proven malignant tumour surgery with a probability of 30 % and 70 %, respectively. Time should be allocated for both surgery types within one week, because it is not known in advance which surgery type might occur.

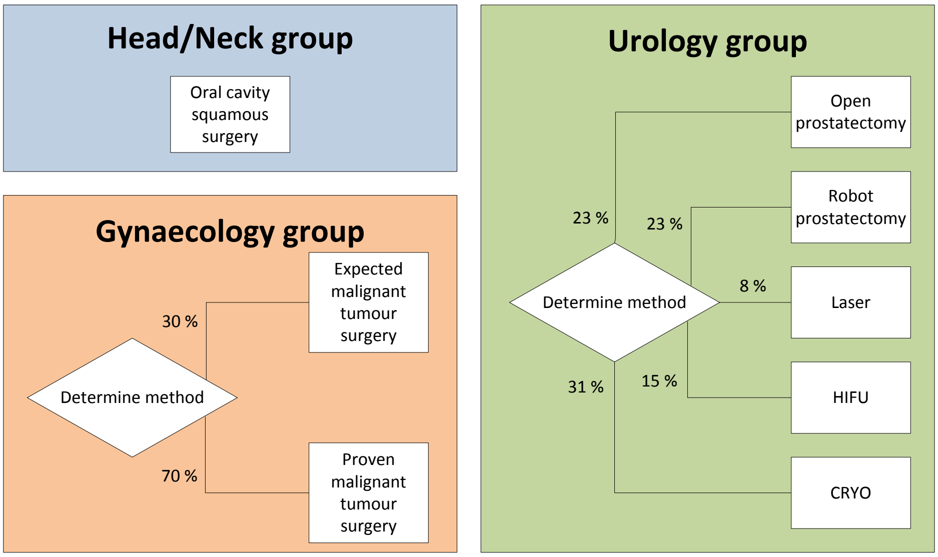


Figure 8: Surgical groups used in scenario 1

In Figure 9 the proposed cyclic surgery schedule is provided. This schedule will repeat itself in each working week

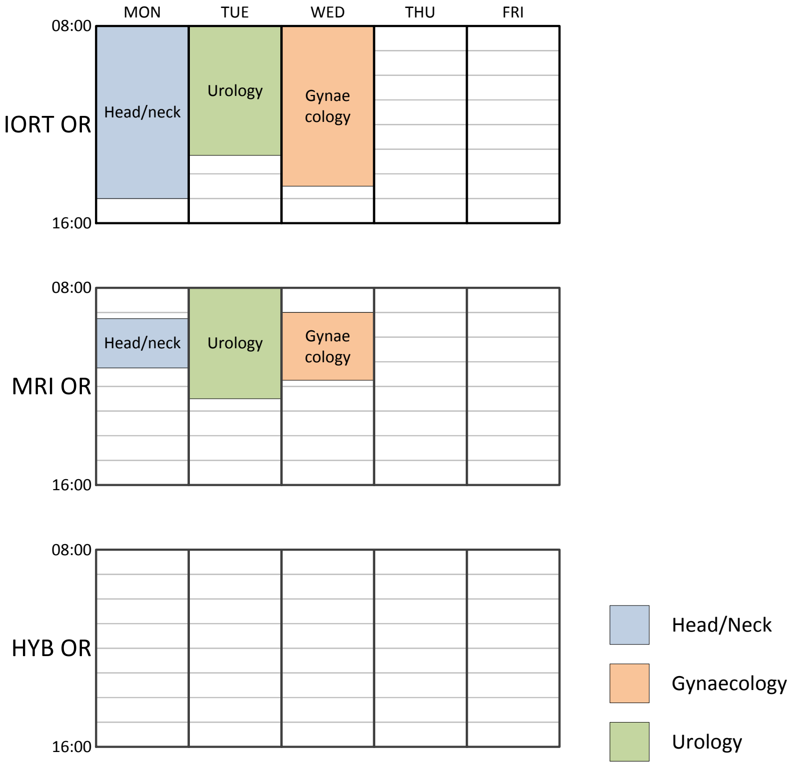


Figure 9: CSS reference point using 95% interval (scenario 1)

In this scenario 46 % of the tumour surgeries and 18 % of all treatments are scheduled. It is expected no patient waiting time, avoidable personnel waiting time, or significant personnel overtime occurs.

Scenario 2 (four IORT OR and/or MRI OR days)

For scenario 2 it is assumed that four days in either the IORT OR and/or the MRI OR can be used for the different surgery types as illustrated in Figure 10. Multiple surgeries at the same day from the same discipline are allowed. We chose to illustrate this scenario in case the ORs will be occupied by several other surgery types in the future or in case the project is in its initiation phase. For this scenario it makes sense to split up the surgeries for prostate tumours from the urology SG into two different groups. One group with MRI guided surgeries (HIFU, cryo, or laser) and one group without MRI guided surgeries. This is convenient because in the previous case the IORT OR was allocated for urology surgery types while the MRI guided surgeries do not need this OR and this would lead to unutilized OR time. Furthermore the maximum surgery time for an MR guided surgery is four hours, so two surgeries can be allocated on one day at 08:00 and 12:00. Two of the three MRI guided surgery types have been executed at least five times at the moment of writing this thesis, so the procedure is rather familiar. For the MRI guided surgeries it is convenient to have a whole surgery day since this can reduce setup times and in some cases even three patients or more patients might be treated during a whole day. However, for now it is assumed two cases can be done in one day with two blocks of four hours allocated for MRI guided surgeries.

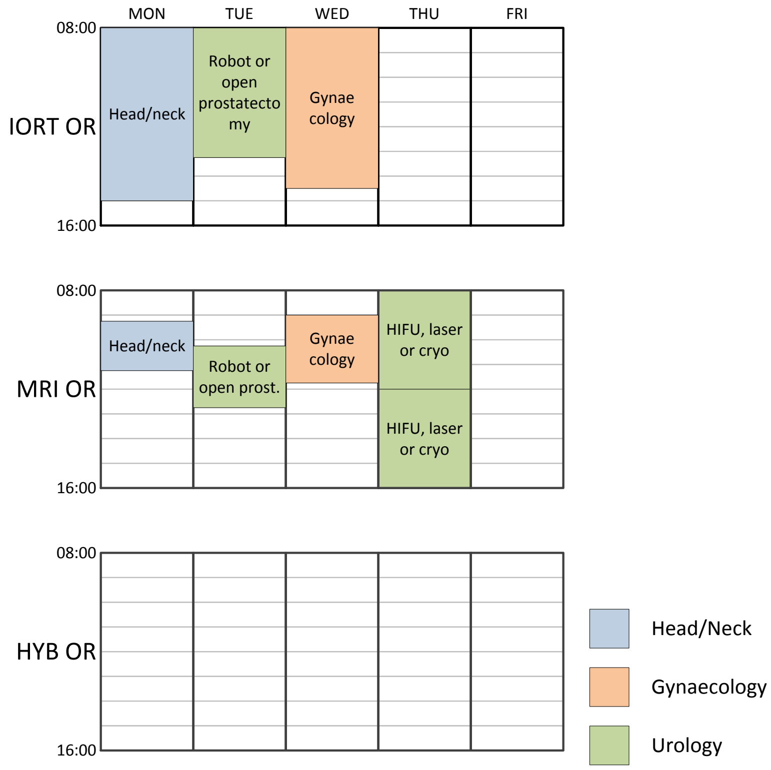


Figure 10: CSS using 95% interval (scenario 2)

Compared to the previous scenario, both the surgery rate and the overall OR utilization will increase, since more patients are scheduled. Personnel waiting time between the urology surgeries scheduled on Thursday will occur. This waiting time is caused by: (1) the clean-up time between the subsequent surgeries and (2) a possible early end of the first surgery, resulting in a waiting time for the second surgery to start at the scheduled time.

Scenario 3 (five IORT OR and/or MRI OR days) – two options

For scenario 3 we will investigate the situation in which five days of the IORT OR and/or MRI OR can be filled. This scenario is used to show the RUNMC management what would happen if the HYB OR is left idle, so other surgeries can be allocated to the HYB OR (as previously mentioned, the HYB OR is more useful to some other surgery types, due to its equipment, instead of the surgery types used in this research). In this case either two days per week can be allocated to the head/neck department (scenario 3a) or two days can be allocated to the gynaecology department (scenario 3b). Both options are provided in Figure 11. The MRI guided surgeries can be allocated in different ways, although results will be the same as long as surgeries do not overlap. The advantage of scenario 3a is that the head/neck department can operate on Monday, which is the preferred option. The advantage of scenario 3b is that the patients treated versus patients expected rate is better divided.

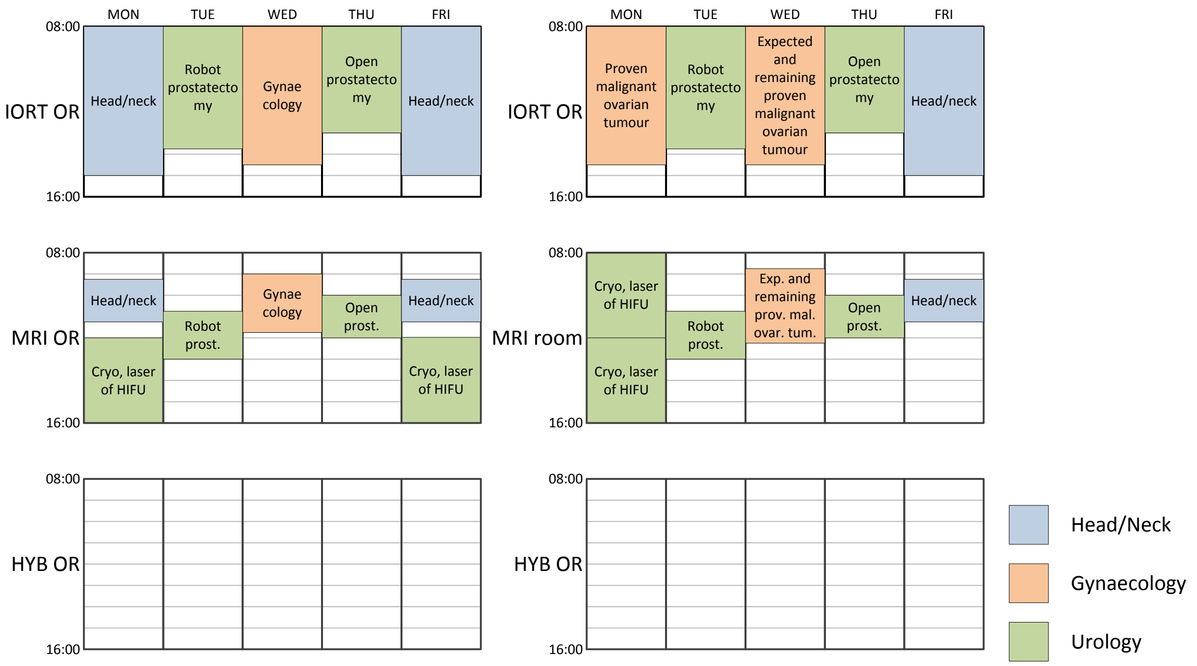


Figure 11: CSS using 95% interval (scenario 3a (right-side) and scenario 3b (left-side))

Compared to the previous scenario, both the surgery rate and the overall OR utilization will increase, since more patients are scheduled. Personnel waiting time between the urology surgeries scheduled on Thursday will only occur for scenario 3b.

Scenario 4 (five IORT OR and/or MRI OR days, cycle length is 2 weeks)
A more honest and fitting allocation of operating OR capacity can be provided when the cycle length is changed from one week to two weeks as illustrated in Figure 12. Currently a cycle length of two weeks does exist for some SGs in the RUNMC as well, so it would not ask for a dramatic change in planning methods. This allows us to play a little with the allocation of surgery blocks to different SGs.

For this scenario both head/neck and gynaecology can operate on Monday every other week. This way the operating OR blocks are more fairly distributed. In addition, urology gets one day less every other week, because in that case they can still treat their expected number of patients (60 per year allocated and 60 per year expected) and it increases the flexibility since on this "empty day" either an extra urology surgery can take place or some other surgery that has a high waiting list before surgery or has a high urgency. Again MRI guided surgeries can be allocated in different ways, although results will be the same as long as surgeries don't overlap. For example, one full surgery day for MRI guided surgeries is preferred by the personnel, but for CSS consistency it might be convenient to allocate them every week on Monday afternoon and Friday afternoon.

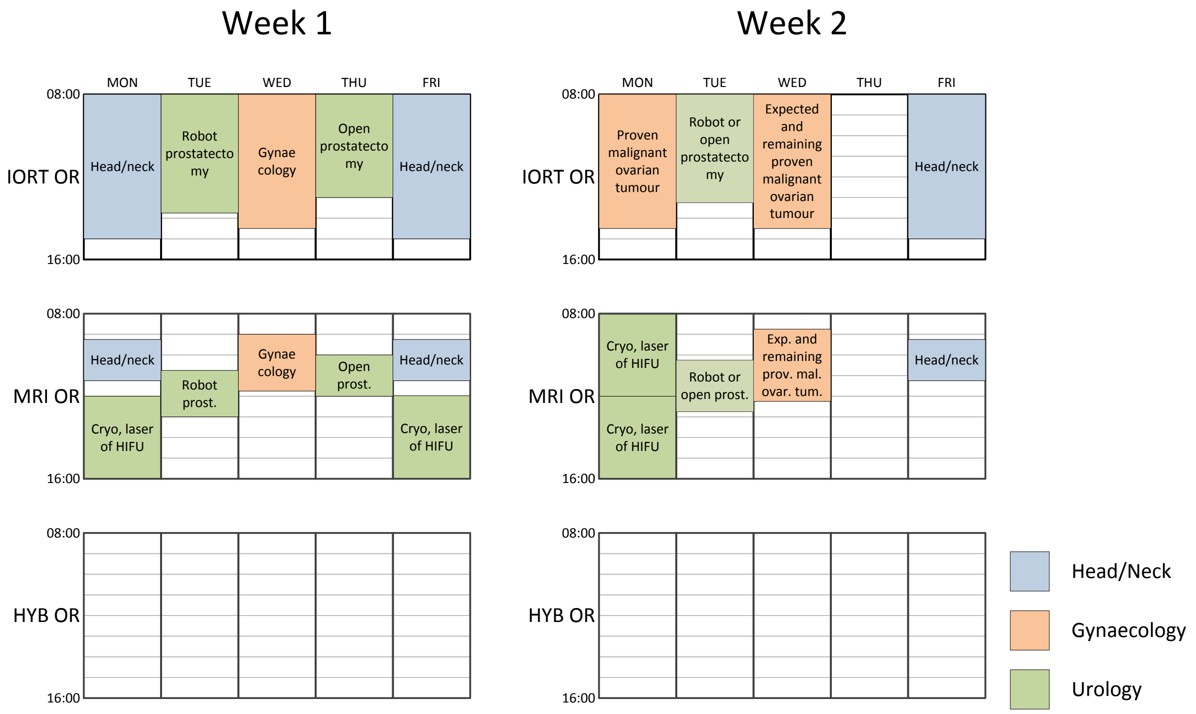


Figure 12: CSS using 95% interval (scenario 4)

Compared to the previous scenario, the overall surgery rate will be equal, but the surgeries are more evenly distributed between the head/neck and gynaecology SG. The overall OR utilization will decrease since urology can now execute three surgeries in two weeks, whereas in the previous situation four surgeries per four weeks were allocated. The personnel waiting time for urology personnel between surgeries will be half of the waiting time from scenario 2 and 3b, because in the first week these surgeries are not executed sequentially and in the second week they are.

Scenario 5 (five IORT OR and/or MRI OR days, change in current OR days required)
Since gynaecology can still use some more OR time because they cannot treat all expected patients yet, the first solution that comes to mind is to convince either the personnel of the gynaecology department or the head/neck department to conduct the new surgeries on Tuesday or Thursday as well at least once every two weeks. This would be the most optimal solution since conducting two surgeries at the same time in both the IORT OR and HYB OR would lead to scarce resources that are required at the same time and other SGs are allocated less time in the HYB OR. This is illustrated in Figure 13. In this scenario MRI guided surgeries are allocated for a full day on Thursday every two weeks and on Monday every two weeks, respecting the SG's wish to have one entire surgery day. Note: only 60 non-MRI guided surgeries can take place each year in this scenario, which is exactly the amount of expected patients. If the number of patients arriving in reality is more than 60 they can use the ORs if they are unoccupied by the gynaecology surgeries on Wednesday, since they have 10 spare places each year if indeed 70 gynaecology patients will arrive.

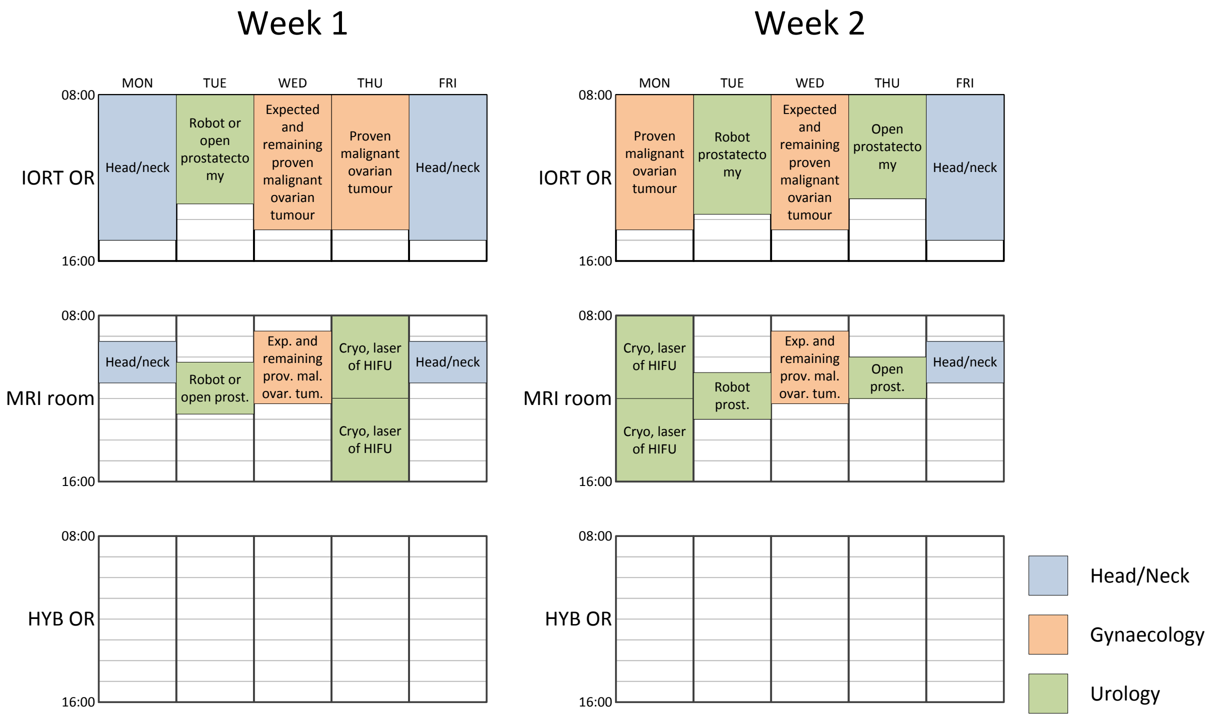


Figure 13: CSS using 95% interval (scenario 5)

The surgery rates for all tumour surgeries are all 100 % for the first time. The personnel waiting time for urology personnel between surgeries is equal to scenario 2 and 3b. Avoidable patient waiting time during surgery and personnel overtime are not expected.

Scenario 6 (all tumour surgeries scheduled, proven ovarian (12:00) and OCS (08:00))
If gynaecology or head/neck cannot or will not conduct surgeries on either Tuesday or Thursday once every two weeks, it is required to start using the HYB OR if all expected patients should be scheduled in a year. The only solution seems to allocate both a head/neck surgery and a gynaecology surgery for a proven malignant tumour on one day, since the gynaecology surgeries can only be done on Monday and Wednesday. Both surgeries require an in vivo microscope and only one will be available at the start of the project. For this scenario it is assumed a proven malignant overian tumour surgery starts at 08:00 in the IORT OR and an OCS tumour surgery in the HYB OR at 08:00. If we now take a look at the probabilities that an in vivo microscope is required during these two surgeries in Figure 14 and Figure 15. As you can see the in vivo microscope might be required between 08:45 and 14:15 in the at least 95 % of the cases during a proven malignant overian tumour surgery and it might be required between 09:15 and 11:45 in at least 95 % of the cases during an OCS tumour surgery. Obviously these two time periods have a probability to overlap.

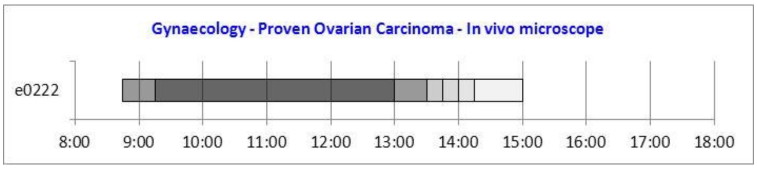


Figure 14: Probability that the microscope is required during a proven malignant tumour surgery

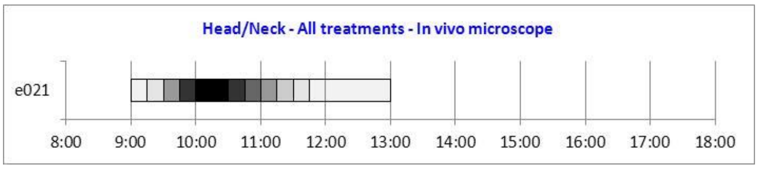


Figure 15: Probability that the in vivo microscope is required during a head/neck surgery

If we depict the in vivo microscope similarly to the ORs in an IORT CSS the overlap becomes more obvious, as can be seen in Figure 16. This Figure shows the overlap when both a proven malignant overian tumour surgery and an OCS tumour surgery start at 08:00 in the 95 % interval. In this case a trade-off exists between a low amount of overtime and a high amount of patient waiting time during surgery or vice versa.

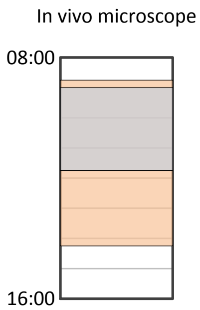


Figure 16: Microscope overlap if both a head/neck and gynaecology surgery start at 08:00

Since we would like to avoid both patient waiting time and personnel overtime it makes sense to let one surgery start later than 08:00. This way patient waiting time might be reduced but personnel overtime might increase. However, if the waiting time is quite long this can also cause overtime.

By analysing Figure 14 and Figure 15 it makes more sense to shift the proven malignant overian tumour to a later starting time since the probability of patient waiting time will almost be eliminated (less than 5 %) after shifting a proven malignant tumour surgery to 11:00. To achieve approximately the same probability when shifting the OCS surgery backwards would mean this should be shifted backwards to 13:00. In addition, 95 % of the proven malignant overian tumour surgeries finish before 14:30 when starting at 08:00 compared to 15:00 for an OCS tumour surgery. This gives the impression that the probability of overtime is less when shifting the proven malignant overian tumour surgery than when shifting an OCS tumour surgery backwards.

Since we would like to avoid a very long patient waiting time, which will occur if a proven malignant overian tumour requires the in vivo microscope before the head/neck surgery, a gynaecology surgery should start at 12:00, since according to Figure 14 and Figure 15 there would be no probability of patient waiting time.

No surgeries are taking place on Thursday in order to spread the workload about evenly over two weeks (seven surgeries per week) as illustrated in Figure 17. If other SGs would like to use the ORs as well in this case they have about the same amount of time to do this in both weeks.

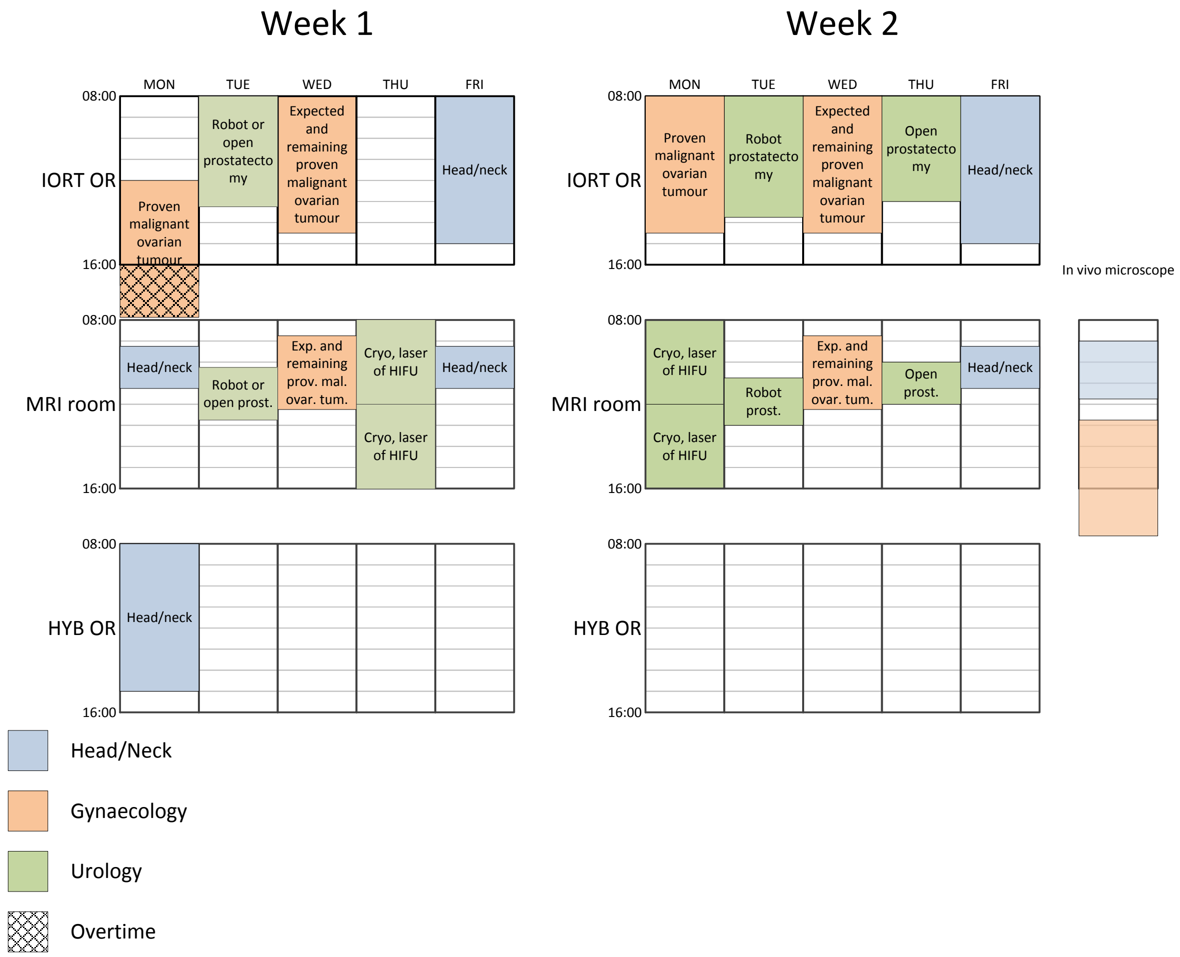


Figure 17: CSS using 95% interval (scenario 6)

Similar to the previous scenario the surgery rates for all tumour surgeries are all 100 %. The personnel waiting time for urology personnel between surgeries is equal to scenario 2 and 3b. A significant amount of personnel overtime for gynaecology personnel is expected with a maximum of approximately three hours.

Scenario 7 (all tumour treatments, expected ovarian (12:00 / 12:30) and OCS (08:00))
Similar to the previous scenario, it is also possible to treat a patient with an expected malignant overian tumour on the same day as a patient with an OCS tumour, as illustrated in Figure 18. Obviously, the same problem will occur as in the previous scenario, namely that both patients require the in vivo microscope. However, in this scenario fewer patients are treated with a proven malignant overian tumour than in the previous situation, because patients with an expected malignant tumour are treated as well. The expected number of patients with a proven malignant tumour drops from 40 to 9 in the current scenario. Therefore, the microscope is required for fewer patients, which reduces the probability that the instrument is required in two ORs at the same time.

On the other hand, a patient with an expected malignant overian tumour needs the MRI OR and a patient with an OCS tumour requires this OR as well. Again we tried to find an optimal balance between minimizing both patient waiting time and overtime. In this case, due to the MRI that is required for both surgeries, starting the gynaecology surgery at 12:00 might cause some patient waiting time, but this might be a very small patient waiting time. Therefore, we will provide the results when starting this surgery at 12:00 (scenario 7a) and 12:30 as well (scenario 7b).

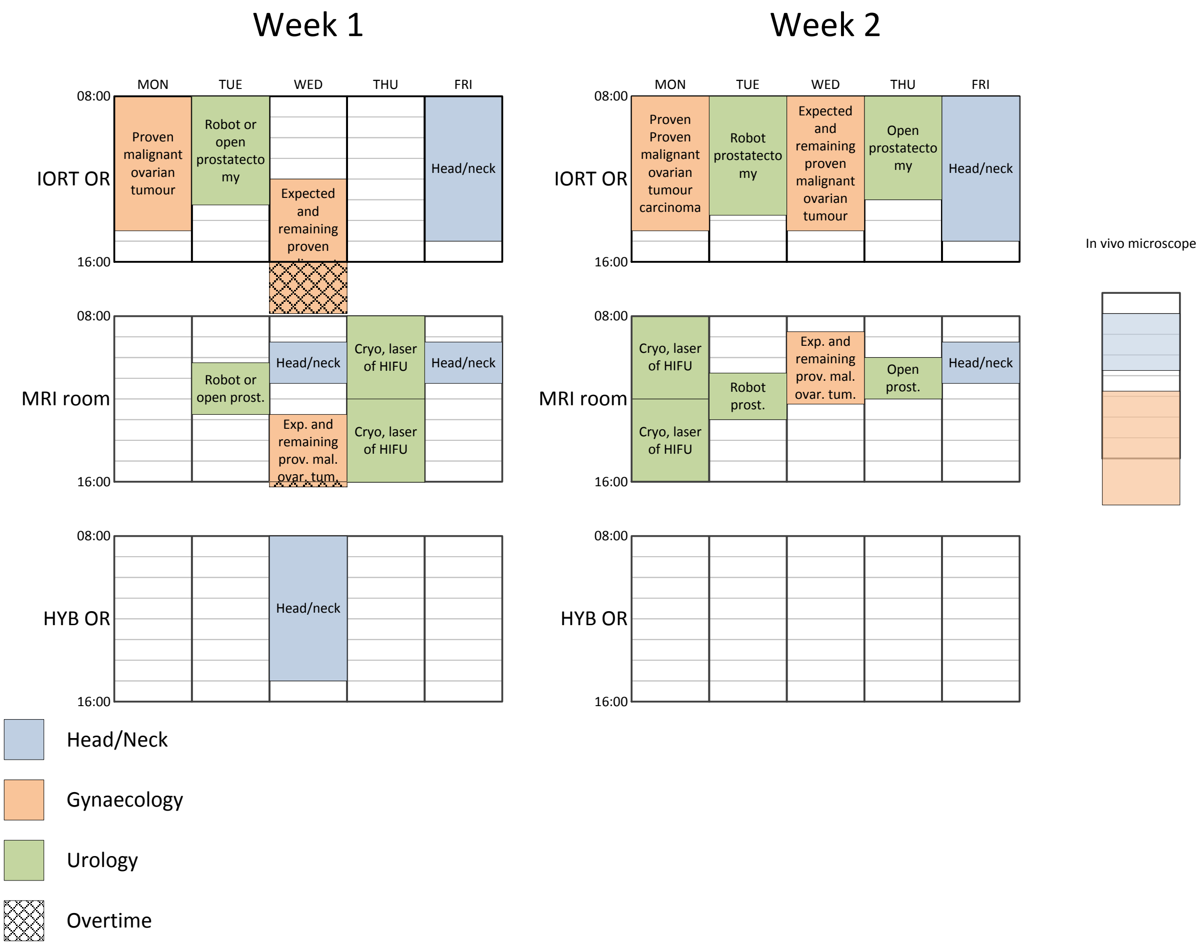


Figure 18: CSS using 95% interval (scenario 7a)

Similar to the previous scenario the surgery rates for all tumour surgeries are all 100 %. The personnel waiting time for urology personnel between surgeries is equal to scenario 2 and 3b. The average amount of personnel overtime for gynaecology personnel is expected to decrease, whereas the maximum amount of overtime will be equal compared to the previous scenario.

4.5 Development of Scenarios for CSSs Including All Patient Types

Thus far, we have described several scenarios to schedule all expected malignant tumour surgeries. With the current OR days the previous scenarios included all reasonable options, so now it is time to allocate the patients receiving a diagnostic MRI as well. The personnel involved with performing the MRIs would like to work in three blocks of four hours all on a different day of the week, because this is convenient for the anaesthesia teams (in general planning's are made for blocks of four or eight hours) and it is preferable to have multiple MRI moments. On average 3.35 MRIs can be conducted during a four hour block. MRIs can be made throughout the whole week.

Scenario 8 (partly patients having a tumour and all diagnostic MRI patients)

For this scenario it is assumed the HYB OR will not be used to see whether it is possible to leave this OR empty and treat all patients. One possible solution to meet the desire of the radiology department to get three OR blocks of four hours is presented in Figure 19 in which MRIs are scheduled on Monday-, Wednesday-, and Friday afternoon. In each four-hour block an average of 3.35 patients can be treated. This schedule does not differ much in both weeks. Not all patients from the gynaecology SG are included because three four-hour blocks could not be allocated in that case.

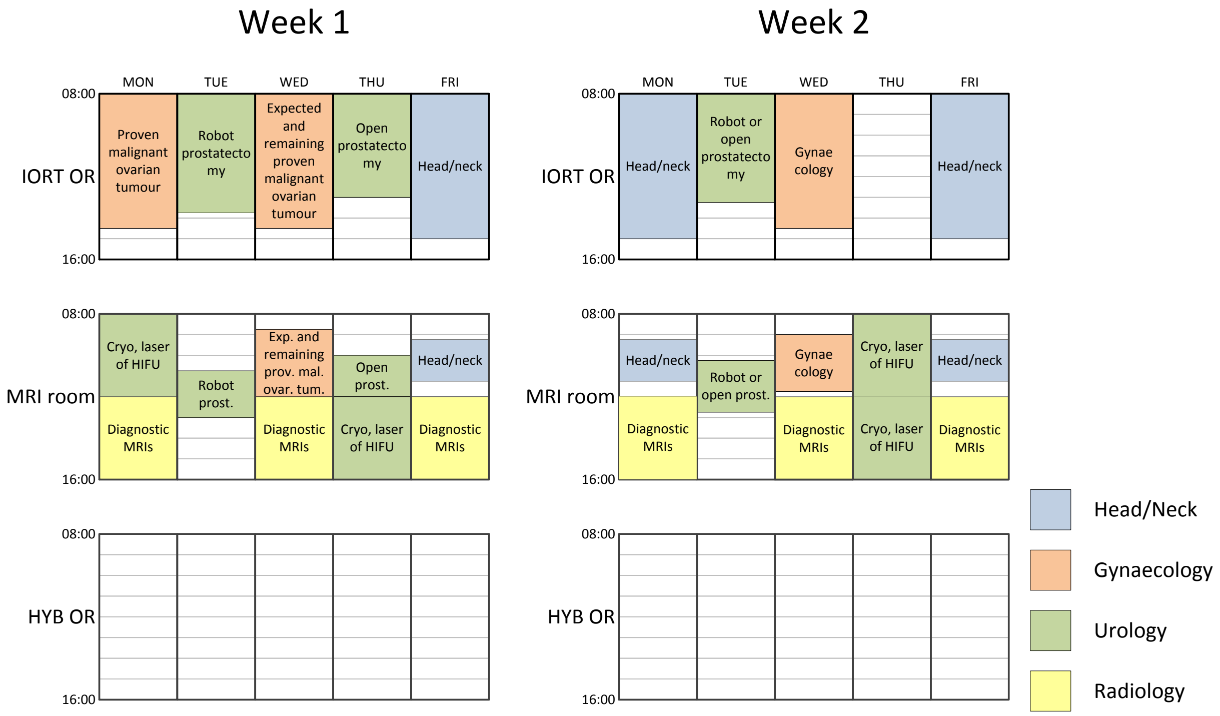


Figure 19: CSS using 95% interval (scenario 8)

Compared to the previous scenario the surgery rate including all patients will increase significantly since approximately ten patients per week will be treated in addition to all allocated tumour surgeries. Due to these patients the MRI OR utilization will increase significantly. Some overtime might occur for radiology personnel due to the fact that the executed diagnostic MRIs can take longer than four hours. However, the estimated time of these blocks is exactly four hours (retrieved from OKsimed).

Scenario 9 (partly patients having a tumour and all diagnostic MRI patients including µMRI)

For scenario 9, illustrated in Figure 20 it is assumed a table-top micro MRI is available, positioned close to the new ORs, which can be used for analysing tissue removed from the patients. In this scenario the MRI in the MRI OR can be used for patients only or for analysing tissue if the micro MRI is occupied. This will increase planning flexibility and results in a better satisfaction of different wishes. First of all, MRI guided surgeries can take place on the same day in both weeks. In addition, three four hour blocks for diagnostic MRI's can be allocated as well and we have tried to allocate them in a way they are evenly distributed throughout the week.

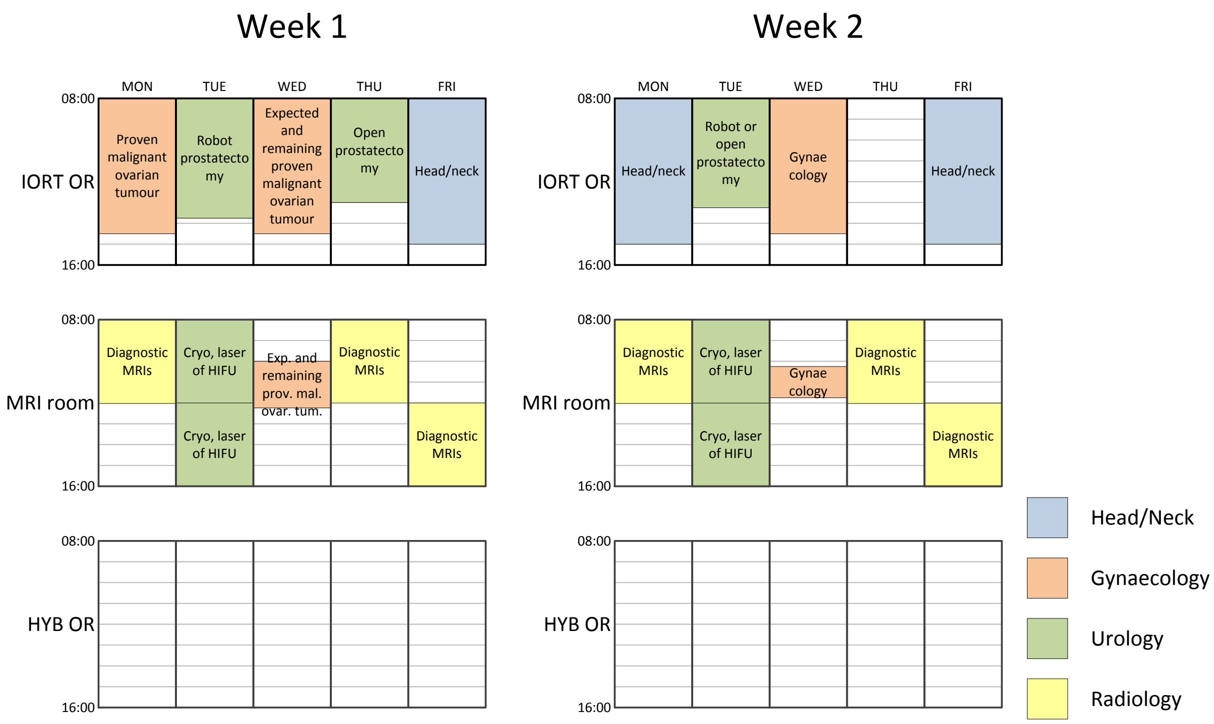


Figure 20: CSS using 95% interval (scenario 9)

Compared to the previous scenario, MRI OR utilization will decrease and personnel overtime for radiology will decrease as well. Furthermore, personnel waiting time for urology will increase, due to potential waiting for the second surgery on Tuesday to start. However, as explained before, this can be avoided by starting the second surgery immediately after the first surgery. The surgery rate and IORT OR utilization will be similar to the previous scenario.

Scenario 10 (partly patients having a tumour and all diagnostic MRI – only morning MRIs)
In scenario 10 illustrated in Figure 21, overtime occurs due to the diagnostic MRIs. This is caused by the MRIs taking place on Friday afternoon. For this scenario we allocated diagnostic MRIs to Friday morning with the objective to eliminate overtime. However the diagnostic MRIs are now less evenly distributed over the week.

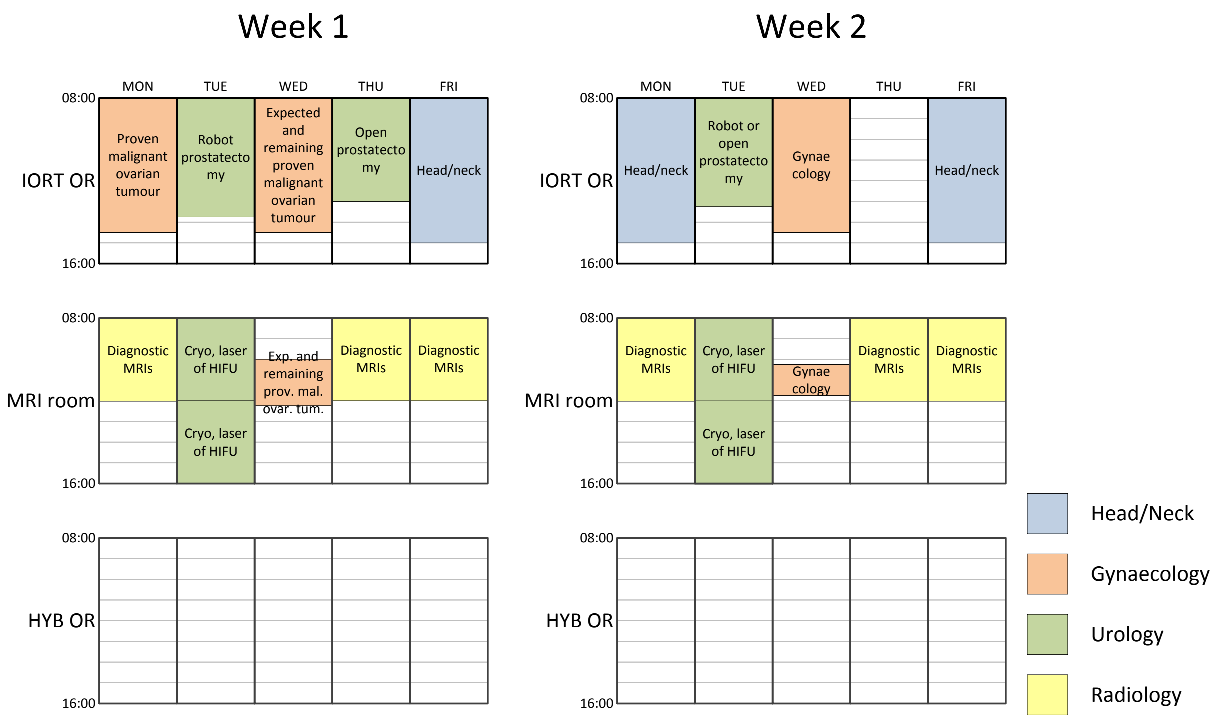


Figure 21: CSS using 95% interval (scenario 10)

Compared to the previous scenario only personnel overtime for the radiology SG will decrease. All other performance measures will be similar.

Scenario 11 (all patients including µMRI and two in vivo microscopes)
For this scenario, illustrated in Figure 22, it is assumed both a table-top micro MRI and two in vivo microscopes are available instead of only one as in the previous scenario. All patients can be treated.

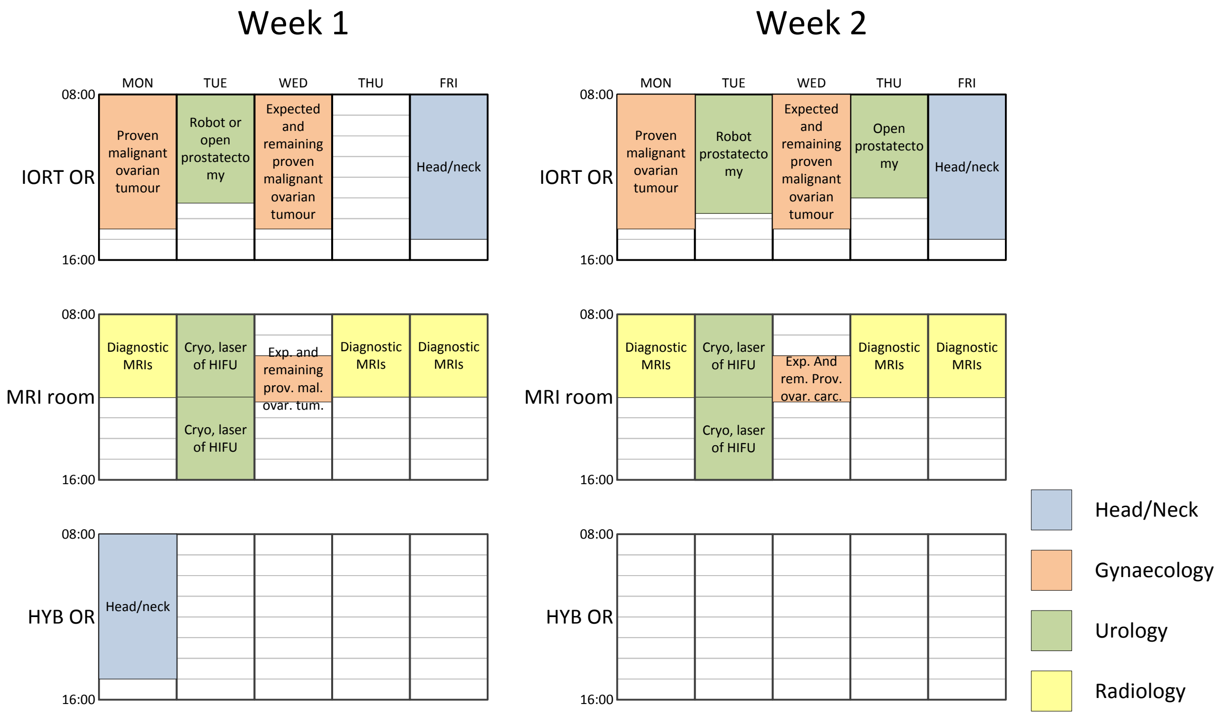


Figure 22: CSS using 95% interval (scenario 11)

The surgery rate will now be 100 %, which is more than in any of the previous scenarios. It is expected HYB OR utilization will be approximately 5 %, instead of 0 % as in the previous scenario. All other performance measures are equal.

4.6 Chapter Summary

In this chapter the used method is described to generate the stochastic simulation model including the desired performance measures. For a more extensive description of the Arena model you are referred to Appendix III: Arena Model. The first step was to develop the process flows per surgery type and the second step was to use the probabilities that resources are busy or idle retrieved from the Arena model to provide different scenarios for a CSS in a way that is consistent with the desires and requirements.

5 Verification and Validation

In this chapter the verification and validation methods for the developed model are described. Terminology in the area of verification and validation is not standard; see for example Barlas and Carpenter (p. 164, footnote2), and Davis (p. 4) [27] [28]. We use the definitions given in the textbook from Law and Kelton [29]. "Verification" is determining that a simulation computer program performs as intended, i.e., debugging the computer program. "Validation" is concerned with determining whether the conceptual simulation model is an accurate representation of the system under study. So it is assumed that verification aims at a "perfect" system, in the sense that the used codes have no programming errors left and validation, on the other hand, cannot be assumed to result in a perfect model since the perfect model would be the real system itself (by definition, any model is a simplification of reality), so the model should be "good enough", which depends on the model objective.

5.1 Verification

In order to verify the simulation model we have used different techniques, discussed in the paper of Kleijnen i.e. (1) general good programming practice, (2) checking of intermediate simulation outputs through tracing, (3) comparing final simulation outputs with analytical results, and (4) run length [30].

5.1.1 General Good Programming Practice

In general simulation models are very big, requiring a modularly designed computer code (instead of "spaghetti" programming"). In the MS Excel file we distinguished a different sub module for each particular Arena module. These sub modules can be turned on and off very easily. Using these different models, the total computer code has been verified module by module.

5.1.2 Verification of Intermediate Simulation Output

During the building process of the model different intermediate simulation results have been compared with manually calculated results. In order to demonstrate what we did we provided an example in Appendix VII: Verification of Model Results, concerning a patient with an expected malignant overian tumour that will be treated once every week. It appeared all values were equal to the expected values. Since for all performance measures the same method was used, it seemed that the calculations of all performance measures were correct.

5.1.3 Comparing Final Simulation Outputs with Analytical Results

The final output of the stochastic simulation run will be obtained after a large number of runs and is impossible to verify by hand. Therefore a simplified version of the simulation is created with a known analytical solution. We developed two different models to make sure the stochastic simulation model would be correct: (1) a model similar to a product data model (PDM) based on theory of Markov decision processes (MDPs), and (2) a simulation model using deterministic durations. In Figure 23 the three methods have been illustrated in the three circles. The PDM has been described in detail in Appendix VIII: Product Data Model. When all mistakes were corrected from the deterministic simulation model by verifying it with the PDM, the deterministic durations were changed to stochastic durations.

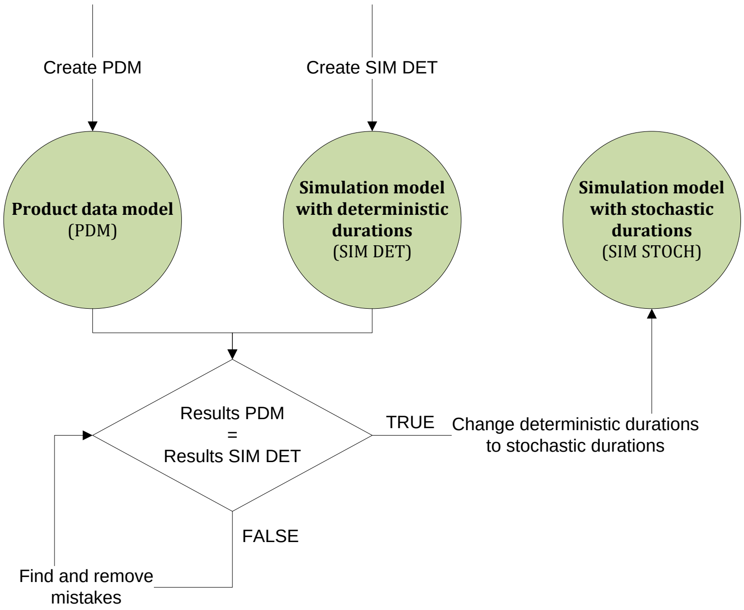


Figure 23: PDM, SIM DET en SIM STOCH

5.1.4 Run Length

Because one patient cannot only follow several different sequences for one particular surgery, the duration per process step within this sequence can also vary. As a result, the number of possible sequences combined with the duration of these sequences leads to a large number of scenarios. For an OCS tumour treatment this number is 6 864 320, to give an impression. If we would like to be have a 99 % probability that the longest possible duration would be included, we would need to let at least 45 568 130[1] patients flow through the system.

In Table 4 the results are provided of all the run length trials. The used computer was an IBM ThinkPad, Intel(R) Core™2 CPU, T7200 @ 2.00 GHz, 2.00 GB of RAM. When including 45 568 130 patients, Arena stopped at 921 minutes. When letting 11520723 patients flow through the system to have a 50 % probability of the longest duration included, Arena stopped after 932 minutes. Then we decided to use trial and error with 100 000 patients but this resulted in an MS Excel error. The same occurred for 5 000 patients. Excel did work for both 2 000 and 3 000 patients. When either using 2 000 or 3 000 runs, the 95% range, i.e. the duration interval in which 95% of the surgeries would fall, was equal 10 out of 10 trials, so a run length of 3 000 patients was considered adequate.

Table 3: Run length trials

Trial Number	Run time (min)	# patients per surgery type	Reason	Not chosen because:
1	Stopped at 921 minutes (>15 hrs)	45 568 130	99 % sure longest duration included	Stopped at 921 minutes (>15 hrs)
2	Stopped at 932 minutes (>15 hrs)	11520723	50 % sure longest duration included	Stopped at 932 minutes (>15 hrs)
3	97	10000	Trial and error	Excel error
6	7	1000	Trial and error	95 % interval might be more accurate/might change when including more patients and run time is acceptable
7	16	2000	Trial and error	95 % interval might be more accurate/might change when including more patients and run time is acceptable
7	31	3000	Trial and error	95 % interval is equal to run with 2000 patients 10 out of 10 uncorrelated runs.

[1] $1 - cumulativebinomialdistribution \;\; n, p, N \quad \geq 0.99$ where $n = 1, p = \frac{1}{6864320} => N = 45\,568\,130$

5.2 Validation

Once the simulation seems to be working correct we face the next question: is the conceptual simulation model (as opposed by the computer program) an accurate representation of the system under study? In order to determine this, we discuss: (1) obtaining real-world data, and (2) sensitivity analysis.

5.2.1 Obtaining Real-World Data

All process step durations found via the OKsimed database, literature or other hospitals were intensively discussed with several field experts. The largest deviation found from an average surgery duration estimation of an expert and the average duration found in OKsimed was 22 %. In all cases the OKsimed values have been used. Data ranges from January 2010 to December 2012 or June 2013 (earlier data was not available). This timeframe has been discussed with members of the MITeC project team and seems appropriate. Data has also been checked for trends, either increasing or decreasing durations over time, by using regression analysis and no significant trends in process step durations have been found.

5.2.2 Sensitivity Analysis

Sensitivity analysis can be described as the systematic investigation of the reaction of the model outputs to drastic changes in the model inputs and model structure. The objective is to determine which inputs are considered important. In our model many inputs could be changed. We decided to change the following inputs:

- Number of patients entering the system
- Cycle length of either one or two weeks
- Micro MRI available or not
- One or two in vivo microscopes available

The results of these scenarios are described in the next chapter. These scenarios and its results have been discussed with members of the MITeC project team and seem to represent the real world.

5.3 Chapter summary

In this chapter an explanation is given of how the model is verified and validated. The verification is done by using the following elements: (1) general good programming practice, (2) checking of intermediate simulation outputs through tracing, (3) comparing final simulation outputs with analytical results, and (4) run length [30]. Validation is done by describing: (1) how real world data is obtained and whether it reflects reality and (2) a sensitivity analysis by changing different input variables.

6 Results

This chapter presents the results of the Arena simulation model, extensively described in Appendix III: Arena Model. In accordance to the three sub questions, this chapter is divided in three sections. The first section (6.1) gives the results belonging to sub question 1, namely which personnel and equipment should be available at which locations at what times during each particular surgery. The second section (6.2) provides the results regarding sub question 2 and presents different scenarios for CSSs including only patients receiving a cancer treatment. The final section (6.3) describes scenarios for CSSs for patients receiving a cancer treatment or patients receiving a diagnostic MRI.

6.1 Personnel and Equipment Availability

In this section the results are given in accordance with the first sub question and should provide us an overview of every surgery type showing at what times during each particular surgery the resources or resource groups might be required. These figures are provided for every surgery type in Appendix IV: Probability that Resources are Busy or Idle. Between approximately 09:30 and 10:30 the OR can get really crowded in case of an OCS surgery. A surgery team (3 people), anaesthesia team (3 people), radiology team (2 people), and cell biologist (1 person) will be present in the OR all at the same time. The pathologist team (2 people) can work in a separate room but will also enter the OR a few times. This results in at least nine people working in the OR excluding any people in training.

Another result that can be extracted from these results is that each surgery starting at 08:00 will finish before 15:00 in at least 95 % of the cases. This indicates that overtime will only be an issue in less than 5 % of the cases.

The last aspect that can be retrieved is the estimated time of completing a surgery, since this estimated time will change during surgery. For example, in the process flow chart of a head/neck surgery in Appendix II: Process Flow Charts, it will become clear after approximately 110 minutes, whether the remaining nodes will be removed. If they will not be removed, the surgery will finish approximately three hours earlier than previously taken into account. This information can be used to initiate a surgery that was already scheduled and can start earlier or another surgery from another OR that seems to have less time available than scheduled.

6.2 Scenarios for CSSs Including Only Tumour surgeries

In this section only the scenarios are considered which include patients receiving a cancer treatment in compliance with the second sub question. Patients undergoing a diagnostic MRI will be included in a later section, i.e. section 6.3. The table with results from scenario 1 are given in this section. All other tables are provided in Appendix V: (Performance) Measures per Scenario.

6.2.1 Scenario 1 (one surgery per surgical group per week)

In Table 4 the results for scenario 1 are provided. In this table the performance measures are printed **Bold**. In the first part of the table the results regarding the patients have been given per SG. Forty patients are allocated in the CSS per SG per year. The number of patients that can be treated compared to the expected number of patients to arrive is 18%. This amount is rather low because only 46 % of the tumour surgeries can be allocated and none of the patients from radiology have been allocated.

The second part of the table provides the average utilization of the MITeC ORs, i.e. IORT OR, MRI OR, and HYB OR. The average utilization is 24 %, 7 %, and 0 %, respectively.

In the third part of the table the performance measures are provided that belong to the personnel types. Some unavoidable waiting time occurs for a number of personnel types (for example for the gynaecology surgery team). This waiting time is caused by the analysis of the adnex. During this process step the surgery team simply waits for the results of this analysis. No avoidable waiting time occurs. The average overtime in all cases is zero, which is expected since 95 % of all the included surgeries finish before 15:00.

This scenario can definitely be improved by allocating more patients in the CSS, because the overall OR utilization is low (only 10 %), not all expected patients have been allocated, and no overtime, patient waiting time, or avoidable personnel waiting time occurs in this scenario.

Table 4: SG-, OR-, and personnel results for scenario 1

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	40	60	0	**67%**	**0:00**
Gynaecology	40	70	0	**57%**	**0:00**
Urology	40	130	0	**31%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	120	660	0	**18%**	**0:00**

OR	**Utilization**
IORT OR	**24%**
MRI OR	**7%**
HYB OR	**0%**
TOTAL	**10%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		*31:47*		*31:22*		***0:25***		***0:00***
Surgery team	4:15	12:46	4:15	12:46	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	4:15	12:46	4:15	12:46	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	1:41	3:23	1:31	3:03	**0:10**	**0:20**	**0:00**	**0:00**
Radiology team	0:40	1:20	0:40	1:20	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:11	1:11	1:06	1:06	**0:04**	**0:04**	**0:00**	**0:00**
Pathology team2	0:09	0:19	0:09	0:19	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		*27:19*		*25:35*		***1:44***		***0:00***
Surgery team	3:39	10:58	3:09	9:27	**0:30**	**1:30**	**0:00**	**0:00**
Anaesthesia team	3:39	10:58	3:39	10:58	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:18	0:36	0:18	0:36	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:30	1:01	0:24	0:48	**0:06**	**0:13**	**0:00**	**0:00**
Cell biologist	1:34	1:34	1:34	1:34	**0:00**	**0:00**	**0:00**	**0:00**
Nucl. Med. physician	1:46	1:46	1:46	1:46	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:12	0:24	0:12	0:24	**0:00**	**0:00**	**0:00**	**0:00**
Urology		*22:43*		*22:34*		***0:08***		***0:00***
Surgery team	1:57	5:53	1:55	5:47	**0:01**	**0:05**	**0:00**	**0:00**
Anaesthesia team	3:10	9:30	3:10	9:30	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:27	0:54	0:27	0:54	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:21	0:43	0:20	0:40	**0:01**	**0:03**	**0:00**	**0:00**
Cell biologist	0:27	0:27	0:27	0:27	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	1:20	2:40	1:20	2:40	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	1:20	1:20	1:20	1:20	**0:00**	**0:00**	**0:00**	**0:00**
OK Assistant	1:12	1:12	1:12	1:12	**0:00**	**0:00**	**0:00**	**0:00**
Radiology		*0:00*		*0:00*		***0:00***		***0:00***
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		81:50		79:32		**2:18**		**0:00**

6.2.2 Scenario 2 (four IORT OR and/or MRI OR days)

Instead of 18% of the expected patients that were scheduled in scenario 1, 30% of the expected patients are scheduled in scenario 2, which is an improvement. In addition, utilization values of both the IORT OR and MRI OR have increased, respectively from 24% to 30% and from 7% to 16%. These increases of surgery rate and utilization were expected because simply more patients were allocated to the schedule in scenario 2 than in scenario 1. Similar to the previous scenario, no significant personnel overtime occurred.

Avoidable waiting time arises for urology personnel due to two MRI guided urology surgeries that are conducted sequentially. In case the first surgery ends earlier than 12:00, waiting time will occur for the required personnel. This is caused by the fact that the second surgery is scheduled to start at 12:00. In reality these waiting periods do not have to exist, since the personnel can choose to start the second surgery when the first one has finished.

6.2.3 Scenario 3 (five IORT OR and/or MRI OR days) – two options

For both scenario options in scenario 3, the surgery rate has increased with 5 % compared to the previous scenario and IORT OR utilization and MRI OR utilization have increased with 20 % and 4 %, respectively.
In scenario 3a no avoidable patient waiting time occurs, whereas in scenario 3b avoidable waiting time does occur, similar to the previous scenario.

6.2.4 Scenario 4 (five IORT OR and/or MRI OR days, cycle length is 2 weeks)

Compared to the previous scenario, the time blocks are more evenly distributed between the different SGs. The amount of spare places for urology has decreased from 30 to 10. IORT OR utilization also decreased with approximately 5 %. The amount of avoidable personnel waiting time is half of the waiting time in scenario 3b.

6.2.5 Scenario 5 (five IORT OR and/or MRI OR days, change in current OR days required)

In this scenario all expected patients receiving a cancer treatment can be treated and even some spare places are left for patients from gynaecology (ten places) and urology (ten places. IORT OR utilization increased from 45% to 49% compared to the previous scenario and MRI OR utilization is slightly higher than in the previous scenario. This is caused by the additional surgery of gynaecology once every two weeks. Avoidable waiting time occurs similar to scenarios 2 and 3b, caused by subsequent MRI guided surgeries. No avoidable waiting time during surgery or significant personnel overtime occurs which is in line with our expectations.

6.2.6 Scenario 6 (all tumour surgeries scheduled, proven ovarian (12:00) and OCS (08:00))

Similar to the previous scenario, all expected patients receiving cancer treatment are scheduled in this scenario. IORT OR utilization decreases slightly compared to the previous scenario and 5 % of the HYB OR is now utilized. Although starting at 11:30 caused an average patient waiting time of zero minutes, the maximum patient waiting time for a head/neck and gynaecology patient was about 4 hours and 25 minutes and 15 minutes, respectively. Furthermore, maximum overtime hours per week were about 5 hours and 3 hours, respectively. Both patient waiting time and overtime are caused by the in vivo microscope that was required at the same time.

When starting at 12:00 maximum patient waiting time turned out to be zero, and therefore average waiting time was zero as well. However, due to the limited amount of patients that run through the system, i.e. 3000, a large amount of patient waiting time might occur with a very small probability.

For the head/neck SG the maximum overtime was 12 minutes per week, with an average of 0 minutes. Personnel of the gynaecology department experienced a maximum overtime of 3 hours and 30 minutes, with an average overtime of 25 minutes per week.

6.2.7 Scenario 7 (all tumour treatments, expected ovarian (12:00 / 12:30) and OCS (08:00))

In this scenario all expected patients receiving cancer treatment are scheduled in as well and 5 % of the HYB OR is utilized. In case the proven or expected malignant overian tumour surgery starts at 12:00 (scenario 7a), the maximum patient waiting time is 4 minutes and the average patient waiting time is 0 minutes. Maximum overtime for head/neck personnel is 18 minutes and for gynaecology personnel is approximately 3 hours. When the proven or expected malignant overian tumour surgery starts at 12:30 (scenario 7b), the maximum and average patient waiting time are zero minutes, and head/neck and gynaecology maximum overtime are about 30 minutes and 3 hours and 30 minutes, respectively. Average overtime is zero for head/neck and 30 minutes for gynaecology.

Compared to the previous scenario, when starting the gynaecology surgery at 12:00, the maximum patient waiting time increases from zero to four minutes. Furthermore, the average overtime of head/neck personnel increases with 6 minutes. On the other hand, overtime for the gynaecology department decreases with approximately 30 minutes.

6.3 Scenarios for CSSs Including All Patient Types

In this section the results of four scenarios are presented. These scenarios included both patients receiving cancer treatment and patients receiving a diagnostic MRI, in compliance with sub question 3.

6.3.1 Scenario 8 (partly patients having a tumour and all diagnostic MRI patients)

In this scenario, ten gynaecology patients that should receive a cancer treatment are not scheduled. On the other hand, 100 % of the patients receiving a diagnostic MRI are scheduled, leading to an MRI OR utilization increase of 20% to 43%, compared to the previous two scenarios. On the other hand, HYB OR utilization is zero in this scenario where it was approximately 5 % in the previous two scenarios.

Some radiology personnel overtime occurs caused by the fact that the MRIs in a four-hour block can take longer than four hours. The average radiology personnel overtime is 13 minutes on average per week with a maximum of 90 minutes.

6.3.2 Scenario 9 (partly patients having a tumour and all diagnostic MRI patients including μMRI)

Similar to the previous scenario ten expected gynaecology patients are not scheduled. Radiology personnel overtime per week was reduced from an average of 13 to 4 minutes per week, since two four-hour radiology blocks are taking place in the morning instead of the afternoon as was the case in the previous scenario.

Because a table-top micro MRI is available, MRI OR utilization has decreased from 43% to 39%, since it is not used for tissue analysis anymore. All other performance measures are equal to the previous scenario.

6.3.3 Scenario 10 (partly patients having a tumour and all diagnostic MRI – only morning MRIs)

Since all diagnostic MRI blocks are taking place in the morning all overtime has been eliminated. The diagnostic MRIs are less properly distributed throughout the week compared to the previous scenario.

6.3.4 Scenario 11 (all patients including μMRI and two in vivo microscopes)

All expected patients including both patients receiving cancer treatment and patients receiving a diagnostic MRI can now be treated. No overtime or patient waiting time is present. IORT OR-, MRI OR-, and HYB OR utilization are 45%, 39%, and 5%, respectively.

6.4 Overall Results

In section 6.2 and 6.3 of this chapter, different scenarios were developed in discussion with employees of the RUNMC to provide a general overview of what is possible with the decision support system and to provide insight in different options. The scenarios are listed below:

Only tumour surgeries

- Scenario 1 (one surgery per surgical group per week)
- Scenario 2 (four IORT OR and/or MRI OR days)
- Scenario 3 (five IORT OR and/or MRI OR days) – two options
    - 3a: two head/neck surgeries per week
    - 3b: two gynaecology surgeries per week
- Scenario 4 (five IORT OR and/or MRI OR days, cycle length is 2 weeks)
- Scenario 5 (five IORT OR and/or MRI OR days, change in current OR days required)
- Scenario 6 (all tumour surgeries scheduled, proven ovarian (12:00) and OCS (08:00))
- Scenario 7 (all tumour treatments, expected ovarian (12:00 / 12:30) and OCS (08:00))
    - 7a: expected ovarian surgery starts at 12:00
    - 7b: expected ovarian surgery starts at 12:30

Both tumour surgeries and diagnostic MRIs

- Scenario 8 (partly patients having a tumour and all diagnostic MRI patients)
- Scenario 9 (partly patients having a tumour and all diagnostic MRI patients including μMRI)
- Scenario 10 (partly patients having a tumour and all diagnostic MRI – only morning MRIs)
- Scenario 11 (all patients including μMRI and two in vivo microscopes)

In Figure 24 to Figure 27 overviews for each scenario are provided of the most important performance measures.

1. Patient waiting time during surgery
No significant patient waiting time occurs during any of the scenarios.

2. Patient surgery rate
In Figure 24 (left) the contribution per SG to the surgery rate is provided for all tumour surgeries. In scenario 1 to 4, 8, 9, and 10 not all expected patients to receive a cancer treatment were. Only in scenario 11 all expected patients including patients receiving a diagnostic MRI were scheduled as shown in Figure 24 (right).

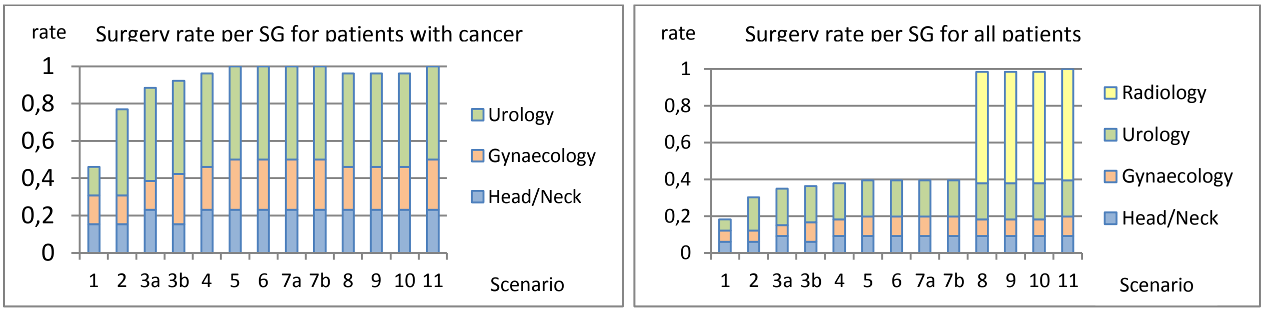


Figure 24: Surgery rate per SG for each scenario

3. Personnel overtime
In Figure 25 the average personnel overtime hours per SG per week are depicted. In each scenario a very small probability of overtime for the head/neck personnel and urology personnel occurs. Scenarios 6 and 7 led to a significant average amount of overtime hours for the gynaecology SG, caused by gynaecology surgeries starting at 12:00 and 12:30. Scenario 8 and scenario 9 have led to some overtime as well. In scenario 8, three four-hour diagnostic MRI blocks were scheduled in the afternoon, causing overtime. In scenario 9 only one four-hour block from radiology took place in the afternoon which resulted in less overtime than in scenario 8.

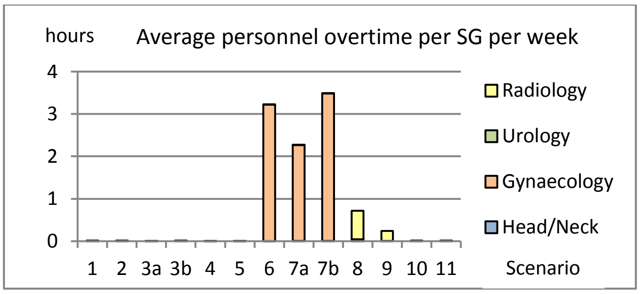
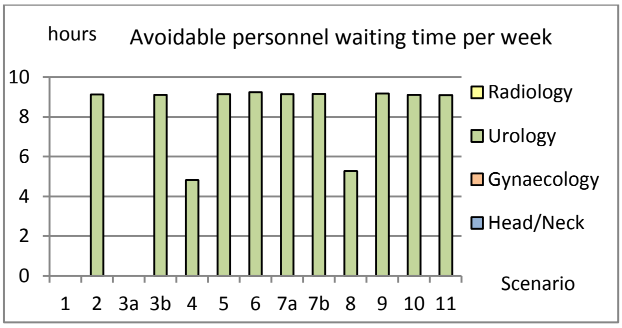


Figure 25: Average personnel overtime per SG per week for each scenario

4. Personnel waiting time during surgery

No avoidable personnel waiting time during surgery takes place in any of the scenarios, similar to the patient waiting time during surgery. Avoidable personnel waiting time between surgeries occurs in almost each scenario (except for scenario 1 and 3a) as can be extracted from Figure 26 (left). In scenarios 2, 3b, 5, 6, 7a, 7b, 9, 10, and 11 this waiting time between surgeries is caused by the two sequential MRI guided surgeries of urology that are taking place every week. In scenario 4 an 8 this only occurs once every two weeks, so the waiting between surgeries is halved in this case. This waiting time can easily be reduced by starting the second surgery of the day immediately or when the clean-up of the OR has finished after the first surgery of the day.

For every SG in each scenario unavoidable personnel waiting time occurs as illustrated in Figure 26 (right) for gynaecology the amount of unavoidable waiting time is the highest in each scenario, caused by an MRI taking place during this process.



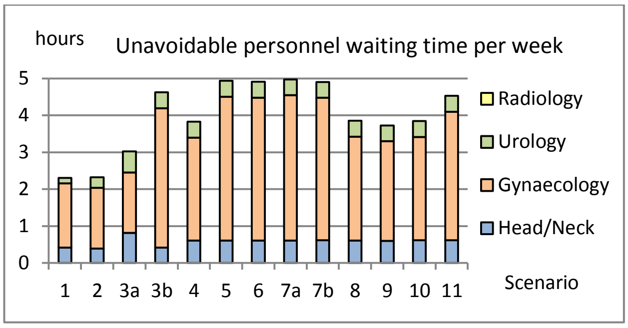


Figure 26: Average personnel waiting time per SG per week for each scenario

5. OR utilization

As illustrated in Figure 27, OR utilization is lowest for scenario 1 and scenario 2, i.e. 10 % and 15 %, respectively. This is caused by the fact that the surgery rate is low in these scenarios. The highest utilization is achieved for scenario 11, i.e. 30 %, when all patients receiving a diagnostic MRI are allocated in addition to all tumour surgeries. In this case an average of ten patients each week is treated.

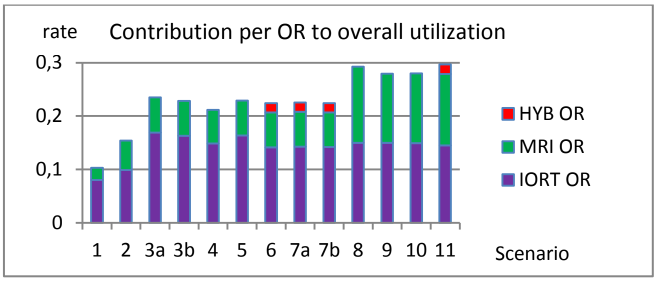


Figure 27: Contribution per OR to overall utilization for each scenario

6.5 Chapter Summary

In section 6.1 of this chapter the results were described in accordance with the first sub question and showed us that the OR can get really crowded during some surgery periods. Another result that could be extracted was that all included surgeries in this research will finish before 16:00 in 95 % of the cases, indicating overtime will only be an issue in less than 5 % of the cases. Furthermore, information retrieved during surgery can be used to provide information that can be helpful for planning subsequent surgeries.

In section 6.2 we have proposed numerous schedules to allocate the expected patients that would receive a cancer treatment. It appeared that if no adjustments will be made to the current OR days or to the available equipment (in this case an in vivo microscope), approximately ten patients cannot be treated without resulting in patient waiting time, avoidable personnel waiting time during surgery, or overtime.

In section 6.3 we have added patients receiving a diagnostic MRI in addition to the patients receiving a tumour surgery to the schedule. The only option to treat all patients without generating patient waiting time, avoidable personnel waiting time during surgery, or overtime would require the acquisition of a table-top micro MRI. In addition, similar to section 6.2 either the current OR days should be adjusted or additional equipment should be purchased.

7 Overall Conclusion

In this chapter the overall conclusion for this research is provided. The first section (7.1) describes the contribution of this research to science and society, and the second section (7.2) provides an answer to the questions raised by the RUNMC, i.e. the research question and its associated sub questions. In the final section (7.3) some model limitations are discussed.

7.1 Contribution to Science and Society

Throughout the literature, this topic has received quite some attention as described in Chapter 3. However, in this model some unique elements are included, that have not been used in any CSS development model thus far throughout the literature. This research has provided a simulation model for operating room scheduling that can be used in similar hospitals.

The possibility of multiple steps and multiple sequences for one particular surgery has not been included in any of the models that have been used to allocate surgeries in the existing literature. A number of properties are associated with the fact that one surgery can consist of multiple steps and sequences: (1) Several resources are only required during a certain part of the surgery. Throughout the literature it was assumed all resources would be required during the complete surgery. (2) A possibility exists to relocate a patient from one OR to another within the same surgery. Thus far, all authors assumed a patient would be treated in a single OR. (3) Patient waiting time during surgery might occur whereas all authors so far only considered patient waiting time before surgery. Patient waiting time during surgery might increase the risk of complications, ranging from fever to pneumonia and heart attack, whereas patient waiting time before surgery might increase the anxiety and stress of patients. (4) Personnel waiting time during surgery might now occur since multiple process steps are involved requiring different resources. This performance measure has not been considered thus far either, even though waiting can be annoying, frustrating and therefore it might reduce personnel satisfaction levels. In addition, personnel waiting time is costly if these resources cannot perform other required activities during their waiting time.

Including the aforementioned elements in the model provides a unique model including the following elements: (1) duration uncertainty, (2) multiple possible sequences per surgery, (3) resources that are only required during a part of the surgery, (4) relocations of patients from one OR to another, and (5) the five performance measures included in this research. Since many elements are covered in this model, it might become a useful tool for other hospitals to develop an OR schedule (cyclic or non-cyclic). Not only surgeries can be scheduled with this model but other production processes as well.

7.2 Contribution to the RUNMC

In this research a Decision Support System has been developed in Arena, providing a multi-objective simulation model with stochastic durations. This model was developed to answer the three sub questions and research question raised by the RUNMC. This question was raised since an entire new project will start in the RUNMC resulting in (1) an increase in treatment duration uncertainty, (2) an increase in the amount and diversity of required resources during treatment, (3) a change in average treatment duration, and (4) a possible relocation of a patient under anaesthetics from one RO to another. In this section the proposed questions will be answered.

Sub question 1:
Which personnel and equipment should be available at which locations at what times during each particular surgery?

In order to provide answer this sub question we provided an overview of every surgery type including at what times during this surgery the resources or resource groups might have to be available. From these overviews one can extract the specific duration intervals in which a resource might be required and with what probability. Some periods during a surgery will lead to a very crowded OR with nine people in the OR (excluding any personnel members in training).

Sub question 2:
How to optimize the utilization of the MITeC ORs and their accompanying personnel and equipment for the three tumour surgeries under study?

This question was answered by developing different scenarios for a CSS. The most optimal schedule according to the performance measures, in which all patients having an expected malignant ovarian tumour could be treated in the IORT OR without additional equipment purchase costs, was scenario 5. This scenario would require a deviation from the current SG OR days. It included all patients having a tumour, leading to the optimal surgery rate and a high OR utilization. In addition, no patient waiting time, avoidable personnel waiting time, or personnel overtime occurred. Furthermore, the HYB OR is not required, as is desired.

If the OR days could not be adjusted and a similar surgery rate is desired, it is required to buy two in vivo microscopes instead of one and implement the CSS of scenario 6 to avoid patient waiting time, avoidable personnel waiting time, or overtime. In this scenario the HYB OR is required (which is not desired) with a utilization of 5 %, because two surgeries are executed simultaneously in the IORT OR and the HYB OR.

If neither the OR days can be changed or two in vivo microscopes can be purchased, either ten expected gynaecology patients cannot be allocated to the schedule or patient waiting time, personnel waiting time, and overtime would occur. In case the gynaecology will not be allocated, scenario 4 would seem the most appropriate scenario in this case. Obviously, the surgery rate is a little less good than in the previous two scenarios. In this scenario the surgeries are allocated as equally as possible between the different SGs. This CSS has a cycle length of two weeks in which the head/neck SG conducts two surgeries in the first week of the cycle and one surgery in the second week. The gynaecology SG conducts one surgery in the first week and two in the second week.

In conclusion, with the current requirements it is not possible to treat all patients having an expected malignant ovarian tumour without creating patient waiting time, avoidable personnel waiting time, or personnel overtime. Either the OR days have to be adjusted or new equipment has to be purchased. If this is not possible, ten patients of gynaecology will not receive treatment according to the new surgery processes.

Sub question 3:

How to improve the utilization of the MRI OR and its accompanying personnel and equipment by scheduling patients that will receive a diagnostic MRI in the spare time of this OR?

With the current requirements it is not possible to treat all patients without creating personnel overtime, patient waiting time, personnel waiting time, and respect the desire of the radiology SG to perform MRIs in four-hour blocks. Four-hour blocks allocated to radiology in the afternoon (from 12:00 onwards), will lead to personnel overtime.

The only situation in which no patient waiting time, personnel waiting time, or overtime will occur and all patients can be treated is when a tabletop micro MRI will be purchased and all four hour blocks of radiology will be scheduled in the morning. A major advantage of purchasing a micro MRI is the increase in scheduling flexibility, since the MRI OR will be less occupied for only short periods of time often in the middle of the day. On the other hand, this purchase will cost money. In addition to buying a micro MRI, either the OR days should be adjusted of either head/neck or gynaecology or two instead of one in vivo microscope should be acquired. Compared to a surgery schedule including only tumour surgeries, MRI OR utilization increased with 19 to 24 %.

RESEARCH QUESTION

Which personnel and what equipment should be available in which ORs and at what times to utilize the MITeC ORs in an optimal manner?

Since the project is entirely new scenario 2 seems the most suitable scenario to start this project with. In this scenario four to five surgeries can be executed per week in the IORT OR and MRI OR. Two full IORT OR days will not be occupied. The acquisition of a table-top micro MRI or in vivo microscope is not required for executing this scenario, so this can be postponed. During the allocated surgery days the SGs should decide which surgeries to perform as long as this is in line with the requirements of the OR management. The SGs have one full week for each surgery to review it and make adjustments when required. If the surgeries run smoothly more surgeries can be added to the CSS, but in the meantime the unutilized OR time should be used for training purposes, research purposes or other surgeries whenever possible.

In light of the future developments of the RUNMC, with respect to filling the MRI OR with surgeries as much as possible, scenarios 10 or 11 seem to be the most appropriate scenarios in the longer term when all surgeries run well. Both scenarios need the acquisition of a table-top micro MRI. Not acquiring this micro MRI leads to a complicated planning because MRI OR interruptions will occur generally between 09:00 and 13:00 for tissue analysis if no table-top micro MRI is available. This seems undesirable if more surgeries should be allocated in the near future to the MRI OR.

The difference between scenario 10 and 11 is that in scenario 10 not all expected patients can be and only one in vivo microscope is available. For scenario 11 it is assumed two in vivo microscopes are available and in this case all

expected patients can be treated. Scenario 11 seems the most favorable scenario, because all expected patients can be treated and even a few spare places are left. However, we do not have any knowledge about the costs involved with purchasing an extra in vivo microscope. They might be too high in the eyes of the RUNMC management and by all means the benefits must outweigh the costs.
For every surgery in the chosen CSS the periods that the different resource types are required can be extracted from Appendix IV: So, the combination of the CSS together with the overviews of which personnel and equipment should be available at which locations at what times during each particular surgery provides an answer to the research question.

7.3 Limitations

To the best of our knowledge we have been the first to develop a model including the following elements: (1) multiple possible sequences per surgery, (2) resources that are only required during a part of the surgery, (3) relocations of patients from one OR to another, (4) patient waiting time during surgery as performance measure, and (5) personnel waiting time as performance measure. Although this model covers many aspects and can definitely become a useful tool for similar hospitals to develop an OR schedule (cyclic or non-cyclic), some potential limitations should be discussed.

- **Costs**
  Even though we believe costs are an important performance measure for decision making, we did not include any costs in the model. However, currently a project is taking place to include the costs in the developed model. In addition, some effects on finances can be retrieved from the current model even though no exact numbers are included. For example, in case additional equipment is required to treat some patients it is obvious this will cost more money than when no additional equipment is required.

- **Patient waiting time before surgery**
  One performance measure often used throughout literature but not included in this research is the patient waiting time before surgery, starting from the moment a patient is placed on the surgery waiting list until the surgery takes place. However, since more capacity is made available for the same amount of patients, we do not expect patient waiting time before surgery to increase in the foreseen future. In addition, patients that cannot be treated according to the new processes will be treated in other ORs of the RUNMC. To include this performance measure, these other ORs should be considered in the model as well, resulting in a very complicated task to include this waiting time.

- **Processes before surgery and after surgery not included**
  Processes before and after surgery must be streamlined to ensure a proper treatment execution. Although the prior and sub sequent surgeries are not included in the model, this does not mean processes cannot be streamlined. The RUNMC is currently cooperating with the Radboud University Centre for Oncology (RUCO) to align the processes involving the patient. They are currently working on the coordination and alignment of care with all the professionals involved and are continuously improving the cancer treatment processes. The developed model can be helpful in streamlining the processes since it provides the days in which particular surgeries will take place and an estimation of the start and end time of each surgery.

- **Missing data for process or process step durations**
  Since many process steps and even some entire surgery processes are new, for some of them no data or only a few data points have been found. The durations of these processes or process steps have been based on expert estimations which are less reliable than an estimation based on both data and expert estimations. However, from the data that has been found it appeared expert estimations were surprisingly reliable. The largest deviation found was 22 %.

- **Model has not been tested**
  The developed cyclic schedules have not been tested in practice, so it is not clear whether they are similar to reality or not. Though, the results have been discussed with numerous involved personnel members and all results seemed to match their expectations.

7.4 Chapter summary

In this chapter the overall conclusion has been provided that could be drawn from the results. It appears that the developed model has not been developed in the literature, due to a number of unique elements. This model can be used for similar hospitals or other processes as well.

To provide an answer to the research questions, it appeared that with the current requirements it is not possible to treat all patients without creating personnel overtime, patient waiting time, avoidable personnel waiting time. The only situation in which no patient waiting time, avoidable personnel waiting time, or overtime will occur and all patients can be treated is when a tabletop micro MRI will be purchased and all four hour blocks of radiology will be scheduled in the morning. In addition to buying a micro MRI, either the OR days should be adjusted of either head/neck or gynaecology or two instead of one in vivo microscope should be acquired. If this will not be done, ten gynaecology patients cannot be treated.

8 Recommendations

In this chapter recommendations are provided for implementing and using the developed model in section 8.1. In section 8.1.1 recommendations are given for future model improvements.

8.1 Recommendations for implementation

The implementation of a project can be described using different phases. In the traditional approach, five developmental components of a project can be distinguished: (1) initiation, (2) planning and design, (3) executing, (4), monitoring and controlling, and (5) closing [31]. These different phases will be used to describe the steps that are recommended to be taken when implementing a new CSS.

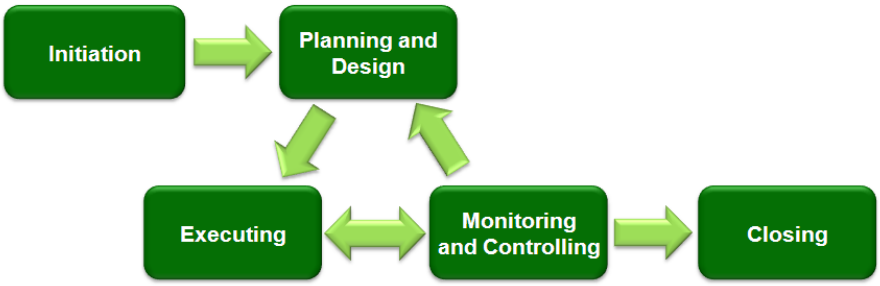


Figure 28: Five project phases [31]

8.1.1 Initiation phase

The initiation phase is a mixture of selling the idea, establishing business value, brainstorming possible approaches, forming the team, and getting everyone on board and excited about what they are about to undertake. Team building is an important part of this phase. For the included surgery types this phase has been (partly) completed.

8.1.2 Planning and design

At the moment of writing this thesis the project is in the planning and design phase and we should identify the following:

- The activities required to produce and deliver the outputs,
- The resources required
- The time required

All three aspects are present in a CSS. Whenever new surgeries will be implemented, the number of expected patients arriving increases, the process step durations change significantly, or fixed surgery days change, the CSS should be updated. Every time the CSS is adjusted the following steps should be executed:

1. Develop process flow chart for each surgery type

Before a CSS can be developed one must make sure all the different surgery types that will be included in this schedule are defined. For each surgery type a process flow should be developed including: (1) room in which the process step takes place, (2) required resources or resource teams to execute the step, and (3) duration of the process step. In Appendix II: Process Flow Charts several process flow charts have been provided that can serve as an example. It is useful to register the source(s) that are used to gather all previous information for verification purposes. Use a combination of both expert knowledge and historical data for the process step durations, since historical data is available but seems unreliable at some points, whereas expert estimations might be incorrect as well. Developing process flow charts might require one to two months, which should be taken into account. However, without an appropriate process flow chart the simulation model cannot be used.

2. Physically simulate crowded ORs

For each surgery type considered in this research the probabilities that a resource is busy or idle during a certain surgery have been provided in Appendix IV: From these probabilities the crowded OR periods can be extracted for this particular surgery type. It will be useful to physically simulate these surgery moments for each included surgery type to check whether conducting the surgery is physically possible in the specific OR(s). If it is physically impossible to execute a surgery, it might be required to either change or exclude the surgery from the CSS.

3. Systematically develop a CSS

If all the process flow charts of the surgery types are included and the physically impossible surgeries are excluded, a CSS can be developed. It will be helpful to find a systematic way to allocate the surgeries. For example, in this research we started with one surgery per specialism per week with the logical reason that surgeries should be divided as evenly as possible between different specialisms. Consider different scenarios before a definite CSS will be implemented. Every scenario will lead to different results, not only regarding the five performance measures used in this research, but regarding many other performance measures as well, such as patient and personnel satisfaction, patient waiting time before surgery, etcetera. These different scenarios can be used to explain why a certain CSS has been selected above all others. In addition, considering multiple scenarios provides more insight in the CSS and its possibilities than considering one or a few scenarios. When updating the CSS it is beneficial to use the current CSS as reference point, since deviation from the previous CSS is to be minimized to reduce organizational effort related to a CSS update. Use the developed DSS from this research to determine what influence an updated CSS has on different performance measures and whether it is feasible to change the CSS.

4. Discuss possible changes that lead to cyclic surgery schedule improvement with involved personnel

Once it has been decided which CSS seems the most appropriate one, discuss this schedule with the most important involved personnel that will have to work with this schedule. Some additional requirements or desires might become apparent, leading to a revision of the proposed CSS. Before implementation one has to increase the likelihood that it will work in reality as much as possible.

In addition, it might be of interest for the RUNMC as a whole to discuss possible changes in the current practice that lead to CSS improvement with involved actors. For example, for the developed scenarios it seems most optimal to treat all patients having an expected malignant ovarian tumour if either gynaecology or head/neck could conduct one surgery on Tuesday or Thursday per two weeks. The second best scenario can be used to demonstrate and talk about what would be the alternative if they would not be willing to implement this change. For example we have seen that when either the head/neck SG or the gynaecology SG can perform one surgery once every two weeks on Tuesday or Thursday (Scenario 5) this might avoid either purchasing an extra in vivo microscope, treating less patients, or patient waiting time and overtime. Demonstrating and explaining what will occur if no adjustments in the current practice are made, might help in the understanding and willingness to change of personnel members.

5. Make sure resources are sufficient

Before the project starts the amount and expertise of included resources should be sufficient. From the different developed scenarios for CSSs the amount of these resources can be extracted.

According to the included scenarios thus far it is interesting to look at the purchase of a micro MRI and two in vivo microscopes instead of one in order to: (1) increase the flexibility of the current planning, (2) increase the number of patients that can be treated, (3) increase OR utilization, and (4) decrease patient waiting time and personnel overtime.

In addition to equipment acquisition, extra required hours of personnel, such as pathologists or OR assistants, can be extracted partly from the resulting performance measures in Appendix V: (Performance) Measures per Scenario. One should have a look into these hours to investigate whether the current staff is sufficient to treat all the patients according to the CSS that will be implemented. Furthermore, they should have the appropriate expertise to treat the patients. Training is very important, not only for patient treatment, but also for personnel's safety. For example, in the presented scenario's, some OR assistants might be dealing with radiology in the nearby future, whereas in the past they didn't.

8.1.3 Execution

As illustrated in Figure 28 a project will go through phase "planning and design", "executing", and "monitoring and controlling" multiple times. Since the project considered in this research has many unique and new characteristics, it will be useful to start with a few surgeries at the beginning and expand them if the surgeries are executed properly as explained in the previous section. Some information that becomes available during surgery can be useful for the OR planning for the rest of the day as described below.

1. Recommended scenario to start the MITeC project

We would recommend starting with the surgeries as proposed in scenario 2, in which five surgeries can be executed per week. This does not require the acquisition of a table-top micro MRI or in vivo microscope. In this scenario, both the head/neck and gynaecology SG can execute one surgery per week on Monday and on Wednesday, respectively. The urology SG can perform surgery on two different days during the week other than Monday or Wednesday. One day can be used to perform one or two MRI guided surgeries and one day for non-MRI guided surgeries. Since the expected number of patients for the urology SG is approximately twice as high as for the head/neck and gynaecology SGs it makes sense to allocate more surgeries to urology than to the other two SGs. In addition, the surgeries differ significantly in their resource requirements because the MRI guided surgeries only require the MRI room for their surgery and the non-MRI guided surgeries require the IORT OR and possibly the MRI OR if no MRI table top is available. During the allocated surgery days the SGs should decide which surgeries to perform as long as this is in line with the requirements of the OR management. The non-allocated OR days can be used for different purposes, such as diagnostic MRIs, research or additional surgeries from the regular OR program. If the surgeries are executed smoothly, which can be evaluated by monitoring and controlling the surgery processes, additional surgeries can be added to the OR schedule in the next planning and design phase.

2. Use information during surgery executions

Information gathered during surgery can be helpful in order to let specific personnel know they are not required anymore or to start initiating a subsequent surgery on the very same day. A subsequent surgery can be a surgery that was already scheduled as a subsequent surgery or another surgery from another OR that seems to have less time available than planned. An example of useful information retrieved during surgery occurs during the execution of an OCS tumour surgery. During this particular surgery an analysis result will become available after the pathologist has analysed tissue. These results will be used to determine whether remaining lymph nodes will be removed or not. Removing lymph nodes takes approximately three hours, so the surgery is expected to finish three hours earlier than the duration that was taken into account previous to the new information. Sufficient communication about surgery progress during surgeries might result in more patients that can be treated and less overtime.

8.1.4 Monitoring and controlling

With the proposed CSS from scenario 2, for each surgery type a full working week is available to monitor, control, and discuss the progress of the surgery and adjust it accordingly in the next planning and design phase. In addition, during this first trial one might determine the used equipment does not work properly or is not required at all, which might save money or lead to a different equipment supplier for the next planning and design step. Gathering the data as described in this section will be useful to further improve the processes.

1. **Register every change in resource combination during surgery**
   Register every occasion when the combination of required resources for a surgery changes. By registering these time stamps, a valuable database will be developed that can be used to predict the periods of time in which these resources should be available. Currently these durations are estimated with the help of the OKsimed database, literature, involved personnel members, and other hospitals but since the processes are entirely new these durations might differ. In addition, learning curves might be involved causing durations to change over time. When registering these durations it is possible to keep track of involved learning curves. Registration can be done by implementing a swipe card required to enter the OR or MRI OR, which registers the resource type.

2. **Monitor patient waiting time before surgery**
   As mentioned earlier, keep in mind the waiting time before surgery. Reducing the throughput time from only a part of the process, does not mean the entire process takes a shorter period of time. If expected patient numbers grow and the CSS for the new processes remains the same, waiting lists before surgery might increase. Monitor the patient waiting time before surgery to make sure the total throughput time (from being placed on the waiting list until the first external therapy) does not increase.

If the surgeries from the start scenario are executed adequately after a certain learning period, additional surgeries can be added to the CSS as done in the different scenarios described in this research. Adding surgeries might lead to choices that have to be made about the amount and types of patients to treat, the acquisition of personnel and material, etcetera. Therefore it is important to start thinking about the next project phase early enough to account for all required changes in activities, time, and resources.

8.1.5 Closing

The closing phase is the phase in which the project is completed and all deliverables are met. In this case this might be when all expected patients for the new treatments can be treated and all participants are familiar with the processes.

8.2 Recommendations for Future Model Improvements

In section 7.3 the limitations of this model have been described. In this section, some recommendations for future model improvements will be given responding to these limitations.

1. Describe and streamline OR processes of prior and subsequent departments

Performing surgery is not the start and the end of a full treatment process. Before patients enter the OR and after patients leave the OR, many activities are taking place. Some of these activities are different from the current processes and could be added to the currently developed model. Describing and streamlining the concurrent processes will most probably lead to less errors and as a result less case cancelations. The development of an OR schedule can be a first step to align these processes.

2. Include cost analysis

Because costs are becoming a major issue, especially during the current crisis, including a cost analysis in the model would be helpful. This model can be used to justify why it is useful to purchase or lease equipment or hire personnel for an optimal CSS.

3. Emergency patients

In case there is spare time in the HYB OR, emergency patients will be treated in this OR in the future. Including these patients in the model will provide a more realistic view of the HYB OR utilization than only including the elective patients. It might provide an insight in the additional capacity in the other ORs in which the emergency patients are currently treated.

4. Include patient waiting time before surgery as a performance measure

As described previously, the future waiting time before surgery should not exceed the current waiting time before surgery. When the number of expected patients increases and the RUNMC runs out of capacity to treat these patients it might be useful to include the patient waiting time before surgery in the model as well, even though it is quite complicated.

8.3 Chapter summary

In this chapter recommendations have been provided to implement and execute the developed model with the focus on the planning, design, execution, monitor and control parts. We would recommend starting with the surgery schedule as proposed in scenario 2, in which five surgeries are scheduled per week. If the surgeries are executed well, which can be evaluated by monitoring and controlling the surgery processes, additional surgeries can be added to the surgery schedule in the next scheduling phase. Before a new surgery schedule can be implemented in reality, a number of steps have to be executed which are described in this chapter. In addition, some future model improvements have been described.

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Appendix I: Recent Healthcare Technology Developments

Micro MRI technology
Micro MRI technology is complementary to the in vivo microscopy technology, requiring a micro MRI a radiology team and a pathology team to analyse the tumour when it is removed from the body. This device helps to visualize the edges of the tumour and when the edges contain malignant tissue, the surgeon can decide to remove more malignant tissue. This technique is faster than the previous technique, allowing the surgeon to verify whether he removed the whole tumour during surgery instead of one or two weeks after surgery. The major advantage of this faster technology and the combination with the in vivo microscopy technology is that it will most probably result in less re-surgeries, due to the improved insights during surgery leading to a better final surgery result.

In vivo microscopy technology
In vivo microscopy technologies enable physicians and a pathology team to visualize tissue through innovative tomographic methods using a microscope. This results in more accurate targeting of biopsies and decreases the need for frozen section confirmation that a lesion has been properly sampled. On top of that the surgeon or cellular biologist can accurately search for fluorescent markers inside the patient after primary tumour removal to determine whether he removed the whole tumour. This allows the surgeon to continue surgery until he is certain the primary tumour is completely removed or until the risk of losing important bodily functions is too high.

Sentinel lymph node procedure
A sentinel lymph node procedure consists of the removal of the sentinel lymph node (SLN) under anaesthesia, and an analysis of this SLN by a pathology team for cancer staging. A negative SLN result suggests that cancer has not developed the ability to spread to nearby lymph nodes or other organs whereas a positive SLN result indicates that cancer is present in the sentinel lymph node and may be present in other nearby lymph nodes or organs. One of the major advantages of the SLN biopsy is that it decreases the amount of unrequired lymph node dissections, thereby reducing the risk of lymphedema, a common complication of this procedure [32] [33] [34] [35] [36] [37]. A major drawback of the SLNB is that it can lead to a false negative result, meaning there may still be cancerous cells in the lymph node basin, which might progress to a palpable nodal disease.

Intra-operative Brachy therapy
Intra-operative Brachy therapy (IOBT), conducted by a radiotherapist and an MRI team, is a form of radiotherapy where a radiation source is placed inside or next to the area requiring surgery. A key feature of IOBT is that the irradiation only affects a very localized area around the radiation sources and has cancer cure rates comparable to surgery or external beam radiation therapy, or are improved when used in combination with these techniques [38] [39] [40] [41] [42] [43]. One of the major advantages of IOBT over other radiation techniques is that it can be completed in less time and requires fewer patient visits to the radiotherapy department.

MRI applications
Three new methods can be conducted in the MRI OR. The first method is an MRI guided surgery in which the MRI “guides” the operator or surgeon in the right direction. It can be used for ultra-sound, laser, or freezing applications for example. The second method is to make an MRI during surgery for cancer staging purposes. In the previous situation an MRI could only be made before or after surgery. In some cases this means the patient has to be moved from an OR to the MRI OR and possibly back. The third method is to make an MRI image under general anaesthesia, instead of without general anaesthesia. This is especially useful for children or patients with the Down syndrome.

Appendix II: Process Flow Charts

In this appendix all process flow charts from the different surgery types as described in Table 5 are provided in Figure 30 to Figure 38. Figure 29 gives an explanation of the modelling symbols.

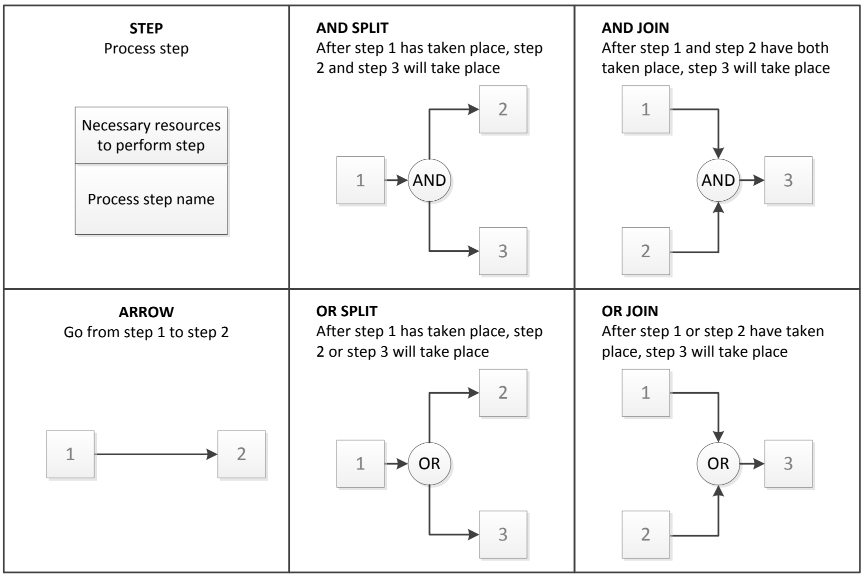


Figure 29: Explanation of modeling symbols

Table 5: Expected number of patients per surgery type

Surgery types per SG	# Expected patients	% surgery type within SG
HEAD/NECK	**60**	
- Oral cavity squamous (OCS)	60	100%
GYNAECOLOGY	**70**	
- Expected malignant overian tumour	21	30%
- Proven malignant overian tumour	49	70%
UROLOGY	**130**	
- Open prostatectomy to treat prostate tumour	30	23%
- Robot prostatectomy to treat prostate tumour	30	23%
- Laser to treat prostate tumour	20	15%
- HIFU to treat prostate tumour	10	8%
- CRYO to treat recurrent prostate tumour	40	31%
RADIOLOGY	**400**	
- Diagnostic MRI	400	100%

Oral cavity squamous tumour (OCS) – head/neck

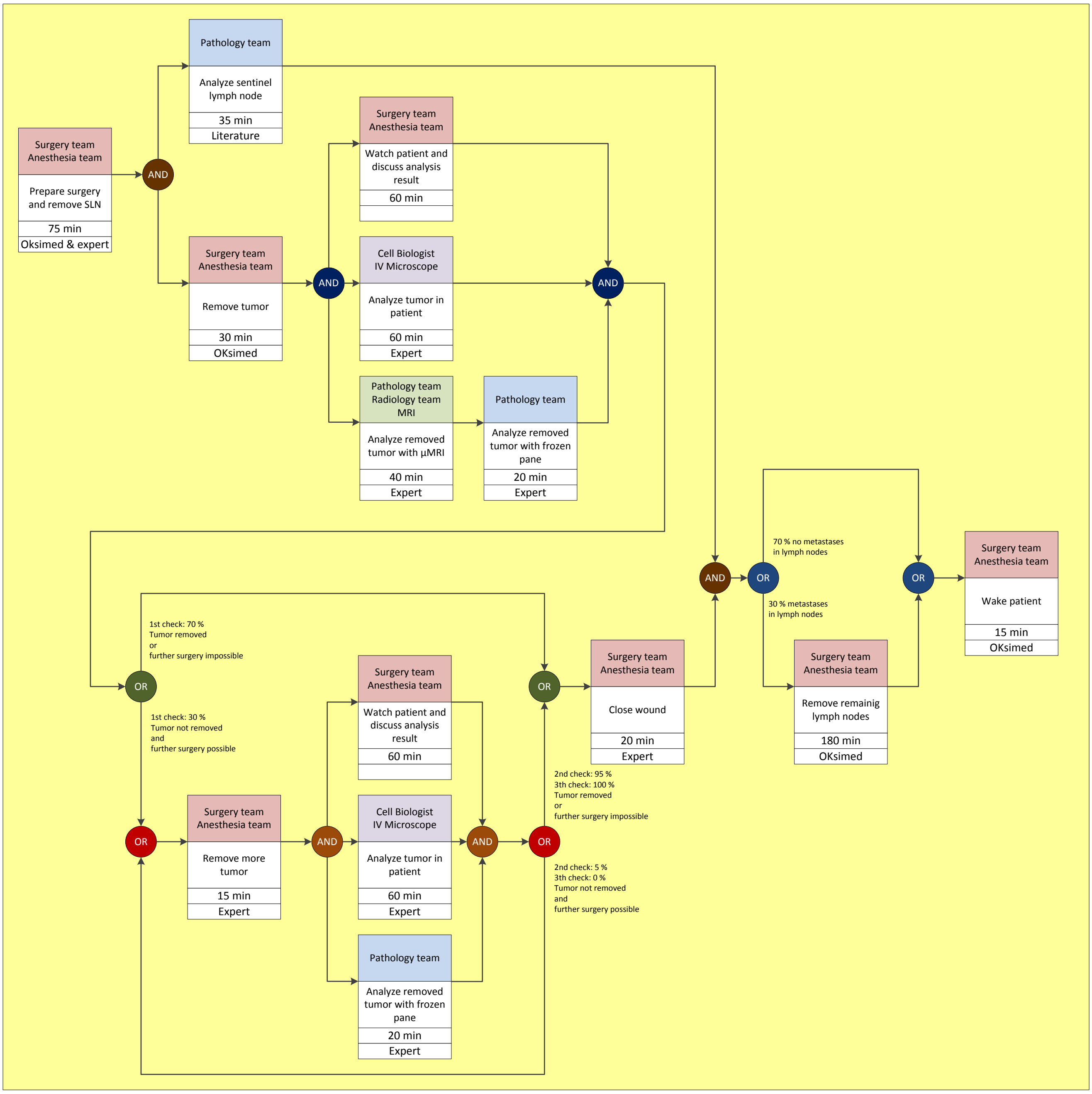


Figure 30: Process flow chart – OCS tumour

Malignant overian tumour - gynaecology

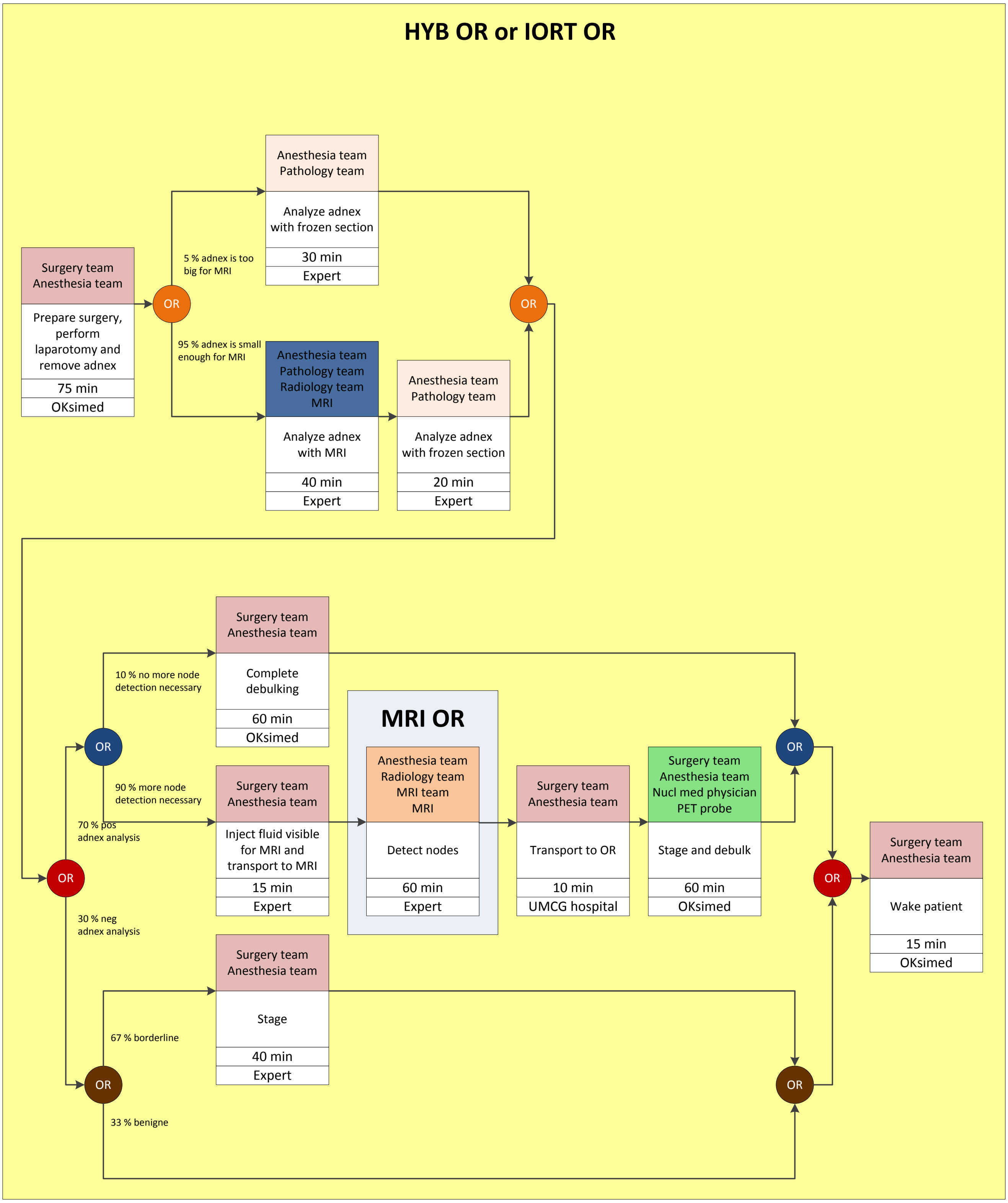


Figure 31: Process flow chart - Gynaecology - Expected malignant overian tumour

Malignant overian tumour – gynaecology

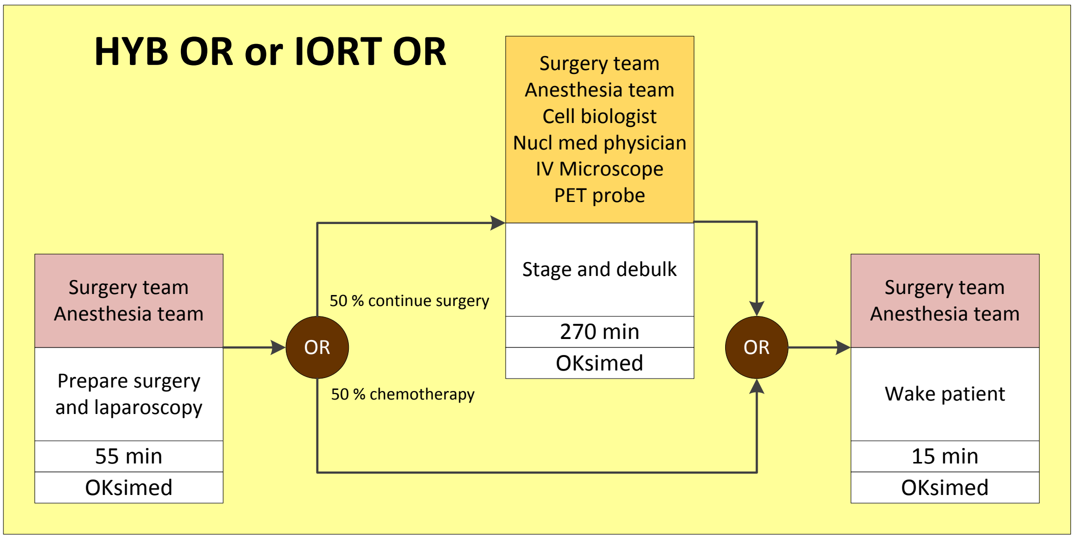


Figure 32: Process flow chart - Gynaecology – proven malignant overian tumour

Prostate tumour – urology

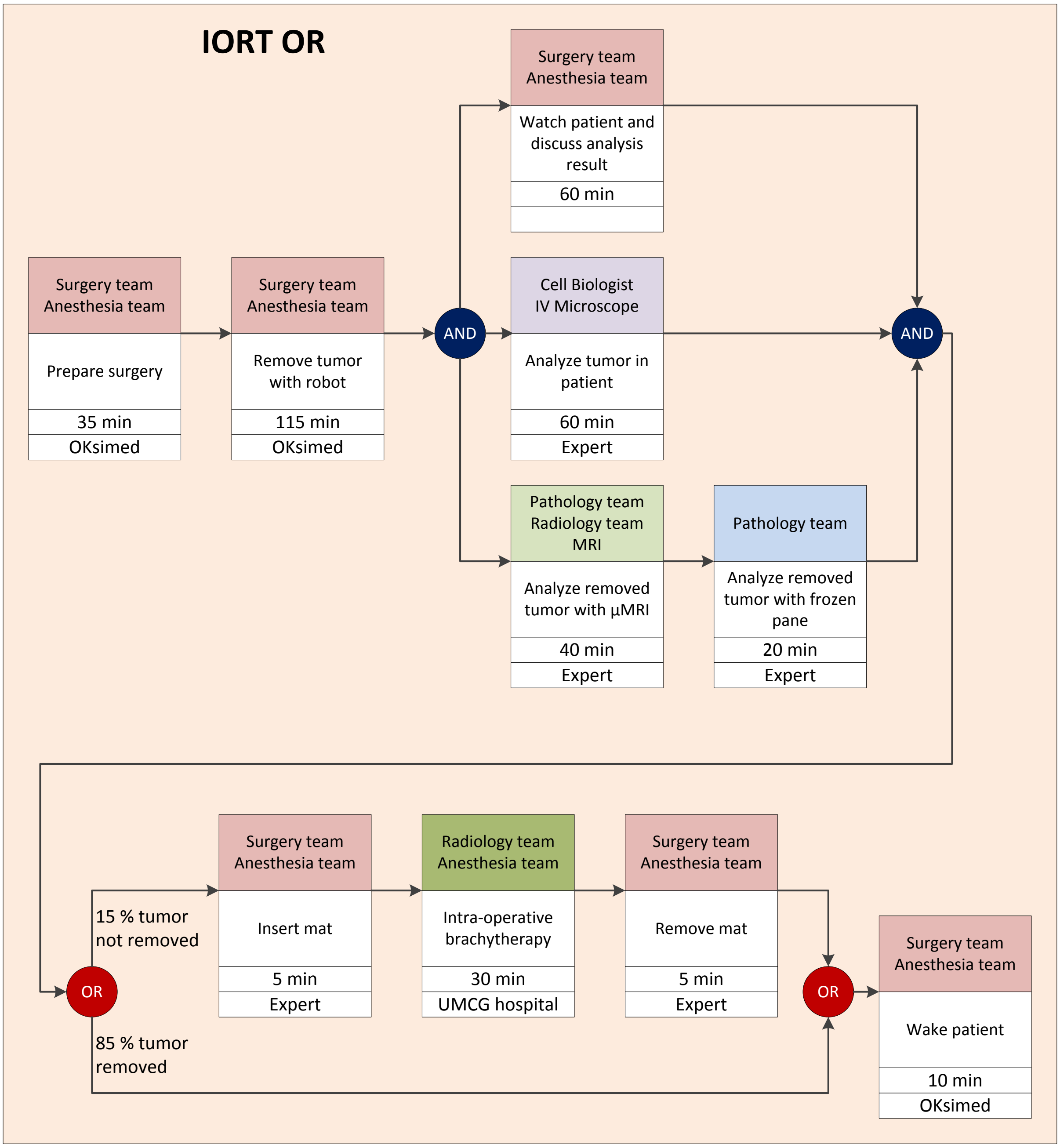


Figure 33: Process flow chart - Urology – Open prostatectomy to treat prostate tumour

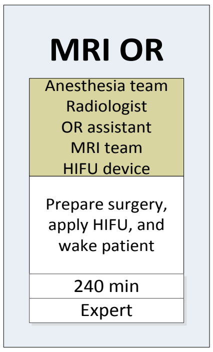


Figure 34: Process flow chart - Urology – HIFU to treat prostate tumour

Prostate tumour – urology

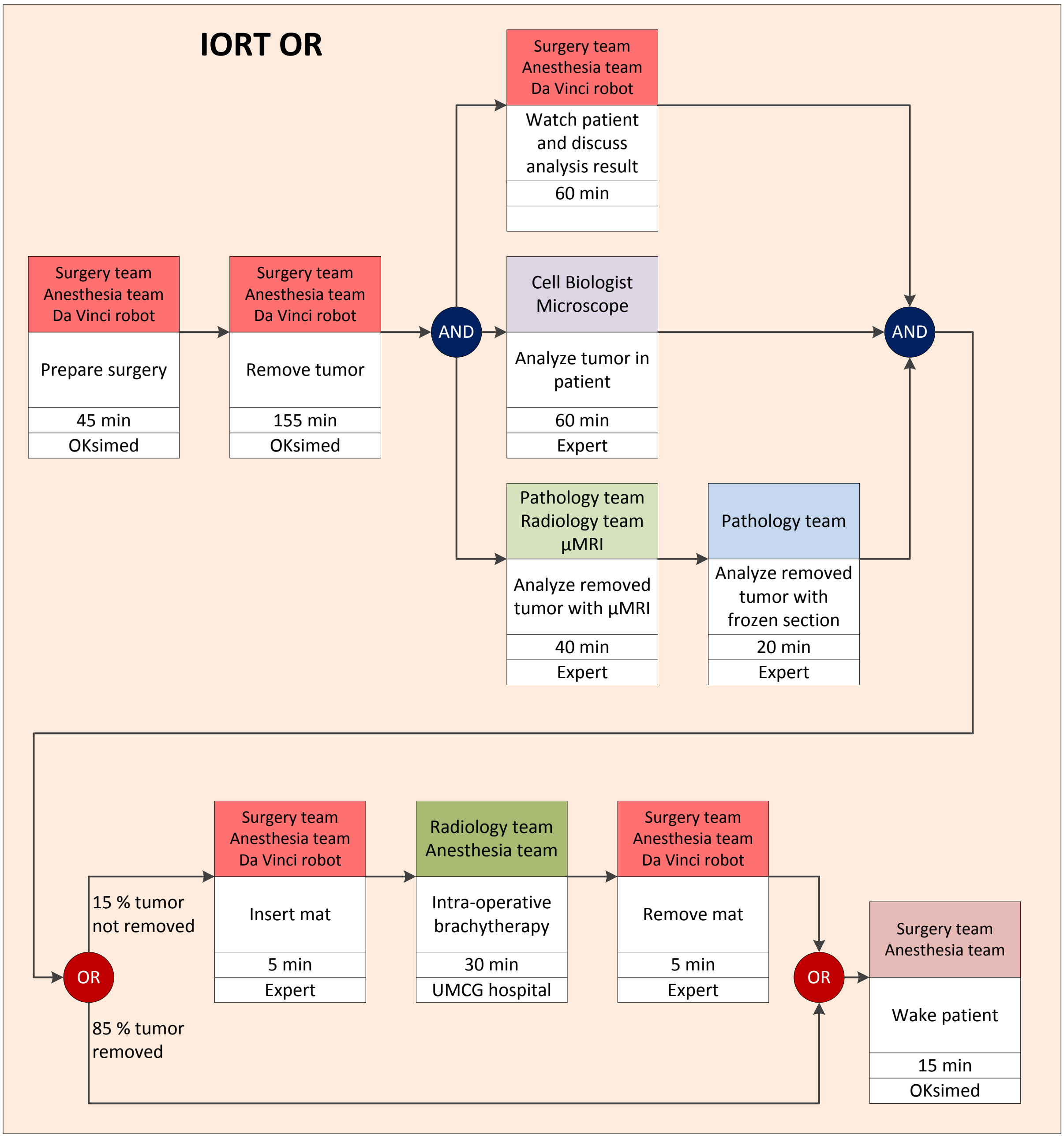


Figure 35: Process flow chart – Urology – Robot prostatectomy to treat prostate tumour

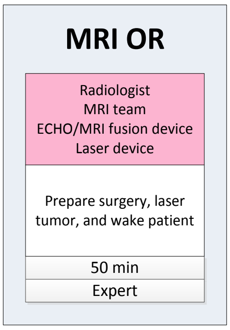


Figure 36: Process flow chart - Urology – laser to treat prostate tumour

Prostate tumour – urology

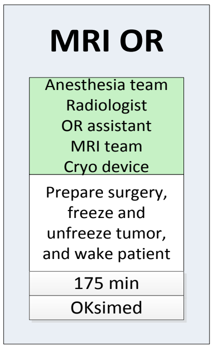


Figure 37: Process flow chart - Urology – Cryosurgery to treat prostate tumour

Diagnostic MRI – radiology

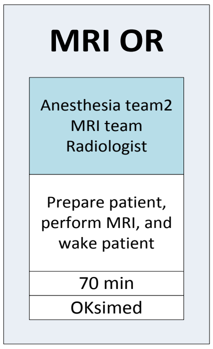


Figure 38: Process flow chart - Radiology – diagnostic MR

Appendix III: Arena Model

In this appendix an explanation is provided of the simulation model developed in Arena.

Run setup

The run set up is illustrated in Figure 39. Note that a day in Arena only has 16 hours. If time is 0 the starting point in "real life" is 08:00.

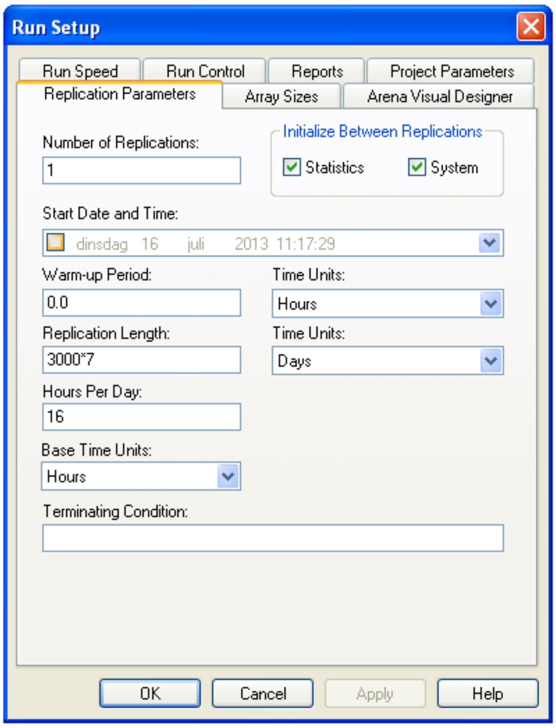


Figure 39: Run Setup

In some cases MS Excel only works when "." and "," are reversed. This can be done by going to: File/Options/Advanced and switch the decimal separator and thousands separator by filling in "." and "," exactly opposite.

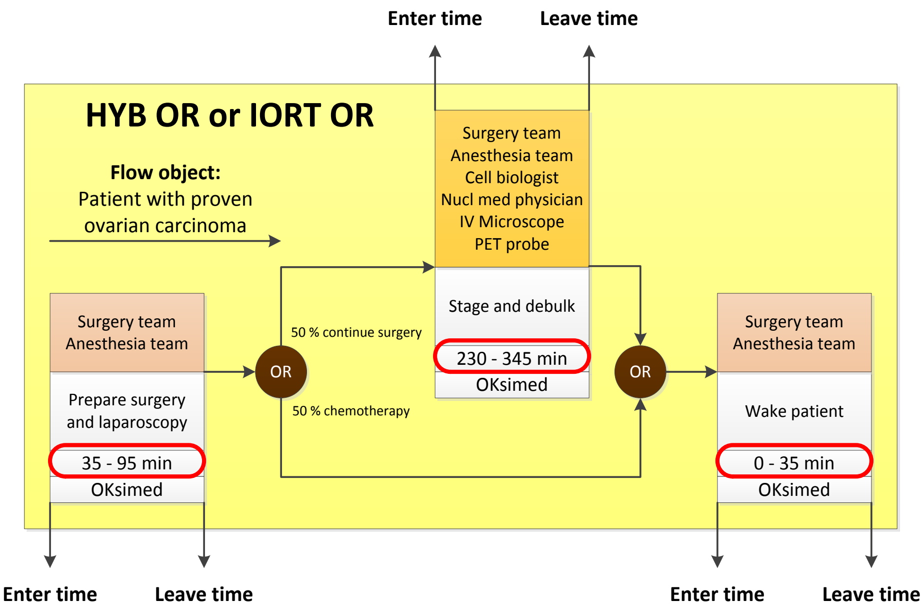


Figure 40: Example to illustrate Arena registration with stochastic durations

Figure 40 will be used as an example to explain the Arena model. The entire model is based on three different steps given in Figure 41: (1) create patients that will flow through the model and assign the right process step sequence, (2) provide process step properties including resources for each process step and assign performance measures, (3) dispose patients.

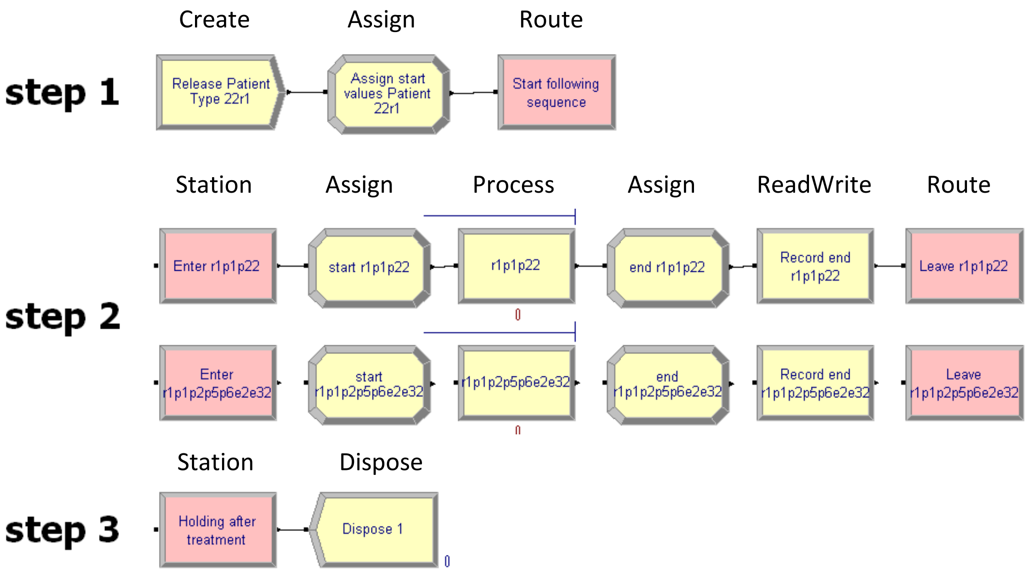


Figure 41: Example of required Arena blocks for a proven malignant overian tumour surgery

Step 1

The first step consists of creating patients, assigning several attributes and variables to this patient, and directing the patient to the right process steps as illustrated in Figure 42.

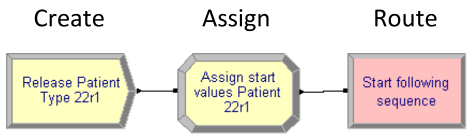


Figure 42: Step 1, used to create patients, assign values, and direct patient

Create block

The first step of a simulation model is to create entities that flow through the steps of the model. In this case the patients with their surgery types have been chosen as the entities. In Figure 43 an example is provided of a “create block” and its content. In this case one patient with type 22r1, describing a patient of SG gynaecology with a proven malignant overian tumour surgery (22) starting in the IORT OR (r1), will arrive every 112 hours at time 0. Because a day has 16 hours in this model and time 0 is time 08:00, this means every Monday morning at 08:00 one patient that will receive an OCS tumour surgery will arrive in the IORT OR. If a patient of a certain type arrives two or three times a week, multiple create blocks are developed for the same patient type.

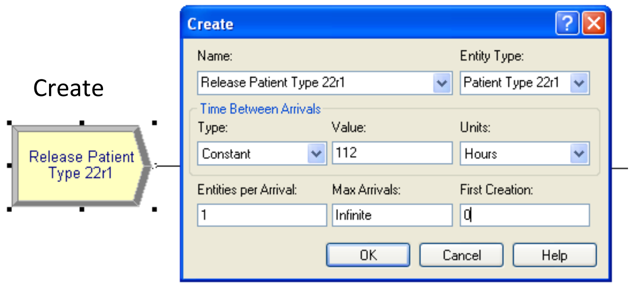


Figure 43: Create block in Arena

Assign block

When a patient has been created, several attributes and variables are given to this patient type as shown in Figure 43, using an "assign block". The first variable, the patient number, is used to count the patients that arrive from each patient type. The amount of patients that arrive in the system is used to generate the performance measure: patient surgery rate, because it simply counts the number of patients of a certain patient type that are treated.

The attribute "Patient Index Type" and "Entity.Sequence" are both used to describe the sequence of process steps that the patient will follow. The "Patient Index Type" provides the probability that every sequence occurs. In this case, a set exists of two sequences: sequence 1 is the sequence including staging and debulking and sequence 2 is the sequence without staging and debulking as depicted in Figure 40. Both sequences occur with a 0.5 probability, so the Patient Index Type value is DISC(0.5,1,1,2). The attribute Entity.Sequence has value "Patient Sequences Type 22r1(Patient Index Type 22r1)", which basically makes sure that the entity follows the assigned sequence, in this case either sequence 1 or sequence 2. In Figure 45 this set of sequences is illustrated by providing a set of sequences called "Patient Sequences Type 22r1" including "Sequence Patient Type 22r11" and "Sequence Patient Type 22r12".

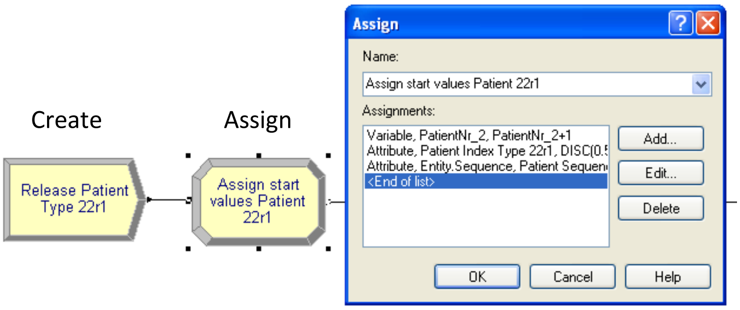


Figure 44: Assign block after create block in Arena

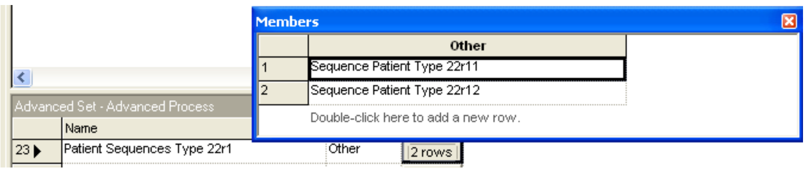


Figure 45: Set of sequences of patient type 22r1, i.e. proven malignant overian tumour starting in the IORT OR

Route block

The "route block" let's Arena know that patients should be routed according to their assigned sequence. This sequence has been assigned to the patient in the "assign block".

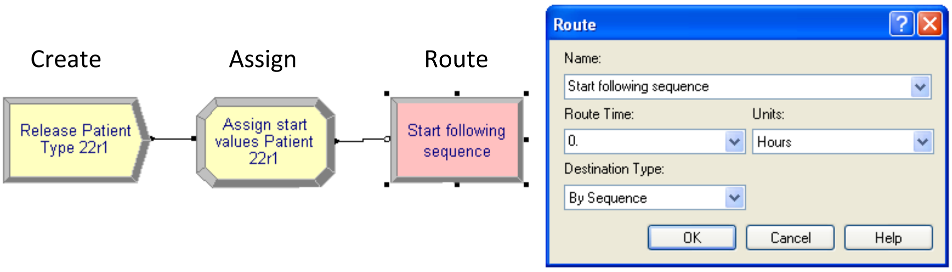


Figure 46: Route block after assign and create block in Arena

Sequence list

We have now directed patients to the right sequence, i.e. sequence 1 or sequence 2, but the sequences themselves haven't been described yet. In Arena this can be done by using sequences modules as illustrated in Figure 47 and Figure 48, describing sequence 1 and sequence 2, respectively. As you can see, sequence 1 consists of going to station "r1p1p22", "r1p1p2p5p6e2e32", and "r1p1p22" sequentially. These codes might seem quite complicated, but are nothing more than the OR, personnel and equipment required for each process step to handle the patient type. The first code "r1p1p22" gives us the following information: patient type number 2 will be treated in the IORT OR (r1) by a surgery team (p1), and an anaesthesia team (p2). No scarce equipment is required. The codes for every resource team are provided in Table 6.

Table 6: Resource team and resource types

	#	Capacity	ArenaCode
ORS			
IORT OR		1	r01
MRI OR		1	r02
HYB OR		1	r03
EQUIPMENT			
MRI		1	e01
IV microscope		1	e02
PET probe		1	e03
Da Vinci Robot		1	e04
HDR device		1	e05
Echo MRI fusion device		1	e06
Laser device		1	e07
HIFU device		1	e08
Cryo device		1	e09
Micro MRI		1	e10
PERSONNEL			
Surgery team	3		p01
- Surgeon	1	No constraint	
- OR assistant	2	No constraint	
Anaesthesia team	3		p02
- Anaesthesiologist	1	No constraint	
- Anaesthetist	2	No constraint	
Pathology team	2		p03
- Pathologist	1	No constraint	
- Analyst	1	No constraint	
Radiology team	2		p04
- Radiologist	1	No constraint	
- Analyst or technician	1	No constraint	
Cell biologist	1		p05
- Cell biologist	1	No constraint	
Nuclear medicine physician	1		p06
- Nuclear medicine physician	1	No constraint	
MRI team	2		p07
- Laboratory technician	2	No constraint	
Radiologist	1		p08
- Radiologist	1	No constraint	
OR assistant	1		p09
- OR assistant	1	No constraint	
Pathology team2	2		p10
- Pathologist	1	No constraint	
- Analyst	1	No constraint	
Anaesthesia team2	2		p11
- Anaesthesiologist	1	No constraint	
- Anaesthetist	1	No constraint	

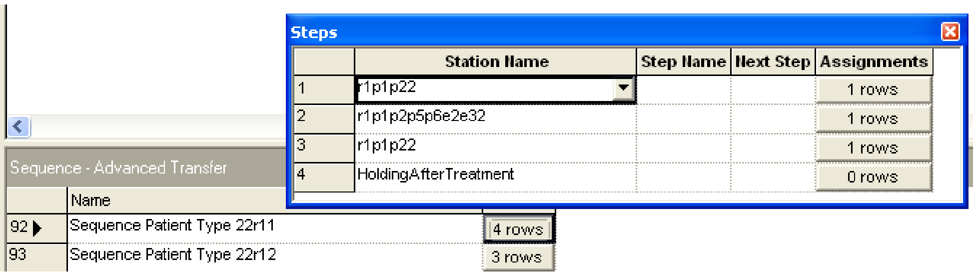


Figure 47: Sequence 1, proven malignant overian tumour surgery

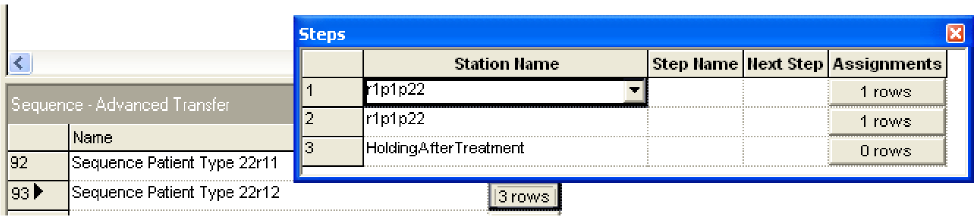


Figure 48: Sequence 2, proven malignant overian tumour surgery

Until now the required resources and the order of process steps are clear, but the duration of each process step is still unknown. Therefore, for every process step in the sequence list, the process step duration is added either retrieved from OKsimed, literature, other hospitals or experts. In Figure 49 is illustrated how these process step durations are added. If process step durations were provided by OKsimed a discontinuous distribution has been developed, as you can see in Figure 49, in which each duration occurs with the same probability. In this case 34 data points were available to provide the duration of the first process step, i.e. “prepare surgery and laparoscopy” from Figure 40. The last station name is for all patients the same and is called “HoldingAfterSurgery”. This station will be explained in Step 3.

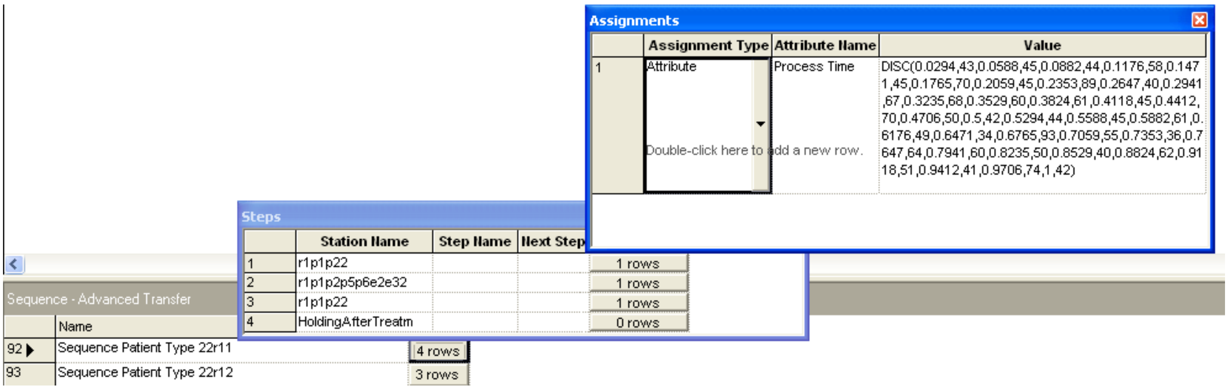


Figure 49: Process step duration included in sequence steps

A special form of process step durations is required for an OCS tumour surgery, which process flow chart is depicted in Figure 30 of Appendix II: Process Flow Charts. The tumour removal can have a duration between 3 and 83 minutes. Depending on tumour removal duration different sequences can occur between prepare surgery & remove SLN and analyse removed tumour with frozen pane:

Sequence 1 (if tumour removal duration is more than 35 minutes)

1. Remove tumour & analyse SLN (r1p1p2p31)
2. Remove tumour (r1p1p21)
3. Watch patient and discuss analysis results & analyse tumour in patient & analyse removed tumour with micro MRI (r1r2p1p2p3p4p5e1e21)

Sequence 2 (if tumour removal duration is equal to or less than 35 minutes)

1. Remove tumour & analyse SLN (r1p1p2p31)
2. Analyse SLN & watch patient and discuss analysis results & analyse tumour in patient & analyse removed tumour with micro MRI (r1r2p1p2p3p4p5p10e1e21 (extra pathology team required (p10)))
3. Watch patient and discuss analysis results & analyse tumour in patient & analyse removed tumour with micro MRI (r1r2p1p2p3p4p5e1e21)

In Table 7 the different stations, their attributes and attribute values are provided to provide the correct durations for an OCS tumour surgery.

Table 7: Introduction part of the process step durations of an OCS tumour

Station	Attribute	Value
r1p1p2p31	Selected Process Time	DISC(0.0156,9,…,1,12)
	Process Time	min(Selected Process Time,35)
r1p1p21	Process Time	max(Selected Process Time-35,0)
r1r2p1p2p3p4p5p10e1e21	Process Time	max(35 – Selected Process Time,0)
r1r2p1p2p3p4p5e1e21	Process Time	40 – max(35 – Selected Process Time)

Step 2

Thus far we have described the sequences for every patient type and the stations to which these patients will be assigned subsequently and how long these steps will take. But we do not have generated performance measures for OR utilization, patient waiting time, personnel waiting time, and personnel overtime. Furthermore, it is not clear yet, which personnel and equipment should be available at which locations at what times during each particular surgery. That is why we need a process step block chain, consisting of a station block, an assign block, a process block, an assign block, a readwrite block and a route block, subsequently. Such a process step block chain is illustrated in Figure 50 and will be explained below.

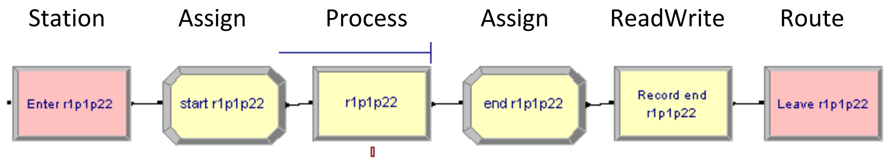


Figure 50: Process step block chain: station-, assign-, process-, assign-, readwrite-, and route block

Station block

A station block is used to be referred to in a sequence list as explained previously. Different stations will be visited by the patient sequentially.

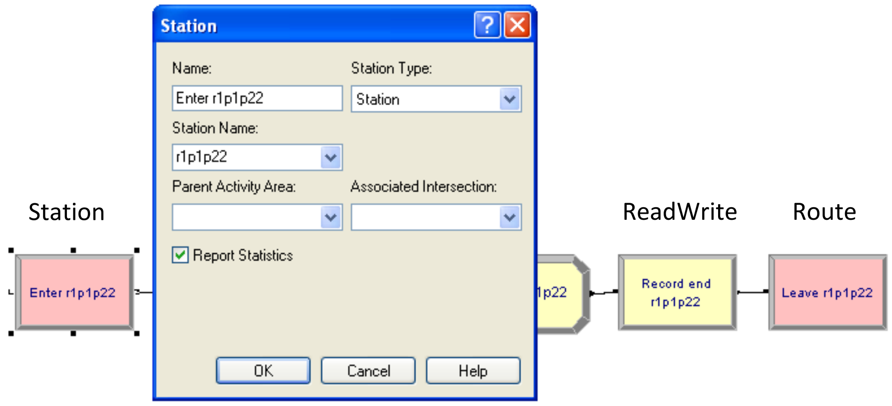


Figure 51: Station block in block chain

Assign block

The assign block is used to give values to attributes and variables and is depicted in Figure 52 and given in Table 8. In this case we assign the time a patient enters the process block by using the current simulation time which is stored in the system attribute "Enter Time" with value "TNOW". TNOW is the current runtime. On top of that we assign a start time for each resource that is required for the process step, for example for the IORT OR this would be variable start_r1 having value TNOW. Furthermore, the first starting time of the day of each resource is assigned provided by firststart_r1 and value min(firststart_r1,start_r1) for the IORT OR. If a resource is surgery type specific both the code for the resource and the surgery code is provided. For example a surgery team is surgery type specific (a gynaecologist cannot treat a prostate tumour), so the full code is p12 for a surgery team (p1) treating a tumour belonging to the gynaecology SG (2). All assigned attributes and variables will be used later on for performance measure development.

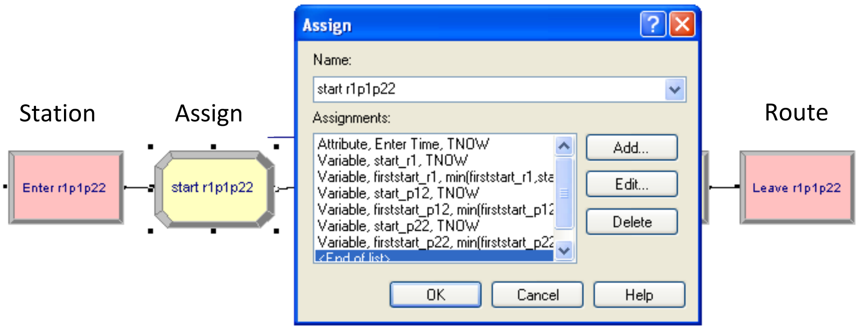


Figure 52: First assign block in block chain

Table 8: Assigned attributes and variables in first assign block (only for IORT OR)

Attribute/variable	Name	Value
Attribute	Leave Time	TNOW
Variable	start_r1	TNOW
Variable	firststart_r1	min(start_r1,firststart_r1)

Process block

The process block, illustrated in Figure 53, is the block that both contain the process step duration and the resources that are occupied during a process step. The process step duration is added as the attribute "Process Time" which will be retrieved from the sequence list (remember we added the process time for every process step as an attribute). The idea is that a patient with a certain surgery type can pass this process block repeatedly in one sequence, but with different process step durations.

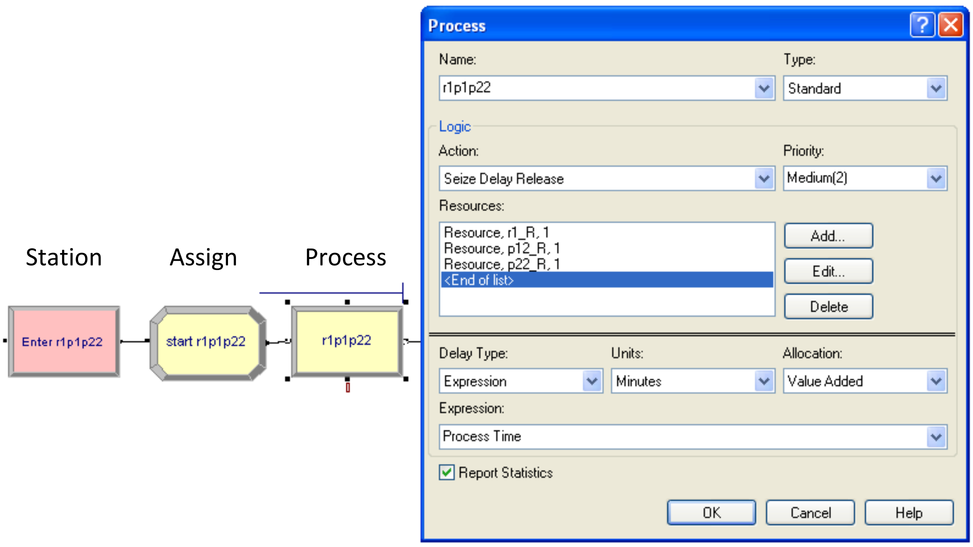


Figure 53: Process block in block chain

Assign block

The second assign block in the chain is used to assign several attributes and variables as described in. First, the time a patient leaves the process block by using the attribute "Leave Time" with value "TNOW". Second, the patient wait time is added, since this is one of the desired performance measures. The patient wait time of a gynaecology patient (code 2) is added as a variable called PatientWaitTime_2 and value PatientWaittime_2 + entity.waittime. entity.waittime is a statistic automatically created by Arena. This variable records the patient wait time every time a patient enters a certain process step and has to wait for some reason (if a required resource is occupied by another patient for example). Third, the end time per resource of the process step is recorded with TNOW and similar to the start time also the final end of each resource is assigned, using the value: max(finalend_r1, end_r1). Finally, the process time, occupied time, and utilized time of each resource are assigned, according to 2.01 till 2.14 from 2.3 Performance Measures Formulas. Shift end time in Arena is set at 16:00 every day and is the time after which overtime occurs.

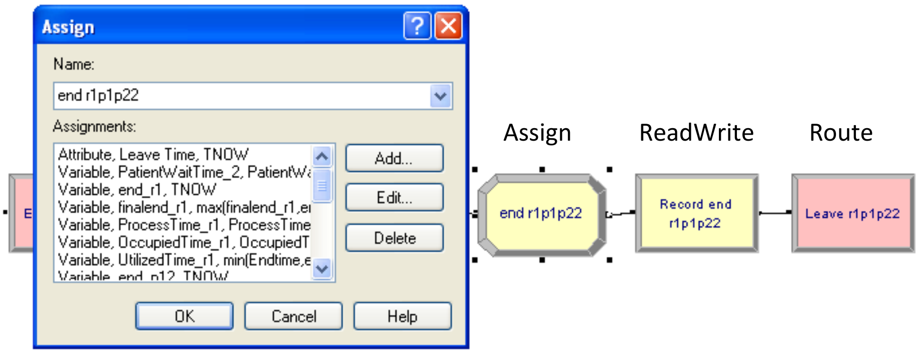


Figure 54: Second assign block in block chain

Table 9: Assigned attributes and variables in second assign block

Attribute/variable	Name	Value
Attribute	Leave Time	TNOW
Variable	PatientWaitTime_2	PatientWaitTime_2+entity.waittime
Variable	end_r1	TNOW
Variable	finalend_r1	max(finalend_r1,end_r1)
Variable	Processtime_r1	ProcessTime_r1+ Process Time / 60
Variable	OccupiedTime_r1	OccupiedTime_r1+max(0,min(ShiftEndTime,end_r1)-start_r1)
Variable	UtilizedTime_r1	UtilizedTime_r1+min(ShiftEndTime,end_r1) - end_r1+ProcessTime_r1

Readwrite block

The ReadWrite block, depicted in Figure 55, is used to write data to a data file, in this case an MS Excel file. Both the enter time and leave time of the process block are now known due to the two assign blocks. These two attribute values will be stored in an Excel file through this block.

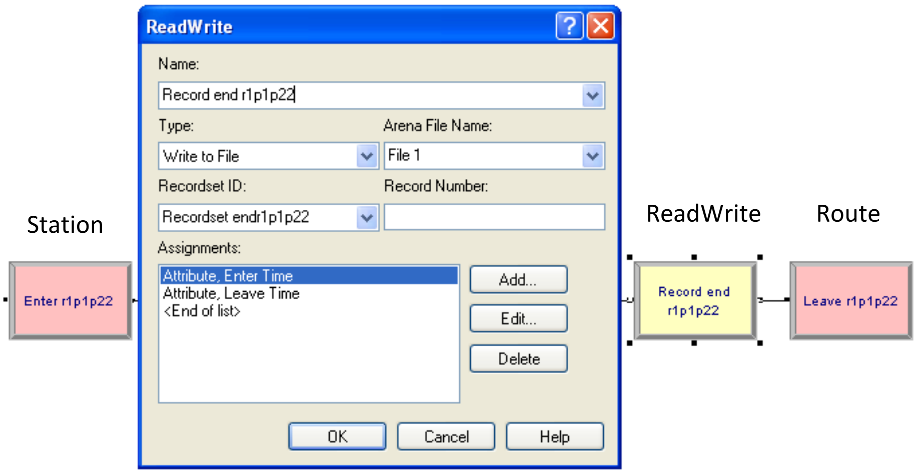


Figure 55: ReadWrite block in block chain

Route block

The route block, as illustrated in Figure 46, is used to move a patient from their current station to the next station according to the sequence list, which has been previously described.

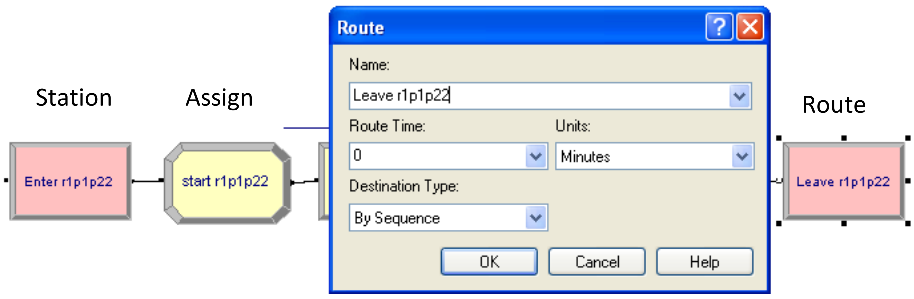


Figure 56: Route block in block chain

Step 3

Step 3 is used to dispose all patients.

Station block

As explained in step 2, every patient has been directed to station "HoldingAfterSurgery", which is the name of this station block as illustrated in Figure 57.

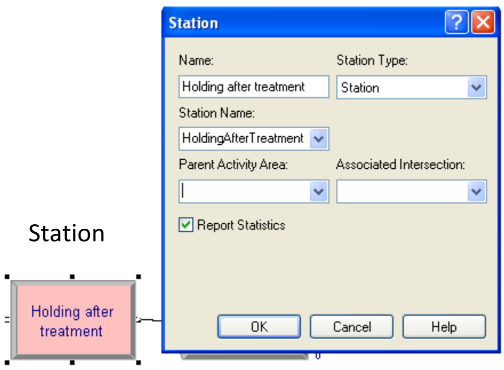


Figure 57: Station block

Dispose block

When a patient has followed the complete surgery he will simply be discarded by using a dispose block as illustrated in Figure 58.

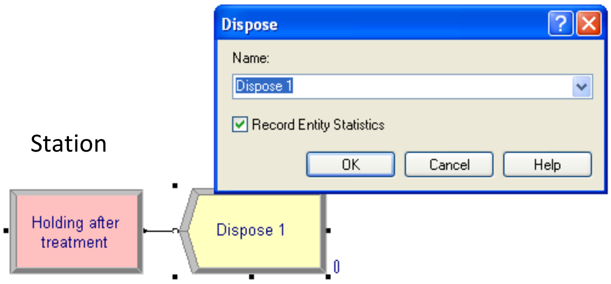


Figure 58: Dispose block

Clock

The clock, provided in Figure 59, is used to generate different performance measures. The clock is required because different values have to be set at zero or infinite at the end of the day to provide the correct performance measures.

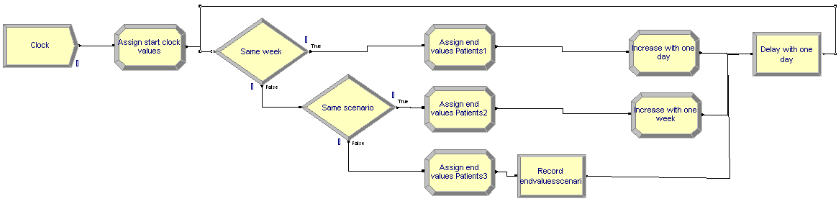


Figure 59: Arena clock

Create block

The create block, illustrated in Figure 60, releases one entity time at time 0. This entity will be in the system until the end of the run.

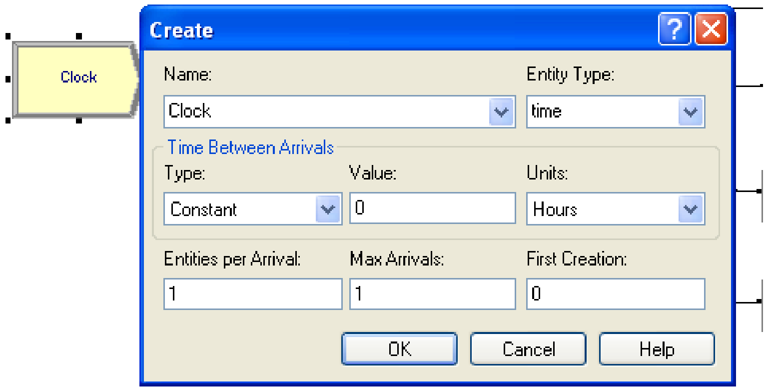


Figure 60: Create block in clock

Assign block

The first assign block in the clock assigns the scenario number, which can be adjusted for each scenario run. Furthermore, it provides the week number (1 to number at end of run), today number (1 = Monday, 7 = Sunday), and ShiftEndTime of the day, which is 8. The ShiftEndTime is used to represent the time after which overtime starts, which is at 16:00. Furthermore, the ProcessTime of each resource is set at zero (note: this is not the same as the attributes Process Time providing the duration of each process step) and the firststart of each research is set at infinite (or at least a very high number). This is required to generate the right performance measures.

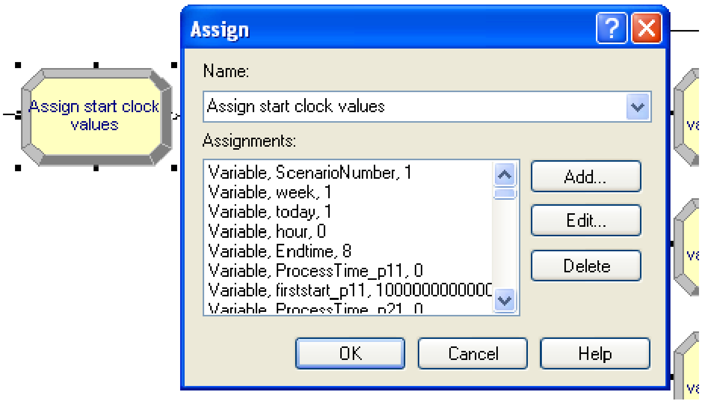


Figure 61: First assign block in clock

Decide blocks

Some measures are calculated each day, such as required time, process time, personnel-, and patient waiting time, and overtime. Some measures are calculated for each week, such as OR utilization. Therefore it is required to make a distinction between days and weeks. In the first decide block the question is therefore asked whether the current day is in the same week as the previous day, i.e. is today < Sunday (7)? If this is true, performance measures are assigned as described in the next assign block. If this is false the next decide block decides whether the run has finished or whether it should still continue.

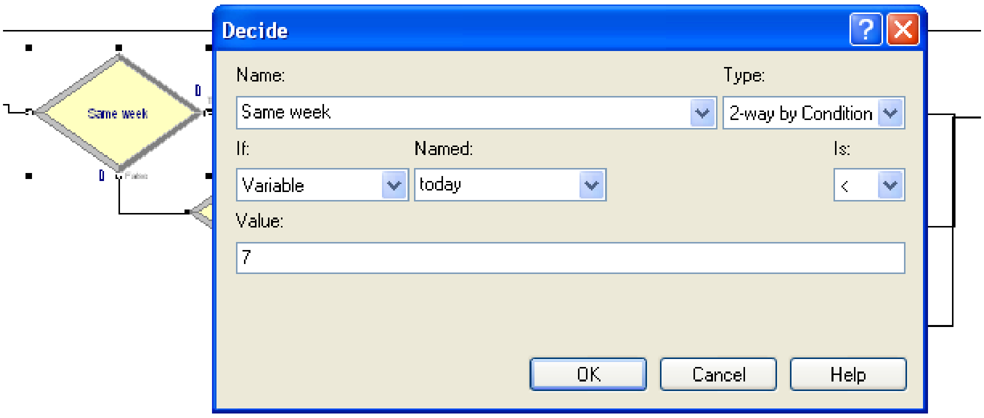
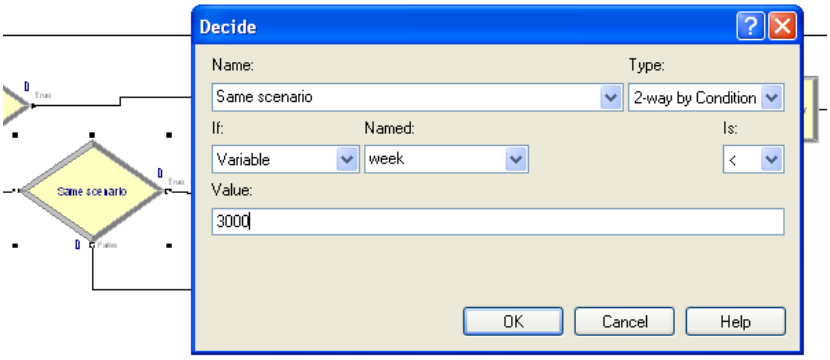
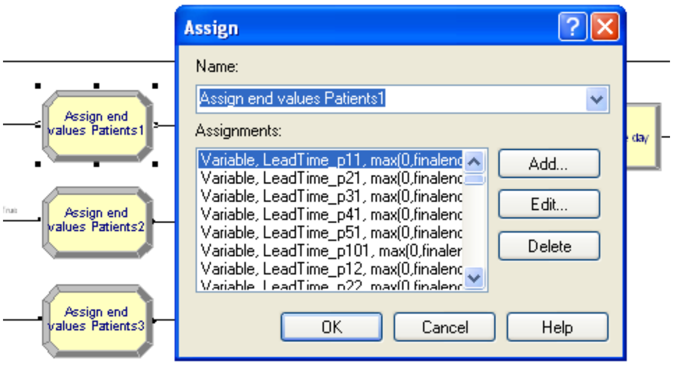


Figure 62: First decide block in clock

The second decide block is only used to end the simulation run and write performance measures to excel. The assign blocks after this decide block, either true or false, are exactly equal. In the example the run takes 3000 weeks.



Assign block
In the assign blocks all performance measures are provided, which are equal to the performance measures of Formula 2.01 till 2.14 from 2.3 Performance Measure Formulas.



Readwrite block
The readwrite block depicted in Figure 63 is used to write all required performance measures to MS Excel. Examples of the output generated from this block are provided later in this section.

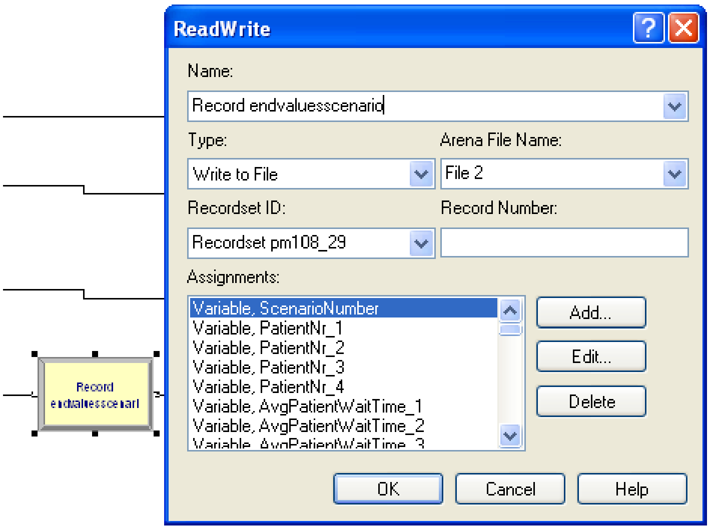
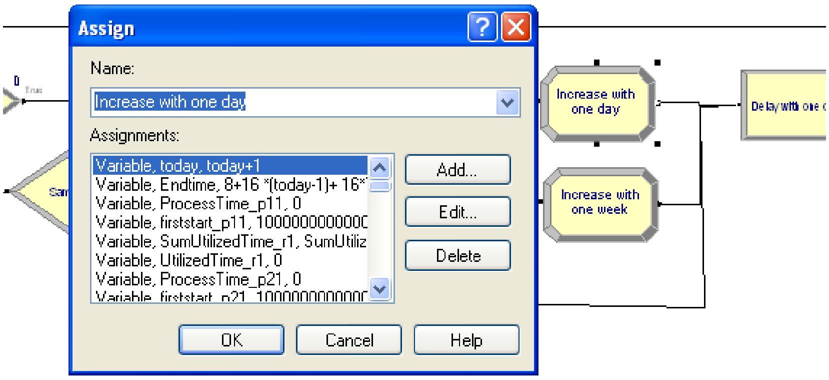
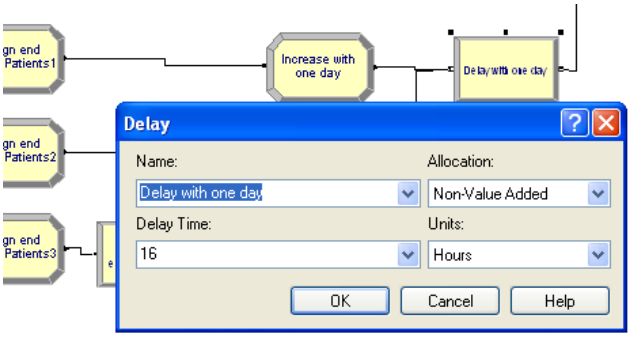


Figure 63: ReadWrite block in clock

Assign block
The assign blocks before the delay block are used to set all values to the initial values of the day to create the right performance measures.



Delay block
The delay block is used to delay the clock with one day. In this case one day is 16 hours.



Transform MS Excel output to desired output

There are two types of output. One type generates all enter and leave times of each block chain. Extracting the enter time from the leave time provides the leadtime of a process step. The other output type generates the values of all performance measures. The performance measures output is ready as it is and is placed in Tables in Appendix V: (Performance) , but the other output has been edited and that will be described in this part.

Remember we created an excel file with the ReadWrite block included in each block chain providing the enter time and leave time of every process step block chain? Now we will explain how to use this information to provide an overview of which personnel and equipment should be available at which locations at what times during each particular surgery in order to conduct a surgery. To make the explanation a little easier, we provided Table 10 to give you an idea what happens when letting 2 patients go through the system that will get a proven malignant overian tumour surgery. The patients will arrive on Monday and on Monday in the next week at 08:00. Arena just spits out all the enter and leave times of every time a patient has passed a process step block chain as shown in column A and B of Table 10. These times have to be converted from text to numbers and to minutes as illustrated in column C and D. 480 minutes in this case means a starting time of 08:00. What we would like to extract from these times is the probability that a resource can be called upon during one surgery of a particular surgery type.

In order to calculate these probabilities we started by placing a “1” or “ ” at every time period of 15 minutes if a process step block chain was (partly) occupied or not, respectively. In column C one can see that the very first enter time of process step block chain “r1p1p22” is 08:00, which seems correct since a patient will always start the day with passing this block chain. He will stay at the process step block chain for 42 minutes (=522 – 480) and then leave this chain at 08:42. This was the preparation and laparoscopy of the surgery.

In row 7 an Enter Time of 522 minutes and leave time of 546 exist. This means the first patient did not undergo staging and debulking but immediately after preparation and laparoscopy was woken up by the exact same group of resources. This waking up took 24 minutes and was ready at 09:06.

In row 8 the arrival of patient 2 is demonstrated. This patient arrives at 112 (=7 days * 16 hrs per day) and leaves the process block chain at 08:54. The second time the patient arrives at this block is given in row 9 and is at 13:54

(834 minutes) indicating that this person did undergo staging and debulking. Waking up this patient took 33 minutes.

In column G to L the time periods between 08:00 and 09:15 are given as you can see in row 2 and 3. For every row in which an enter and leave time is provided a 1 is put in those cells that are occupied during the corresponding time period. In row 4 and column G to L, the part or probability that a process block chain was occupied during 15 minutes has been provided. From 08:00:00 to 08:59:59 the block is occupied in 100 % of the cases and from 09:00:00 to 09:14:59 in 50 % of the cases.

For every block chain this can be calculated. At the end of all calculations we know from every process block chain at which time intervals it was (partly) occupied or not. However, we would like to know this from the resources and not (only) from the whole block chain.

Table 10: Output process step block chain "r1p1p22"

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2						hours	8	8	8	8	9	9
3						min	0	15	30	45	0	15
4						part	1	1	1	1	0,5	0
5	Enter Time (hrs)	Leave Time (hrs)	Enter Time (min)	Leave Time (min)								
6	0	0,7	480	522			1	1	1			
7	0,7	1,1	522	546						1	1	
8	112	112,9	480	534			1	1	1	1		
9	117,9	118,45	834	867								
10												

Let's look at resource IORT OR, denoted by the code r1. A patient that enters the example process flow will either pass the block chains with codes ¨r1p1p22", then "r1p1p2p5p6e2e32", and finally ¨r1p1p22" or he will pass chains with codes ¨r1p1p22" and then ¨r1p1p22" again but with a different process step duration. We can now calculate the probability that resource IORT OR was occupied from 08:00 to 08:15 by adding up all the values from chain ¨r1p1p22" and chain "r1p1p2p5p6e2e32" in this time period and divide it by the number of patients that have entered the model. If we would do the same for the PET probe (code e3) we would only add up the values from block chain r1p1p2p5p6e2e32.

This procedure can be followed for every time period between 08:00 and 18:00 and for every resource, providing us the probability a resource could be called upon during a certain time period, which is exactly what we need to generate output as illustrated in Figure 64 and Figure 65. This output is provided for every resource for every surgery type in Appendix IV:

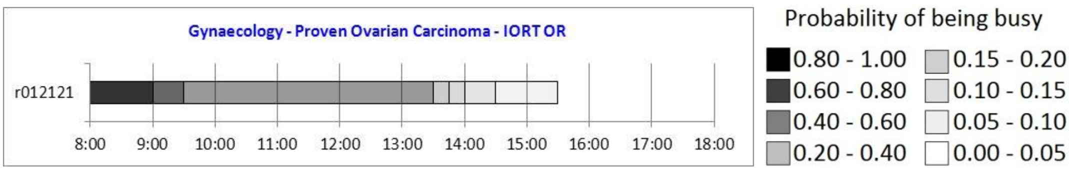


Figure 64: Probability that the IORT OR (r1) is occupied during a proven malignant tumour surgery

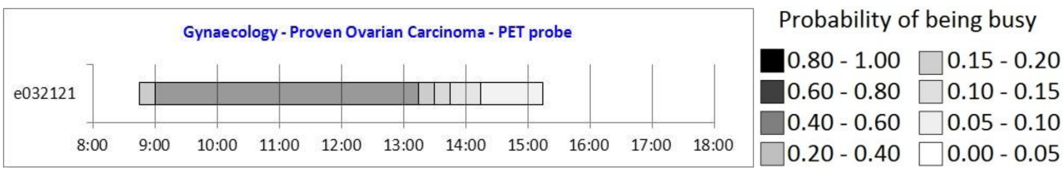


Figure 65: Probability that the PET probe (e3) is occupied during a proven malignant tumour surgery

Appendix IV: Probability that Resources are Busy or Idle

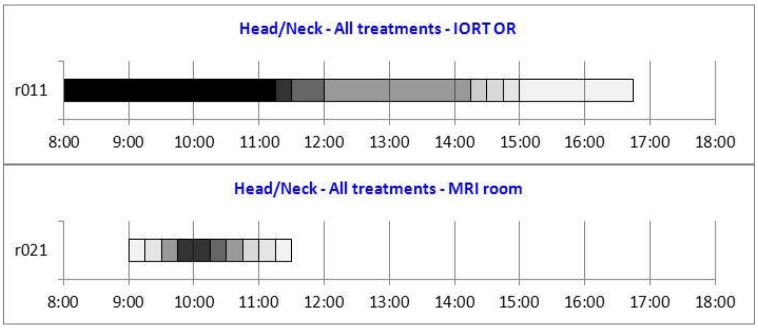
In this appendix the probabilities that resources (rooms, equipment, or personnel) are busy or idle during a surgery that starts at 08:00 are provided. These probabilities are provided for each surgery type. The darker the colour, the higher the probability that a resource is occupied during that time block.

Probability of being busy

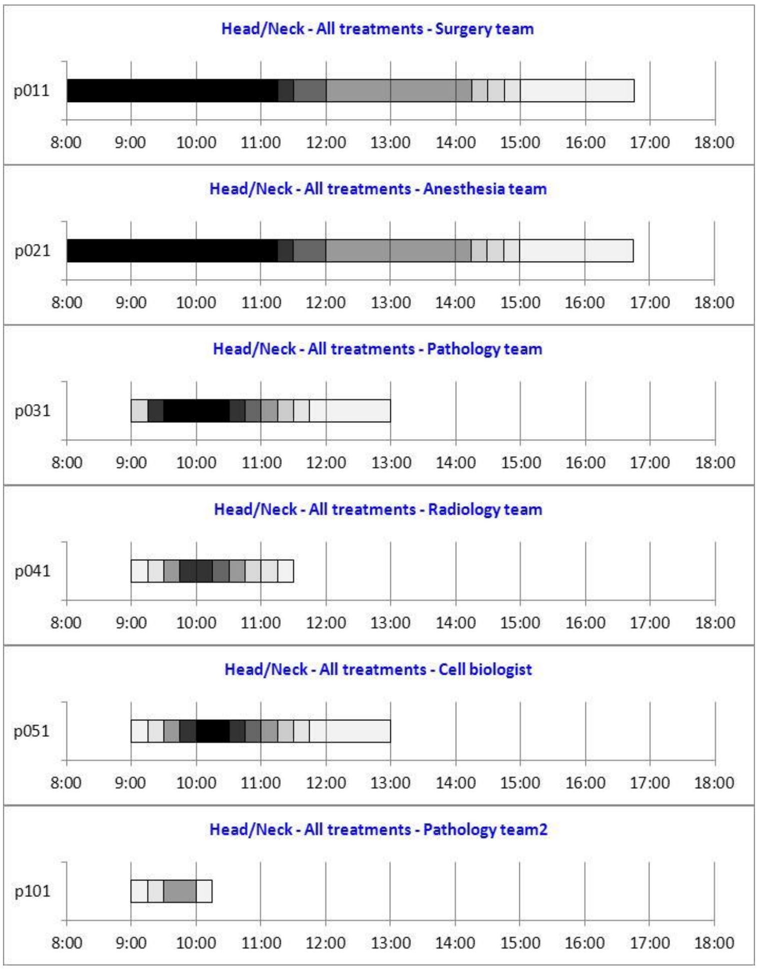
0.80 - 1.00	0.15 - 0.20
0.60 - 0.80	0.10 - 0.15
0.40 - 0.60	0.05 - 0.10
0.20 - 0.40	0.00 - 0.05

Head/neck – OCS tumour

ORs

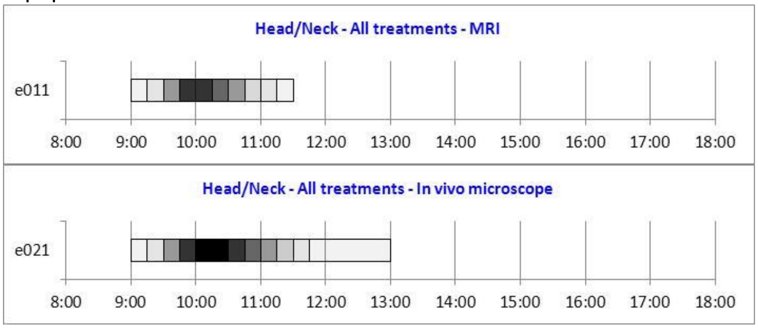


Personnel



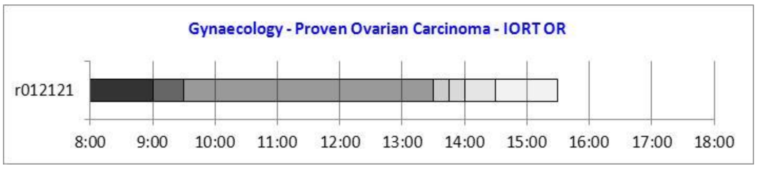
Head/neck – OCS tumour

Equipment

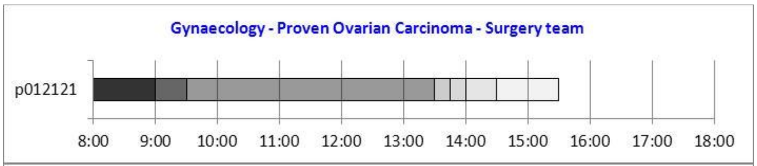


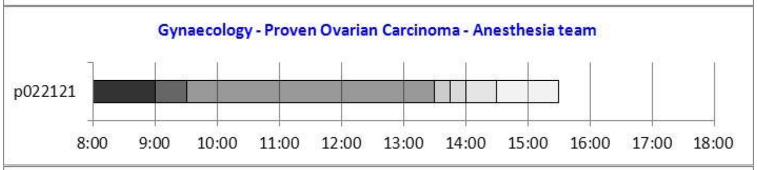
Gynaecology – proven malignant overian tumour surgery

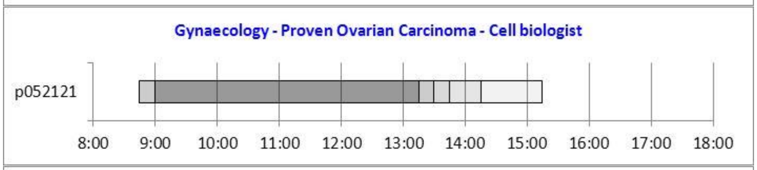
ORs

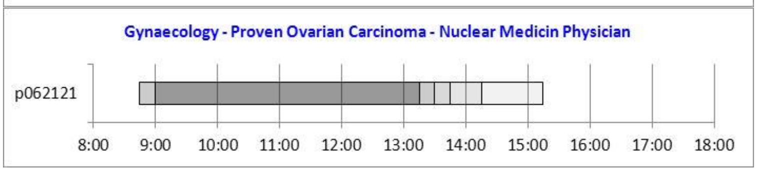


Personnel

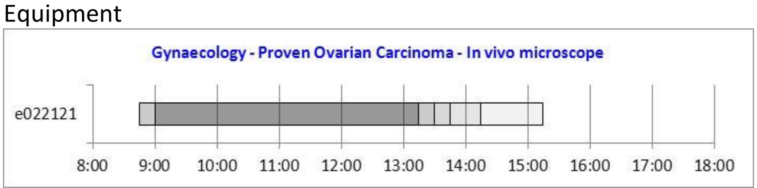


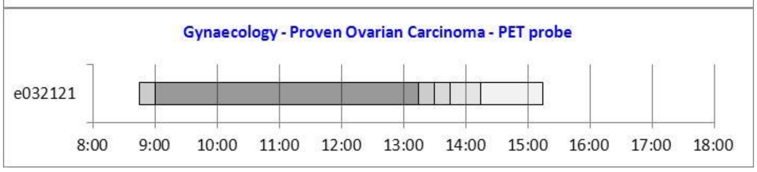






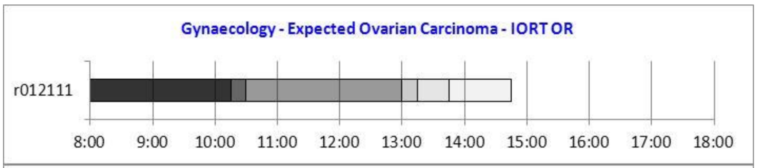
Equipment

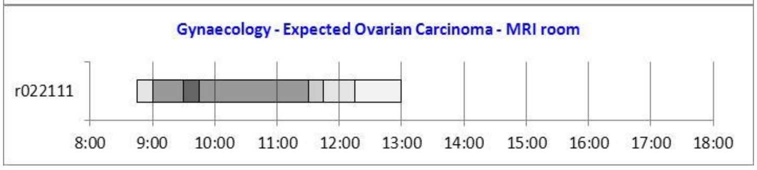




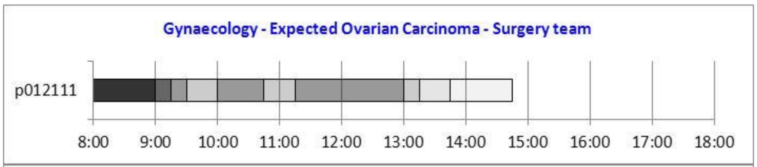
Gynaecology – expected malignant overian tumour surgery

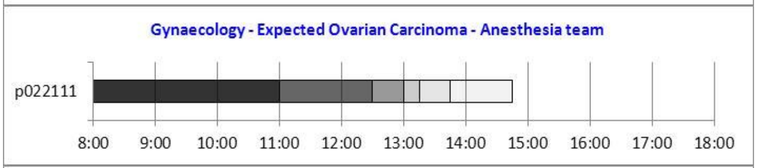
ORs

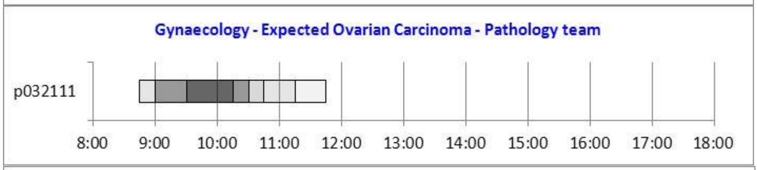


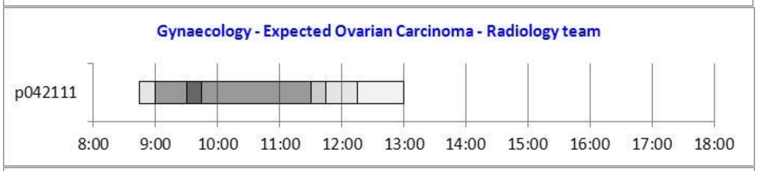


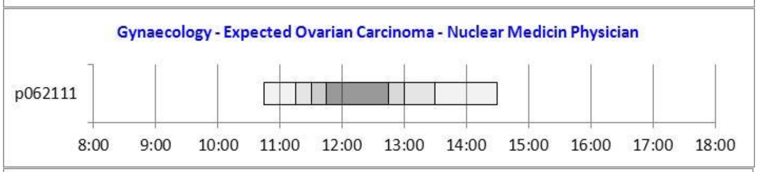
Personnel

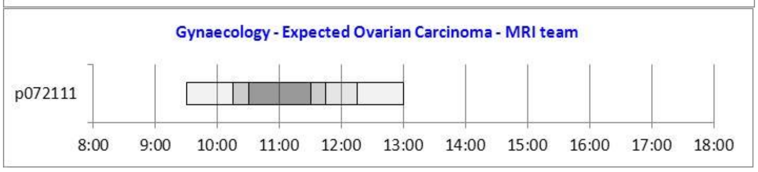




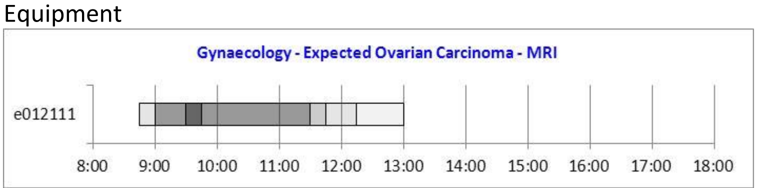


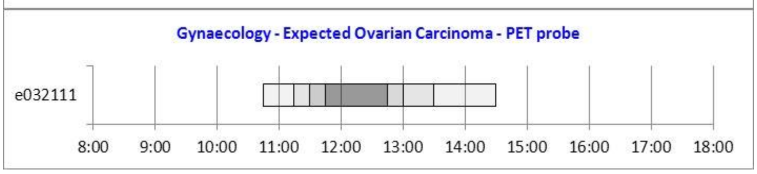






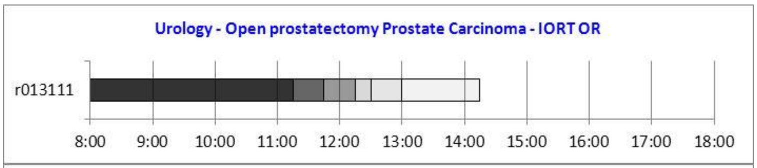
Equipment

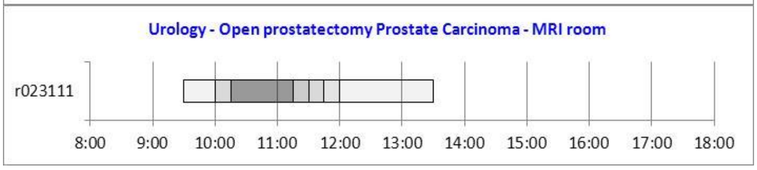




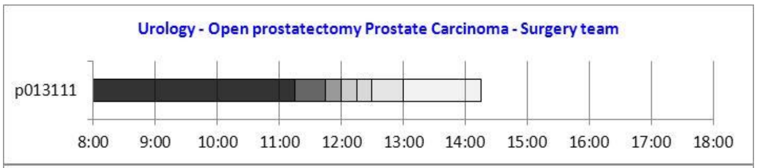
Urology – open prostatectomy

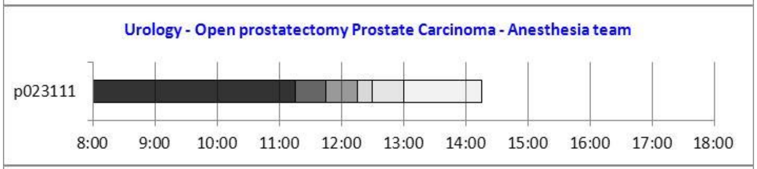
ORs

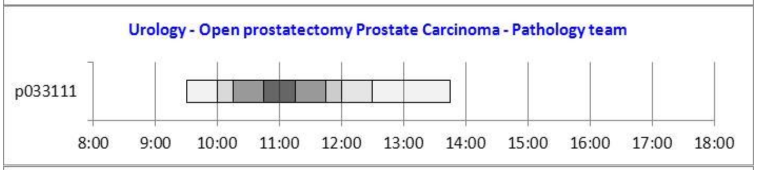


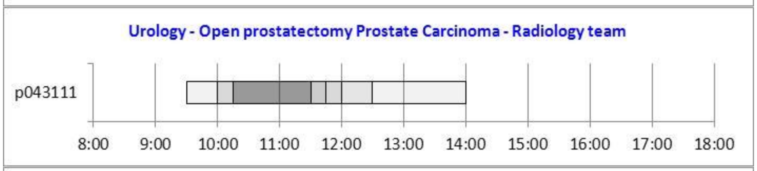


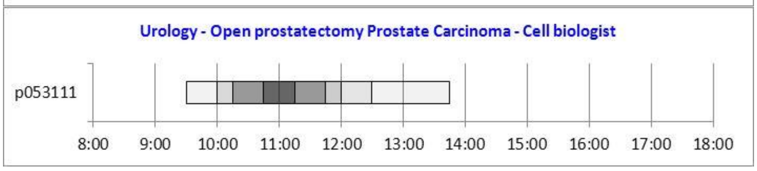
Personnel



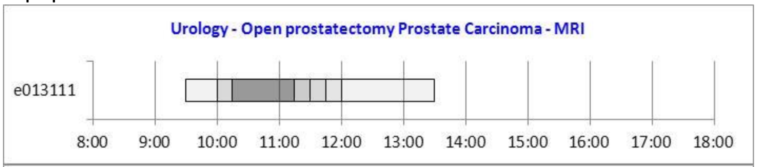


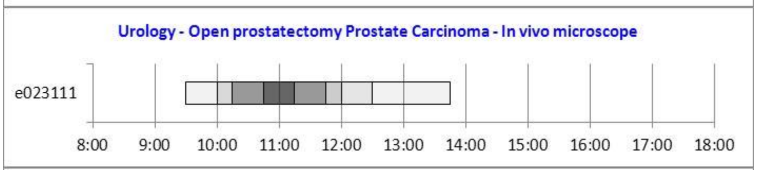


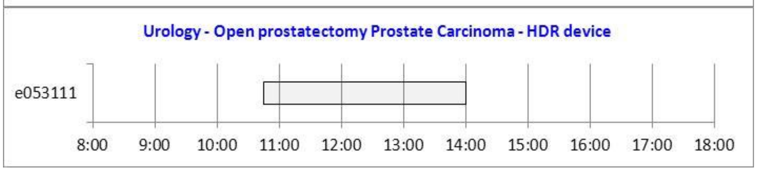




Equipment

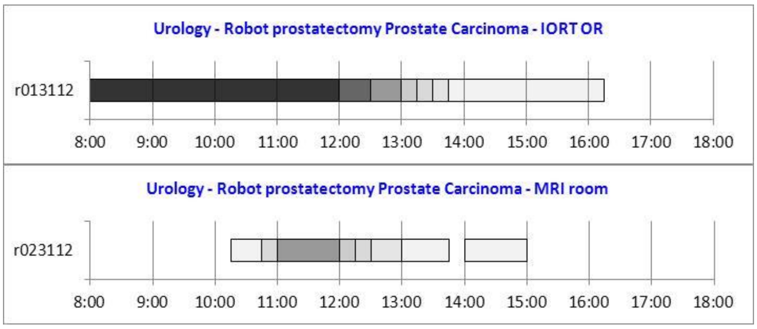




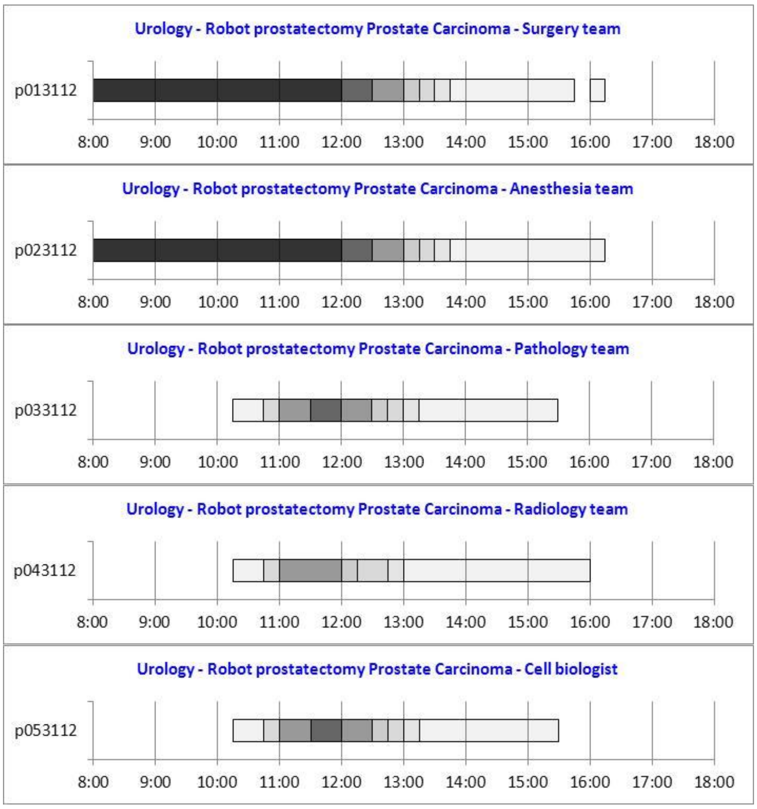


Urology – robot prostatectomy

ORs

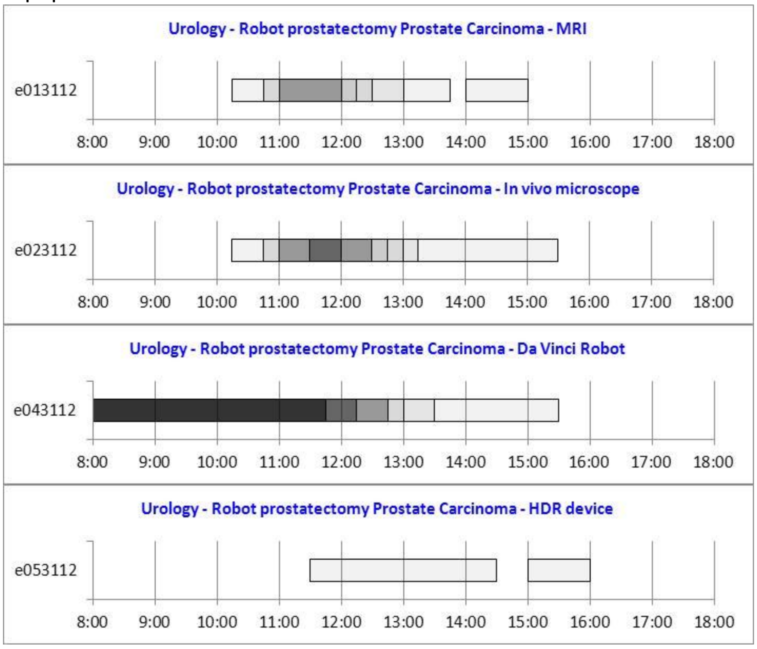


Personnel



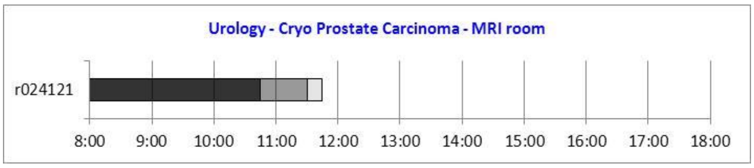
Urology – robot prostatectomy

Equipment

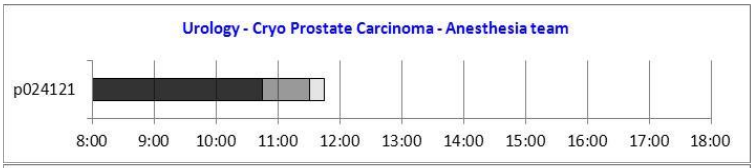


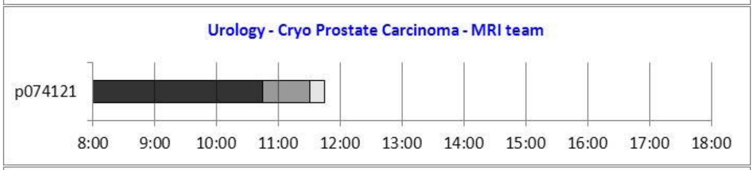
Urology – cryo

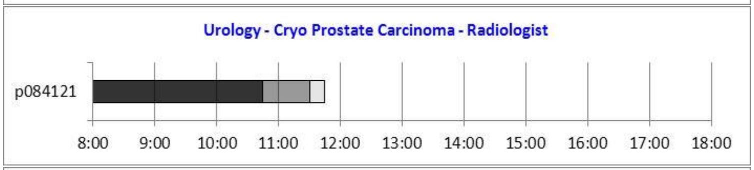
ORs

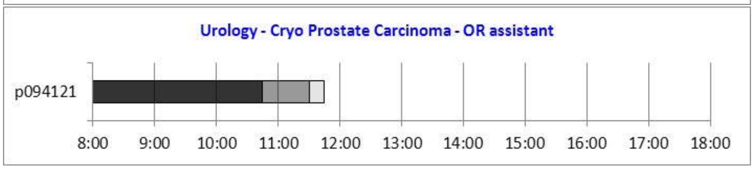


Personnel

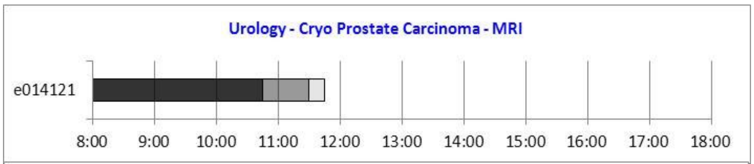


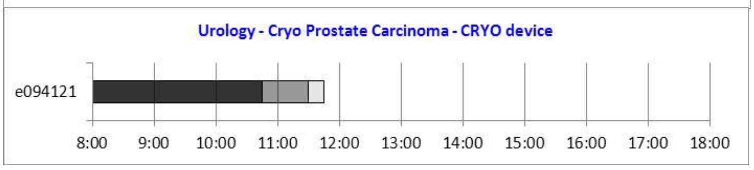






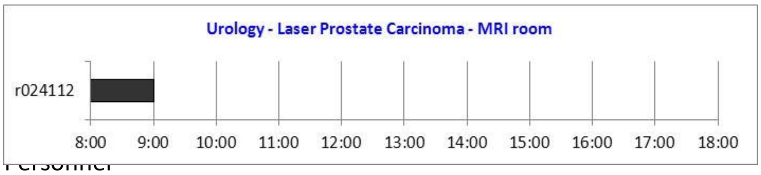
Equipment



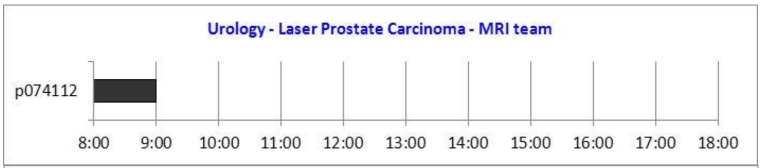


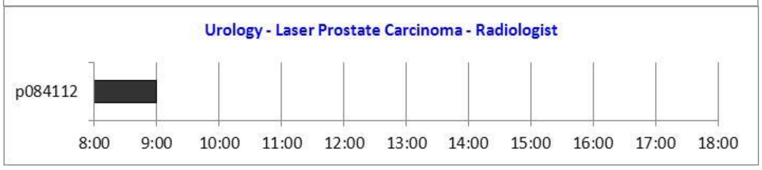
Urology – laser

ORs



Personnel





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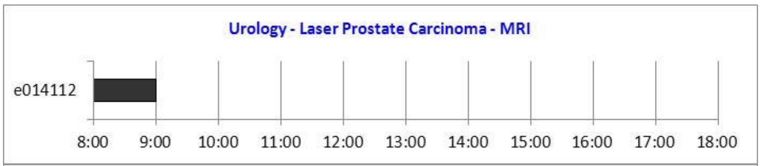
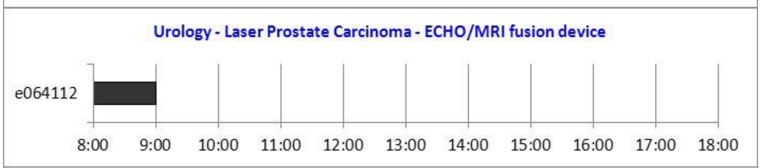
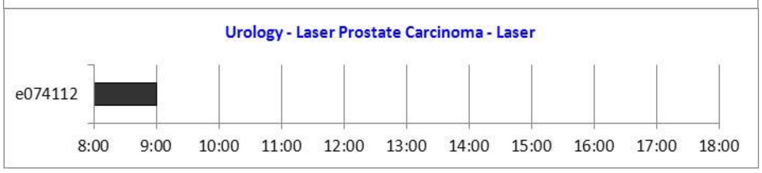
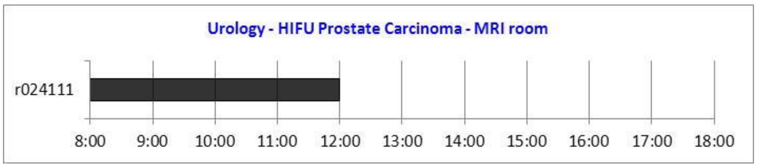




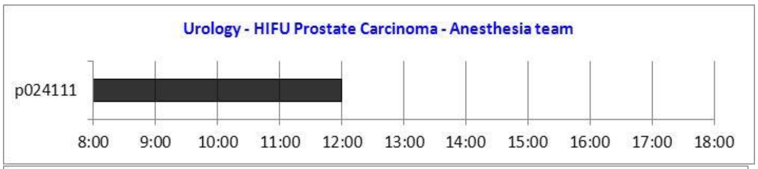


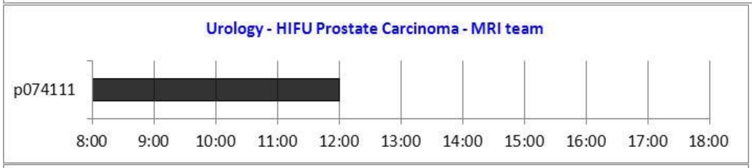
Urology – HIFU

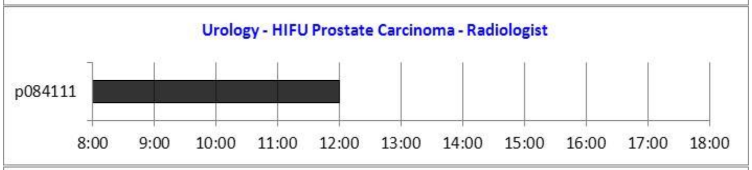
ORs

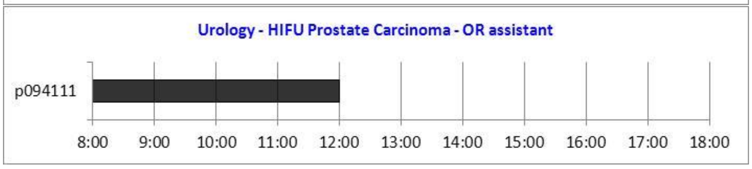


Personnel

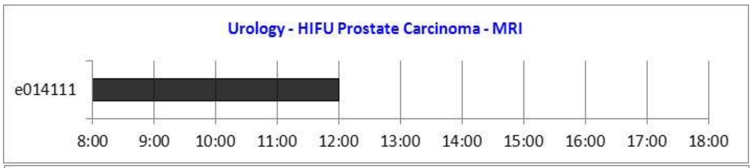


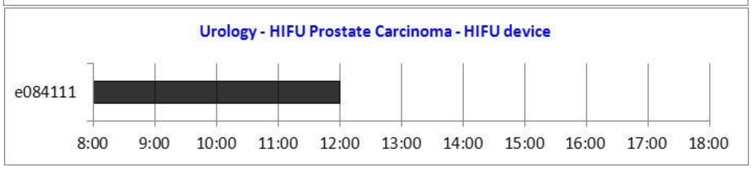






Equipment





Appendix V: (Performance) Measures per Scenario

In this appendix different measures per scenario are provided (see following pages). The performance measures are printed in “Bold”. In the first part of each table the performance measures per patient are described. Column 1 described the SG. Column 2 provides the number of patients scheduled per year. Column 3 includes the number of expected number of patients per year. Column 4 shows the surgery rate which is determined by dividing the number of allocated patients by the number of expected patients. Column 5 provides the patient waiting time during surgery per patient.

The second part of each table provides the performance measures per room. In this case, column 1 provides the particular room and column 2 shows the utilization per room.

Part three of the table delivers the performance measures per personnel member and personnel team. They are grouped by their associated SG as can be seen in column 1. The performance measures include the average number of hours required per member and per team (column 2 and 3, respectively), the average number of hours process time per member and team (column 4 and 5, respectively), the average number of hours waiting time during surgery or between subsequent surgeries on the same day per member and per team (column 6 and 7, respectively), and the number of hours of overtime per member and per team (column 8 and 9, respectively).

Scenario 1 (one surgery per surgical group per week)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	40	60	0	**67%**	**0:00**
Gynaecology	40	70	0	**57%**	**0:00**
Urology	40	130	0	**31%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	120	660	0	**18%**	**0:00**

OR	**Utilization**
IORT OR	**24%**
MRI OR	**7%**
HYB OR	**0%**
TOTAL	**10%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		31:47		31:22		**0:25**		**0:00**
Surgery team	4:15	12:46	4:15	12:46	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	4:15	12:46	4:15	12:46	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	1:41	3:23	1:31	3:03	**0:10**	**0:20**	**0:00**	**0:00**
Radiology team	0:40	1:20	0:40	1:20	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:11	1:11	1:06	1:06	**0:04**	**0:04**	**0:00**	**0:00**
Pathology team2	0:09	0:19	0:09	0:19	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		27:19		25:35		**1:44**		**0:00**
Surgery team	3:39	10:58	3:09	9:27	**0:30**	**1:30**	**0:00**	**0:00**
Anaesthesia team	3:39	10:58	3:39	10:58	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:18	0:36	0:18	0:36	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:30	1:01	0:24	0:48	**0:06**	**0:13**	**0:00**	**0:00**
Cell biologist	1:34	1:34	1:34	1:34	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	1:46	1:46	1:46	1:46	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:12	0:24	0:12	0:24	**0:00**	**0:00**	**0:00**	**0:00**
Urology		22:43		22:34		**0:08**		**0:00**
Surgery team	1:57	5:53	1:55	5:47	**0:01**	**0:05**	**0:00**	**0:00**
Anaesthesia team	3:10	9:30	3:10	9:30	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:27	0:54	0:27	0:54	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:21	0:43	0:20	0:40	**0:01**	**0:03**	**0:00**	**0:00**
Cell biologist	0:27	0:27	0:27	0:27	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	1:20	2:40	1:20	2:40	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	1:20	1:20	1:20	1:20	**0:00**	**0:00**	**0:00**	**0:00**
OK Assistant	1:12	1:12	1:12	1:12	**0:00**	**0:00**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		81:50		79:32		**2:18**		**0:00**

Scenario 2 (four IORT OR and/or MRI OR days)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	40	60	0	**67%**	**0:00**
Gynaecology	40	70	0	**57%**	**0:00**
Urology	120	130	0	**92%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	200	660	0	**30%**	**0:00**

OR	**Utilization**
IORT OR	**30%**
MRI OR	**16%**
HYB OR	**0%**
TOTAL	**15%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		31:35		31:12		**0:23**		**0:00**
Surgery team	4:13	12:41	4:13	12:41	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	4:13	12:41	4:13	12:41	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	1:41	3:22	1:31	3:03	**0:09**	**0:19**	**0:00**	**0:00**
Radiology team	0:40	1:20	0:40	1:20	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:10	1:10	1:06	1:06	**0:04**	**0:04**	**0:00**	**0:00**
Pathology team2	0:09	0:19	0:09	0:19	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		26:40		25:02		**1:38**		**0:00**
Surgery team	3:35	10:45	3:06	9:19	**0:28**	**1:26**	**0:00**	**0:00**
Anaesthesia team	3:35	10:45	3:35	10:45	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:17	0:34	0:17	0:34	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:28	0:57	0:22	0:44	**0:06**	**0:12**	**0:00**	**0:00**
Cell biologist	1:32	1:32	1:32	1:32	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	1:43	1:43	1:43	1:43	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:11	0:22	0:11	0:22	**0:00**	**0:00**	**0:00**	**0:00**
Urology		68:56		62:16		**9:07**		**0:00**
Surgery team	4:17	12:51	4:13	12:40	**0:03**	**0:11**	**0:00**	**0:00**
Anaesthesia team	9:07	27:23	8:41	26:04	**0:46**	**2:18**	**0:00**	**0:00**
Pathology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:46	1:33	0:43	1:27	**0:03**	**0:06**	**0:00**	**0:00**
Cell biologist	1:00	1:00	1:00	1:00	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:25	12:51	4:53	9:47	**1:52**	**3:54**	**0:00**	**0:00**
Radiologist	6:25	6:25	4:53	4:53	**1:52**	**1:52**	**0:00**	**0:00**
OK Assistant	4:50	4:50	4:24	4:24	**0:46**	**0:46**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		127:12		118:30		**11:08**		**0:00**

Scenario 3a (five IORT OR and/or MRI OR days) – two head/neck surgeries per week

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	80	60	20	**100%**	**0:00**
Gynaecology	40	70	0	**57%**	**0:00**
Urology	160	130	30	**100%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	280	660	50	**35%**	**0:00**

OR	**Utilization**
IORT OR	**51%**
MRI OR	**20%**
HYB OR	**0%**
TOTAL	**24%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		63:51		63:02		**0:48**		**0:00**
Surgery team	8:34	25:42	8:34	25:42	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	8:34	25:42	8:34	25:42	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	3:23	6:47	3:03	6:07	**0:19**	**0:39**	**0:00**	**0:00**
Radiology team	1:20	2:40	1:20	2:40	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	2:22	2:22	2:12	2:12	**0:09**	**0:09**	**0:00**	**0:00**
Pathology team2	0:18	0:37	0:18	0:37	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		26:19		24:41		**1:38**		**0:00**
Surgery team	3:31	10:35	3:03	9:10	**0:28**	**1:25**	**0:00**	**0:00**
Anaesthesia team	3:31	10:35	3:31	10:35	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:17	0:35	0:17	0:35	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:28	0:57	0:22	0:45	**0:06**	**0:12**	**0:00**	**0:00**
Cell biologist	1:31	1:31	1:31	1:31	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	1:42	1:42	1:42	1:42	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:11	0:22	0:11	0:22	**0:00**	**0:00**	**0:00**	**0:00**
Urology		91:28		90:52		**0:36**		**0:00**
Surgery team	8:24	25:14	8:16	24:50	**0:07**	**0:23**	**0:00**	**0:00**
Anaesthesia team	12:44	38:14	12:44	38:14	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:00	4:00	2:00	4:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:34	3:08	1:27	2:55	**0:06**	**0:12**	**0:00**	**0:00**
Cell biologist	2:00	2:00	2:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	4:50	9:40	4:50	9:40	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	4:50	4:50	4:50	4:50	**0:00**	**0:00**	**0:00**	**0:00**
OK Assistant	4:20	4:20	4:20	4:20	**0:00**	**0:00**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		181:40		178:37		**3:03**		**0:00**

Scenario 3b (five IORT OR and/or MRI OR days) – two gynaecology surgeries per week

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	40	60	0	**67%**	**0:00**
Gynaecology	80	70	10	**100%**	**0:00**
Urology	160	130	30	**100%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	280	660	40	**36%**	**0:00**

OR	**Utilization**
IORT OR	**49%**
MRI OR	**20%**
HYB OR	**0%**
TOTAL	**23%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		31:58		30:34		**0:24**		**0:00**
Surgery team	4:17	12:52	4:17	12:52	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	4:17	12:52	4:17	12:52	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	1:42	3:24	1:32	3:04	**0:10**	**0:20**	**0:00**	**0:00**
Radiology team	0:40	1:20	0:40	1:20	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:11	1:11	0:06	0:06	**0:04**	**0:04**	**0:00**	**0:00**
Pathology team2	0:09	0:18	0:09	0:18	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		54:26		50:39		**3:46**		**0:00**
Surgery team	7:17	21:52	6:11	18:33	**1:06**	**3:18**	**0:00**	**0:00**
Anaesthesia team	7:17	21:52	7:17	21:52	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:40	1:21	0:40	1:21	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:06	2:12	0:51	1:43	**0:14**	**0:28**	**0:00**	**0:00**
Cell biologist	2:55	2:55	2:55	2:55	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	3:21	3:21	3:21	3:21	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:25	0:51	0:25	0:51	**0:00**	**0:00**	**0:00**	**0:00**
Urology		98:42		91:49		**9:06**		**0:00**
Surgery team	8:23	25:11	8:16	24:50	**0:07**	**0:21**	**0:00**	**0:00**
Anaesthesia team	13:20	40:01	12:53	38:40	**0:46**	**2:18**	**0:00**	**0:00**
Pathology team	2:00	4:00	2:00	4:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:32	3:05	1:27	2:54	**0:05**	**0:11**	**0:00**	**0:00**
Cell biologist	2:00	2:00	2:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:28	12:57	4:57	9:55	**1:50**	**3:40**	**0:00**	**0:00**
Radiologist	6:28	6:28	4:57	4:57	**1:50**	**1:50**	**0:00**	**0:00**
OK Assistant	4:56	4:56	4:29	4:29	**0:46**	**0:46**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		185:08		173:02		**13:16**		**0:00**

Scenario 4 (five IORT OR and/or MRI OR days, cycle length is 2 weeks)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	60	70	0	**86%**	**0:00**
Urology	140	130	10	**100%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	260	660	10	**38%**	**0:00**

OR	**Utilization**
IORT OR	**45%**
MRI OR	**19%**
HYB OR	**0%**
TOTAL	**21%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:40		47:03		**0:36**		**0:00**
Surgery team	6:23	19:09	6:23	19:09	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:23	19:09	6:23	19:09	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:32	5:04	2:17	4:34	**0:14**	**0:29**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:29	0:14	0:29	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		40:34		37:47		**2:47**		**0:00**
Surgery team	5:26	16:18	4:37	13:52	**0:48**	**2:25**	**0:00**	**0:00**
Anaesthesia team	5:26	16:18	5:26	16:18	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:29	0:58	0:29	0:58	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:49	1:38	0:38	1:16	**0:10**	**0:21**	**0:00**	**0:00**
Cell biologist	2:11	2:11	2:11	2:11	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	2:30	2:30	2:30	2:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:19	0:38	0:19	0:38	**0:00**	**0:00**	**0:00**	**0:00**
Urology		80:40		76:58		**4:49**		**0:00**
Surgery team	6:20	19:01	6:15	18:44	**0:05**	**0:16**	**0:00**	**0:00**
Anaesthesia team	11:00	33:02	10:46	32:20	**0:24**	**1:12**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:10	2:20	1:05	2:11	**0:04**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	5:41	11:23	4:55	9:50	**0:56**	**1:52**	**0:00**	**0:00**
Radiologist	5:41	5:41	4:55	4:55	**0:56**	**0:56**	**0:00**	**0:00**
OK Assistant	4:40	4:40	4:26	4:26	**0:24**	**0:24**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		168:55		161:49		**8:12**		**0:00**

Scenario 5 (five IORT OR and/or MRI OR days, change in current OR days required)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	80	70	10	**100%**	**0:00**
Urology	140	130	10	**100%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	280	660	20	**39%**	**0:00**

OR	**Utilization**
IORT OR	**49%**
MRI OR	**20%**
HYB OR	**0%**
TOTAL	**23%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:40		47:04		**0:36**		**0:00**
Surgery team	6:23	19:10	6:23	19:10	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:23	19:10	6:23	19:10	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:32	5:04	2:17	4:34	**0:14**	**0:29**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:28	0:14	0:28	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		54:42		50:48		**3:54**		**0:00**
Surgery team	7:19	21:57	6:11	18:33	**1:08**	**3:24**	**0:00**	**0:00**
Anaesthesia team	7:19	21:57	7:19	21:57	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:41	1:22	0:41	1:22	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:08	2:17	0:53	1:47	**0:14**	**0:29**	**0:00**	**0:00**
Cell biologist	2:53	2:53	2:53	2:53	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	3:20	3:20	3:20	3:20	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:26	0:53	0:26	0:53	**0:00**	**0:00**	**0:00**	**0:00**
Urology		84:24		77:33		**9:08**		**0:00**
Surgery team	6:21	19:04	6:15	18:46	**0:05**	**0:17**	**0:00**	**0:00**
Anaesthesia team	11:20	34:02	10:52	32:38	**0:48**	**2:24**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:10	2:21	1:05	2:11	**0:04**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:28	12:57	4:58	9:57	**1:50**	**3:40**	**0:00**	**0:00**
Radiologist	6:28	6:28	4:58	4:58	**1:50**	**1:50**	**0:00**	**0:00**
OK Assistant	4:59	4:59	4:31	4:31	**0:48**	**0:48**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		186:47		175:26		13:38		0:00

Scenario 6 (all tumour surgeries scheduled, proven ovarian (12:00) and OCS (08:00))

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	80	70	0	**100%**	**0:00**
Urology	140	130	0	**100%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	280	660	0	**42%**	**0:00**

OR	**Utilization**
IORT OR	**43%**
MRI OR	**19%**
HYB OR	**5%**
TOTAL	**22%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:34		46:58		**0:36**		**0:00**
Surgery team	6:22	19:07	6:22	19:07	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:22	19:07	6:22	19:07	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:31	5:03	2:17	4:34	**0:14**	**0:29**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:29	0:14	0:29	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		54:15		50:23		**3:52**		**3:13**
Surgery team	7:15	21:47	6:08	18:24	**1:07**	**3:22**	**0:25**	**1:15**
Anaesthesia team	7:15	21:47	7:15	21:47	**0:00**	**0:00**	**0:25**	**1:15**
Pathology team	0:41	1:22	0:41	1:22	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:07	2:15	0:53	1:46	**0:14**	**0:29**	**0:00**	**0:00**
Cell biologist	2:51	2:51	2:51	2:51	**0:00**	**0:00**	**0:21**	**0:21**
Nucl Med Phys	3:18	3:18	3:18	3:18	**0:00**	**0:00**	**0:21**	**0:21**
MRI team	0:26	0:52	0:26	0:52	**0:00**	**0:00**	**0:00**	**0:00**
Urology		83:57		77:01		**9:14**		**0:00**
Surgery team	6:22	19:07	6:16	18:50	**0:05**	**0:17**	**0:00**	**0:00**
Anaesthesia team	11:15	33:45	10:47	32:22	**0:47**	**2:24**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:10	2:21	1:05	2:11	**0:04**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:26	12:53	4:53	9:47	**1:52**	**3:45**	**0:00**	**0:00**
Radiologist	6:26	6:26	4:53	4:53	**1:52**	**1:52**	**0:00**	**0:00**
OK Assistant	4:52	4:52	4:25	4:25	**0:47**	**0:47**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		185:47		174:23		**13:42**		**3:13**

Scenario 7a (all carc. patients treated, expected ovarian and OCS on Wednesday) - option 1: gyn starts at 12:00

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	80	70	0	**100%**	**0:00**
Urology	140	130	0	**100%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	280	660	0	**42%**	**0:00**

OR	**Utilization**
IORT OR	**43%**
MRI OR	**20%**
HYB OR	**5%**
TOTAL	**23%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:38		47:01		**0:36**		**0:00**
Surgery team	6:23	19:09	6:23	19:09	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:23	19:09	6:23	19:09	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:32	5:04	2:17	4:35	**0:14**	**0:29**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:29	0:14	0:29	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		54:29		50:33		**3:56**		**2:16**
Surgery team	7:17	21:51	6:08	18:25	**1:08**	**3:26**	**0:18**	**0:56**
Anaesthesia team	7:17	21:51	7:17	21:51	**0:00**	**0:00**	**0:18**	**0:56**
Pathology team	0:41	1:23	0:41	1:23	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:09	2:18	0:54	1:48	**0:14**	**0:29**	**0:00**	**0:01**
Cell biologist	2:52	2:52	2:52	2:52	**0:00**	**0:00**	**0:05**	**0:05**
Nucl Med Phys	3:18	3:18	3:18	3:18	**0:00**	**0:00**	**0:14**	**0:14**
MRI team	0:27	0:54	0:27	0:54	**0:00**	**0:00**	**0:00**	**0:01**
Urology		83:51		77:01		**9:08**		**0:00**
Surgery team	6:21	19:03	6:15	18:46	**0:05**	**0:16**	**0:00**	**0:00**
Anaesthesia team	11:13	33:41	10:47	32:22	**0:46**	**2:18**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:10	2:20	1:05	2:11	**0:04**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:28	12:56	4:55	9:50	**1:53**	**3:46**	**0:00**	**0:00**
Radiologist	6:28	6:28	4:55	4:55	**1:53**	**1:53**	**0:00**	**0:00**
OK Assistant	4:52	4:52	4:26	4:26	**0:46**	**0:46**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		186:00		174:36		**13:40**		**2:16**

Scenario 7b (all carc. patients treated, expected ovarian and OCS on Wednesday) - option 2: gyn starts at 12:30

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	80	70	0	**100%**	**0:00**
Urology	140	130	0	**100%**	**0:00**
Radiology	0	400	0	**0%**	**0:00**
TOTAL	280	660	0	**42%**	**0:00**

OR	**Utilization**
IORT OR	**43%**
MRI OR	**19%**
HYB OR	**5%**
TOTAL	**22%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:48		47:11		**0:36**		**0:00**
Surgery team	6:24	19:14	6:24	19:14	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:24	19:14	6:24	19:14	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:32	5:05	2:17	4:35	**0:14**	**0:29**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:28	0:14	0:28	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		54:14		50:23		**3:51**		**3:28**
Surgery team	7:15	21:46	6:08	18:24	**1:07**	**3:22**	**0:27**	**1:23**
Anaesthesia team	7:15	21:46	7:15	21:46	**0:00**	**0:00**	**0:27**	**1:23**
Pathology team	0:40	1:21	0:40	1:21	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:07	2:15	0:53	1:46	**0:14**	**0:29**	**0:02**	**0:04**
Cell biologist	2:52	2:52	2:52	2:52	**0:00**	**0:00**	**0:08**	**0:08**
Nucl Med Phys	3:18	3:18	3:18	3:18	**0:00**	**0:00**	**0:23**	**0:23**
MRI team	0:26	0:53	0:26	0:53	**0:00**	**0:00**	**0:02**	**0:04**
Urology		84:10		77:18		**9:09**		**0:00**
Surgery team	6:22	19:08	6:17	18:51	**0:05**	**0:16**	**0:00**	**0:00**
Anaesthesia team	11:17	33:52	10:50	32:30	**0:47**	**2:21**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:10	2:20	1:05	2:11	**0:04**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:28	12:56	4:55	9:51	**1:52**	**3:44**	**0:00**	**0:00**
Radiologist	6:28	6:28	4:55	4:55	**1:52**	**1:52**	**0:00**	**0:00**
OK Assistant	4:54	4:54	4:27	4:27	**0:47**	**0:47**	**0:00**	**0:00**
Radiology		0:00		0:00		**0:00**		**0:00**
MRI team	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	0:00	0:00	0:00	0:00	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		186:14		174:53		**13:36**		**3:29**

Scenario 8 (partly patients having a tumour and all diagnostic MRI patients)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	60	70	0	**86%**	**0:00**
Urology	140	130	10	**100%**	**0:00**
Radiology	402	400	2	**100%**	**0:00**
TOTAL	662	660	12	**98%**	**0:00**

OR	**Utilization**
IORT OR	**45%**
MRI OR	**43%**
HYB OR	**0%**
TOTAL	**29%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:48		47:12		**0:36**		**0:00**
Surgery team	6:24	19:14	6:24	19:14	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:24	19:14	6:24	19:14	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:31	5:03	2:17	4:34	**0:14**	**0:29**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:29	0:14	0:29	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		41:23		38:34		**2:48**		**0:00**
Surgery team	5:31	16:35	4:42	14:08	**0:49**	**2:27**	**0:00**	**0:00**
Anaesthesia team	5:31	16:35	5:31	16:35	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:29	0:58	0:29	0:58	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:49	1:39	0:38	1:17	**0:10**	**0:21**	**0:00**	**0:00**
Cell biologist	2:17	2:17	2:17	2:17	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	2:37	2:37	2:37	2:37	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:19	0:39	0:19	0:39	**0:00**	**0:00**	**0:00**	**0:00**
Urology		81:18		77:07		**5:16**		**0:02**
Surgery team	6:22	19:08	6:15	18:47	**0:06**	**0:20**	**0:00**	**0:00**
Anaesthesia team	11:08	33:24	10:48	32:25	**0:29**	**1:27**	**0:00**	**0:00**
Pathology team	1:31	3:03	1:30	3:00	**0:01**	**0:03**	**0:00**	**0:00**
Radiology team	1:11	2:22	1:05	2:10	**0:06**	**0:12**	**0:00**	**0:00**
Cell biologist	1:31	1:31	1:30	1:30	**0:01**	**0:01**	**0:00**	**0:00**
MRI team	5:42	11:24	4:55	9:50	**0:56**	**1:53**	**0:00**	**0:00**
Radiologist	5:42	5:42	4:55	4:55	**0:56**	**0:56**	**0:00**	**0:00**
OK Assistant	4:41	4:41	4:27	4:27	**0:24**	**0:24**	**0:00**	**0:00**
Radiology		41:50		41:46		**0:03**		**0:53**
MRI team	10:27	20:55	10:26	20:53	**0:00**	**0:01**	**0:13**	**0:26**
Radiologist	10:27	10:27	10:26	10:26	**0:00**	**0:00**	**0:13**	**0:13**
Anaesthesia team2	10:27	10:27	10:26	10:26	**0:00**	**0:00**	**0:13**	**0:13**
TOTAL		212:20		204:40		**8:40**		**0:56**

Scenario 9 (partly patients having a tumour and all diagnostic MRI patients including µMRI)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	60	70	0	**86%**	**0:00**
Urology	140	130	10	**100%**	**0:00**
Radiology	402	400	2	**100%**	**0:00**
TOTAL	662	660	12	**98%**	**0:00**

OR	**Utilization**
IORT OR	**45%**
MRI OR	**39%**
HYB OR	**0%**
TOTAL	**28%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:56		47:21		**0:35**		**0:00**
Surgery team	6:26	19:19	6:26	19:19	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:26	19:19	6:26	19:19	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:31	5:03	2:17	4:34	**0:14**	**0:28**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:29	0:14	0:29	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		40:44		38:02		**2:42**		**0:00**
Surgery team	5:27	16:22	4:40	14:00	**0:47**	**2:21**	**0:00**	**0:00**
Anaesthesia team	5:27	16:22	5:27	16:22	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:28	0:57	0:28	0:57	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:47	1:34	0:37	1:14	**0:10**	**0:20**	**0:00**	**0:00**
Cell biologist	2:16	2:16	2:16	2:16	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	2:35	2:35	2:35	2:35	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:18	0:36	0:18	0:36	**0:00**	**0:00**	**0:00**	**0:00**
Urology		74:56		76:58		**9:10**		**0:00**
Surgery team	6:22	19:07	6:16	18:50	**0:05**	**0:16**	**0:00**	**0:00**
Anaesthesia team	8:15	24:47	10:46	32:20	**0:47**	**2:21**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:09	2:19	1:05	2:10	**0:04**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:27	12:54	4:53	9:47	**1:53**	**3:46**	**0:00**	**0:00**
Radiologist	6:27	6:27	4:53	4:53	**1:53**	**1:53**	**0:00**	**0:00**
OK Assistant	4:50	4:50	4:24	4:24	**0:45**	**0:45**	**0:00**	**0:00**
Radiology		41:49		41:50		**0:00**		**0:18**
MRI team	10:27	20:54	10:27	20:55	**0:00**	**0:00**	**0:04**	**0:09**
Radiologist	10:27	10:27	10:27	10:27	**0:00**	**0:00**	**0:04**	**0:04**
Anaesthesia team2	10:27	10:27	10:27	10:27	**0:00**	**0:00**	**0:04**	**0:04**
TOTAL		205:28		204:12		**12:27**		**0:18**

Scenario 10 (partly patients having a tumour and all diagnostic MRI – only morning MRIs)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	60	70	0	**86%**	**0:00**
Urology	140	130	10	**100%**	**0:00**
Radiology	402	400	2	**100%**	**0:00**
TOTAL	662	660	12	**98%**	**0:00**

OR	**Utilization**
IORT OR	**45%**
MRI OR	**39%**
HYB OR	**0%**
TOTAL	**28%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:55		47:18		**0:36**		**0:00**
Surgery team	6:25	19:17	6:25	19:17	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:25	19:17	6:25	19:17	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:32	5:04	2:17	4:35	**0:14**	**0:29**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:14	0:29	0:14	0:29	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		40:31		37:43		**2:47**		**0:00**
Surgery team	5:25	16:16	4:36	13:50	**0:48**	**2:26**	**0:00**	**0:00**
Anaesthesia team	5:25	16:16	5:25	16:16	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:29	0:59	0:29	0:59	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	0:49	1:38	0:38	1:16	**0:10**	**0:21**	**0:00**	**0:00**
Cell biologist	2:11	2:11	2:11	2:11	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	2:30	2:30	2:30	2:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:19	0:38	0:19	0:38	**0:00**	**0:00**	**0:00**	**0:00**
Urology		74:44		77:00		**9:06**		**0:00**
Surgery team	6:21	19:04	6:15	18:47	**0:05**	**0:17**	**0:00**	**0:00**
Anaesthesia team	8:13	24:39	10:47	32:22	**0:47**	**2:21**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:10	2:20	1:05	2:11	**0:04**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:25	12:51	4:54	9:49	**1:51**	**3:42**	**0:00**	**0:00**
Radiologist	6:25	6:25	4:54	4:54	**1:51**	**1:51**	**0:00**	**0:00**
OK Assistant	4:52	4:52	4:25	4:25	**0:46**	**0:46**	**0:00**	**0:00**
Radiology		41:47		41:48		**0:00**		**0:00**
MRI team	10:26	20:53	10:27	20:54	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	10:26	10:26	10:27	10:27	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	10:26	10:26	10:27	10:27	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		204:58		203:50		**12:29**		**0:00**

Scenario 11 (all patients including µMRI and two in vivo microscopes)

SG	# Patients allocated per year	Expected # patients per year	Spare places per year	**Patients treated of expected patients**	**# Hours patient waiting time during surgery**
Head/Neck	60	60	0	**100%**	**0:00**
Gynaecology	80	70	10	**100%**	**0:00**
Urology	140	130	10	**100%**	**0:00**
Radiology	402	400	2	**100%**	**0:00**
TOTAL	662	660	12	**100%**	**0:00**

OR	**Utilization**
IORT OR	**44%**
MRI OR	**40%**
HYB OR	**5%**
TOTAL	**29%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	**Avg # hours waiting time per person**	**Avg # hours waiting time per team**	**Avg # hours overtime per person**	**Avg # hours overtime per team**
Head/Neck		47:48		47:11		**0:37**		**0:00**
Surgery team	6:25	19:15	6:25	18:04	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team	6:25	19:15	6:25	18:04	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	2:32	5:03	2:17	4:34	**0:15**	**0:30**	**0:00**	**0:00**
Radiology team	1:00	2:00	1:00	2:00	**0:00**	**0:00**	**0:00**	**0:00**
Cell biologist	1:46	1:46	1:39	1:39	**0:07**	**0:07**	**0:00**	**0:00**
Pathology team2	0:15	0:29	0:15	0:29	**0:00**	**0:00**	**0:00**	**0:00**
Gynaecology		54:34		50:29		**4:05**		**0:00**
Surgery team	7:19	21:56	6:18	18:55	**1:01**	**3:02**	**0:00**	**0:00**
Anaesthesia team	7:19	21:56	7:19	21:56	**0:00**	**0:00**	**0:00**	**0:00**
Pathology team	0:41	1:21	0:41	1:21	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:06	2:11	0:34	1:08	**0:32**	**1:03**	**0:00**	**0:00**
Cell biologist	2:58	2:58	2:58	2:58	**0:00**	**0:00**	**0:00**	**0:00**
Nucl Med Phys	3:22	3:22	3:22	3:22	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	0:24	0:49	0:24	0:49	**0:00**	**0:00**	**0:00**	**0:00**
Urology		74:51		69:24		**9:05**		**0:00**
Surgery team	6:22	19:07	6:17	18:50	**0:06**	**0:17**	**0:00**	**0:00**
Anaesthesia team	8:16	24:47	8:16	24:47	**0:47**	**2:20**	**0:00**	**0:00**
Pathology team	1:30	3:00	1:30	3:00	**0:00**	**0:00**	**0:00**	**0:00**
Radiology team	1:09	2:19	1:05	2:09	**0:05**	**0:09**	**0:00**	**0:00**
Cell biologist	1:30	1:30	1:30	1:30	**0:00**	**0:00**	**0:00**	**0:00**
MRI team	6:26	12:52	4:55	9:49	**1:51**	**3:42**	**0:00**	**0:00**
Radiologist	6:26	6:26	4:55	4:55	**1:51**	**1:51**	**0:00**	**0:00**
OK Assistant	4:50	4:50	4:24	4:24	**0:46**	**0:46**	**0:00**	**0:00**
Radiology		41:50		41:50		**0:00**		**0:00**
MRI team	10:27	20:55	10:27	20:55	**0:00**	**0:00**	**0:00**	**0:00**
Radiologist	10:27	10:27	10:27	10:27	**0:00**	**0:00**	**0:00**	**0:00**
Anaesthesia team2	10:27	10:27	10:27	10:27	**0:00**	**0:00**	**0:00**	**0:00**
TOTAL		219:03		208:54		**13:47**		**0:00**

Appendix VI: Database Description

OKsimed is a database used for data registration in the RUNMC. This data was available to me from January 2010 until December 2012 and in some cases till June 2013. On top of that a list of College Tarieven Gezondheidszorg (CTG) codes and CTG code meanings has been provided. In OKsimed for every surgery the following registrations are covered as given in Table 3: (1) patient nr: gives us the number of the patient and should be unique for every individual patient, (2) SG: the SG that treats the patient, (3) date: the data on which the patient has been treated, (4) initiate time: the time it takes to initiate the surgery which includes letting the patient go to sleep and preparing required surgery resources, (5) prepare time: time it takes to position the patient and surrounding instruments, (6) operate time: time it takes to use manual and instrumental techniques on a patient to treat him, (7) wake up time: time it takes to wake up the patient, (8) CTG codes: codes to assign certain used methods to a patient and (8) CTGCodemeaning: meaning of the CTG code to indicate which method(s) and body location(s) have been used for surgery (For example, a CTG code can stand for an amputation of a toe, which gives us the method, which is an amputation, and the bodily location, which is a toe).

Depending on how precise the method is described in the CTG code list, the data is useful or not. A CTG code can stand for amputation of a toe, but a toe can be removed because a tumour was discovered in the toe or because a cyst was present. The latter has nothing to do with a tumour at all. The wrong level of detail combined with the lack of patient diagnosis data makes it hard to work with the data in some cases.

Table 11: Example of OKsimed data registration (no real patients)

Patient nr	SG	Date	Initiate time	Prepare time	Operate time	Wake up time	CTG Codes	CTGCode meaning
58423	KNO	04-01-2010	0:13	0:00	0:06	0:08	352281	Foot: Amputation tow
24623	KNO	11-01-2010	0:07	0:01	0:26	0:23	337126; 352281	Skin: Dermabrasion Foot: Amputation tow
23462	KNO	18-01-2010	0:04	0:03	0:09	0:06	335126	Prostate: Prostatectomy

Appendix VII: Verification of Model Results

In this appendix the model is verified by using an example of a patient receiving a treatment for an OCS tumour. This verification is done by calculating the expected performance measures and comparing them with the results of the simulation model.

Comparing surgical group results

In the first part of Table 14 you can see 40 patients of gynaecology will undergo surgery. 40 weeks per week with one expected malignant tumour surgery per week indeed leads to 40 surgeries of gynaecology per year.

Comparing personnel results

Using Figure 66 we can calculate the probability that each sequence occurs and the duration per sequence as done in Table 12. These values should be compared with the values generated in Arena as provided in Table 14. As can be extracted from Table 12, which is calculated manually, the process time for an anaesthesia team, which is required during every step of the procedure, should lie around 4 hours and 12 minutes for this patient. Comparing this to the process time provided in Table 14, which is 4 hours and 13 minutes this is about equal (deviation is less than 1 %). Waiting time for the anaesthesia team should indeed be zero minutes.

When looking at the waiting time we can use the example of a surgery team. The surgery team is not involved in the process steps provided in Table 13. This will result in waiting time. This waiting time can be extracted from both the probability that the process steps in which the surgery team is not involved occur and the process step duration. According to this table the waiting time for the surgery team should lie around 1 hour and 36 minutes. In the table extracted from Arena this is 1 hour and 37 minutes, a deviation from approximately 1 %.

The required time is the sum of the process time and the waiting time and is equal by manual calculation and simulation as well. Overtime does not occur as can be seen in the simulation output.

In the third part of the table the performance measures are provided that belong to the personnel types. The second column provides the average hours of required time per personnel type for each particular surgery type. This required time is a sum of the process time (column 3) and the waiting time (column 5). In column 2, 4, and 6 the same results are provided but now for the whole team. For example, a surgery team of the head/neck SG includes three members, as provided in Table 2, so the required time of one personnel member of the surgery team is multiplied by three to result in the required time for the whole team. The final two columns, i.e. column 7 and 8, represent the hours of overtime per personnel type and per personnel team, respectively. Some unavoidable waiting time occurs for a number of personnel types (for example for the gynaecology surgery team). This waiting time is caused by the analysis of the adnex either with a frozen section or both a frozen section and an

Comparing OR results

The utilization should be equal to the process time per day divided by the working time per day. Waiting time is not included in the utilization. In this case the IORT OR has been occupied at all times, except for the process step called “detect nodes”. So, the IORT OR utilization should be equal to:

$$process\ time_{IORT\ OR} = 252\ minutes - 0.7 * 0.9 * 60\ minutes\ = 214\ minutes$$

$$utilization_{IORT\ OR} = \frac{process\ time_{IORT\ OR}}{weekly\ IORT\ OR\ availability} = \frac{214\ minutes}{5\ days * 8\ hours\ per\ day * 60\ minutes\ per\ hour}$$
$$= 0.089 \cong 9\ \%$$

In Table 14 the IORT OR utilization is indeed 9 %. Since all utilization calculations are done similarly we can say that all utilizations are correct.

The presented case is just an example for one case. In several other cases this verification has taken place as well for each performance measure.

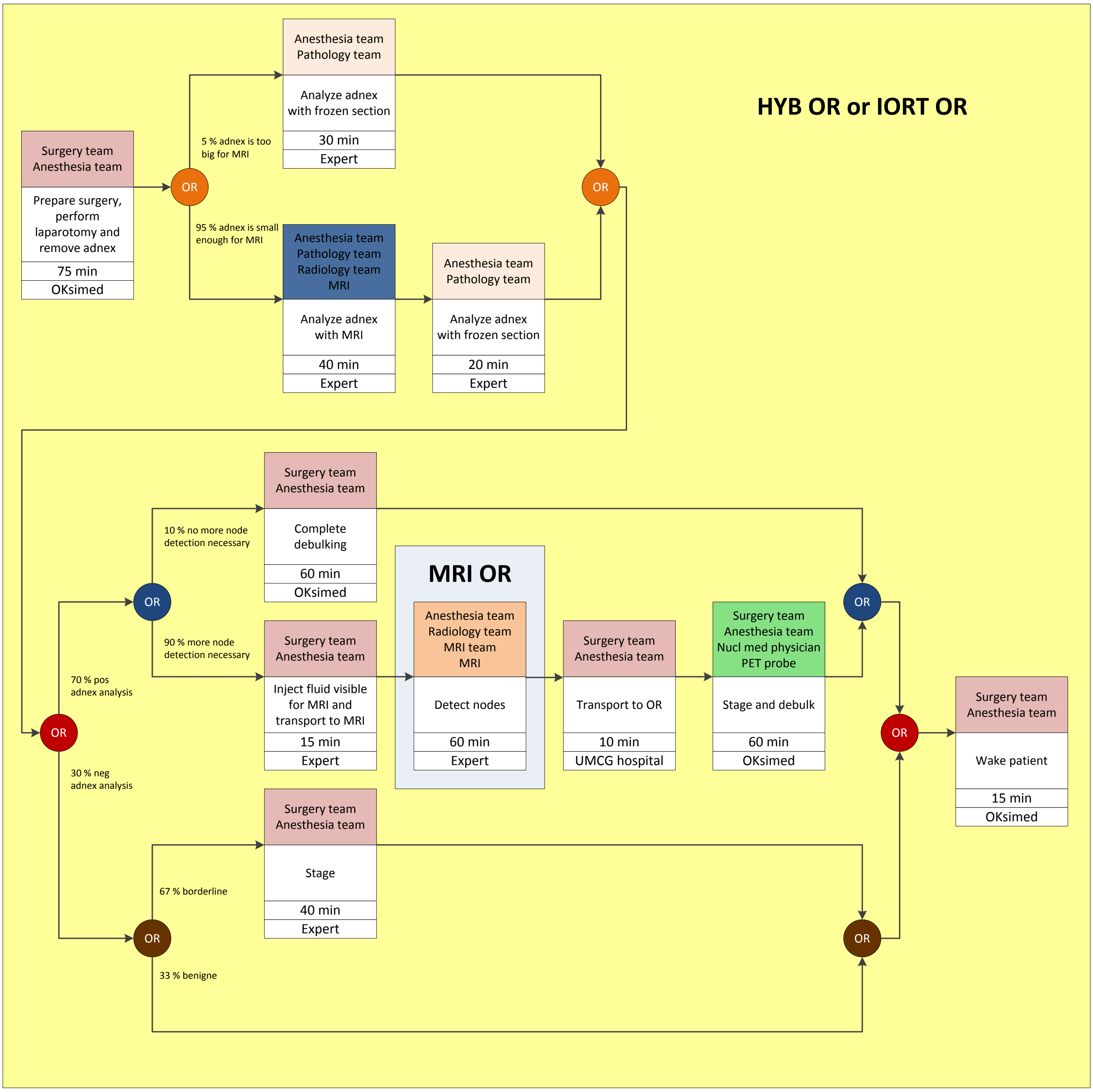


Figure 66: Process flow chart - Gynaecology – expected malignant overian tumour

Table 12: Manual calculations for verification process time - Gynaecology – expected malignant overian tumour

Sequence probability	Sequence process steps	Sequence duration (min)	Seq prob * seq dur (min)	Sequence duration (hrs)	Seq prob * seq dur (hrs)
0,0035	prep sur - anal adn with fs - compl deb - wake pat	180	0,63	3:00	0:00
0,0315	prep sur - anal adn with fs - inject - detect - transport - stag adn deb - wake pat	265	8,3475	4:25	0:08
0,01	prep sur - anal adn with fs - stage - wake pat	160	1,6	2:40	0:01
0,005	prep sur - anal adn with fs - wake pat	120	0,6	2:00	0:00
0,0665	prep sur - anal adn with mri - anal adn with fs - compl deb - wake pat	210	13,965	3:30	0:13
0,5985	prep sur - anal adn with mri - anal adn with fs - inject - detect - transport - stag adn deb - wake pat	295	176,5575	4:55	2:56
0,19	prep sur - anal adn with mri - anal adn with fs - stage - wake pat	190	36,1	3:10	0:36
0,095	prep sur - anal adn with mri - anal adn with fs - wake pat	150	14,25	2:30	0:14
1		avg process time duration	252,05	avg process time duration	4:12

Table 13: Manual calculations for verification waiting time surgery team - Gynaecology – exp.ovarian carc.

Process step probability	Process step name	Process step duration	Process step probability * Process step duration (min)	Process step probability * Process step duration (hrs)
0.05	analyze adnex with MRI	20	1	0:01
0.95	analyze adnex with frozen section + analyze adnex with MRI	20+40	57	0:57
0.7*0.9	detect nodes	60	37.8	0:38
		Average waiting time	**96.3**	**1:36**

Table 14: Arena output for verification - Gynaecology – expected malignant overian tumour

Specialism	# Patients allocated per year	Expected # patients per year	Spare places per year	Patients treated of expected patients	# Hours patient waiting time during surgery
Gynaecology	40	70	0	57%	0:00
TOTAL	**40**	**660**	**0**	**6%**	**0:00**

OR	Utilization
IORT OR	9%
MRI OR	3%
HYB OR	0%
TOTAL	**4%**

Personnel	Avg # hours required time per person	Avg # hours required time per team	Avg # hours process time per person	Avg # hours process time per team	Avg # hours waiting time per person	Avg # hours waiting time per team	Avg # hours overtime per person	Avg # hours overtime per team
Gynaecology		**23:43**		**26:50**		**0:41**		**0:00**
Surgery team	2:36	7:09	4:13	7:50	1:37	0:00	0:00	0:00
Anaesthesia team	4:13	9:31	4:13	12:39	0:00	0:00	0:00	0:00
Pathology team	0:58	1:56	0:58	1:56	0:00	0:00	0:00	0:00
Radiology team	1:36	3:12	1:15	2:31	0:20	0:41	0:00	0:00
Cell biologist	0:00	0:00	0:00	0:00	0:00	0:00	0:00	0:00
Nucl Med Phys	0:37	0:37	0:37	0:37	0:00	0:00	0:00	0:00
MRI team	0:37	1:15	0:37	1:15	0:00	0:00	0:00	0:00
TOTAL		**23:43**		**26:50**		**0:41**		**0:00**

Appendix VIII: Product Data Model

A Markov decision process (MDP) extends the notion of a Markov chain with decisions and is defined by a number of components: (1) the state space, (2) the decision space, and (3) the transition function [44] [45] [46]. In an MDP several decisions can be taken in each state of the Markov chain i.e. several process steps can be chosen to be executed. The state transitions in the Markov chain are given by the transition matrix and are dependent on these executed process steps. Each process step has an associated duration, which depends on the state of the system. An important characteristic is a Markov chain is that it is memory less, i.e. the probability of being in a certain state is only dependent on the previous state and not on earlier states.

The procedure to use a PDM will be explained by an example. Assume we have a patient with a proven malignant overian tumour. The process flow chart of this surgery type is provided in Figure 67.

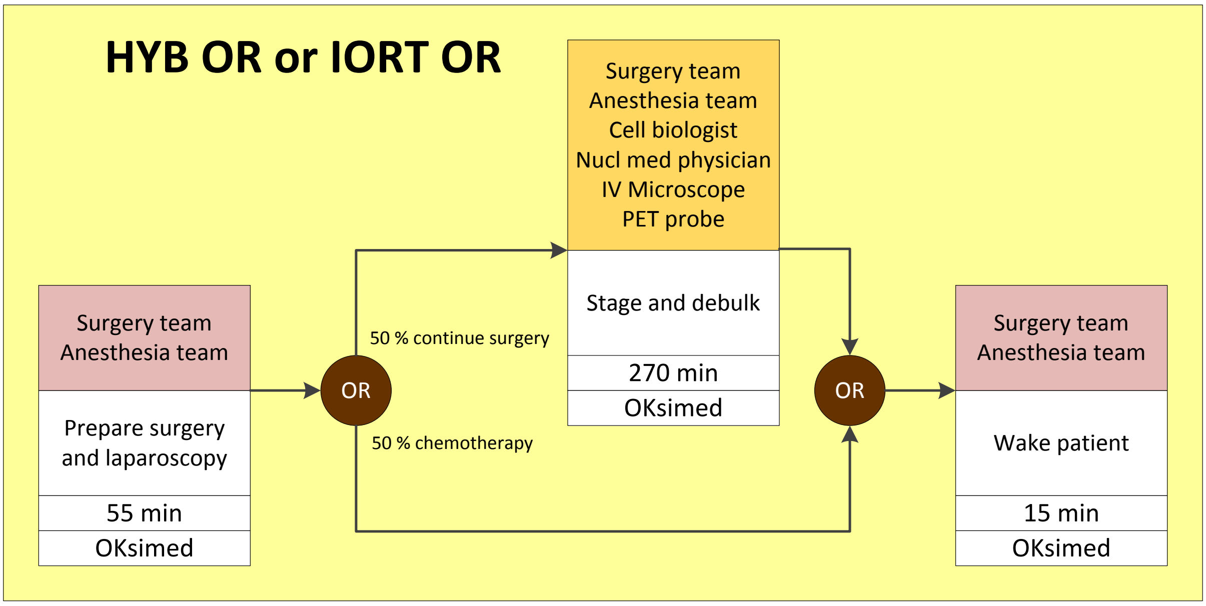


Figure 67: Process flow chart - Gynaecology – proven malignant overian tumour

As is illustrated in Figure 67 the patient will receive intra-operative brachy therapy with a probability of 50%. Before we can develop a PDM we have to transform the process flow chart. This will be done using the following steps:

- Split the arrow between two sequential steps if the resources required for the first step differ from the resources required for the second step
- Split the arrow before an OR SPLIT
- Split the arrow after an OR split
- Name the process between every split and add up the duration. If the duration is 0 then call the process after the process step that is not executed. For example if there is a choice between process step B or no process step, than the duration of the latter is zero and can be called: “nB” where the “n” stands for NOT.
- Make a new process model with the names given, the accumulated durations, and the belonging OR splits and joins

When the process flow chart has been transformed from Figure 67 to Figure 69 via Figure 68, we can determine the probabilities that a resource can be called upon by applying a technique that is similar to the development of a PDM based on the theory of MDPs.

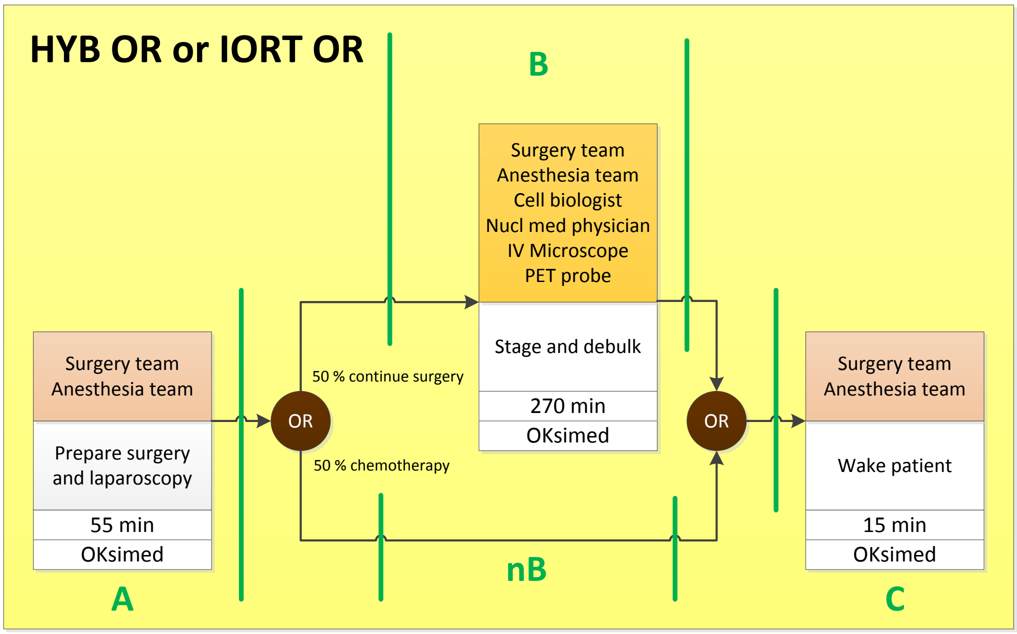


Figure 68: Process flow chart with splits and new names

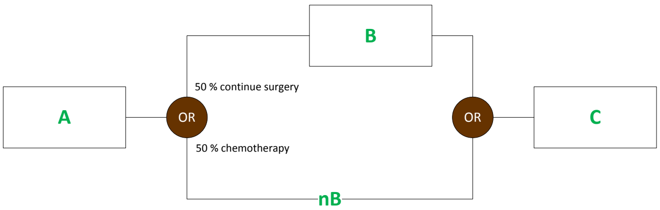


Figure 69: Process flow chart transformed to use for creating a PDM

State space

The state space (S) describes the states the process can be in. the states can be described by the operations that have been executed (together with the data elements for which a value is available. A state space is represented by a tuple consisting of two sets: (i) the executed process steps and (ii) the input elements that are available. In Figure … the state space is provided for the example. The state were step A has been finished ($Afin$) is denoted by $A\ ,\ 0fin, Afin$. Thus, $S \subseteq P\ \ PS\ \ \cdot P(E)$. If a process step has not been executed, which is illustrated by a straight line between an OR split and an OR join in Figure 68, this will be described by adding an "n" to the process step name. So, if B is not executed, we will denoted this by $A, nB\ ,\ 0fin, Afin, nBfin$.

Decision space

In each state a finite number of decisions can be made. For the execution of a PDM these decisions are described by the set of process steps that are executable in the current state of execution (i.e. those process steps of which the input elements are available and that have not yet been executed). Moreover, if there are no executable process steps for a certain state there is only one decision possible, i.e. to stop. Thus, the decision space A is equal to the set of process steps plus the decision to stop, i.e. $A\ =\ (PS \cup \{stop\})$. Furthermore, the decision space in a particular state A_i is a subset of$(PS \cup \{stop\})$.

Transition probabilities

The transition probabilities are given by a matrix P that describes the probabilities that the system moves from the current state to any of the other states in the system. These transition probabilities are dependent on the process step that will be executed. For our application, a process step a in state i can lead to new states: $j_1, j_2, \ldots .J$, each with their own probabilities and where J is the total number of process steps that can be executed when in state i. The transition probabilities under process step a always add up to 1. For example, recall the execution of the example in Figure 68 and Figure 69. If we start in state ({A}, {0fin, Afin}), there are two steps that can be executed, i.e. $B, nB\ \subseteq PS$. This leads to two new states, i.e. state 2 and 3 in Figure 70. The transition probabilities correspond to the probabilities provided in Figure 68. For example, the probability of moving from state 1 to state 2 is 0.7.

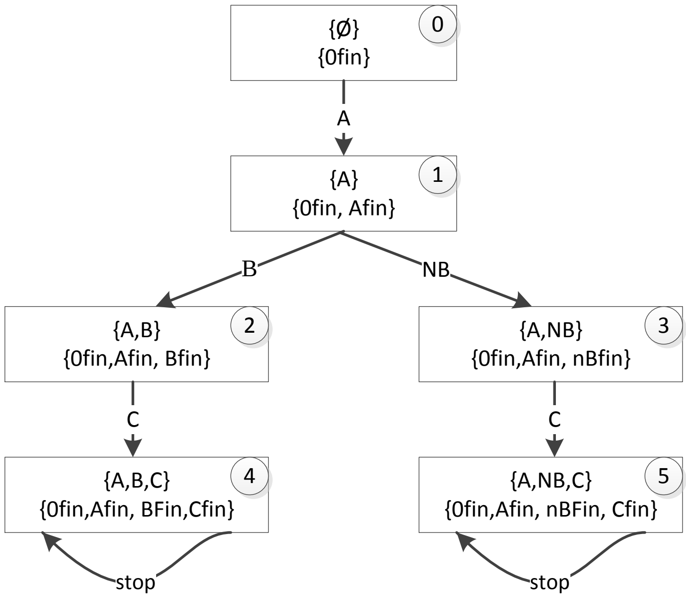


Figure 70: The state space of the process flow example. There are two end states {4,5}.

In order to determine the probabilities that resources can be called upon we are interested in the durations combined with the probability that this duration occurs. This can be determined by using the following two formulas in a recursive manner:

$D_j = D_i + d(i,j)$ where i is a direct predecessor of j. (IX.01)
$P_j = P_i \cdot p(i,j)$ where i is a direct predecessor of j. (IX.02)

Where:
Dj = time it has taken to arrive in state j
Pj = probability to arrive in state j
$D(i,j)$ = time it takes to go from state i to state j
$P(i,j)$ = probability to go from state i to state j
$D_0 = 0$
$P_0 = 0$

In Table 15 the calculations are provided belonging to the example in Figure 68.

Table 15: States and their attributes for the given example

State (j)	PS	E	State (i)	d(i,j) in min	Dj in min	p(i,j)	Pj
0	0fin	-	-	-	0	-	0
1	0fin,Afin	A	0	55	0+55	1	1
2	0fin,Afin,Bfin	A,B	1	270	55+270=325	0.7	1·0.7=0.7
3	0fin,Afin,nBfin	A,nB	1	0	55+0=55	0.3	1·0.3=0.3
4	0fin,Afin,Bfin,Cfin	A,B,C	2	15	325+15=340	1	0.7·1=0.7
5	0fin,Afin,nBfin,Cfin	A,nB,C	3	15	55+15=70	1	0.3·1=0.3

Let's denote a scenario with s(t), which is the scenario number during t, where S(t) is the total number of possible scenarios during t and includes all possible end states, in this case ({A,B,C}, {0fin, Afin,Bfin,Cfin}), and ({A,nB,C}, {0fin, Afin,nBfin,Cfin}), i.e. s = 1 and s = 2. By using Table 15 we can develop Figure 71 providing scenario number, input elements, duration per input element, and the probability per scenario during time period t. Figure 71 can be used to determine the probabilities that a resource can be called upon for every time period t.

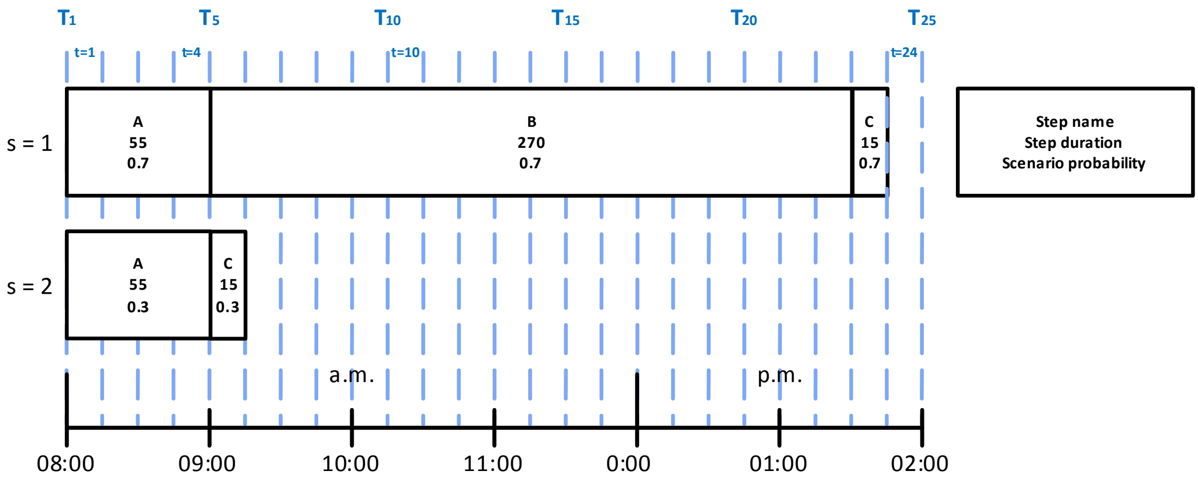


Figure 71: End states over time including the name, duration and probability per step

For example, the resource IORT OR, surgery team, and anaesthesia team are required during process step A, B, and C as you can see in Figure 68. The probability that A, B, or C occur during time period t can be calculated by:

$$p_{A \cup B \cup C}(t) = \sum_{(A \cup B \cup C) \in s(t)} \sum_{s(t)=1}^{S(t)} p_{s(t)} \qquad \text{(XI.03)}$$

Using Formula … we will provide two examples at t=2 and t=8:

$$p_{A \cup B \cup C}(2) = \sum_{A \cup B \cup C \in s(2)} \sum_{s(2)=1}^{S(2)=2} p_{s(2)} = 0.7 + 0.3 = 1$$

$$p_{A \cup B \cup C}(8) = \sum_{A \cup B \cup C \in s(8)} \sum_{s(8)=1}^{S(8)=1} p_{s(8)} = 0.7$$

When calculating the probability that a resource can be called upon for every time period $t$we can generate Table 16 for all resources

Table 16: Probability per time period t that a resource can be called upon

	IORT OR Surgery team Anaesthesia team	Cell biologist Nuclear medicine physician PET probe In vivo microscope
t	$P_{A \cup B \cup C}(t)$	$P_B(t)$
1-4	1	0
5	1	0.7
6-22	0.7	0.7
23	0.7	0
24-∞	0	0

From Table 16 we can generate Figure 72 and finally Figure 73 for which we assume the surgery starts at 08:00. In both Figures the first bar depicts the probability that the IORT OR, surgery team, and anaesthesia team are occupied, the second that the cell biologist, nuclear medicine physician, PET probe, and in vivo microscope are occupied. The lower the density of the bar, the lower the probability that a resource can be called upon. This Figure is clearly showing us which personnel and equipment should be available at which locations at what times during each particular surgery and with which probability.

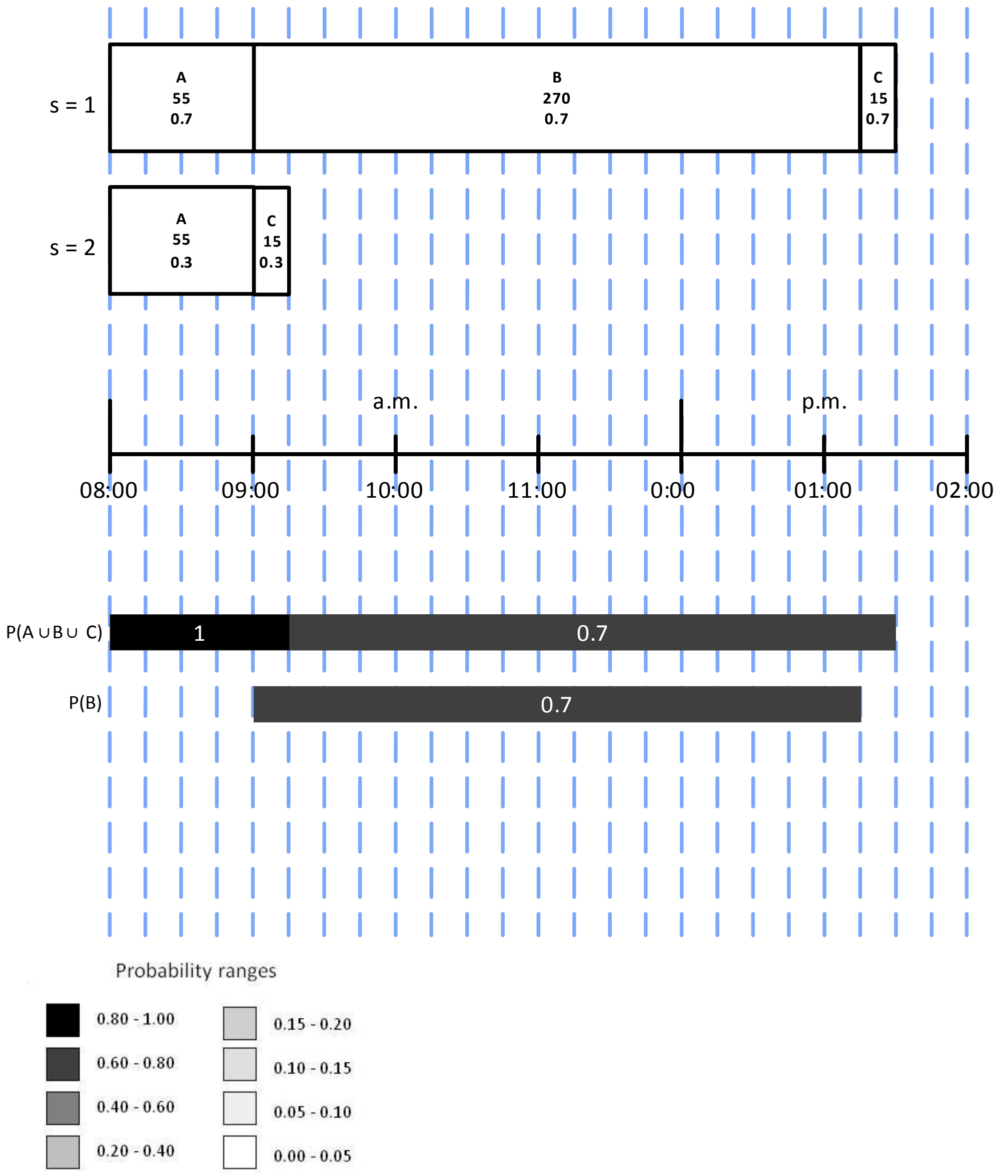


Figure 72: End states over time including the probability that resources can be called upon

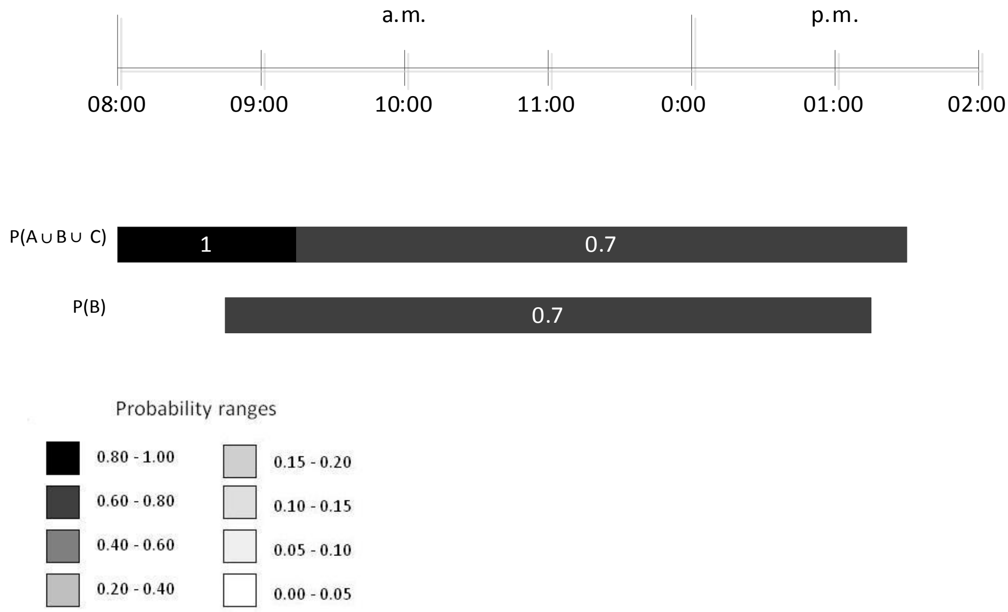


Figure 73: The probability that a resource can be called upon when a surgery starts at 08:00

Using stochastic durations with the PDM is possible, but very time consuming. It would mean many different scenarios would exist all with different process step durations. To give you an indication, for the relatively small example used in the previous deterministic model we would have $34 \cdot 34 \cdot 34 + 34 \cdot 34 = 40\ 460$ scenarios, caused by 34 data points retrieved from OKsimed for every step. Therefore, it seems required to develop a model that can easily handle stochastic durations. Both the PDM and a simulation model with deterministic durations will be used for verification purposes.