An analysis of the patient demand pattern and the capacity planning for a colorectal cancer screening trial

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Award date:
2012

Eindhoven, April 2012

An analysis of the patient demand pattern and the capacity planning for a colorectal cancer screening trial

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in partial fulfilment of the requirements for the degree of

Master of Science

in Operations Management and Logistics for Healthcare

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TUE. School of Industrial Engineering.
Series Master Theses Operations Management and Logistics

Subject headings: capacity planning, System Dynamics, Markov Decision Processes

Abstract

This report contains the results of a research conducted at the endoscopic department of the Elkerliek Hospital to identify the effects of implementing a colorectal cancer screening trial. The report consists of two parts. First, the patient demand pattern resulting from the screening trial is analyzed. Second, the optimal capacity planning for the endoscopic department is determined. The demand pattern analysis is executed with the help of a System Dynamics model. System Dynamics is often used as a method to study the behavior of complex systems when certain aspects of the systems change. In particular, System Dynamics is used to simulate various kinds of time-dependent behavior within one simulation. The developed model is used to gain recommendations about the optimal set-up of the screening trial. The results show that inviting the participants of a period of eighteen months and inviting the participants according to a weekly schedule will result in the most stable demand pattern. In the second part, a weekly planning policy has been created by modeling the planning process as a Markov Decision Process. With the Markov Decision Process, guidelines for determining the capacity for the next week are determined. The capacity depends on the current capacity and on the length of the waiting list. Finally, the developed Markov Decision Process is used to see the effect of different cost parameters to derive the optimal capacity allocation. The main conclusion of the report is that in some situations the maximum capacity available for the screening trial does not seem to be sufficient enough to cope with the demand.

Preface

This report is the end result of the project I have executed for my graduation for the master Operations Management & Logistics for Healthcare at the Eindhoven University of Technology. I would like to devote this page to thank the persons that helped me throughout this master project and the rest of my study period.

First of all I would like to thank my first supervisor Nico Dellaert for guiding me through the whole project. Nico provided me with useful ideas and feedback whenever it was needed. In addition, I would like to thank my second supervisor Arun Chockalingam for bringing up new ideas and insights.

Second, I would like to thank prof. Jan Jansen of the Elkerliek Hospital. Mainly his enthusiasm has ensured that I could perform my project at the endoscopic department. A special thanks for Carmen de Ruijter, with whom I shared an office for almost eight months. She made sure that I immediately felt at ease at the hospital and I could always reach out to her with my endless questions.

Third, I own my thanks for my family and friends. I would like to thank my parents, my brother, my sister and my grandparents for their support and confidence during the past five and a half years. Next to that, I would like to thank my friends for listening and advising when I was struggling. I also would like to thank my boyfriend Bart for keeping up with me during these last stressful weeks.

In the end, I would like to thank everybody who contributed to a fantastic period of my life.

Femke de Langen

April 2012

Management summary

Colorectal cancer is one of the largest cause of death in Western Europe. Although, the exact cause of the disease is still unknown, in early detection the disease can be successfully treated. In 2013, a large national screening program for CRC will be implemented in the Netherlands. The screening program consists of sending participants a home-test, called iFOBT, which is received once every two years. In case of a positive test result, the participant needs to undergo a colonoscopy for diagnosis. Questions arise, for example, what the consequences are for the endoscopic departments of hospitals in the Netherlands. One can think of the highly increasing demand for colonoscopies.

Based on the national program, a screening trial will be implemented at the Elkerliek Hospital. The objective of this trial is to gain more understanding about the optimal screening interval and the number of tests (iFOBT) with regards to the total yield of cancer tumors and the willingness to participate. The same questions as with the national program are raised. Therefore, a research is conducted with the following research question:

How to implement a CRC screening program in an Internal Medicine practice, focusing on patient arrival forecasting and capacity planning?

The research is conducted at the Internal Medicine department at the Elkerliek Hospital.

Project

The report consists of two parts. The first part concerns an analysis of the patient demand pattern. In addition, the second part involves a policy for optimal capacity planning.

The research question is originally divided in two sub questions:

- *What is the additional number of arriving patients due to the introduction of the CRC screening program, taking into account the specified uncertainties?*
- *Considering the forecasted number of arriving patients of the demand scenarios, what is the influence on the capacity planning of the intake nurse practitioners and the endoscopic department and the corresponding access times?*

For the patient forecasting, there are five demand probabilities defined that lead to uncertain number of arriving patients. The values for these demand probabilities are unknown in advance. However, the values will be based on research on other CRC screening trial. In our models, a range of values for these probabilities are analyzed. The following list defines the five demand probabilities:

- *Participant percentage*: percentage of invitees that participates with the CRC screening.
- *Positive first test percentage*: percentage of participants that has a positive first test.
- *Positive second test percentage*: percentage of participants that has a positive second test.
- *Positive third test percentage*: percentage of participants that has a positive third test.
- *Colonoscopy willingness percentage:* percentage of participants with a positive test that wants to undergo a colonoscopy.

Next to these five probabilities, there are two decision variables defined. It is expected that these two elements of the set-up of the screening trial influence the demand pattern.

- *Length of invitation period*: the period in which the persons from the target group are invited.
- *Invitation interval*: the period between two moments persons from the target group are invited.

For the capacity planning, two access times are defined:

- *Intake access time*: the time between the moment a patient is informed about the positive test result and the moment the patient is seen at the intake appointment with the nurse practitioner.

- *Procedure access time*: the time between the moment a patient is informed about the procedure at the intake appointment and the moment the patient undergoes the colonoscopy at the endoscopic department.

To control these access times, two feedback regulation systems are modeled. Both systems perform an action, after the access times increase above a predefined target level. The first feedback system pauses the sent invitation for a certain number of weeks until the access time has reached the target again (*the invitation feedback regulation*). The second feedback system increases the capacity until the access time is equal to the target (*the capacity feedback regulation*).

In the capacity planning, two types of capacity are used. The nurse practitioner capacity is defined by the number of available intake appointments per week and the physician capacity is defined as the number of available colonoscopy procedures per week.

Project approach

To gain an insights in the behavior over time of the patient demand pattern and the resulting access time, a System Dynamics simulation model is developed. Various values for the two decision variables are tested with this model to develop recommendations about the optimal set-up of the screening trial. Next to that, to gain more understanding of the possible demand situations, the various values for the demand probabilities are simulated. In the end, an initial analysis is performed to gain insight in the optimal capacity allocation. For this analysis, the capacity is assumed to be fixed for all demand weeks (i.e. the capacity does not change in between demand weeks) and the allocation is always a multiple of five intake appointments and six procedures.

In the second part of the report, the assumptions about the capacity are loosened to gain a more in-depth analysis of the capacity planning. In this part of the report, the capacity planning process is modeled as a Markov Decision Process, to developed an optimal weekly capacity planning. The nurse practitioner capacity is assumed to be more flexible, therefore only the physician capacity is included into the model. The objective function of the Markov Decision Process is to minimize the overall costs. The cost function exists of three costs; the waiting cost, the capacity cost, and the cost of changing the capacity. The capacity cost is based on information of the hospital. The other two cost are less easier to set. By varying the values of these costs, emphasis can be placed either on keeping the waiting list as short as possible or on stabilizing the capacity allocation. The Markov Decision Process results in an optimal capacity policy that determines the capacity of next week based on the current capacity and the number of patients waiting for a colonoscopy.

Conclusions and recommendations for the hospital

The analysis of the patient demand pattern have led to two main recommendations about the set-up of the screening trial:

- Invite 5500 persons from the target group in a period of eighteen months.
- Phrase the invitations, using a weekly invitation interval, which will lead to inviting approximately 76 persons per week.

An important conclusion of the analysis in the second part is that the optimal capacity policy often leads to extensive use of the maximum physician capacity of eighteen procedures. It can be concluded that the implementation of the screening trial can lead to serious overloading of the capacity of the endoscopic department. Therefore, it can be questioned whether the capacity that is currently available for the screening trial will be sufficient enough to cope with the demand resulting for the screening trial.

Further research

The research leads to the following recommendations for further research:

- It is recommended to update the System Dynamics simulation model with the boundaries generated from the optimal planning policy, i.e. the number of waiting patients at which the policy decides to adjust the capacity.
- Next to that, it is recommended to update the simulation model with the real values for the demand probabilities after the screening trial has started. We think that in particular a more precise value for the participant percentage will lead to more precise insights into the possible patient demand.
- It might be possible to combine an invitation feedback system with the capacity planning policy. especially when it turns out that the endoscopic department is not capable of performing eighteen colonoscopies per week, it is recommended to implement a system that pauses the invitations for a certain number of weeks after the moment that the access time for the colonoscopy becomes too high. Further research could be investigated whether increasing the number of invitees per batch after the invitation are paused leads to less extension of the invitation period.

Contents

1 Introduction

This master thesis contains the results of a research on patient arrival patterns and capacity planning within the context of the screening of colorectal cancer (CRC) trial performed in the Elkerliek Hospital.

Colorectal cancer is one of the largest causes of death in Western Europe. It is treatable, if diagnosed in time. The exact cause of CRC is still unknown. However, in some cases, heredity is the main cause. On the other hand, environmental factors, like nutrition and lifestyle, can play an important role in developing CRC. CRC almost always starts with a polyp in the colon and/or rectum. These polyps can develop into cancer. In the Netherlands, information about the correct treatment a CRC patient should receive is based on the five phases of CRC (Maag Lever Darm Stichting, 2011). In Phase 0, there is suspected cancer. In case of Phase I, there is a local tumor in the colon and no dissemination. The appropriate treatment consists of surgical removal of the tumor. When the tumor has grown through the intestinal wall, but not (yet) reached the lymph nodes, this is seen as Phase II. Again, surgical removal of the tumor is appropriate. If necessary, chemotherapy can be applied. In Phase III, the cancer has spread to the lymph nodes, but not to the organs. Here, the appropriate treatments are surgical removal and chemotherapy. The last phase, Phase IV, includes dissemination of other parts of the body (like the organs). In case of CRC, this dissemination is often in the lungs or liver. Standard treatment is chemotherapy, sometimes in combination with medicine. In addition, surgical removal of the tumor can be applied. The dissemination can be treated with radiation.

In 2013, a large national screening program for CRC will be implemented in the Netherlands. The screening program consists of sending participants a home-test, called iFOBT, which is received once every two years. In case of a positive test result, the participant needs to undergo a colonoscopy for diagnosis. Questions arise, for example, what are the consequences for the resource use of the endoscopic departments of hospitals in the Netherlands. One can think of the highly increasing demand for colonoscopies.

Based on the national program, a screening trial will be implemented at the Elkerliek Hospital. The objective of this trial is to gain more understanding about the optimal screening interval and the number of tests (iFOBT) with regard to the total yield of large adenomas and carcinomas and the willingness to participate. Adenomas and carcinomas are cancer tumors. The same questions as with the national program are raised. The goal of this research is to forecast the demand pattern of participants of the CRC screening trial that will need a colonoscopy and to create a policy for the capacity planning. Next to that, some useful recommendations can be made about the set-up of the screening trial.

The report has the following outline. In the next chapter, the project context is discussed. A short introduction about the environment and about the situation is given. Also the research questions and deliverables are given. Finally, some relevant literature is discussed. In chapter 3, the project approach is elaborated. The project is delineated, the research methods are given and the needed data is shortly discussed. The remainder of the report consists of two parts. The first part comprises of the analysis of the patient demand pattern. For the analysis of this pattern, a System Dynamics model is built. The model is used to gain insights in the optimal set-up of the screening trial. In chapter 4, the System Dynamics model is discussed and in chapter 5 the results of the simulations with the model are analyzed. The focus of the second part of the report is on a more in-depth analysis of the weekly capacity planning. By modeling the capacity decision process as a Markov Decision Process, a policy for the weekly capacity planning is created. Chapter 6 and 7 will explain the Markov Decision Process and the developed policy for the capacity planning. In the end, chapter 8 will describe the overall conclusions and recommendations for the Elkerliek Hospital.

2 Project context

In this chapter the context of the project is described. First, a short introduction of the Elkerliek Hospital is given. After that, the specialism Internal Medicine in general and within the Elkerliek Hospital is explained. The next two parts cover the national CRC screening program and the CRC screening trial. Then, two important steps of the screening trial, the intake appointment and colonoscopy processes at the Elkerliek Hospital are clarified. In the end, relevant literature about some elements of the screening trial is discussed.

2.1 The Elkerliek Hospital

The Elkerliek Hospital is a general hospital that provides high-quality primary care for patients from the areas Deurne, Gemert-Bakel, Helmond and Laarbeek. Also patients from Asten, Boekel, Helden, Meijel, Mierlo and Someren make use of the services of the Elkerliek Hospital.

The hospital is located in three locations: Helmond, Deurne and Gemert. The main location is in Helmond. Here, patients can go for long and intensive care, complex surgery and outpatient care. The Emergency Department is also located in Helmond. Next, the location in Deurne is focused on day care, such as outpatient care, blood tests, dialysis and minor surgery. And third, in Gemert minor surgery and simple tests are performed (Elkerliek, Wie zijn wij, 2012).

From the annual report of 2010, some data can be extracted to see the size of the hospital (Table 2-1). From the table, it can be seen Helmond is clearly the main location of the hospital. The focus of the hospital mainly lies in performing second-line care, with excellent quality at a personal approach (Elkerliek, Wie zijn wij, 2012).

Table 2-1: Elkerliek Hospital data from annual report 2010 (Elkerliek, Annual report 2010, 2012)

Number of specialists	145
Number of employees	2,183
Number of available beds	494
Number of beds in use	437
Number of admissions for longer than one day	18,522
Number of day admissions Helmond	16,269
Number of day admissions Deurne	2,881
Number of consultations	299,618
Number of first consultations	115,198
Number of follow-up consultations	184,420
Number of visits to ER	23,871
Number of surgeries Helmond	14,986
Number of surgeries Deurne	2,784

The Elkerliek Hospital has an organizational venture structure, in Dutch called ‘maatschappen’. This means that specialists of each medical specialism organize their own organization within the hospital. Each venture has a board that determines the policy of the organization. The 145 specialists of the Elkerliek Hospital are distributed over thirty ventures. Examples of ventures are cardiology, pediatrics and urology.

The master thesis project takes place at the Internal Medicine/Gastroenterology medical department. In the following section, Internal Medicine and the sub-specialism Gastroenterology are shortly explained.

2.2 Internal Medicine

Internal medicine deals with treating patients with diseases of the internal organs. The diagnosing of these kind of diseases is of importance. Internal medicine physicians are often called internists. The diagnosis of a disease of the internal organs is often done with an endoscopic procedure. A specialism within internal medicine is gastroenterology (in Dutch: maag-darm-lever), which deals with the digestive system (Figure 2-1).

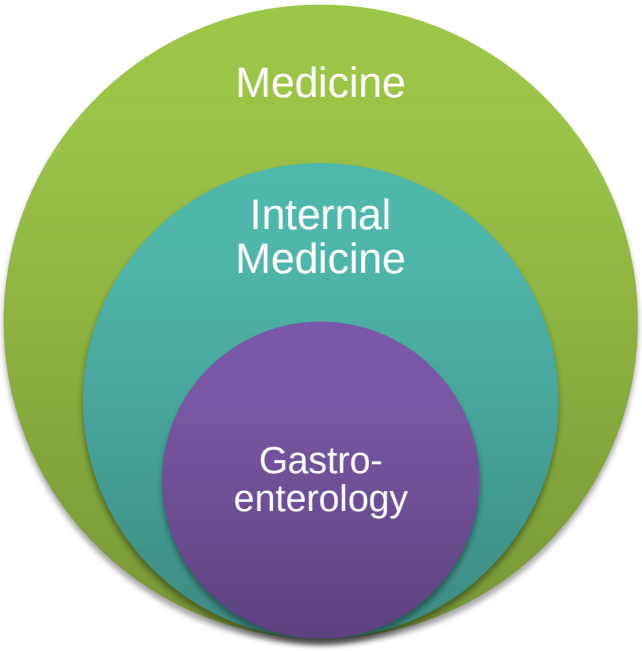

Figure 2-1: Relation of medicine, internal medicine and gastroenterology

The Internal Medicine venture at the Elkerliek Hospital consists of two departments located in Helmond. There is an outpatient department where the physicians have consultations with their patients. Next to that, there is a separate endoscopic department where the endoscopic examinations are performed. At this department, colonoscopies, sigmoidoscopies, gastroscopies, and bronchoscopies are performed for diagnosis.

Within the venture, there are twelve specialists who have their own specialism within internal medicine, like oncology, infectious diseases and nephrology. From these twelve, three specialists are specialized gastroenterologists who are allowed to perform colonoscopies. A colonoscopy is used with the diagnosis of patients who received a positive test result from the screening trial. With this endoscopic procedure, the physician enters the body with a flexible tube with at the end a camera. During a colonoscopy, polyps can be removed which are sent to the pathology department for further analysis. In section 2.4, the colonoscopy process at the endoscopic department of the Elkerliek Hospital is depicted.

2.3 Colorectal cancer screening process

In this section, first the national colorectal screening program is discussed. After that, the set up for the CRC screening trial is discussed.

2.3.1 National colorectal cancer screening program

Commissioned by the Dutch minister of Health, Welfare and Sport, a feasibility study into a national CRC screening program was conducted by the National Institute of Public Health and the Environment (Dutch: RIVM). The results of the study show that the introduction and implementation of this screening program is feasible in the Netherlands (van Veldhuizen-Eshuis, et al., 2011).

The steps in the CRC screening process can be listed as follows (responsible institutes between brackets):

1. Selection of participants (screening organizations)
2. Sending invitations (screening organizations)
3. Testing of the iFOBTs (laboratories)
4. Communicating of result (screening organizations or general practitioner)
5. Scheduling and communicating of colonoscopy appointment (colonoscopy centers)
6. Diagnostics/colonoscopy (colonoscopy centers and pathology laboratories)
7. Treatment, if necessary (hospitals)
8. Surveillance and follow-ups (hospitals)

The screening target group consists of people between 55 and 75 years old. They will receive a home test, called iFOBT, once every two years. The selection of participants and the submission of invitations are the responsibilities of five screening organizations. The screening organizations are already performing these steps in the breast cancer screening and the cervical cancer screening programs. The participants must send the iFOBTs to an indicated laboratory. The laboratory communicates the result of the test with the screening organization. In case of a normal result, the screening organization communicates this with the participant. When the result is abnormal, the screening organization notifies the general practitioner of the participant. He informs the participant about the result. The screening organization arranges an appointment for the participant with the colonoscopy center.

If during a colonoscopy tissue is removed, this is sent, together with the clinical data, to a designated pathology laboratory. The colonoscopy center informs the participant about the colonoscopy results and arranges, if necessary, the transfer to a hospital for further treatment and surveillance. Next to that, the screening organization and general practitioner are informed about the treatment plan.

In order to provide a well-run process, some agreements need to be established. Between the screening organization and the laboratory and between the colonoscopy center and the pathology laboratory contracts have to be made and signed. Next to that, between the screenings organization and the colonoscopy center service level agreements (SLAs) need to be agreed on.

The feasibility study indicated two important possible problems: (1) the capacity needed to perform the additional colonoscopies and (2) the quality of the colonoscopies that needs to be guaranteed (van Veldhuizen-Eshuis, et al., 2011).

2.3.2 Colorectal cancer screening trial

In August 2011, the Elkerliek Hospital applied for permission to start a research based on the above described CRC screening. The target group consists of residents of Helmond and surroundings between 55 and 75 years old. As random sample, 5500 persons will be taken from the target group. These participants will receive in a period of twelve months; three times two home tests (see Figure 2-2). In order to level the needed capacity, the invitations are sent in phases.

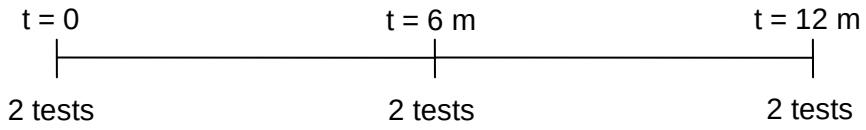

Figure 2-2: Trial timeline

The same steps as described in the above are followed in this CRC screening process. In addition, a patient who will undergo a colonoscopy, first needs to visit a nurse practitioner for an intake appointment (step 6). The intake appointment takes place at the Internal Medicine outpatient department and needs to be before the colonoscopy. The execution of the steps will be performed by several institutes (between brackets).

1. Selection of participants (ECR data manager)
2. Sending invitations (ECR data manager)
3. Testing of the iFOBTs (laboratory Elkerliek Helmond)
4. Communicating of result (nurse practitioner or general practitioner)
5. Scheduling and communicating of intake and colonoscopy appointment (nurse practitioner)
6. Intake appointment with nurse practitioner (Elkerliek Internal Medicine department)
7. Diagnostics/colonoscopy (Elkerliek colonoscopy department)
8. Treatment, if necessary (Elkerliek surgery and oncology department)
9. Surveillance and follow-ups (Elkerliek oncology department)

The first two steps of the screening trial are performed by the Eindhoven Cancer Registry (ECR), in Dutch: Integraal Kankercentrum Zuid (IKZ). The ECR is an organization that coordinates high quality, safe and efficient care for cancer patients in southern Netherlands (IKZ, 2011). ECR is an innovation and integration partner of all parties within cancer care and has expertise about cancer registration, research, knowledge sharing and care innovation.

Agreements about performing the necessary tests within the required time frame of the iFOBTs are made with the laboratory department of the Elkerliek. It is assumed that the laboratory department has enough capacity to cope with the addition demand. The expected number of patients that will be diagnosed with cancer is small (0.07%), so the same assumption about sufficient capacity is made for the surgery and oncology department.

For the intake appointment and the colonoscopy procedure, this assumption cannot be made. It is expected that there will be a significant increase in demand, that will have its effect on the capacity. Therefore, the research will be focusing on the balance between the demand and the capacity of the nurse practitioners for the intake appointments and the capacity of the endoscopic department where the colonoscopies are performed.

2.4 Intake appointment and colonoscopy process at Elkerliek Hospital

Two steps of the CRC screening trial are of importance to the project. First is the intake appointment with the nurse practitioner at the outpatient department and second the colonoscopy procedure at the endoscopic department. At the intake appointment, the nurse practitioner provides the patient with information about the appointment at the endoscopic department. This information includes how the procedure is performed, what needs to be prepared at home (use of other medicine, laxative), and how the procedure day is formed. Next to that information sharing, the intake appointment is used to consider whether the patient is appropriate for the anesthesia that is needed during a colonoscopy. This judgment is made by the nurse practitioner.

After the patient has visited the nurse practitioner for the intake appointment, the patient is considered ready for the diagnosis with the colonoscopy procedure, which is the second important step of the CRC screening trial. The secretary of the outpatient department schedules a procedure appointment right after the intake appointment. At the endoscopic department, patients are allocated to a free time slot. This results in an appointment with a predefined arrival time at a specific day. The different procedures at the endoscopic department have different presumed task times. For a colonoscopy, thirty minutes per patient are reserved. All procedures at the endoscopic department are scheduled in advance of the procedure day.

At the scheduled date and time, the screening patient presents himself at the desk of the endoscopic department. Here a secretary checks the patient in and asks the patient to wait in the waiting room. During the procedure, two nurses and one physician are present. When the endoscopic procedural room is available, one nurse guides the patient to this room. The patient gets some time to undress and he gets an intravenous for the anesthesia. The other nurse prepares the procedural room and the physician prepares himself by reading the patient file. Sometimes the physician is still filling in patient forms from the previous procedure. When all parties are ready, the patient takes place on the bed and the procedure starts. One nurse assists the practitioner with the scope, while the other nurse comforts the patient, assists with taking a biopsy or polyps and other things. After the procedure, the patient is transferred to a ward, where he has to stay for one to one-and-a-half hour until he has recovered from the anesthesia.

One nurse cleans the room after the procedure, while the physician fills in the forms of the patient. In the meanwhile, the other nurse collects the taken biopsies and polyps, and puts them in a container. At specific times, this container is collected by the pathology department of the hospital. When the nurse is done, a new patient is collected from the waiting room and the process starts again. In Appendix A, a simplified graphical representation of the process, seen from the perspective of a patient, is shown.

At the pathology department the biopsies and polyps taken from the colonoscopy are examined whether there are cancer cells or other abnormalities present. If this is the case, the physician is informed by the pathologist. Each patient has a follow-up consultation, some weeks after the colonoscopy. At this consultation, the patient is informed about the results of the colonoscopy. When the pathologist has found abnormalities in the removed tissues, a treatment plan is discussed. A patient could need for instance surgery or radiation. The further treatment is then performed by the surgery department or the oncology department of the hospital.

2.5 Research questions

One important sub question of the CRC screening trial at the Elkerliek Hospital is how to implement this trial in an Internal Medicine practice. The research question of this project follows this sub question and is formulated as follows:

How to implement a CRC screening program in an Internal Medicine practice, focusing on patient arrival forecasting and capacity planning?

2.5.1 Patient forecasting

From the research question, it can be concluded that the goal of the research will be two-fold. First, the number of arriving patients at the department is uncertain. Figure 2-3 shows the process that determines the total number of CRC screening participants that will undergo a colonoscopy. For simplicity, the intake appointment is disregarded in this figure. In practice, the number of arriving patients will be considered first as demand for the intake nurse practitioners. From the target group, a number of persons is invited to take part of the screening program. From this group of invitees, a certain percentage will decide to participate (in all three tests). It is expected that from the first, second and third test different percentages of the participants have a positive test result. Next, a number of positive test results participants choose to undergo the procedure.

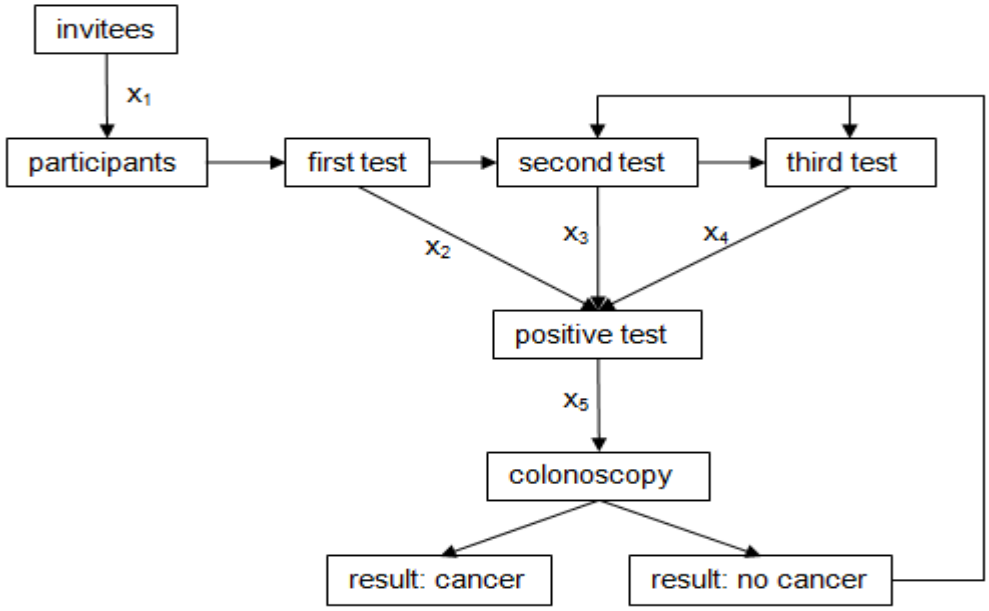

Figure 2-3: Patient forecasting process

In Table 2-2, the probabilities that exist in the patient forecasting process are summarized. Based on different values of the five percentages, an analysis with different demand scenarios can be performed. The demand scenarios will give a clear understanding of the possible situations in which the Elkerliek Hospital can be during the screening trial.

Table 2-2: Probabilities in patient forecasting process

	Name	*Definition*
x_1	participant percentage	Percentage of invitees that participate with the CRC screening
x_2	positive first test percentage	Percentage of participants that have a positive first test
x_3	positive second test percentage	Percentage of participants that have a positive second test
x_4	positive third test percentage	Percentage of participants that have a positive third test
x_5	colonoscopy willingness percentage	Percentage of participants with a positive test that want to undergo a colonoscopy

Next to the demand probabilities, two other elements of the screening trial are expected to influence the demand pattern. To make a decision about the optimal value of these elements, various simulations will be analyzed. The first decision variable is the length of the invitation period. One can imagine that inviting 5500 persons in six months will yield in higher demand for a shorter period in comparison with inviting those persons in two years. The second decision variable, the invitation interval is also assumed to have effect on the total demand. The invitation interval is defined as the period between two batches of invitations sent. It is expected that the smaller the invitation interval the more spread out the demand pattern will be.

2.5.2 Capacity planning

After the demand of the different scenarios is analyzed, the capacity planning for the nurse practitioners and the physicians of the Internal Medicine department can be determined. It is assumed that the total capacity of the two resources is flexible, the former slightly more than the latter. Due to this flexibility, the effect of different amount of resources can be analyzed. The so-called supply scenarios will be worked out to determine the optimal capacity for the nurse practitioners and for the physicians.

The end goal is to determine the (weekly) optimal number of resources taking into account the target access times. Two different access times are being defined (see Figure 2-4). First, the *intake access time* is defined as the time between the moment a patient is informed about the positive test result and the moment the patient is seen at the intake appointment with the nurse practitioner at the Internal Medicine department. Second, the *procedure access time* is defined as the time between the moment a patient is informed about the procedure and the moment the patient undergoes the colonoscopy at the endoscopic department.

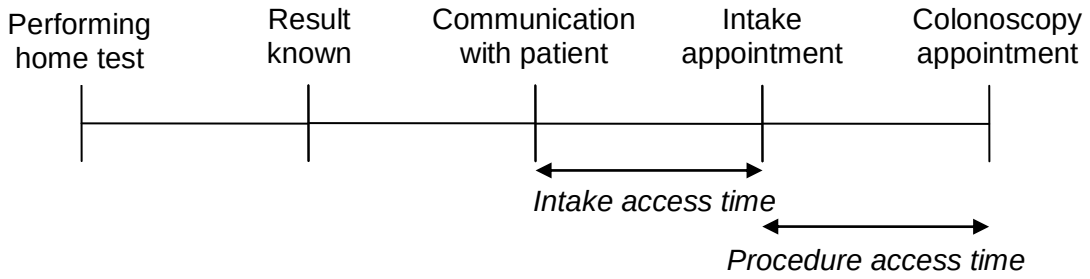

Figure 2-4: Timeline with corresponding access times

The above defined access times have influence on the perceived anxiety of the waiting patients. Patients who receive a positive result of the home test are expected to be worried about whether they have cancer or not. It is likely that the longer a patient has to wait, i.e. the longer the access time, the more anxious he becomes. It is expected that this anxiety will hold until the patient undergoes the colonoscopy. The goal is to minimize the two access times.

An important part of the patient arrival forecast and the capacity planning includes a feedback system that can regulate the access times. With such a system, the utilization of the capacity or the number of invites can be adjusted to obtain the target access time. The effect of an implementation of such a system can be of interest for the hospital.

2.5.3 Research questions and deliverables

The following list summarizes the above part in two sub questions and one deliverable:

- What is the additional number of arriving patients due to the introduction of the CRC screening program, taking into account the specified uncertainties?
- Considering the forecasted number of arriving patients of the demand scenarios, what is the influence on the capacity planning of the intake nurse practitioners and the endoscopic department and the corresponding access times?
- Create a feedback system that regulates the utilization of the capacity and the corresponding access time at a certain period in time and the number of invitees at the following period.

In the original set-up of the project, a determination of the optimal point of time to communicate the positive test result with the participant was one of the deliverables. During the execution of the project this deliverable was presumed to be not interesting enough.

In chapter 3 the methods used to approach the above questions and deliverable are elaborated. In the next section, literature about some elements of the research questions and deliverable is discussed.

2.6 Literature review

In this section, a summary of the literature review conducted at the beginning of the master project is given. First, literature about the possible consequences of the implementation of a CRC screening program is reviewed. Next, the choices for the approaches to analyze the patient demand pattern and to create capacity planning are explained based on arguments from literature. Then, the feedback system is related with the input/output control concept used in inventory and production systems. Finally, patient anxiety with screening programs is analyzed by means of the literature.

2.6.1 Screening programs

In the following part, literature about the consequences of implementing a screening program will be discussed. National CRC screening programs are introduced in many other countries besides the Netherlands and much research is already done after the consequences.

First, Price et al. (2005) studied the impact of the CRC screening pilot in the United Kingdom. The results showed that colonoscopy activity increased significantly, e.g. an increase of 31% in Scotland and an increase of 21% in England. A remarkable observation was a simultaneous increase in the number of symptomatic patients. In contrast, Vijan, Inadomi, Hayward, Hofer and Fendrick (2005) reasoned that an increase in colonoscopies due to screening may lead to a decrease in diagnostic colonoscopies. According to them, patients who have had a screening colonoscopy may not be referred to another colonoscopy if they have symptoms. However, there is no data that supported this statement.

Second, screening increases the workload for the pathology department significantly (Price et al., 2005; Reynolds & Finlayson, 2009). According to Reynolds and Finlayson (2009), the samples obtained from positive patients tend to be more complex than those of symptomatic patients. These samples require more in-depth and longer analyses of the pathology department.

From this literature, it can be concluded that not only the endoscopic department, but also the pathology department of the Elkerliek Hospital will need to deal with the consequences of implementing the screening trial. Next to that, it might be interesting to see whether the implementation will also lead to an increase of symptomatic patients.

2.6.2 Solution approaches

After analyzing the possible consequences of the implementation of a CRC screening trial, the following part discusses the arguments for using System Dynamics and Markov Decision Process as approaches for modeling the demand pattern process and creating an optimal capacity policy.

The demand pattern process for the screening trial, as described above, can be considered as a complex system with many uncertainties. Worthington, Goulsbra and Ranking (2005) advise to use simulation models when systems become too complex for other approaches. Simulation is seen as a good approach when understanding of the system's dynamics needs to be increased (Worthington, Goulsbra, & Rankin, 2005). Next to that, simulation is considered to be a good approach since it has the ability to deal with variability and uncertainty more easier than other approaches (Brailsford & Hilton, 2001).

From the above literature it can be concluded that the best approach to model the demand pattern process is simulation. System Dynamics (SD) is chosen as simulation approach, because it is often used at a strategic level in healthcare to yield insights into the relations between different parts of a system. For the screening trial, it is, interesting to see the relations between for instance the invitation period, the demand and the capacity usage. An example of the use of System Dynamics

in healthcare to gain insights in the admission system of a hospital is the model of Santos, Belton and Howick (2002). They used System Dynamics to identify and understand the causes of poor performance of the hospital.

System Dynamics can be used as simulation method for capacity planning. However, from literature it turned out that Markov Decision Process (MDP) also is an appropriate method for capacity planning. Schaefer, Bailey, Shechter and Roberts (2005) compared MDP with other simulation techniques. An advantage of MDP over discrete-event simulation is that MDP creates a policy that optimizes the model, while discrete-event simulation only evaluates one particular policy at the time. In other words, although the latter approaches can predict the behavior of the system under uncertainty, it is not possible to make optimal decision policies within one simulation. On the other hand, an MDP can consider decision rules or policies implicitly and will result in a single policy that behaves optimal under a given cost function. Nunes, de Carvalho and Rodrigues (2009) model the patient admission control of hospital elective admissions as a Markov Decision Process. The model is used to generate optimal admission control policies that maintains resource usage close the desired levels, while optimizing the determined costs. Schaefer, Bailey, Shechter and Roberts (2005) indicate an important modeling issue of MDPs. The determination of costs or rewards associated with actions and states can be difficult in some situations. Therefore, it is advised to pay additional attention to the determination of the elements in the cost function.

Since the goal is to create a weekly capacity planning, it is chosen to use a MDP approach to model the capacity planning policy. In the next chapter, the way in which System Dynamics and Markov Decision Processes are used in the project will be explained.

2.6.3 Feedback system as input/output control system

Next to the two sub research questions, a deliverable of the project is to develop a feedback system to balance the capacity utilization with the corresponding access time. The mechanism behind the feedback system can be compared with the input/output (I/O) control concept used in production (inventory) systems. I/O control settles the work-in-process (WIP) within a production system and the number of job releases for that system (Hopp & Spearman, 2008). Translating this concept in health care terms, this means that I/O control regulates the number of patients on the waiting list and the number of new appointments. A high number of patients on the waiting list will lead to a high access time for other patients.

Rouppe van der Voort, van Merode and Berden (2010) explained about how pull logistic can be used to effectively balance demand and supply in an outpatient clinic. They concluded that flexibility in supply without changing resources is needed. The authors defined three types of flexibility: (1) the ability to serve different mixes of patients/appointments in one session (mix); (2) the ability to deal with changes in the mix of types of patients/appointments (changeover); and (3) the ability to increase the number of appointments offered (volume).

In this master thesis project, the first two types of being flexible are not applicable since the focus is only on one type of patient, namely patients that need a colonoscopy. Therefore, from the article of Rouppe van der Voort et al. (2010) it can be concluded that flexibility in the volume of the capacity is needed for the capacity planning of the endoscopic department.

2.6.4 Patient anxiety

As stated before, it is expected that patients who receive a positive result from the home test will be worried about their health. Literature is reviewed to see whether this is indeed observed within previous CRC screening programs. Thiis-Evensen, Wilhelmsen, Hoff, Blomhoff and Sauar (1999) and Parker, Robinson, Scholefield and Hardcastle (2002) conducted studies to evaluate the psychological effect of participating in a CRC screening program. Both studies showed that attending in such a screening program did not cause sustained anxiety. However, Parker et al. (2002) stressed that keeping the access time (for the colonoscopy) at a minimum is necessary to eliminate the patient anxiety. Therefore, it is chosen to use the access time of the intake appointment and of the colonoscopy as decision criteria in the remainder of this master thesis.

3 Project approach

After describing the project context, this chapter explains the way the project will be approached. First, the project is delineated, in order to keep the project manageable within the time span and available resources. Second, the research methods used to solve the research questions are explained. The third section contains a discussion of the required data.

3.1 Project delineation

In order to keep the project controllable, it is decided to focus only on the Internal Medicine department of the Elkerliek Hospital. Although, literature shows that with implementing a CRC screening program an increase in workload can arise for the pathology department (Price, et al., 2005 and Reynolds & Finlayson, 2009), the effect of introducing the CRC screening trial on the pathology department of the Elkerliek Hospital is left out of scope.

Moreover, it is decided to focus only on the CRC screening patients and to leave the symptomatic patients out of the analyses. Literature is undecided about whether the implementation of a CRC screening program leads to an increase or decrease in the number of symptomatic patients (Price, et al., 2005 and Vijan, Inadomi, Hayward, Hofer, & Fendrick, 2004). Since the trial at the Elkerliek Hospital will be fully implemented after the finish of the master thesis project, the question whether there is an increase or decrease of symptomatic patients in this situation cannot be answered yet.

Last, since the CRC screening patients will undergo a colonoscopy, the project will focus only on the colonoscopy procedure. The other endoscopic procedures and combination of other endoscopic procedures with a colonoscopy are ignored.

3.2 Research methods

This section elaborates on the research methods that will be used in the project. First, in order to gain a clear understanding of the patient forecasting process, a System dynamics model will be used. Next, the planning problem is approached as a Markov Decision Process to develop a capacity policy.

3.2.1 System Dynamics model

As stated, a System Dynamics model is developed to gain insights into the patient forecasting process. SD “models a system as a series of stocks and flows, in which the state changes are continuous” (Brailsford & Hilton, 2001, p. 1). SD combines qualitative and quantitative analyses and is often used at a conceptual level. This simulation method seems appropriate because SD model is usually used to gain an understanding of feedback dynamics and long-term system behavior (Brailsford & Hilton, 2001). In addition, SD is used to look at the behavior of a complex system when certain aspects of the system change.

The first step in modeling a SD model is to develop an influence diagram. Coyle (1984) introduced three different types of influences that need to be considered when making an influence diagram. The first of these types is the flow mechanism, which are the patients in the system. These patients can be stated in states, like the waiting list or in the hospital. Control mechanisms are the second type. These are applied by the managers of the system. Last are the behavioral mechanisms. These are indirect influences from the environment which the managers have no control over. These three types of influences together can be used to make an organized, clear, diagram of the system (Coyle, 1984).

An important phase is to attain feedback from the process users and incorporate this feedback into the model. Therefore, while developing the model, frequent checks with the physicians of the endoscopic department will be performed. The second step of modeling a SD model is to convert the influence diagram into a flow diagram with the help of computer software (i.e. Vensim PLE). Vensim PLE is considered to be a simple, though extensive, computer program. The advantage of using SD for modeling the patient arrival forecasting is that it gives a clear overview of the process. It is a relatively simple method to reveal the different relations between elements of the process.

The SD model will be simulated with different values of the input parameters. By varying the values for the input parameters, multiple possible situations will be analyzed. The results will be analyzed and recommendations for the Elkerliek Hospital will be made.

3.2.2 Markov Decision Process

After generating some first insights about the capacity planning with SD, the control of the capacity planning is modeled as a Markov Decision Process. The goal is to develop a policy about the optimal capacity planning. A policy is called “the rule that specifies what action to choose as a function of the system evolution” (Kulkarni, 1999, p. 317). Markov Decision Processes are mainly used to solve dynamic decision-making problems (Guo & Hernández-Lerma, 2000).

To design a Markov Decision Process, five components are of importance (Guo & Hernández-Lerma, 2000):

$$\{S, A(i), p_{ij}(a), r(i,a), V\}$$

The components and their definitions are listed in Table 3-1.

Table 3-1: Definition of MDP components

Component	*Definition*
S	State space, $i \in S$
$A(i)$	Action set
$p_{ij}(a)$	Transition probabilities
$r(i,a)$	Cost function
V	Objective function

First, the set of all possible states of the process are listed in the state space. The elements of the state space are in this case the number of patients on the waiting list and the number of available time slots. Second, when the process is in a certain state from the state space, an action from the action set can be chosen. Thus, the action set consists of all possible actions that can be taken in each random state of the state space.

After specifying the state space and the action set, the transition probabilities that the process transfers from one state to another state have to be defined. For the screening trial situation, the transition probabilities depend on the arrival distribution of the new patients on the waiting list. The fourth element of a MDP is the cost function. A cost function can be determined in two ways. With the first way, there can be a cost of being in a specific state of the state space. The second way is that there can be a cost of transferring from one state to another state. As stated, attention should be given to the determination of the cost function (Schaefer, Bailey, Shechter, & Roberts, 2005). Therefore, the Planning & Control department of the Elkerliek Hospital is approached for precise numbers for the costs.

Finally, the policy is developed by minimize or maximize the objective function. In fact, the objective function leads to optimizing the performance of the process. Often the objective function is to minimize the cost function. The goal is to develop a policy that determines how to increase or decrease the capacity based on a certain number of waiting patients. The current number of patients on the waiting list can be transferred into the current access time. It will be tried to determine the boundaries of access time in which a certain number of capacity is optimal.

In sum, the two approaches, System Dynamics and Markov Decision Processes, will be used to give useful advice for the Elkerliek hospital. First, the developed System Dynamics model will be used to gain insights in the patient demand pattern and will lead to advice about the optimal set-up for the screening trial. Initial insights in the capacity utilization are gained from the System Dynamics. For a more in-depth and weekly capacity planning, in the second part, a policy is created by modeling the capacity planning as a Markov Decision Process.

3.3 Discussion of data

In this section, first a consideration between practical and theoretical data will be made. Next to that, the information already known is discussed. Also, assumptions about data that are not known are made.

3.3.1 Practical vs. theoretical data

Before the Elkerliek Hospital is allowed to start with the CRC screening trial, the Ministry of Health, Welfare and Sport have to approve the research application. While writing this master thesis report, an advisory committee has advised the Ministry to approve the application. Unfortunately, an agreement has first to be reached with the insurers about the financial outline. The negotiations are still taking place, thus the trial has not been started yet. In the beginning of the master project, it was expected that during the time span the trial would have been accepted and started. The expectation was that during the project the data would be more practical than theoretical. Unfortunately the results of the project are still based on the values that were experienced during other CRC screening trials.

3.3.2 Needed data

As mentioned before, some information about the screening trial is already known. For the demand probabilities for the screening trial in Helmond, there is no data available yet. Therefore, the initial values for these percentages will be based on experiences values during other CRC screening trials. These other trials were performed in Nijmegen en Rotterdam. Table 3-2 depicts the initial assumed values for the demand probabilities. For the demand scenarios of the forecasting analysis, the percentages will vary within reasonable margins to gain insights in multiple possible situations.

Table 3-2: Demand probabilities based on previous research

Participant percentage	60%
Positive first test percentage	12-13%
Positive second test percentage	8-9%
Positive third test percentage	5-6%
Total positive test percentage	25-28%
Colonoscopy willingness percentage	90%

Based on the probabilities, the numbers of arriving patients for certain demand scenarios are simulated. The probabilities will be also used for the transition probabilities of the Markov Decision Process. These transition probabilities will in turn be used to develop an optimal policy for the capacity planning. The available capacity for the endoscopic department is defined in number of procedures. In the following part, this capacity is called the physician capacity. The capacity for the nurse practitioners is defined in available intake procedure slots.

It is important to keep the access time as short as possible to avoid high patient anxiety (Parker, Robinson, Scholefield, & Hardcastle, 2002). In consultation with the endoscopic department, two targets for the access times should be set. With these access time targets, the performance of the endoscopic department can be determined. The time unit chosen for the access time is in weeks. Both access times are set at one week (also see Table 3-3).

Table 3-3: Target access times

Access time	*Definition*	*Target*
Intake access time	Time between the positive test communication and the intake appointment with nurse practitioner	1 week
Procedure access time	Time between the intake appointment and the procedure at the endoscopic department	1 week

After elaborating the project context and the project approach, the remainder of the report consists of two parts. The first part focuses on modeling the patient demand pattern (chapter 4 and 5).

4 System Dynamics model

As stated in the project approach, a System Dynamics model is developed to gain insights into the patient demand pattern of the screening trial. This chapter describes this developed model. For the development of the System Dynamics model, the approach that Coyle (1984) used in his article is followed. In the first part of this chapter, the development of the (qualitative) causal loop diagram is discussed. The second part involves the second step, the development of the stock and flow diagram. In the end, the four important input parameters that will form the basis of the analyses with the System Dynamics model are explained.

4.1 Causal loop diagram

The first step of building a System Dynamics model is to develop a causal loop diagram. Developing a causal loop diagram is a clear method to depict the relations between different variables within a system. In Figure B-1 in Appendix B, the causal loop diagram for the CRC screening trial is shown.

The elements of the patient forecasting process are connected by arrows. These arrows indicate causal relations. A “+” sign show that the effect is positively related to the cause (Sterman, 2001). Next to that, a “-“ sign indicates a negative relation. The dotted arrows are used to indicate the relations of the demand probabilities.

The important element in the process is the waiting list for screening patients. In the diagram there is no distinction made between patients waiting for an intake appointment or a colonoscopy. The total number of screening patients on the waiting list depends in the first place on the colonoscopy willingness percentage of the participants.

First, the two loops show that the outflow from the waiting list depends on the rate of intake and procedure admissions, i.e. when the rate of intake or procedure admissions increases, the number of screening patients on the waiting list decreases. In addition, the number of patients on the waiting list is positively related with the length of the access times of an intake appointment and a colonoscopy. The right side of the diagram shows that the rate of both admissions depends on the capacity (utilization) of the resources. For example, if the capacity of the nurse practitioners rises, the capacity utilization will decrease. Furthermore, the rate of intake admissions will increase when the capacity utilization of the nurse practitioners will increase. This mechanism also holds for the colonoscopy capacity (utilization) and the rate of procedure admissions.

Second, the rate of new screening patients determines the inflow on the waiting list of screening patients. The rate of new screening patients depends on the different test outcome rates. As stated previously, there are three tests with screening intervals of six months, so there will be three different positive test rates. The rate of new screening patients also depends on the number of participants in the screening trial. This number is related to the number of invitees and the participant percentage.

4.2 Stock and flow diagram

After modeling the causal loop diagram of the screening trail process, a stock and flow diagram is developed. This diagram is modeled with the computer software Vensim (Figure 4-1). The clouds in Figure 4-1 represent a source and several sinks where the participants start or end the process. The rectangles indicate stocks of people, while the thick arrows represent the flow of people (Homer & Hirsch, 2006). The valves in the thick arrows are rates and the thinner arrows show causal influence. In the following part, some design choices are explained.

First, the colonoscopy willingness rate is not included in the stock and flow diagram. This rate is assumed to be more than 90%. Therefore it is considered to be negligible. Second, inviting the target group is done in phases using the invitation rate. The invitation rate determines the invitation interval, the invitation batch (number of invitees at the same time) and the invitation period. For the initial model, it is assumed that 76 persons are invited each week over a period of three years. In the following chapter, the effect of variation in the invitation period and in the invitation batches on the demand pattern will be analyzed.

Third, every step in the model is performed at a certain rate. The time it takes to perform the step partly determines this rate. The other inputs are the inflow and the probability that the step will be performed. Before the participants can start with the second and third test, they are 24 weeks delayed at the four different 'waiting places'.

A problem arises at the determination of the false positive first and second test rate. It cannot be tracked in which test phase the participant was before receiving a false positive result from the procedure. Therefore, a ratio of the positive first and second test rate is used to determine the false positive first and second test rate. The following equations show the determination of the false positive first and second test rates.

$$False\ positive\ first\ test\ rate = \frac{Positive\ first\ test\ rate}{Positive\ first\ test\ rate + Positive\ second\ test\ rate} \cdot Percentage\ test\ false\ positive$$

$$False\ positive\ second\ test\ rate = \frac{Positive\ second\ test\ rate}{Positive\ first\ test\ rate + Positive\ second\ test\ rate} \cdot Percentage\ test\ false\ positive$$

A downside of this approach is that the moment the ratio is determine, is not the same as the moment the participant(s) went through the positive test rate. Thus, the determined ratio shows the relation between number of positive first and second test participants of a later point of time. However, the ratio is assumed to be a useable approximation and is therefore used in the model.

Fourth, the intake admission rate and the procedure admission rate are determined by the inflow from the waiting lists and from the available capacity of the resources. For example, the intake admission rate in a certain week is equal to the following equation.

$$Intake\ admission\ rate = \min\left(\frac{Patients\ on\ the\ intake\ waiting\ list}{Target\ intake\ access\ time}, Nurse\ practitioner\ capacity\right)$$

In the end, for the analysis of different scenarios, four outputs of the model are used. The following four equations show the calculations for the actual intake access time and the nurse practitioner capacity utilization.

$$Actual\ intake\ access\ time = \frac{Patients\ on\ intake\ waiting\ list}{Intake\ admission\ rate}$$

$$Nurse\ practitioner\ capacity\ utilization = \frac{Intake\ admission\ rate}{Nurse\ practitioner\ capacity}$$

For the actual procedure access time and the physician capacity utilization the same equations can be used, though for these calculations the patients on the procedure waiting list, the procedure admission rate and the physician capacity need to be used.

A benefit of the model is that the model includes false positive test participants. The percentage of positive tested participants that return on the screening process after no deviations are found is assumed to be fifty percent. A downside of modeling the screening trial in the above described manner is that the procedure admission rate is determined and often limited by the capacity of the nurse practitioners. If the capacity of the nurse practitioners is equal or lower than the capacity of the colonoscopy, the procedure admission rate is always equal to the intake admission rate.

Despite the above mentioned downside, the stock and flow diagram as designed below is assumed to be a good model for gaining more valuable insights for the demand forecasting and the capacity planning. Several elements of the process can be adjusted to create several possible scenarios. These input parameters will be discussed in the following section.

The underlying formulas of the System Dynamics models are listed in Appendix B2-B4.

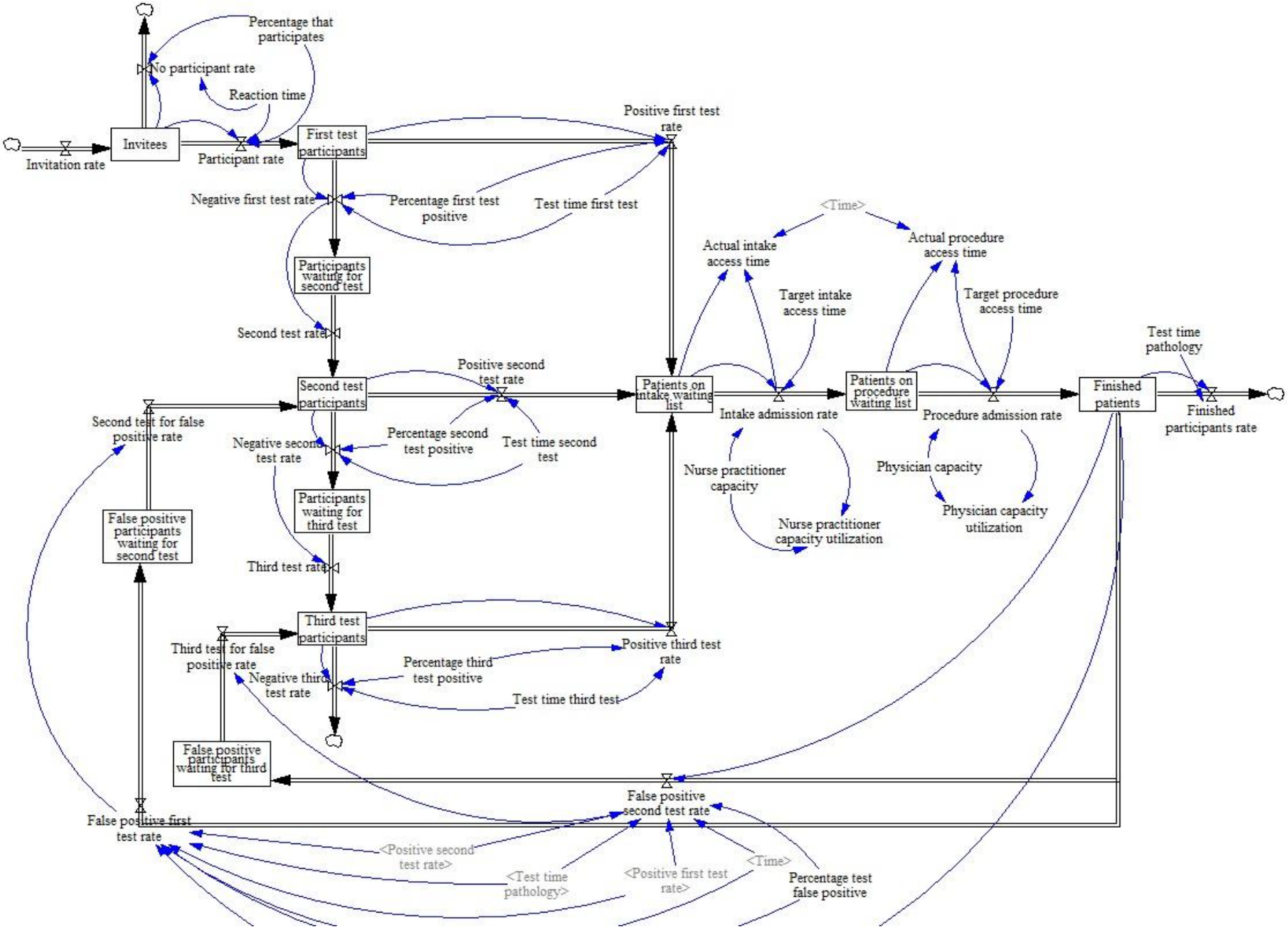

Figure 4-1: Stock and flow diagram

4.3 Important parameters

The System Dynamics model, described above, will be used to gain a first insight in the demand pattern. In this chapter, the important input parameters of the process are explained (Figure 4-2). These four input parameters are used to contrive multiple what-if situations.

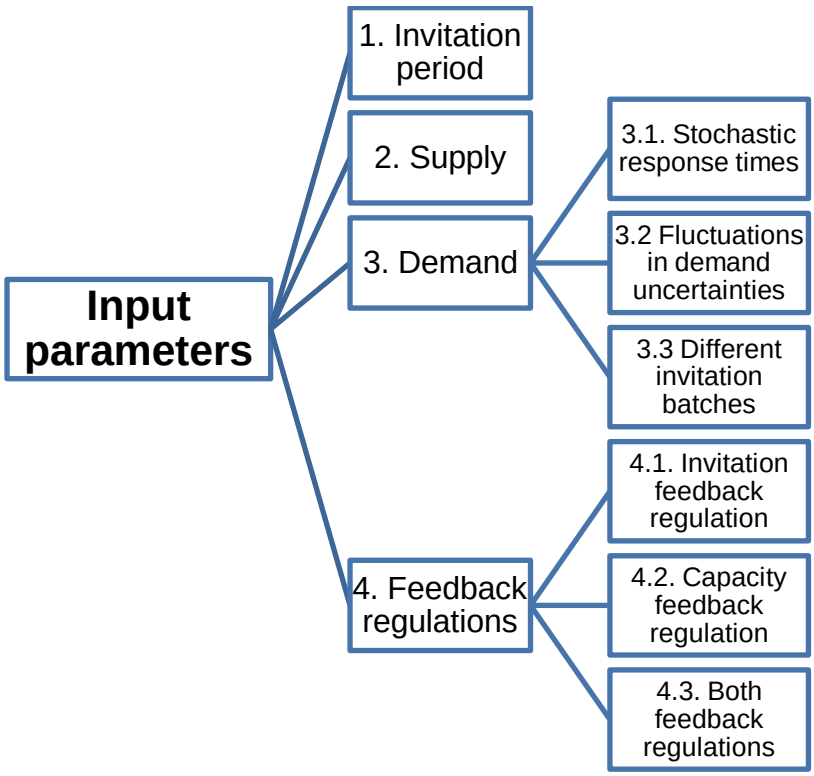

Figure 4-2: Simulation scenarios

First, the length of the *invitation period* is an important input parameter. The length of the invitation period determines the number of invitees per invitation batch. The invitation period is expected to have an effect on the number of patients on the waiting list and on the access time for the intake appointment and the colonoscopy procedure. Different lengths of invitation period will be simulated to see the effect.

Next, the *supply* side of the process is interesting to examine. With the supply scenarios, the effect of variation in available capacity is analyzed. The capacity planning process consists of two capacities: the nurse practitioner capacity and the physician capacity. The nurse practitioner capacity is defined as the number of available intake appointments. The physician capacity is equal to a certain number of available procedures.

The third parameter is the demand pattern. In the System Dynamics model, the demand is defined as the number of patients that need a colonoscopy. First, this number depends on the participation rate, the percentage first test positive, the percentage second test positive and the percentage third test positive (*demand probabilities*). In addition, the demand distribution depends on the time it takes for invitees to decide whether to participate and on the time it takes to take the home tests (*responses times*). Furthermore, the overall demand distribution depends on the rate of invitations (*invitation batches*).

Finally, there are two ways to perform control over the process when in a certain week the access times rise above the target access times. One way is to lower or minimize the invitation rate in the following week (*invitation feedback regulation*). Another way is to increase the capacity of the nurse practitioners and/or the physician for the following week (*capacity feedback regulation*). If one of these feedback regulations does not reduce the access time on its own, there is a possibility to include both regulations in the process.

4.3.1 Invitation period

The first step in analyzing the patient demand forecasting process is to determine the optimal invitation period of the screening trial. The goal is to invite 5500 persons for the trial. The invitation period partly determines the number of invitees per week (invitation batch). Naturally the invitation interval also determines the invitation batch.

It is chosen to study three different invitation periods in the analysis. Table 4-1 lists the three scenarios with the corresponding number of invitees. The preference of the endoscopic department is to invite all participants within six months. It is expected that this will result in an overflow of patients for the initial capacity. Therefore, it is chosen to also study invitation periods of twelve and eighteen months. The number of invitees per invitation batch is on weekly basis. In part 4.3.3.3, scenarios with different invitation batches are discussed.

Table 4-1: Invitation period scenarios

Scenario	*Situation*	*Number of invitees per week*
IP1	Invitation period is 18 months	76 invitees
IP2	Invitation period is 12 months	115 invitees
IP3	Invitation period is 6 months	229 invitees

4.3.2 Supply scenarios

The second type of parameter leads to the supply scenarios. In the capacity planning for the endoscopic department, the capacities of two resources are included. First, the capacity of the nurse practitioners is included, which is defined in the number of available intake appointment. Second, the physician capacity is included, where the capacity is defined in the number of available procedures. Due to treatment times and specific day schedules, it is assumed that the capacity of the nurse practitioners is always a multiple of five intakes. In addition, one gastroenterologist is expected to perform approximately six procedures per session. Therefore, the physician capacity is always a multiple of six procedures. It is expected that the three gastroenterologists can schedule one day session per week for performing screening colonoscopies. However, it is more likely that only two physicians have time to perform these procedures. As a result, the initial physician capacity is equal to twelve procedures, as the maximum physician capacity is equal to eighteen procedures.

The design of the system dynamics model forces that the procedure intake rate is determined and at the same time limited by the capacity of the nurse practitioners. In the case in which the nurse practitioner capacity is less than colonoscopy capacity, the maximum number of performed colonoscopies in one week will be equal to the capacity of the nurse practitioners. The supply scenarios therefore consist only of number of capacities close together. Table 4-2 lists these supply scenarios.

Table 4-2: Fixed supply scenarios

Scenario	*Situation*	*Number of intakes*	*Number of procedures*
FS1	Low nurse practitioner capacity; low physician capacity	5	6
FS2	Initial nurse practitioner capacity; low physician capacity	10	6
FS3	Initial nurse practitioner capacity; initial colonoscopy capacity	10	12
FS4	Medium nurse practitioner capacity; initial physician capacity	15	12
FS5	Medium nurse practitioner capacity; high physician capacity	15	18
FS6	High nurse practitioner capacity; high physician capacity	20	18

The supply scenarios will be used to gain information about a best fitted capacity without adjusting the number of available intake appointments or available procedures between the demand weeks.

4.3.3 Demand scenarios

As explained above, the demand pattern is influenced by the patient behavior in three ways, which all will be discussed in following parts.

4.3.3.1 Stochastic response times

In the demand forecasting process are two types of response times: the reaction time and the test times. The reaction time is the time that it takes for an invitee to decide whether he wants to participate in the screening trial. The test time involves the time it takes for the laboratory of the Elkerliek Hospital to obtain the result of the sent home tests. It is assumed that the test times of the laboratory at the three screening moments are equal. In the initial model the reaction time of participants and the test times are assumed to be deterministic and fixed at one week. In reality this is probably not the case. Although on average the response times will be one week, it can vary between participants or between tests. It is interesting to see the effect on the demand when the response times are stochastic.

With the System Dynamics model, the response times are made stochastic with the addition of noise by a random normal distribution. It is assumed that the response time consists of a minimum time of one week plus a random normal distributed time. The analysis in the chapter 5 will compare the results of four different simulations (see Table 4-3). The goal of the analysis is to see the effect of including fluctuations in the response time on the demand and access times.

Table 4-3: Stochastic response time scenarios

Scenario	*Situation*
SR1	Deterministic reaction time; deterministic test times
SR2	Deterministic reaction time; stochastic test times
SR3	Stochastic reaction time; deterministic test times
SR4	Stochastic reaction time; stochastic test times

4.3.3.2 Fluctuations in demand probabilities

The goal of the second demand scenarios is to see the effect of differences in the demand probabilities on the demand for the endoscopic department. As stated, there are four demand probabilities defined in the process: participant percentage, positive first test percentage, positive second test percentage and positive third test percentage. In Table 4-4, the different scenarios with fluctuating demand probabilities are listed.

Table 4-4: Demand probabilities scenarios

Scenario	*Situation*
DD1	Initial participant percentage; initial positive test results
DD2	Initial participant percentage; high positive test results
DD3	Initial participant percentage; low positive test results
DD4	High participant percentage; initial positive test results
DD5	High participant percentage; high positive test results
DD6	High participant percentage; low positive test results
DD7	Low participant percentage; initial positive test results
DD8	Low participant percentage; high positive test results
DD9	Low participant percentage; low positive test results

The initial participant percentages and the initial positive test results are the percentages that are expected, based on other CRC screening trials performed in Nijmegen en Rotterdam. It is assumed that the differences in the high, initial and low percentages of a positive test results are the same for all three test moments. Therefore, all three test moments vary with minus or plus five percent. However, this rule is not possible for the low positive test results of the third test percentage. Therefore, it is chosen to lower this percentage from five to one

percent. The following list shows the respectively values for the participant percentage, and for the three positive test percentages in the initial, high and low situation:

- Initial: 0.60; 0.12, 0.08, 0.05
- High: 0.80; 0.17, 0.13, 0.10
- Low: 0.40; 0.07, 0.03, 0.01

4.3.3.3 Different invitation batches

The third interesting question is what the effect of different invitation batches on the total demand is. It is expected that about 5500 persons need to be invited in a certain invitation period. It is chosen to study several different invitation batches, which are listed in Table 4-5. The number of persons invited per invitation batches presumes an invitation period of eighteen months.

Table 4-5: Invitation batch scenarios

Scenario	*Situation*	*Number of persons per invitation batch*
IB1	Invitees every one week	76 persons per week
IB2	Invitees every one month	305 persons per month
IB3	Invitees every three months	917 persons per three months
IB4	Invitees every day	15 persons per day

4.3.4 Feedback regulations

It is expected that in scenarios the maximum available capacity needs to be used to gain desirable access times. Using the maximum capacity is highly unfavorable, since there probably will be no room for peculiarities or emergencies. Two feedback regulations are developed to regulate the access times without using the maximum capacity as initial capacity. First, a feedback regulation on the demand side, i.e. the invitation feedback regulation is included in the model. Second, the capacity feedback regulation is included. The capacity feedback regulation can be seen as the feedback regulation of the supply side.

4.3.4.1 Invitation feedback regulation

The invitation feedback regulation system comprises a link between the actual intake access time and the invitation rate. It functions as follows: when in a specific week the actual intake access time is higher than the target access time, a trigger goes to the invitation rate. This trigger ensures that the number of invitations for the next week is set back to zero invitations. The target access time is determined at one week. So for example, when the actual intake access time is increased to higher than one week in week 16, the number of invitations for week 17 is zero.

An interesting outcome of the capacity feedback regulation, next to the effect on the overall access time, is by how many weeks the demand period is extended. In case the invitations for a certain week are set back to zero, these invitations still have to be sent in the week(s) after the initial invitation period. This will lead to longer invitation period and therefore to a longer demand period.

4.3.4.2 Capacity feedback regulation

For the capacity feedback regulation a link between the actual intake access time and the nurse practitioner capacity is created. First, it is checked whether the intake access time of previous week is higher than the target. If this is the case, the nurse practitioner capacity is increased by five intake appointments. The same method is applied to adjust the physician capacity. Here, it is checked whether the procedure intake access time is larger than one week. When this is the case, the physician capacity is increased by six procedures. Since the physicians of the endoscopic department indicated that eighteen procedures per week is the maximum capacity, it is chosen to use with twelve procedures as start capacity. The start capacity will be increased to the maximum capacity (eighteen procedures) in case of a procedure access time of above one week.

5 Results of System Dynamics model

After explaining the developed model, this chapter describes the results of certain what-if situations. The results of the simulations of these situations will be used to gather insights in the optimal set-up of the screening trial.

The goal is to see the effect of different input parameters on the total patient demand for the endoscopic department of the Elkerliek Hospital. In fact, the patient demand for the department is the total number of participants that have positive test results for the home test and need a colonoscopy for diagnosis. In the System Dynamics model this is indicated by the variable named 'patients on intake waiting list'. Therefore, when in the following parts the term 'patients on intake waiting list' is used, actually patient demand is meant. It is preferred that the participants who receive a positive result of their home test are diagnosed as soon as possible. Therefore, in consultation with the Elkerliek hospital, the target intake access time and the target procedure access time are both set at one week.

First, the different invitation periods are analyzed in combination with situations with different demand probabilities to develop an advice about the optimal length of invitation period. Second, the demand scenarios are studied. The three ways in which the demand pattern can be influenced are discussed. Both the invitation period scenarios and the demand scenarios are combined with the supply scenarios to gain an insights in the best capacity allocation, keeping in mind that there is no intermediate adjustment of the capacity. The feedback systems are used in both situations to see the effect of the implementation. Special attention is given to the order of triggering the feedback systems.

The final part summarizes the findings and conclusions are drawn based on these findings.

5.1 Invitation period

The analyses of the invitation period scenarios will be based on the number of patients on the waiting list and on the intake access time. These values are plotted against the simulated weeks. For each invitation period, the simulation ends six months after the week in which the last participant receives the third test.

5.1.1 Invitation period scenarios with demand scenarios

To gain a general picture, the first analysis is based on expected values for the input parameters. Therefore, it is assumed that the participants are invited per week. All response times are considered to be deterministic and have a value of one week. Next to that, the demand percentages used are the ones of demand scenarios *DD1*, which involves 60, 12, 8 and 5 percent for respectively the participant rate, and the first, second and third positive test rates. Last, the initial capacity, supply scenario *FS3* (ten intake appointments, twelve procedures), is used in the first analysis.

The results of scenario *IP1* (Figure 5-1) show a clear patient arrival pattern of the different test moments. Between week 5 and week 10, the first test participants arrive, then around week 30 the second test participants arrive. Last, around week 55 the third test participants start arriving at the waiting list. This is also the moment the access time starts to rise above one week. Although the access time rises above the target time, the maximum access time is above two weeks (Figure 5-2).

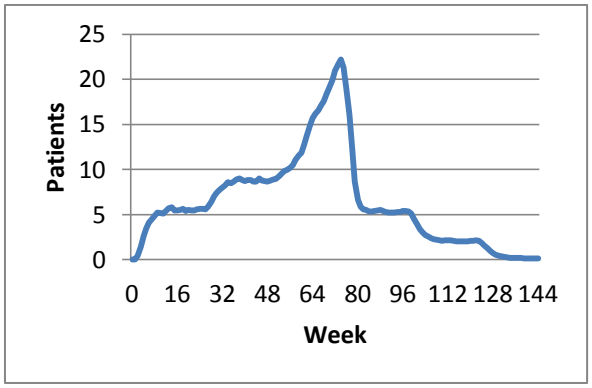

Figure 5-1: Demand of scenario *IP1* with *DD1*

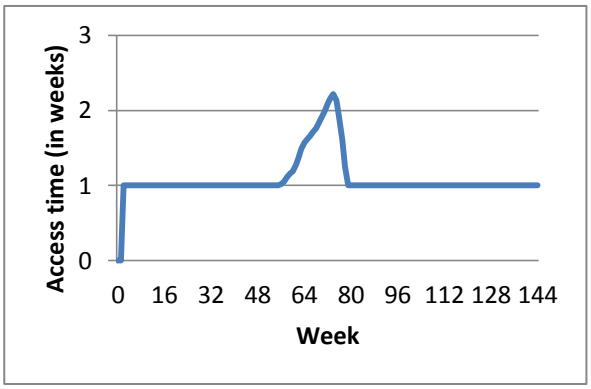

Figure 5-2: Access time of scenario *IP1* with *DD1*

For scenario *IP2*, the moment the waiting list increases significantly and the access time arises above one week is around week 30 (see Appendix C1). At this period, the waiting list will consist of first and second test participants. The number of patients on the waiting list increases to approximately 75 patients in a period of forty weeks. At the maximum, the access time is 7.5 weeks which is just under two months. Scenario *IP3* already results in an overflow for the capacity at week 5 (see Appendix C1). This observation means that from the first moment patients are arriving for intake appointment and an endoscopic procedure, the waiting list and corresponding access time start increasing rapidly. The maximum access time is around 3.5 months, which is highly unacceptable compared to the target of one week.

Next to the waiting list and access time, it is interesting to see how long the period is in which there are patients on the waiting list. This period will be referred to as the demand period for the endoscopic department. As expected the demand periods are approximately the invitation period plus the one year the screening trial takes per participant.

It can be concluded that the best invitation period for the expected situation seems to be eighteen months. During the 2.5 years of demand period, the intake access time rises to maximum two weeks. Comparing this value for the intake access time with 7.5 weeks for the twelve months period and fifteen for a six months period, only two weeks seem the most acceptable.

The above results show that an invitation period of six months is highly undesirable in case of the expected participant percentage. Therefore, it would be interesting to analyze the situation with participant percentage and low positive test results (*DD9*). To analyze this, a simulation is run with *IP3* and *DD9*. The results of this simulation show that in case of low participant percentage, the access time is constant and equal to one week. As a result, an invitation period of six months is sufficiently enough in the situation with low demand probabilities.

The same question can be asked about the invitation period of twelve months. As stated above, using the expected demand percentages, this scenario resulted in an access time of almost two months. The results of the simulation with *IP2* and *DD9* also show a constant access time of one week, equal to the simulation *IP3* and *DD9*. It can be concluded that in case the demand probabilities of the screening trial are lower than expected, the invitation periods of six months and of twelve months are sufficient in resulting in the target access time. However comparing both, six months is probably the best solution. Since the overall time the trial will take is shorter, an invitation period of six months is expected to be cheaper.

An invitation period of eighteen months turned out to be sufficient when the demand probabilities are based on experiences of other screening research (demand scenario *DD1*). The question rises what happens to the waiting list and corresponding access time in case the demand probabilities are higher than expected. To study this effect, invitation period scenario *IP1* is simulated with the demand percentages of *DD5*. The results of *IP1* combined with *DD5* show that in case of high demand probabilities, eighteen months of invitation period

results in a high access time (Figure 5-3). The access time raises to almost fifty weeks around the moment the second test participants arrive at the waiting list. The results show that in the situation of high demand probabilities even an invitation period of eighteen months will not lead to the desired access times.

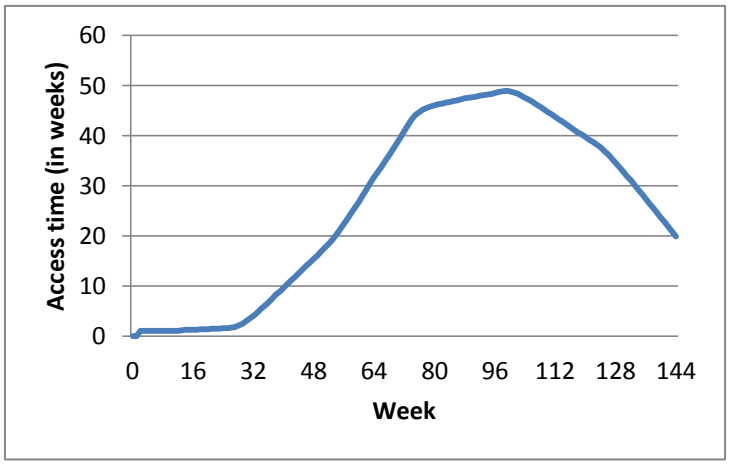

Figure 5-3: Access time of scenario *IP1* with *DD5*

In the following section, an insight is given about the capacity allocation in case of an invitation period of twelve and of six months.

5.1.2 Invitation period scenarios and capacity allocation

The analyses above are based on initial capacity of ten intakes and twelve colonoscopies. Invitation period scenarios *IP2* and *IP3* result in high access times in case of expected demand probabilities. In the part below, capacity allocations for these two scenarios with expected demand probabilities (*DD1*) are determined with help of the supply scenarios. The supply scenarios are defined in part 6.2. Note that the outcomes of these capacity allocation analyses give insights in the best capacity allocation assuming fixed capacity. Since the previous simulations with *FS3* already resulted in high access times, the supply scenarios *FS1* and *FS2* are not included in the following analysis.

The average and maximum values of scenario *IP2* with the supply scenarios are listed in Table 5-1. The graphs of all outputs are shown in Appendix C2.

Table 5-1: Best capacity allocation for scenario *IP2*

Invitation scenario	*Supply scenario*	*Avg. intake access time*	*Avg. procedure access time*	*Avg. NP capacity utilization*	*Avg. P capacity utilization*
IP2	*FS3*	2 weeks	1 week	76%	64%
IP2	*FS4*	1 week	1.2 week	52%	64%
IP2	*FS5*	1 week	1 week	52%	43%
Invitation scenario	*Supply scenario*	*Max. intake access time*	*Max. procedure access time*	*Max. NP capacity utilization*	*Max. P capacity utilization*
IP2	*FS3*	7 weeks	1 week	100%	83%
IP2	*FS4*	1 week	2.5 weeks	90%	100%
IP2	*FS5*	1 week	1 week	90%	74%

The results of scenario *IP2* show that supply scenario *FS5* leads to intake and procedure access times of one week during the whole demand period. Although the average numbers do not seem very high, the maximum capacity utilizations are 90% for the nurse practitioner (NP) and 74% for the physician (P). In conclusion, when the invitation period is decided to be one year, the overall needed capacity comes down to fifteen appointments and eighteen colonoscopies. Eighteen colonoscopies are equal to the very maximum physician capacity. However, when the available capacity is lower than this, this leads to access times up to

seven weeks and significant high capacity utilizations that already exist from the moment the first positive test participants arrive.

The values of the outputs of an invitation period of one year are listed in Table 5-2. Considering the maximum values, the best capacity allocation seems to be twenty intakes and eighteen procedures (*FS6*). However, it can be argued that a maximum intake access time of three weeks can be manageable. In that case, fifteen appointments and eighteen colonoscopies could be also considered as a good solution. Nevertheless with both possibilities, the needed physician capacity is equal to the maximum available capacity of the endoscopic department. This makes it very unfavorable to choose an invitation period of six months, since there will be no room for changing circumstances or emergencies.

Table 5-2: Best capacity allocation for scenario *IP3*

Invitation scenario	*Supply scenario*	*Avg. intake access time*	*Avg. procedure access time*	*Avg. NP capacity utilization*	*Avg. P capacity utilization*
IP3	*FS3*	8 weeks	1 week	95%	80%
IP3	*FS4*	1.2 week	3 weeks	66%	80%
IP3	*FS5*	1.2 week	1 week	66%	55%
IP3	*FS6*	1 week	1 week	50%	55%
Invitation scenario	*Supply scenario*	*Max. intake access time*	*Max. procedure access time*	*Max. NP capacity utilization*	*Max. P capacity utilization*
IP3	*FS3*	14 weeks	1 week	100%	83%
IP3	*FS4*	3 weeks	7 weeks	100%	100%
IP3	*FS5*	3 weeks	1 week	100%	83%
IP3	*FS6*	14 weeks	1 week	82%	94%

Instead of using the maximum available capacity, it is also possible to control the access times with two feedback regulation systems, which is discussed in the following sections.

5.1.3 Invitation period scenarios and feedback regulation systems

First, the invitation feedback system is introduced for both *IP2* and *IP3* with expected demand probabilities (*DD1*). Second, the capacity feedback system is implemented into the simulation model. For both *IP2* and *IP3*, it is chosen to use initial supply scenario *FS3* as start capacity. Especially when using the invitation feedback system it is possible that the demand period will expand. Therefore the simulation time is widened to 144 weeks for both invitation period scenarios to be sure to capture all necessary information.

5.1.3.1 Invitation period scenarios and invitation feedback regulation

The first simulation is done with an invitation period of one year and an invitation feedback system. The results show that at seven months the invitations are set back to zero per week for the first time, because the intake access time has raised above one week. A consequence is that the demand period is expanded by thirteen weeks. The total demand period results in almost thirty weeks. Next to that, the access time is brought down significantly (Figure 5-4). Thus in conclusion, when looking at the regulated access time, an invitation period of one year can be reasonable with implementation of an invitation feedback system.

In case of using an invitation period of six months and an invitation feedback system, the results are not really satisfying (see Figure 5-5). Here, the invitations are also set back at six moments; however, the access time is usually between one and four weeks. Next to that, the invitation period is widened by fifteen months which means that the total invitation period is around 21 months. Thus, the effect of lower costs with a smaller invitation period has declined with implementing the feedback regulation.

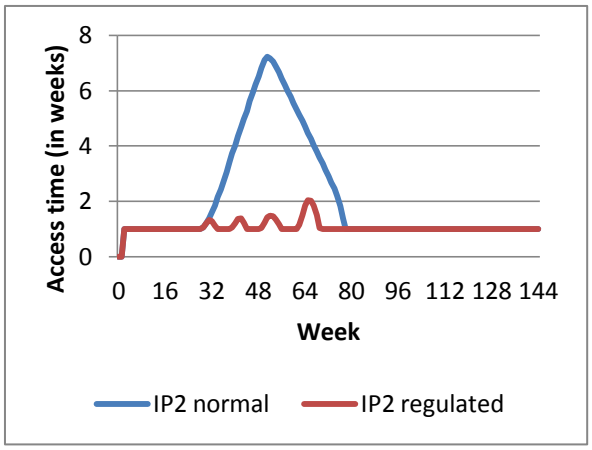

Figure 5-4: Comparison access time normal vs. invitation regulated situation scenario IP2

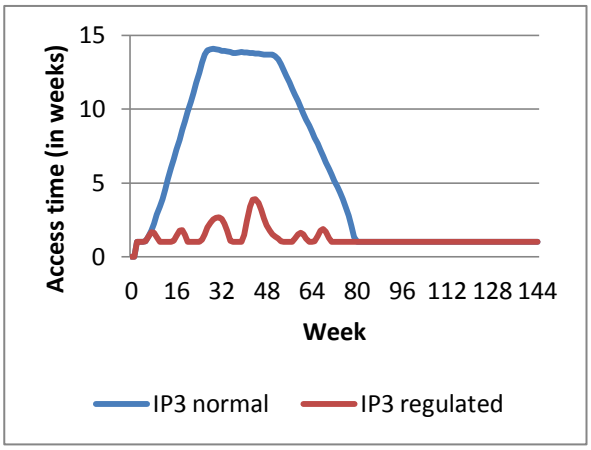

Figure 5-5: Comparison access time normal vs. invitation regulated situation scenario *IP3*

It is expected that the invitation feedback system has better results in case of more available resources. Therefore, the invitation feedback regulation is implemented with fifteen intake appointments and twelve colonoscopy procedures (*FS4*). Now, the invitations are only set back three times and the demand period is extended with three months. The total invitation period turned out to be thirteen months, which is less than the 21 months that resulted from the previous simulation. Finally, the access time has decreased to more desired values (Figure 5-6).

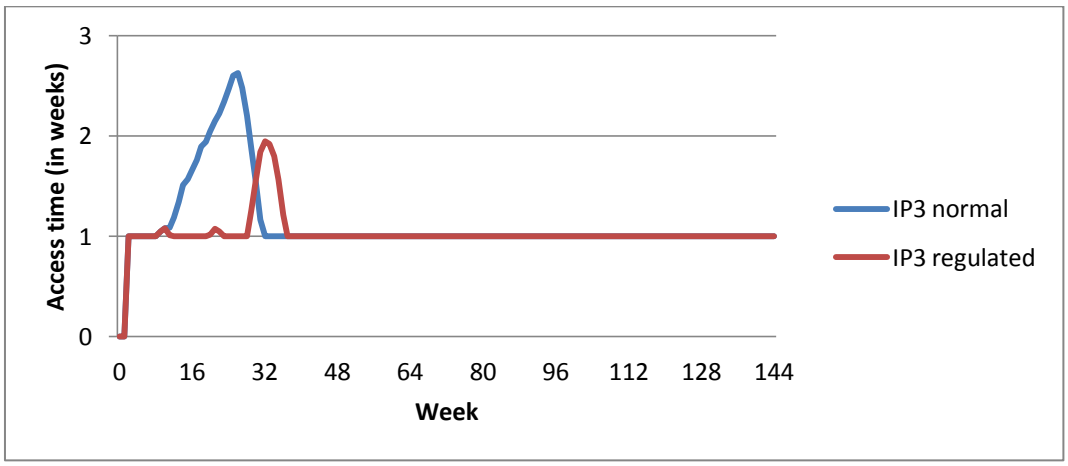

Figure 5-6: Comparison access time normal vs. invitation regulated situation *IP3&FS4*

In conclusion, when it is decided to work with an invitation period of six months, this will only result in desired access times with capacities of fifteen intake appointments and twelve colonoscopies and the implementation of an invitation feedback system. The graphs that depict the progress of the number of invitees per week for all the invitation regulated scenarios are shown in Appendix C3.

5.1.3.2 Invitation period scenarios and capacity feedback regulation

In addition to the invitation feedback system, the capacity feedback system can be introduced to control the access times. Again, the start capacity is ten intake appointments and twelve procedures. As stated, the number of intake appointments is increased to fifteen in case of an intake access time higher than one week. The physician capacity is increased to eighteen procedures when a higher procedure access time is present. It is decided to only increase and not decrease the capacity, since the invitation feedback system will only be used in situations where the intake access time is above one week.

With both invitation periods, in the situations without feedback the procedure access time is constant and equal to one week. However, at the moment the nurse practitioner capacity is increased by the feedback regulation, the procedure access time will start to rise. This increase is due to that the nurse practitioner capacity is higher than the physician capacity at that moment. Therefore, the waiting list for the procedure will start and the procedure access time will increase to a level above one week. A comparison of the normal and the regulated procedure access time is included in the following analysis.

For the invitation period of twelve months, the implementation of the regulation results that the procedure access time rises above one week in nine weeks. However, these increases are very small, especially compared to the decreases of the intake access time in comparison to the 'normal' situation (Figure 5-7). The nurse practitioner capacity is increased fifteen times, while the physician capacity is increased nine times. The implementation of a capacity feedback regulation makes an invitation period of twelve months more useful.

For the invitation period of six months the capacity feedback regulation results in an increased procedure access time for sixteen weeks and a decreased overall intake access time. However, the intake access time is still too high compared to the target (see Figure 5-8). Next to that, the nurse practitioner capacity is increased during 32weeks, which is one third of the simulation time. Another disadvantage of this type of feedback system in combination with an invitation period of six months is that the physician capacity changes every week from twelve to eighteen procedures. In practice, it is not desirable to have changing capacity each week. Weekly changing capacity results in weekly changing schedules for the physicians. Therefore, the invitation feedback regulation has an advantage over the capacity regulation of this scenario.

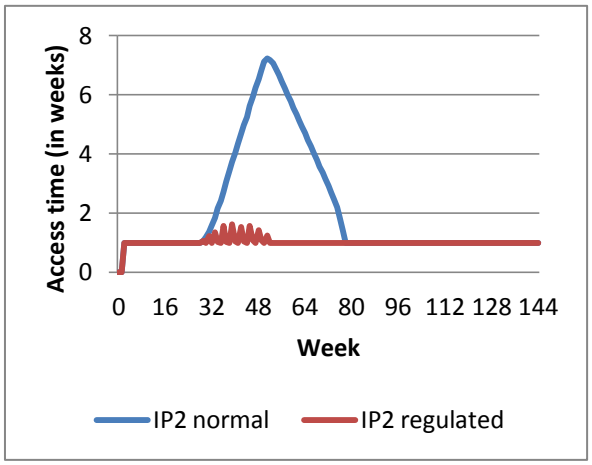

Figure 5-7: Comparison access time normal vs. capacity regulated situation scenario *IP2*

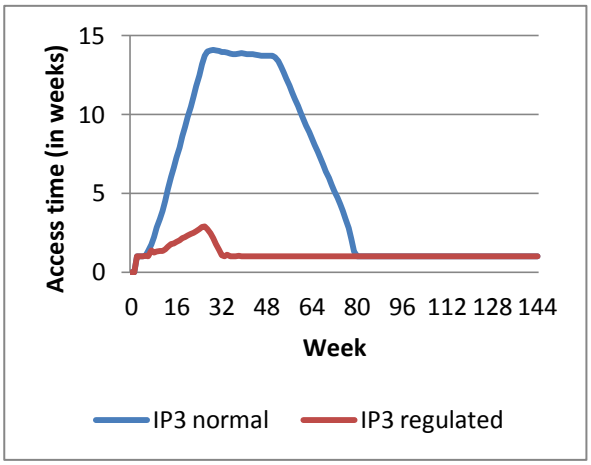

Figure 5-8: Comparison access time normal vs. capacity regulated situation scenario *IP3*

For both simulations, the simulations results are shown in graphs in Appendix C3. For the scenario with an invitation period of twelve months the disadvantages are smaller when using a capacity feedback system. However, a higher initial capacity for both the physicians and nurse practitioners in combination with an invitation feedback system seems also for this situation the better solution over the capacity feedback system.

5.2 Demand scenarios

As stated, three different demand scenarios are contrived. It is chosen to use an eighteen month invitation period of, since it is the best starting position for simulations without feedback regulation. The following parts discuss the results of the three types of scenarios.

5.2.1 Stochastic response times

First the different situations with stochastic response times, as formulated in part 4.3.3.1, are simulated. The results in Appendix C4 show that including stochastic fluctuations in the response times does not lead to much difference in the patient demand pattern. Surprising to see is that the maximum demand of the scenario without any fluctuation is the highest of all scenarios. Two other important things can be obtained from the results. First, although the maximum demand is not higher, the graphs of the scenarios with stochastic reaction times show a more fluctuating demand. Therefore, there are also some fluctuations in the access times, though this is not very much. Second, from the results it can be concluded that the period that patients are on the waiting list for the stochastic scenarios is one to five weeks longer than the scenario with deterministic reaction times. To summarize, the addition of variation in the response times leads to more fluctuating demand and a longer period of demand.

5.2.2 Fluctuations in demand probabilities

The part describes the analysis with the demand probabilities scenarios, referred in the following parts as demand scenarios. Since the introduction of stochastic response times does not influence the actual demand, it is decided to use deterministic response times. First, the demand scenarios are simulated with the initial capacity allocation (*FS3*). Since the capacity of the nurse practitioner is lower than the physicians, the procedure admission rate will be equal to the intake admission rate. In the following parts, when discussing the intake access time, this is simply referred to as the access time.

Naturally, the scenarios with higher values for the percentages result in higher demand and accompanying higher access times. As happened with the invitation period simulation, the results of most scenarios show the same patient arrival pattern. The situations with low positive test results (*DD3*, *DD7* and *DD9*) result in stable intake access times equal to one week. This result is also observed for scenario *DD6*. With the other scenarios, the access time increases above one week at some point during the demand period (see Figure 5-9). The expected percentages (*DD1*) lead to a maximum around two weeks. The same pattern is found with a low participant percentage and high positive test results (*DD8*). The scenarios with a high participant percentage and low positive test results (*DD4*), and vice versa (*DD2*) lead to high access times, with maximums of just below fifteen for the first and of around twenty weeks for the latter. Obviously the situation with all high demand probabilities (*DD5*) leads to the highest access time. The maximum access is for this scenario is over 45 weeks.

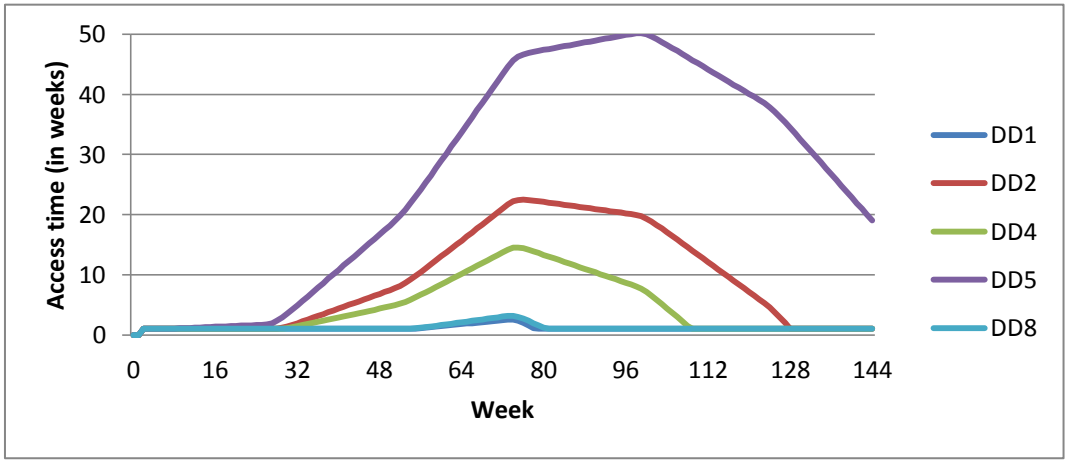

Figure 5-9: Access times of scenarios *DD1*, *DD2*, *DD4*, *DD5* and *DD8*

For the scenarios with increased access time, it is interesting to see at which moment this growth takes place. For the demand scenarios *DD1* and *DD8*, the increase in access time starts around week 55, which is when the third test participants arrive. Next, for demand scenarios *DD2* and *DD4* the increase is around week 30, i.e. the moment the second test participants arrive. The access time of *DD5* rises around week 10, so here the access time becomes already too high when the first test participants arrive.

Since these last five demand scenarios result in access time higher than the desired one week, these scenarios are interesting to simulate with the invitation and capacity feedback regulations. This especially applies for demand scenarios *DD2*, *DD4* and *DD5*.

5.2.3 Fluctuations in demand probabilities and capacity allocation

To gain a better understanding of the different demand scenarios, in this part the best capacity allocation for each scenario is determined. In this way, it is clear for the endoscopic department how to set the initial capacities after it is known which scenario the trial is in.

Since both the nurse practitioner and the physician capacity are going to change, in this analysis the intake and the procedure access time are included. Also the capacity utilizations of both resources used to base a conclusion. When choosing the best fitted capacity allocation, the supply scenarios are used. As a result, it could be that the best supply scenario is in reality not the optimal capacity allocation. For example, when the results show that scenario *FS4* (fifteen appointments and twelve colonoscopies) is the best, it could be that fourteen appointments and thirteen colonoscopies is better. However, since it is assumed that the nurse practitioner capacity is always a multiple of five and the physician capacity is always a multiple of six, the supply scenarios are assumed to result in the optimal capacity allocation. In addition, as stated earlier, the results of the capacity allocation analysis result in a best overall capacity, without considering the possibility to adjust the capacity in between weeks. A more in-depth capacity planning on weekly basis is analyzed in the second part of this master thesis report.

The best capacity allocations for each demand scenario are listed (see Table 5-3). The complete table of all demand scenarios can be found in Appendix C5. As criterion and in perfection, both access times needs to be one week. In addition, the capacity utilization needs to be as high as possible, though preferably not hundred percent. It is expected that the analyses will result in a trade-off between access time and capacity utilization. High capacity utilizations can lead to access times higher than desired and access times which are considered to be perfect can lead to low capacity utilizations. The simulation outputs are also plotted against the 144 week simulation time. The graphs can be found in Appendix C5.

Table 5-3: Best capacity allocation for each demand scenario

Demand scenario	*Supply scenario*	*Average intake access time*	*Average procedure access time*	*Average nurse practitioner capacity utilization*	*Average physician capacity utilization*
DD1	*FS3*	1.1 week	1 week	64%	53%
DD2	*FS5*	1.2 week	1 week	65%	54%
DD3	*FS1*	1 week	1 week	70%	24%
DD4	*FS5*	1 week	1 week	67%	55%
DD5 *DD5*	*FS5* *FS6*	5 weeks 1.2 week	1 week 1.4 weeks	86% 65%	72% 72%
DD6	*FS2*	1 week	1.2 week	47%	76%
DD7	*FS3*	1 week	1 week	43%	70%
DD8	*FS3*	1.2 weeks	1 week	65%	54%
DD9	*FS1*	1 week	1 week	47%	39%

In the anticipated situation (*DD1*) the best capacity allocation seems to be fifteen intakes and twelve procedures. However, an average intake access time of 1.1 week seems surmountable. Therefore, a better capacity allocation will be ten intakes and twelve

procedures, since in this case higher capacity utilizations are yielded. The same reasoning can be applied to demand scenario *DD8*. For scenario *DD2*, the optimal allocation contains the maximum available procedures, i.e. eighteen colonoscopies and fifteen intake appointments. In this case, again the target intake access time is considered to be less strict. Demand scenarios *DD3* and *DD9,* with respectively initial and low participant rates in combination with low positive test rates, need the minimum available resources in order to maintain constant access times that are equal to one week.

For *DD4*, a clear trade-off has to be made between having an average procedure access time of two weeks and having an average nurse practitioner capacity utilization of 55%. Though the average access time is two weeks, the maximum can rise to five weeks, which is clearly too high. Therefore, the best solution is to have eighteen colonoscopies and fifteen intake appointments. The optimal capacity allocation for demand scenario *DD6* seems to be ten intakes and six colonoscopies, though it will lead to an average procedure access time of 1.2 weeks. The simulations with demand scenario *DD7* with low participant rate and initial positive test rates result in the initial capacity allocation as best solution.

In the end, for demand scenarios *DD5*, it is less easy to decide on the best capacity allocation. For the situation with high participant rate and high positive test rates the trade-off is between fifteen or twenty intake appointments. The first leads to a high intake access time with a maximum of fifteen weeks. The latter results in a lower overall intake access time, though the procedure access time is higher in comparison with the first situation. In addition, in the latter both capacity utilizations have a maximum of 100%. Unfortunately, the demand period is also not decisive, since in both situations the demand period is around 126 weeks. In conclusion, demand scenario *DD5* seems to be a nice candidate to simulate with the feedback regulations.

5.2.4 Fluctuations in demand probabilities and feedback regulation systems

As is done with the invitation period scenarios, instead of using the maximum capacity it is also possible to gain the targeted access times with a regulated system. For the feedback regulation systems, we are only interested in the scenarios that turned out to have in some period(s) access times higher than one week when using eighteen months as invitation period and the initial determined capacity allocation.

5.2.4.1 Fluctuations in demand probabilities and invitation feedback regulation

First the invitation feedback system is implemented for the demand scenarios. For all situations, the progress of the number of invitees is plotted against the simulation time (see Appendix C6). These graphs provide a clear picture of when and how frequently the invitations are set back. Furthermore, the access time of the initial model and of the regulated model are compared to see whether the situation is improved.

Implementing the invitation feedback regulation with *DD1* has a significant effect, since the regulated access time is almost always one week (Figure 5-10). It takes three weeks to bring a higher access time back to one week. In week 96, all 5500 persons are invited. Thus, the invitation period is widened with 24 weeks. However, the demand period is in the end widened with only six weeks.

The results of *DD2* with the feedback regulation show a significant decrease in the access time over the whole simulation period (Figure 5-11). In the normal simulation, the maximum access time rose to almost twenty weeks, while for the regulated situation the maximum is below two weeks. It takes approximately four to six weeks to bring back the access time. Next to that, all 5500 persons are invited around week 138. Unfortunately, after three years there are still some patients on the waiting list, i.e. not all participants with a positive test results are diagnosed within three years.

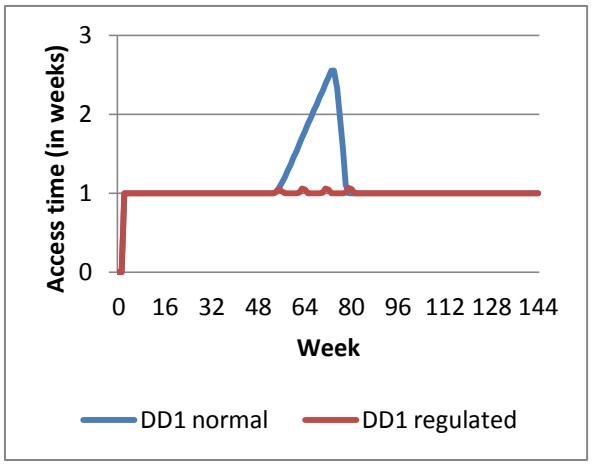

Figure 5-10: Comparison access time normal vs. invitation regulated situation *DD1*

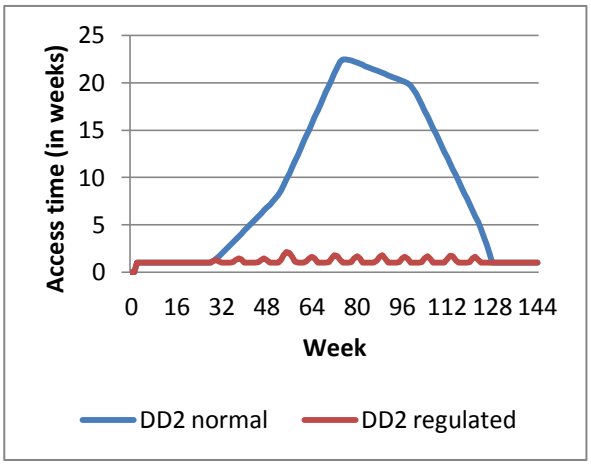

Figure 5-11: Comparison access time normal vs. invitation regulated situation DD2

For *DD4*, the last persons are invited in week 125. The significant decrease in intake access time is shown in Figure 5-12. The intake access time is almost decreased to one week for all simulation weeks. It takes around three or five weeks to bring back the access time. Again as with scenario *DD2*, there are still some patients on the waiting list at week 144.

Scenario *DD8* show similar results as scenario *DD1*. For *DD8* it also takes three weeks to bring back the increased access time. The invitation feedback regulation ensures an almost constant intake access time equal to one week (Figure 5-13).The demand period is extended with approximately ten weeks.

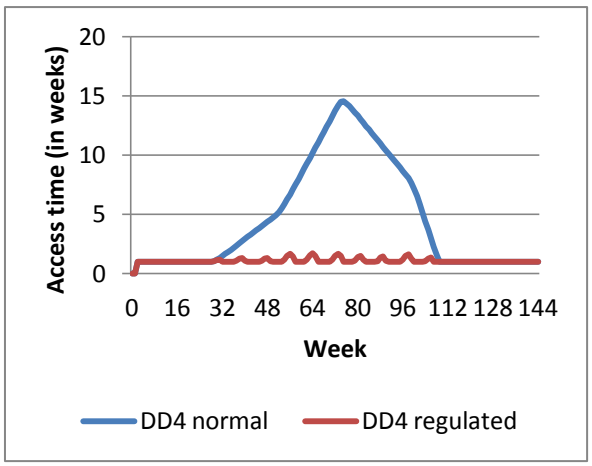

Figure 5-12: Comparison access time normal vs. invitation regulated situation DD4

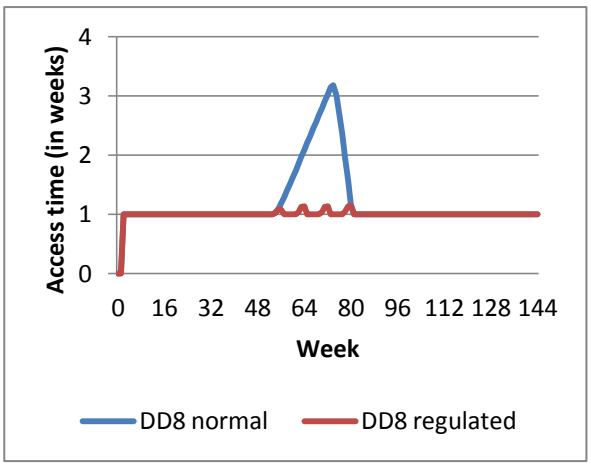

Figure 5-13: Comparison access time normal vs. invitation regulated situation DD8

The regulated simulation results of *DD5* are shown in Figure 5-14. The graph is slightly misleading, the maximum access time for the regulated situation is still around 2.7 weeks. However, when these results are compared to the very high access time of the non-regulated simulation, these results show big improvements. Downside of the regulated simulation is that not all 5500 persons are invited in the simulation run of three years. About 11% still needs to be invited. Next to that, it takes at maximum thirteen weeks to bring back the intake access time, which causes that the access time rises to 2.5 weeks. The results give rise to the question what improvements can be done with implementing both the invitation and the capacity feedback regulations.

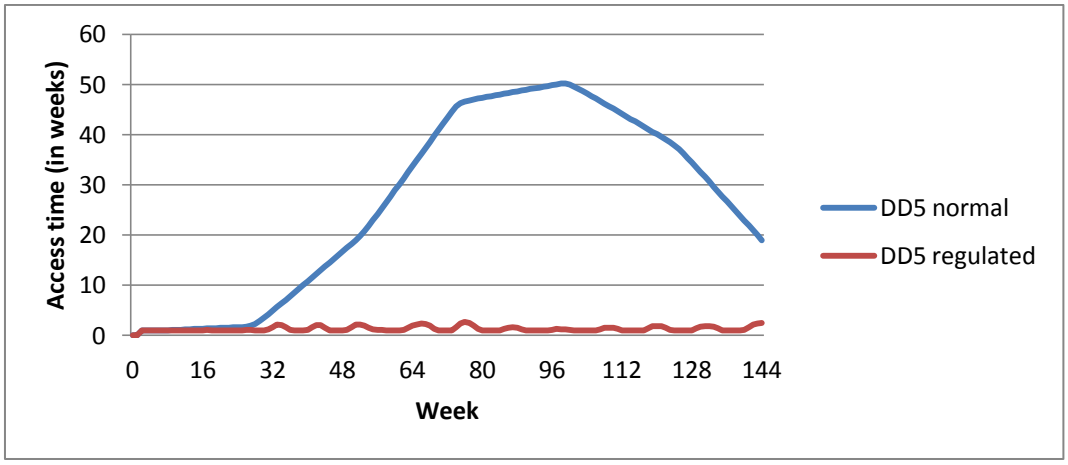

Figure 5-14: Comparison access time normal vs. invitation regulated situation DD5

To conclude, for scenarios *DD1, DD4* and *DD8* the implementation of an invitation feedback regulation results in the desired situation of a more constant intake access time of around one week. For scenario *DD2*, it can be discussed whether the implementation provides enough improvement in the intake access time, since the results show still some higher intake access times. Last, for scenario *DD5*, although the implementation results in a decrease of almost hundred percent, the regulated intake access times are still too high.

5.2.4.2 Fluctuations in demand probabilities and capacity feedback regulation

In addition to the invitation feedback system is also possible to regulate the access times with a capacity feedback system. The same five demand scenarios are simulated to see the effect of the implementation of a capacity feedback regulation. A comparison with the access times of the normal simulation and the access times of the regulated simulation are interesting. Next to that, the progress of the available capacity of both resources is of interest (found in Appendix C6).

The implementation of the capacity feedback regulation clearly decreases the intake access time of scenario *DD1* almost one week (Figure 5-15). For the procedure access time, this was already sufficient in the non-regulated simulation and it stayed the same. From the graph of the nurse practitioner capacity it is seem that the capacity is increased for about eleven times. Next to that, the number of the colonoscopies has not increased.

The intake access time of *DD2* was quite high in the normal simulation. Figure 5-16 shows that including the capacity feedback regulation leads to a significant decrease in the access time. An important consequence of increasing the nurse practitioner capacity is that the procedure access time also increases. However, this increase is very small and the access time stays below 1.5 weeks. A downside of the implementation of the capacity feedback system with demand scenario *DD2* is that the physician capacity fluctuates almost every week between twelve and eighteen procedures. This may be the best regulated solution; in practice this is very unpractical.

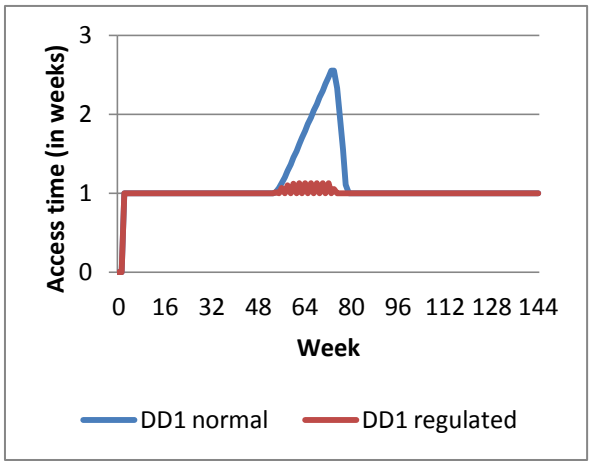

Figure 5-15: Comparison access time normal vs. capacity regulated situation for *DD1*

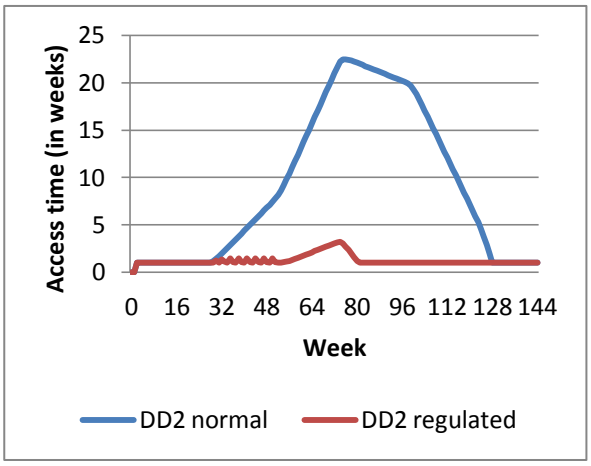

Figure 5-16: Comparison access time normal vs. capacity regulated situation for *DD2*

The same observations can be made with scenario *DD4 (*Figure 5-17). The intake access time has significantly decreased with implementing the capacity feedback regulation. The maximum intake access time stays well below two weeks. Again this implied that the procedure access time increased, though this increase is not very worrying. Both the nurse practitioner and physician capacity have been increased multiple times. As with demand scenario *DD2*, the capacity of the nurse practitioners and the physicians vary per week what makes it very unpractical.

For DD5, it is clear that the capacity feedback regulation decreases the intake access time, but these numbers are still very high (maximum lies above fifteen weeks as can be seen in Figure 5-18). The increasing effect on the procedure access time is still manageable. Because of the high intake access times, *DD5* seems also a good candidate for the simulation with the both feedback regulations. The results of scenario *DD8* are similar to those of scenario *DD1*. The implementation of the capacity feedback regulation fully regulates the higher intake access time of the non-regulated simulation.

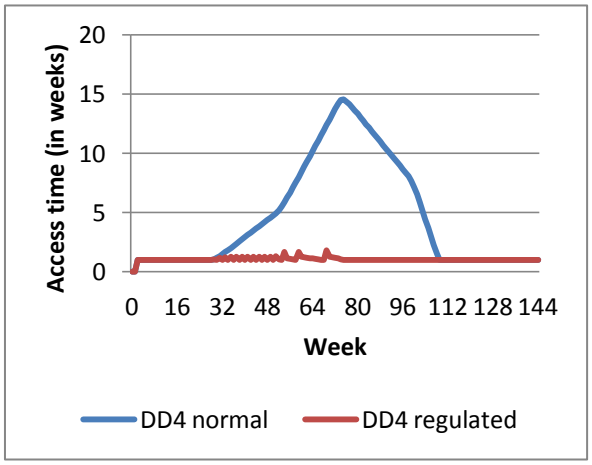

Figure 5-17: Comparison access time normal vs. capacity regulated situation for *DD4*

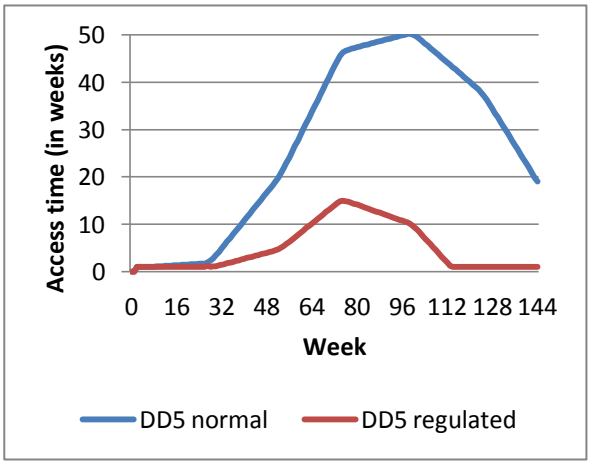

Figure 5-18: Comparison access time normal vs. capacity regulated situation for *DD5*

In sum, the capacity feedback regulation decreases the intake access time for all scenarios. Only demand scenario *DD5* still results of a high intake access time. One disadvantage of the feedback system is that the procedure access time increased for some scenarios. However, these increases are still manageable, though these are higher than the target for some periods. Another disadvantage is that the capacity allocation differs each week. This is especially a problem with demand scenarios *DD2* and *DD4*.

5.2.5 Order of feedback regulation systems

The results from the simulations with implementing separately the invitation and the capacity feedback regulations showed that the intake access time of scenario *DD5* is not decreased as desired. Therefore, scenario *DD5* will be simulated with both feedback regulations implemented. Interesting is to study which feedback system needs to be triggered first. In other words, which order of feedback has the most effect on decreasing the access time? In the following part, two different situations are analyzed. With the first situation, the invitation feedback system is triggered at an intake access time of one week, while the capacity feedback system is triggered at access times of 1.5 weeks. The second situation is contrary: the capacity feedback system is triggered at access times of one week, as the invitation feedback system is at an intake access time of 1.5 weeks. The outputs results of the two simulations are depicted in Appendix C6.

For the first situation, the simulation time is extended to three years (42 months), since it is expected that the invitation period will expand extensively due to the invitation feedback regulation. The last persons are invited during week 155 which is three years and two months after the first invitation is sent. This means that the invitation period is 83 weeks longer than in the non-regulated situation. The result of the regulations is that the intake access time decreases significantly with a maximum of just over two weeks (Figure 5-19). The procedure access time has increased during some weeks; however the increase stays almost always below 1.5 week. As a consequence, the physician capacity is only triggered to increase for two times during the whole simulation period.

In the second situation the capacity feedback system is triggered first. Naturally, this situation results in highly fluctuating capacities for the nurse practitioner and physician. As a consequence, the overall intake access time is decreased, with a maximum of approximately two weeks (Figure 5-20). The procedure intake access time has increased, though as with the first situation, it stays below 1.5 weeks. The invitation period is approximately forty weeks longer than with non-regulated situation, which is approximately fifty percent less than the extension of the invitation period in situation 1.

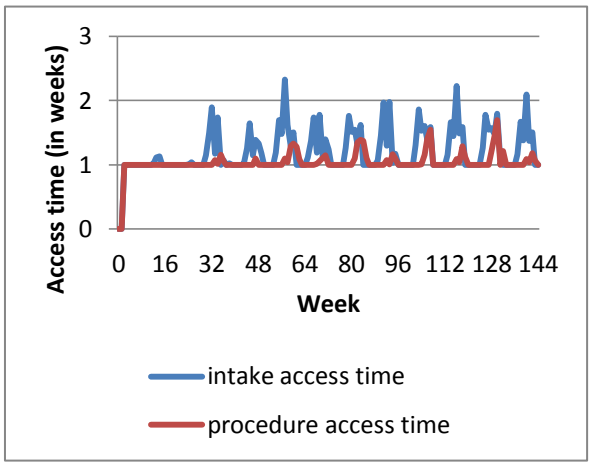

Figure 5-19: Intake and procedure access time of situation 1 with scenario *DD5*

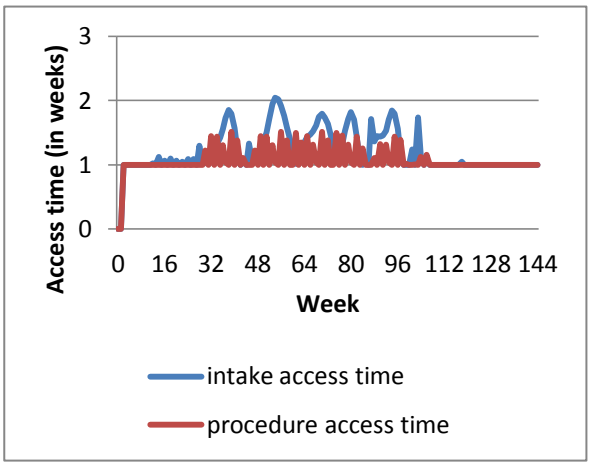

Figure 5-20: Intake and procedure access time of situation 2 with *DD5*

In sum, a disadvantage of first triggering the invitation feedback system is that the invitation period is extended significantly. On the other hand, the physician capacity does not need to be increased, it stays at the initial value. With the capacity feedback system triggered first, the nurse practitioner and physician capacity changes almost every week, which is highly unpractical, especially for the nurse practitioner(s) and physicians themselves. The advantage of the second situation is that the invitation period is not extended as much as with the first situation. In the end, both situations lead to decreased intake access times and manageable procedure access time.

Note that, although the intake access time decreased, in both situations the implementation of the combined feedback systems has failed to result in a constant intake access time of one week. To conclude, the choice for one of the situations depends on the preferences of the screening trial owners. In case of a priority of an invitation period that is not extended too much, the best solution is to trigger the capacity feedback system first. On the opposite side, when the priority is to use the initial determined capacity and preferably not the maximum available capacity, the best solution is to trigger the invitation feedback system first.

A limitation of the study above and perhaps of all simulation using the capacity feedback system is that the procedure access time can only be regulated by increasing or decreasing the physician capacity. Another limitation is that the invitation feedback regulation is only triggered by the intake access time and not the procedure access time.

5.2.6 Different invitation batches

The third type of demand scenarios is about the pattern of inviting participants. The same values for the invitation period and initial capacity are used as in the previous demand scenario analysis.

In general, the demand graphs of scenarios *IB2* and *IB3* contain of a more peaky demand pattern than the *IB1* scenario (see Figure 5-21). Therefore, the invitation patterns of *IB2* and *IB3* result in more fluctuating demand. As a consequence the capacity should be adjusted week from week to result in desirable capacity utilizations.

Based on access times, depicted in Figure 5-22, inviting fifteen participants each day is most optimal. However this is only feasible if the used invitation system is capable of inviting a certain number of participants per day. Inviting 76 participants seems to be the second best, since this seems more easily to implement in an invitation system and leads to less fluctuating demand and access times. Inviting 305 participants each month is also possible; however this leads to a highly fluctuating access time. In the end, inviting 917 participants each three months is highly unfavorable, due to high fluctuating demand and access time and possible corresponding capacity planning difficulties.

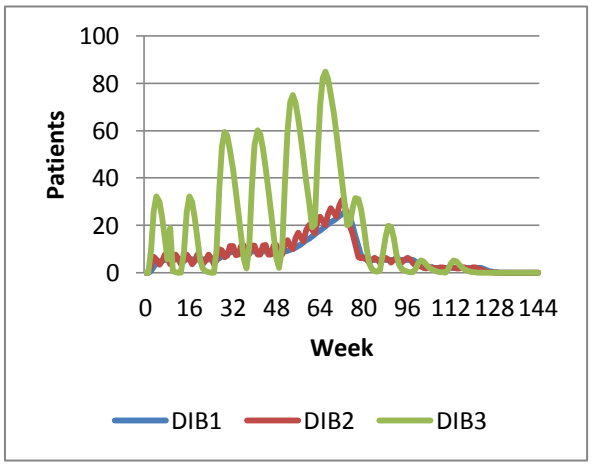

Figure 5-21: Demand pattern of scenarios *IB1*, *IB2* and *IB3*

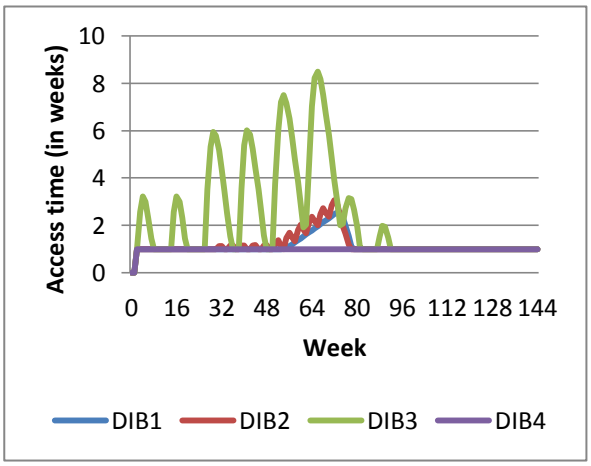

Figure 5-22: Access time for scenarios *IB1*, *IB2*, *IB3* and *IB4*

In the following part, the invitation batch scenarios are combined with the supply scenarios to determine the best overall capacity allocation.

5.2.7 Different invitation batches and capacity allocation

The following part discusses the best capacity allocation in case it is chosen to use monthly or three months invitation batches. First, the simulations of the monthly invitation batch resulted in the maximum outputs listed in Table 5-4.

Table 5-4: Best capacity allocation for scenario *IB2*

IB scenario	*Supply scenario*	*Avg. intake access time*	*Avg. procedure access time*	*Avg. NP capacity utilization*	*Avg. P capacity utilization*
IB2	*FS3*	1.2 week	1 week	64%	53%
IB2	*FS4*	1 week	1 week	43%	53%
IB2	*FS5*	1 week	1 week	43%	35%
IB scenario	*Supply scenario*	*Max. intake access time*	*Max. procedure access time*	*Max. NP capacity utilization*	*Max. P capacity utilization*
IB2	*FS3*	3 weeks	1 week	100%	83%
IB2	*FS4*	1 week	1.1 week	87%	100%
IB2	*FS5*	1 week	1 week	87%	68%

The determination the best capacity allocation for the scenario *IB2* results in a tradeoff between access times and capacity utilization. When only considering the access time, supply scenario *FS5* is clearly the best solution. However, this scenario results in low capacity utilizations, especially for the physician capacity. In that respect, the best solution is *FS4* which results in higher utilizations. Important to note is that the physician capacity utilization of hundred percent is for only five weeks of the total 144 weeks. These five weeks are precisely the weeks the third participants arrive. In other words, the capacity utilization becomes hundred percent and therefore the corresponding access time rises to 1.1 weeks when the waiting list consists of first, second and third test participants. In conclusion, the best solution seems to go for fifteen intake appointments and twelve colonoscopies (*FS4*) and be aware of the periods the third participants arrive at the waiting list.

The results of the three months invitation batch are shown in Table 5-5. From the results in the table, it can be concluded that none of the supply scenarios is a good fit for inviting participants each three months. The results show that inviting 917 participants per each three months is probably not a good idea at all. However, perhaps with the implementation of a feedback regulation, this invitation batch period will be slightly more favorable.

Table 5-5: Best capacity allocation for scenario *IB3*

IB scenario	*Supply scenario*	*Avg. intake access time*	*Avg. procedure access time*	*Avg. NP capacity utilization*	*Max. P capacity utilization*
IB3	*FS3*	2 weeks	1 week	68%	56%
IB3	*FS4*	1.3 week	1.2 week	45%	56%
IB3	*FS5*	1.3 weeks	1 week	45%	37%
IB3	*FS6*	1 week	1 week	34%	37%
IB scenario	*Supply scenario*	*Max. intake access time*	*Max. procedure access time*	*Max. NP capacity utilization*	*Max. P capacity utilization*
IB3	*FS3*	8 weeks	1 week	100%	83%
IB3	*FS4*	4 weeks	3 week	100%	100%
IB3	*FS5*	4 weeks	1 week	100%	83%
IB3	*FS6*	2 weeks	1.3 weeks	100%	100%

Next to the maximum outputs listed in the tables, the graphs with the intake access time, the procedure access time, the nurse practitioner capacity utilization and the physician capacity utilization, all plotted against the simulation time, are depicted in Appendix C7.

5.2.8 Different invitation batches and feedback regulation systems

As concluded in the above part, inviting each three months seems not desirable. Therefore, scenario *IB3* will be simulated with a capacity feedback regulation to see what the effect of an implementation could be. Next to that, it is interesting to see whether the simulation shows better outputs when the *IB2* scenario is simulated with the capacity feedback regulation. It is chosen to perform these analyses only with a capacity feedback system, since it is expected that an invitation feedback system will expand the invitation period too much to cope with.

5.2.8.1 Different invitation batches and capacity feedback regulation

First, the scenario of inviting each month is simulated with the capacity feedback regulation. It is clear that the access time has decreased, especially in the periods the third test participants arrive at the waiting list (Figure 5-23). The maximum access time is around 1.5 weeks, which is manageable regarding the target of one week. The procedure access time rises above one week for some periods; however this increase is negligible (only one day above the target). Therefore, it can be concluded that the implementation of a capacity feedback regulation makes it more favorable to use a monthly invitation batch.

Second, the situation of each three months and the feedback regulation is simulated. The maximum intake access time is decreased, though still the maximum lies around four weeks (Figure 5-24). A consequence is that the procedure access time rises to almost 1.5 weeks. Another disadvantage is that the physician capacity is increased twenty moments to sixteen procedures. These increases are often just for one week. In reality, these shifts of capacity for each week are unpractical. In sum, the implementation of the capacity feedback for scenario *IB3* leads to some improvements of the access times, however, these improvements are not sufficient enough to become favorable to implement in the trial.

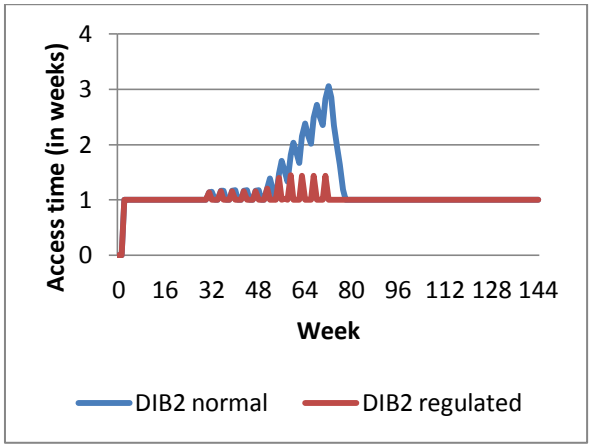

Figure 5-23: Comparison access time normal vs. capacity regulated situation for *IB2*

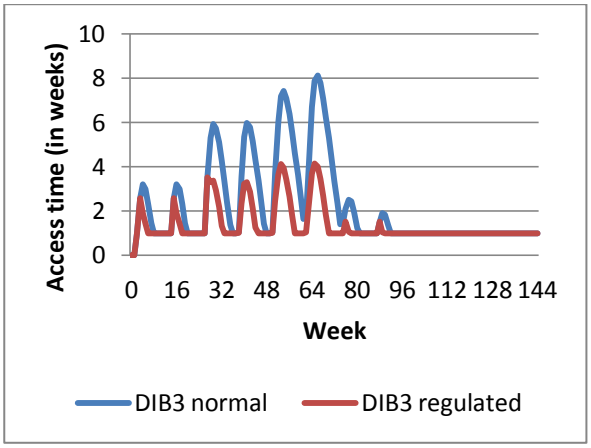

Figure 5-24: Comparison access time normal vs. capacity regulated situation for *IB3*

In Appendix C8 the results of the simulations with *IB2* and *IB3* with capacity feedback regulation are depicted.

5.3 General conclusions of the System Dynamics model

Based on several what-if scenarios described above, some essential conclusions can be drawn about the patient demand pattern of the endoscopic department. Different values for two decision variables, i.e. the invitation period and the invitation interval, are analyzed to form useful advice.

First, the length of the invitation period needs to be chosen on. The analysis of different invitation periods showed that an invitation period of eighteen months is the best solution compared to six or twelve months. With eighteen months, the initial determined capacity leads to lower access times than the other two scenarios. To obtain desired access times, the best start capacity allocations for six and twelve months are respectively fifteen intake appointments and eighteen colonoscopies and twenty appointments and eighteen colonoscopies. Since it is not preferred to use the maximum capacity available, the effect of implementing a feedback regulation system is studied. For an invitation period of twelve months both the invitation and capacity feedback systems resulted in lower and desirable access times. For a six months invitation period, both feedback systems yield still high access times. Therefore, it is advised to not use an invitation period of six months. Table 5-6 summarizes the findings about the invitation period.

Table 5-6: Advise on invitation period

Invitation period	*Advise*
Six months	Do not use
Twelve months	With a feedback regulation system
Eighteen months	Excellent to use

The results of second decision variable showed that the optimal quantity of invited persons is 76 persons per week. Inviting each day a certain number of persons shows more desired results. However, after consultation with the Eindhoven Cancer Registry, it turned out that this was not physically possible. Inviting a larger quantity in a larger time span leads to highly fluctuating demand, as is shown in the results of inviting 305 persons per month and 917 persons per three months. For the first scenario, the best fitted determined capacity allocation is respectively fifteen appointments and twelve procedures. For the latter scenario none of the predefined supply scenarios fit. Even after conducting the analysis with a feedback system, the scenario did not result in desirable outcomes. Therefore, using invitation intervals of three months even with a feedback system is highly unadvisable. Using an invitation batch each month is only favorable with a capacity allocation of fifteen intakes and twelve colonoscopies or the initial capacity allocation in combination with a capacity feedback system. In Table 5-7, the advise about the invitation interval are listed.

Table 5-7: Advise on invitation interval

Invitation interval	*Advise*
Weekly	Yes
Monthly	With fifteen appointments and twelve procedures or with capacity feedback system
Tri-monthly	Not

Next to the two elements that can be chosen on, there is some uncertainty coming from the demand probabilities. With the demand scenarios different possible what-if situations are tested. For the simulations for the first insights and the ones with the feedback systems the initial capacity is used. The results show that for multiple scenarios the initial capacity results in high access times. For example, for the situation with higher than initial expected percentages not even the maximum capacity of eighteen procedures is sufficient enough to cope with the demand. For this and all other scenarios with access times above one week, the invitation and capacity feedback regulation systems are implemented to see the effect on the access times. For demand scenarios *DD1*, *DD4* and *DD8* both feedback systems lead to more desired access times. For scenario *DD2* the invitation feedback regulation results in still higher access times, while the capacity feedback system results in more desired values. For

scenario *DD5* both feedback regulations are needed to control the access time. All the findings are summarized in Table 5-8.

Table 5-8: Advise on demand scenarios

Demand scenario	*Advise*
Initial demand probabilities (*DD1*)	Initial capacity with a feedback regulation system
Initial participant percentage; high positive test results (*DD2*)	Initial capacity with capacity feedback system or capacity of fifteen intakes and eighteen procedures
Initial participant percentage; low positive test results (*DD3*)	Capacity of five intakes and six procedures
High participant percentage; initial positive test results (*DD4*)	Initial capacity with a feedback regulation system or capacity of fifteen intakes and eighteen procedures
High participant percentage; high positive test results (*DD5*)	Even implementation of both feedback systems leads to high access times
High participant percentage; low positive test results (*DD6*)	Capacity of ten intakes and six procedures
Low participant percentage; initial positive test results (*DD7*)	Initial capacity
Low participant percentage; high positive test results (*DD8*)	Initial capacity with a feedback regulation system
Low participant percentage; low positive test results (*DD9*)	Capacity of five intakes and six procedures

The order in which these systems are more successful depends on the preferences of the owners. This is the same with which feedback system to use when only using one is satisfying enough. The invitation feedback system results generally in a longer demand period, while the capacity feedback system can lead to weekly fluctuating optimal capacity and increased procedure access times. In case the department wants to have an invitation period as short as possible, the capacity feedback regulation is the best solution. On the other hand, when the focus is more on the use of the initial capacity, the invitation regulation is better to use.

Both the feedback regulations have some disadvantages in their use. For the capacity feedback regulation, the optimal number of resources of the nurse practitioner and the colonoscopy can vary within weeks. Naturally this is not desirable in practice, since it is not practical to vary the capacity each week. In comparison, the invitation feedback regulation has a much smaller disadvantage. By reducing the invitations for a certain number of weeks, the period wherein persons are invited becomes larger. For example, when the invitations are set back to zero six times, the demand period is extended from 144 weeks to 150 weeks. However, it is expected that this disadvantage has less impact on the organization of the endoscopic department then the weekly fluctuating capacity with the capacity feedback regulation. Therefore if a choice has to be made between the two feedback system, in case of the Elkerliek hospital, the invitation feedback system would have be the preferred one.

Above mentioned disadvantage of the invitation feedback regulation system is that it is likely that the invitation period will extend after the invitations are set back to zero in certain weeks. An interesting extension of the above preformed analysis would be to study the effect of increasing the number of invitees per week when the invitation period is expected to extend. By increasing the number of invitees per week, it can be imagined that the desired invitation period can still be obtained.

It should be noted that the conclusions about the capacity allocation are based on the determination of overall capacities. The analysis includes capacities with a fixed value, i.e. they are not adjusted. This has resulted in low capacity utilizations for some of the demand weeks. For a more in-depth analysis, the following part of this master thesis describes an optimal weekly capacity planning generated with a Markov Decision Process.

6 Markov Decision Process

After gaining some initial insights in the optimal capacity planning without adjusting the capacity in between weeks, the following two chapters are dedicated to a more in-depth analysis of the capacity planning. The capacity control will be modeled as a Markov Decision Process (MDP). The MDP will be used to develop a policy for the optimal weekly capacity planning of the endoscopic department. In this chapter, the Markov Decision Process is introduced. Nunes et al. (2009) stated in their article about elective patient admissions that the final decision will be made by a human decision maker, because it will take into account a variety of factors. However, the developed MDP will provide the decision maker with some decision support. The goal of the MDP modeled in this thesis is to help in making decisions about the capacity allocation.

It is decided to only include the physician capacity in the MDP. It is assumed that the nurse practitioner capacity is more flexible than the physicians. It will be easier to adapt the nurse practitioner capacity to the patient demand. In the following two chapters, the physician capacity is defined as the number of available (colonoscopy) time slots. As mentioned in part 3.2.2, a MDP comprises of five components. In the following, these five components for the MDP that will develop the capacity policy are explained in the following sections.

6.1 State space and action set

A state space consists of the all possible states of the process. Schaefer et al. (2005) stated that from a modeling perspective, the more detailed the state space the better. However, increasing the state space makes it more difficult to solve. For the capacity planning process, it is decided to include two components in the state space: the number of patients waiting for a colonoscopy and the number of available time slots. First, from the System Dynamics stock and flow diagram, it can be concluded that there are seven different possible pathways in which a participant may receive a positive test result and may arrive at the procedure waiting list. In Table 6-1, the seven different probabilities are listed.

Table 6-1: Different ways leading to a positive test result

Path	*First test result*	*Second test result*	*Third test result*	*Number of new arriving patients*
1	Positive	Unknown	Unknown	n_1
2	Negative	Positive	Unknown	n_2
3	Negative	Negative	Positive	n_3
4	False-positive	Positive	Unknown	n_4
5	False-positive	Negative	Positive	n_5
6	Negative	False-positive	Positive	n_6
7	False-positive	False-positive	Positive	n_7

The number of new arriving participants that come from these seven ways lead to the overall number of new arrivals on the waiting list (N) for each week (Equation 6-1).

$$N = n_1 + n_2 + n_3 + n_4 + n_5 + n_6 + n_7$$

Second, the number of available time slots (E_t) will be determined by the policy. As with the System Dynamics model, the physician capacity is restricted with a maximum of eighteen and a minimum of six time slots per week. The main difference with the SD model is that with the SD model the capacity could be six, twelve or eighteen, while with the MDP steps of one time slot can be made.

Next, the action set includes all possible actions that can be taken in each random state of the state space. As stated, the number of available time slots will be determined by the capacity policy. The possible actions that can be taken are increasing or decreasing the number of available time slots within the predefined restriction.

6.2 Transition probabilities

The transition probabilities include the probabilities that the process transfers from the one state to another state of the state space. Since the number of time slots is determined by the policy, only the number of waiting patients is determined by probability. Suppose that before arrival of the new patients in week t, k_t patients are on the waiting list. After the arrival of new patients, the number of waiting patients in equal to $k_t + N_t$. Next, after the admissions of that week, the number of waiting patients is $(k_t + N_t - E_t)^+$.

As stated above, there are seven pathways in which a participant can arrive at the procedure waiting list. The probabilities that a participant goes through one of these ways are shown in Table 6-2. For each participant, the chance of a positive test is p_i and the chance of a negative test is $(1 - p_i)$. Therefore, the new arrival process can be approached as a binomial distribution with different probabilities for the seven different possibilities. The binomial distribution holds the probabilities of N_t new patients arriving on the waiting list per week, taking into account 76 persons invited to take the home test and a certain participant percentage. Note that the probabilities as listed in Table 6-2 need to be corrected according to the assumed participant percentage.

Table 6-2: One patient's probabilities

Path	*Probability*	
1	p_1 = 0.12	= 0.12
2	p_2 = 0.88*0.08	= 0.07040
3	p_3 = 0.88*0.92*0.05	= 0.04048
4	p_4 = 0.12*0.50*0.08	= 0.00480
5	p_5 = 0.12*0.50*0.92*0.05	= 0.00276
6	p_6 = 0.88*0.08*0.50*0.05	= 0.00176
7	p_7 = 0.88*0.50*0.08*0.50*0.05	= 0.00012

For calculating the probabilities for N_t new arriving patients, a cumulative approach is used. It is assumed that 76 persons arrive at each of the seven path ways. First, the probabilities of zero until 76 positive tests resulting from the first path way are calculated. These probabilities are used at the start of calculating the cumulative first and second path way probabilities. Again, the gained probabilities are used as starting point of the cumulative first, second and third path way probabilities, and so on until all path ways are included into the probabilities. The following example depicts the calculation approach. The probability of six positive tests from ten persons is equal to $(1 - p_i)$ times the probability of six positive tests from nine arriving persons plus p_i times the probability of five positive tests from nine arriving persons. Using this binomial principle going from one arriving persons until seven times 76 person will lead to the cumulative probability of having six positive tests from all arriving persons.

Table 6-3 shows the arrival distribution when the participant percentage is 60%. After determining this arrival process, it turned out that the probability of 29 or more arriving patients is almost zero. Therefore, it is decided to assume that there will be no more than 29 arriving patients per week and thus the vector is cut off at 29 patients.

Table 6-3: Binomial arrival distribution (60% participant percentage)

N_t	q_{N_t}	N_t	q_{N_t}	N_t	q_{N_t}	N_t	q_{N_t}	N_t	q_{N_t}
0	0.000013	6	0.039946	12	0.111972	18	0.013016	24	0.000173
1	0.000149	7	0.064110	13	0.093888	19	0.007241	25	0.000071
2	0.000859	8	0.089580	14	0.072730	20	0.003807	26	0.000028
3	0.003282	9	0.110707	15	0.052316	21	0.001896	27	0.000010
4	0.009355	10	0.122519	16	0.035100	22	0.000897	28	0.000004
5	0.021229	11	0.122644	17	0.022051	23	0.000404	29	0.000001

In sum, on the basis of the binomial distribution, the distribution of new arrivals on the waiting list are calculated. This distribution is in fact equal to the transition probabilities.

6.3 Cost function and objective function

For each week, the state space consists of a number of waiting patients and a number of available time slots. The objective of the MDP is to determine the optimal number of available time slots, aimed at preventing high numbers of waiting patients and stabilizing the usage of the capacity. Therefore, the cost function includes a cost of both elements. First, the cost of waiting patients is assumed to be linear. Waiting patients lead to access time for the colonoscopy. Since it is wanted to keep the access time as low as possible, there is a fixed fee per waiting patient (c_k). Second, the cost of available time slots can be determined with two approaches. The first approach is to assume that the time slot cost is also linear. This means that there is a cost for each available colonoscopy (c_E). The second approach is to use the linear cost in combination with a cost for changing the number of time slots ($c_{\Delta E}$). It can be imagined that increasing the number of time slots this week in comparison with previous week includes more costs than only the costs of the extra colonoscopies.

It is chosen to work with the second approach for the capacity costs. This results in the following cost function.

$$r_t = k_t \cdot c_k + E_t \cdot c_E + (E_t - E_{t-1})^+ \cdot c_{\Delta E}$$

Table 6-4 summarizes the cost elements of the cost function as formulated in Equation 7-3. The capacity cost is built of personnel costs, material costs, equipment costs and overhead costs. For the Elkerliek Hospital, these costs are equal to 200 Euros per available colonoscopy. The waiting cost and changing cost are less easy to value. It is hard to pin a value on a waiting patient. The heights of the waiting cost and the changing cost will influence the optimal capacity possible. The effect of differences in these costs will be analyzed in chapter 8.

Table 6-4: Definitions of cost elements

	Definition	*'Short name'*
c_k	Cost of one waiting patient	Waiting cost
c_E	Cost of one colonoscopy	Capacity cost
$c_{\Delta E}$	Cost of increasing or decreasing one time slot	Changing cost

The objective of the MDP is to find an optimal number of time slots, taking in account the costs of waiting patients (i.e., the access time of a colonoscopy procedure) and the costs of the available capacity. For a patient point of view, the access time should be minimized. However, for the hospital this will lead to extensive high needed capacity. The objective should be to minimize the combination of the waiting patient costs and the capacity costs. Therefore, the objective function is to minimize the cost function.

In sum, Table 6-5 lists the five components of the capacity control process needed to model it as a MDP.

Table 6-5: MDP components

Component	*Definition*	
S	State space	$\left\{\sum_{i=1}^{7} n_{i,t}, E_t\right\} = \{N_t, E_t\}$
A	Action set	Increasing or decreasing E_t
p_{ij}	Transition probabilities	Binomial arrival distribution
r_t	Cost function	$k_t \cdot c_k + E_t \cdot c_E + (E_t - E_{t-1})^+ \cdot c_{\Delta E}$
V	Objective function	$\min(r_t)$

7 Results of Markov Decision Process

In this chapter, the results of the MDP, i.e. the optimal capacity policy, are discussed. As mentioned in chapter 6, it is hard to pin a cost on a waiting patient or on changing the amount of capacity. The capacity cost is based on information of the hospital and is therefore fixed at 200 Euros. For the other two costs, it is chosen to determine a low, medium and high value (see Table 7-1) to form so-called cost scenarios. Note that the medium cost are equal to the capacity cost.

Table 7-1: Low, medium and high waiting and changing cost

Low waiting or changing cost	50 Euros
Medium waiting or changing cost	200 Euros
High waiting or changing cost	500 Euros

The chapter has the following outline. First, a short part is dedicated to the average physician capacity and average access time resulting from different waiting and changing costs to gain some perceptions of the policies. Next, the optimal policies of different cost scenarios with different demand are analyzed.

7.1 Average physician capacity and average access time

Often with capacity planning there is a trade-off between capacity and waiting time. In the planning for the endoscopic department there exists a trade-off between physician capacity and access time for the procedure. In this section, the optimal average physician capacity and average access time for multiple cost scenarios are given. For this analysis, the objective function of the MDP is optimized, i.e. the total costs are minimized, for six situations. For the transition probabilities, the probabilities from Table 6-3 are used, i.e. 60% participant percentage is assumed. In two situations, the waiting cost is varied between low and high and the changing cost is fixed at 200 Euros. For the other two situations, the changing cost is varied and the waiting cost is fixed at 200 Euros.

Figure 7-1 shows the average number of time slots of the four situations. It can be concluded that the average physician capacity lies between eleven and fourteen time slots. Next to that, the effect of varying the changing cost has lower effect on the optimal capacity than the effect of the waiting cost. The initial demand scenario (*DD1*) used in the System Dynamics analysis has the same probabilities as used in this analysis. From the SD analysis, it was concluded that the best capacity was twelve colonoscopies. Only in the situation of waiting cost of only 50 Euros, the MDP shows the same amount. For the other situations, the average number of time slots is higher than twelve. A possible reason for this is that the obtained twelve time slots in the SD analysis was fitted for the whole demand period. The MDP analysis results in an average number of time slots, so in between weeks the capacity has been adjusted to the demand.

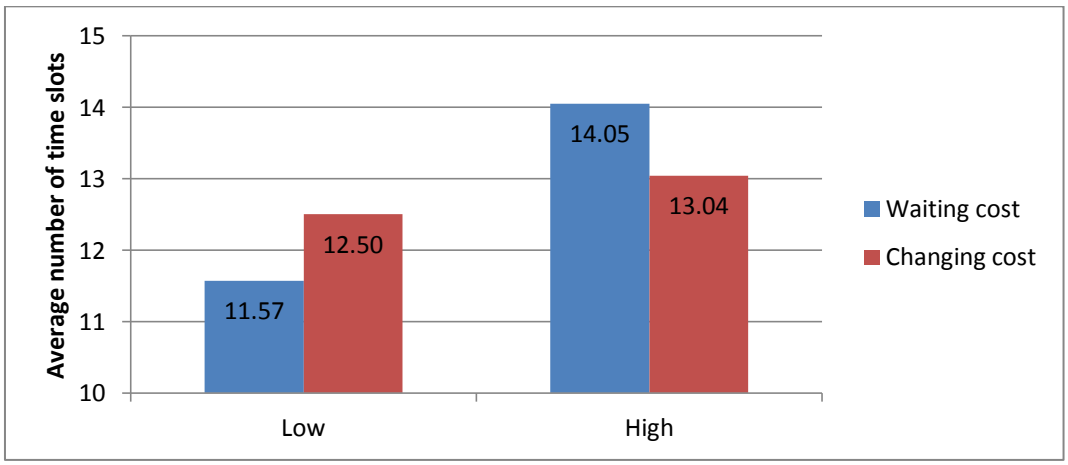

Figure 7-1: Average number of time slots when varying waiting cost and changing cost

Figure 7-2 shows the average access time for the four cost situations. As with the average physician capacity, the difference in waiting cost has the most effect. An overall conclusion is that the average access time even with high waiting cost is just two days. In the System Dynamics model, the access time had been calculated in such a way that the minimum was always one week. A big advantage of the MDP analysis is that the results show access times of below one week. Waiting times, as measured in hospitals, are comprises of three different parts: (1) the minimum period of time it takes a patient to be ready, (2) the time until the first available time slot, and (3) the time spent on a waiting list in case there is no available time slot. It is important to note that the access times resulting from the MDP policy only involve the third part of the waiting time. Therefore, although an access time of two days does not seem to raise much concern, in reality this could still mean a waiting time of one week.

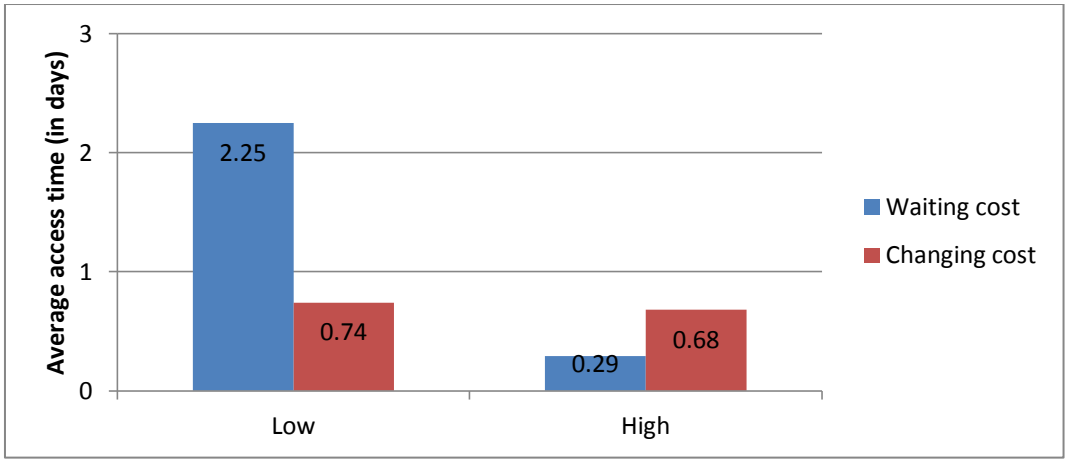

Figure 7-2: Average access time (in days) when varying waiting cost and changing cost

In case of very low waiting costs (10 Euros), the optimal number is always six time slots, since the average number of change in the number of time slots is zero. Naturally, the capacity is kept at a minimum, since the capacity costs are much higher than the waiting cost. The effect of keeping the capacity at its minimum is that the average access time is approximately 64 days, which is just over nine weeks. With trial-and-error, it turned out that the model decides for the minimum number of time slots in case of a waiting cost of 11 Euros or lower, assuming integer numbers for the costs. If the waiting cost are equal to 12 Euros, the average number of time slots increases to eleven slots. Assuming very high and probably unrealistic waiting cost (2,500 Euros), the average number of time slots is equal to sixteen. In this cost scenario the average access time is negligible.

When the changing cost are very low (10 Euros) or very high (2,500 Euros), the number of time slots are not very different compared to the gained number of above situations. The average physician capacity is respectively 11.31 and 12.00 time slots. The average access time shows the same results. It comes to 1.90 days for the very low and 2.08 days for the very high cost.

Although the capacity cost is fixed by the costs of the hospital, it is interesting to see what happens with the optimal average number of time slots when the capacity cost is low and when it is high. In case of capacity costs of 50 Euros the optimal number of time slots is equal to 13.09 and in case of costs of 500 Euros the optimal number is 11.12.

7.2 Optimal capacity policies

In this section, the optimal capacity policy for some cost functions are discussed. The cost function is built with the three different costs: waiting cost – capacity cost – changing cost. For example, the first cost function analyzed is 50-200-50, which means waiting cost of 50 Euros, capacity cost of 200 Euros, and changing cost of 50 Euros.

Often in capacity planning problem, there exists a trade-off between efficient utilizing of capacity and the length of the waiting times. With the capacity planning for the endoscopic department with the above mentioned cost function, the trade-off exists between a stable capacity pattern and the length of the access time for the colonoscopy. By varying the values for the costs, the emphasis can be placed on different elements on the decision. Naturally, a cost of 500 Euros per waiting patient or per changed time slot it not realistic. However, these high numbers are used to really put the emphasis on a specific element of the capacity planning. Table 7-2 shows where the emphasis is on for the different cost scenarios that are discussed in the following parts.

Table 7-2: Emphasis of the cost scenarios

Cost scenario	*Emphasis on*
50-200-50	Both stable capacity and low access time
500-200-50	Low access time
50-200-500	Stable capacity

7.2.1 Optimal policy for 50-200-50 cost function

For the 50-200-50 cost function, the trade-off between stable capacity and low access time is clearly present, since the costs of these two outputs are equal to each other. The overall average costs of the policy are equal to 2,480 Euros. Figure 7-3 shows the capacity policy depending on the number of waiting patients before new arrival. The minimum and the maximum number of time slots are respectively ten and eighteen time slots. Next to that, there are maximum 23 patients on the waiting list. The average number of changes in the number of time slots for this cost scenario is 0.81 time slots.

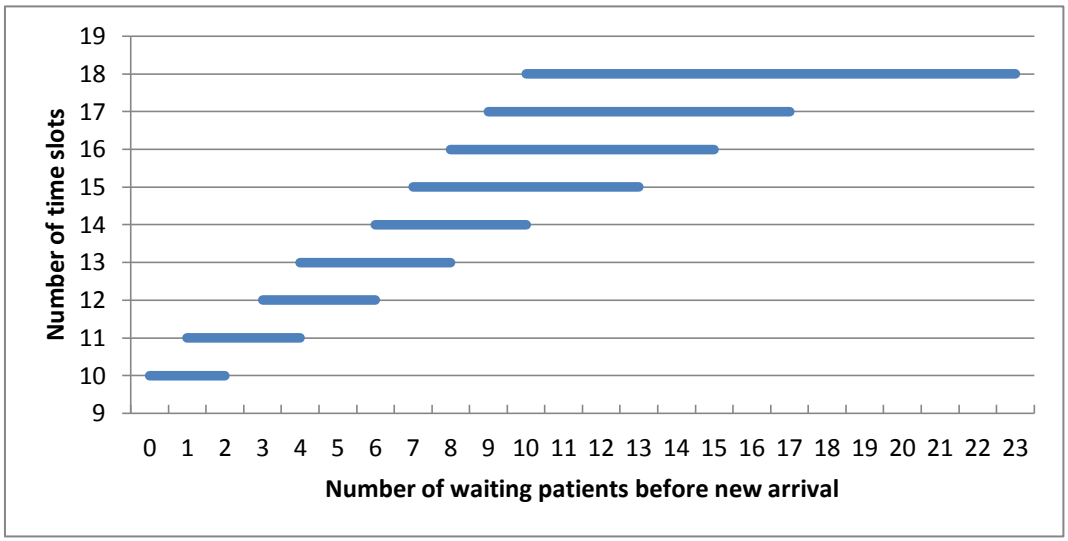

Figure 7-3: Capacity policy for 50-200-50 cost function

The above figure show what decision about the capacity should be made on the basis of the number of patients on the waiting list. The decision about the capacity of next week also depends on the number of arrival during that week. Therefore, switching points for adjusting the capacity are determined on basis of the optimal policy. A switching point indicates the total number of patients on the waiting list after the arrival of new patients. Since the moment of increasing the capacity will not be equal to the moment of decreasing the capacity, there are two types of switching points.

Table 7-3 lists the switching points for the above discussed cost function. Note that it seems confusing that the switching point is higher than the maximum number on the waiting list. However, it should be kept in mind that the switching point takes place before the admissions and that the number of waiting patients before new arrival is measured just after the admissions. The table can be used to decide whether the increase or decrease the capacity based on the current available capacity and the number of patients on the waiting list after the arrival of new patients.

Table 7-3: Points for switching capacity for 50-200-50 cost function

Current capacity	*Decrease one time slot if number of waiting patients is*	*Increase one time slot if number of waiting patients is*
10	N.A.	13
11	11	16
12	14	19
13	16	22
14	18	25
15	21	29
16	23	32
17	25	35
18	27	N.A.

7.2.2 Optimal policy for 500-200-50 cost function

In this part, the optimal policy of the situation in which high waiting cost is considered is given. This scenario can also be seen as the situation in which the amount of waiting patients are considered to be more important than the used or stable capacity.

The optimal capacity policy leads to an average cost of 3,011 Euros. Figure 7-4 depicts the policy in which the minimum and maximum capacity is determined at respectively thirteen and eighteen time slots. Notable is that the 'start' capacity of thirteen time slots is higher than in the previous discussed situation. The maximum number of waiting patients is fifteen. This is an indication that by increasing the cost for waiting patients, the emphasis lies on keeping the amount as low as possible. This conclusion can also be drawn on the fact that the average number of changes in the physician capacity is 0.58 time slots per change.

In the figure it can be seen that the policy already advises to use the maximum number of capacity when there are five patients on the waiting list. An disadvantage of focusing on the access time is that the chance of idle capacity is clearly less important that waiting patients. Therefore, the probability of idle capacity is large in this situation.

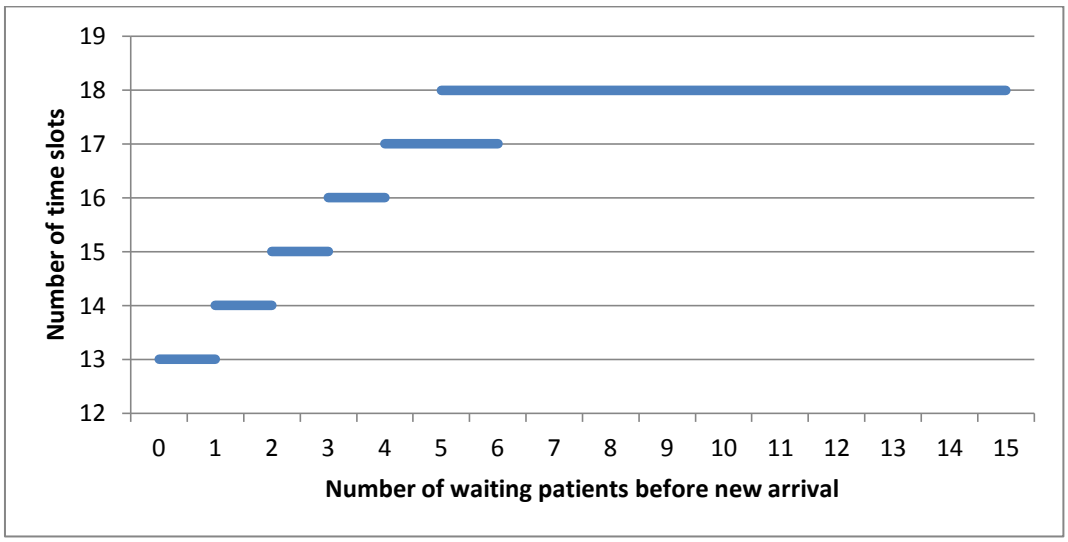

Figure 7-4: Capacity policy for 500-200-50 cost function

Again the total number of patients on the waiting list after the arrivals at which the capacity has to be changed are determined based on the policy gained of the MDP. The total numbers of patients on the waiting list before admissions can be found in Table 7-4. For instance, when the current available capacity is equal to fifteen time slots, the capacity should be increase to sixteen when the number of patients is equal to nineteen and the capacity should be decrease when the number of patients in equal to sixteen patients.

Table 7-4: Points for switching capacity for 500-200-50 cost function

Current capacity	*Decrease one time slot if number of waiting patients is*	*Increase one time slot if number of waiting patients is*
13	N.A.	15
14	14	17
15	16	19
16	18	21
17	20	24
18	22	N.A.

7.2.3 Optimal policy for 50-200-500 cost function

In cost scenario with cost function 50-200-500, clearly more emphasis will be placed on keeping the capacity as stable as possible. Figure 7-5 shows the optimal capacity policy for this scenario. The minimum and maximum capacity are respectively ten and fifteen time slots. The observation that the maximum of eighteen time slots is not used, fits the fact changing capacity is more expensive than waiting patients. Next to that, the maximum number of patients on the waiting list 32 patients, which is quite higher than with the other two cost scenarios. The overall average cost of this policy is 2,558 Euros.

The figure also clearly shows that the range of number of waiting patients for each number of time slots is larger than in the previous cost function. For instance, when there are ten waiting patients, the policy gives four different possible number of time slots. The reason for this is that it cost less money to keep the capacity idle than it cost to change the capacity.

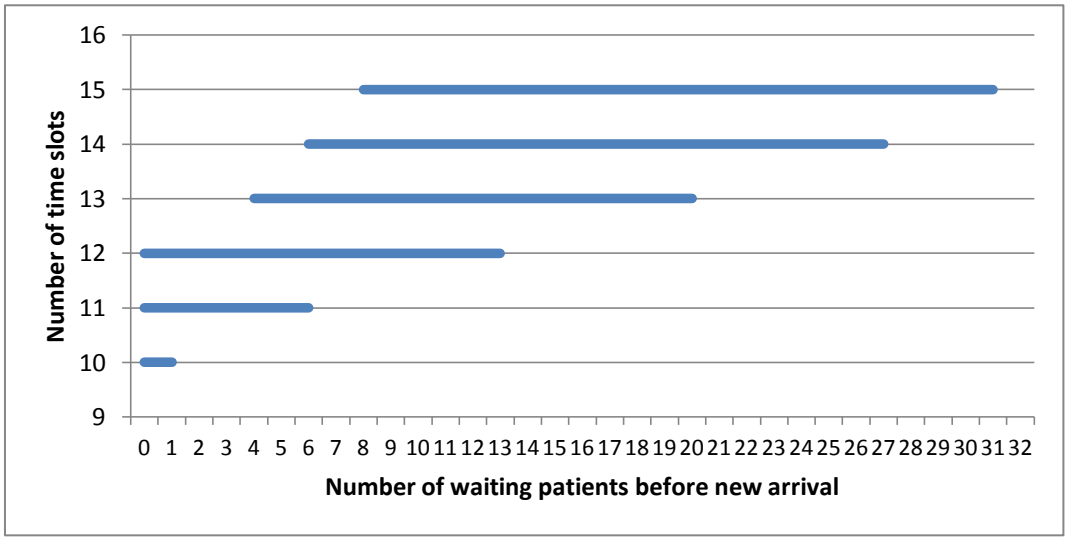

Figure 7-5: Capacity policy for 50-200-500 cost function

Table 7-5 lists the switching points for changing the number of time slots for this cost function. From the table it can be concluded that in case the current available capacity is eleven or twelve time slots, the policy will never lead to decreasing the capacity with one or more time slots. The table can used to determine the optimal number of time slots for next week. The decision is based on the current available capacity and the number of waiting patients after the arrival of new patients.

Table 7-5: Points for switching capacity for 50-200-500 cost function

Current capacity	*Decrease one time slot if number of waiting patients is*	*Increase one time slot if number of waiting patients is*
10	N.A.	12
11	N.A.	18
12	N.A.	25
13	16	34
14	19	42
15	22	N.A.

7.2.4 Optimal policy for a high participant percentage

In the above analyses, a participant percentage of 60% is assumed. However, it is also interesting to see what the optimal capacity policy is when the participant percentage would be 80%. The first step is to adjust the transition probabilities by correcting the one patient's probabilities of Table 6-2 with 80%. The determined transition probabilities are used in optimizing the objective function of the MDP.

For this analysis, it is assumed that the emphasis lies on both the access time and on stable capacity, therefore, the function with 50 Euros waiting cost, 200 Euros capacity cost and 50 Euros changing cost is used. First, the outputs of the policy will be compared to the outputs of a 60% participant rate situation. Second, the optimal capacity policy will be analyzed.

Table 7-6: Outputs of optimal policy 60% vs. 80% participant percentage

Output	*60% participant percentage*	*80% participant percentage*
Total costs (Euros)	2480	3254
Avg. waiting time (days)	2.05	1.71
Avg. number of time slots	11.40	15.21
Avg. number of change in time slots	0.808	0.708

In Table 7-6, the outputs of the optimal policy with 60% participant percentage are compared with those of the policy assuming 80% participant percentage. Naturally, the result of increasing the participant percentage is that the overall demand for the endoscopic department will increase. This is reflected in the average number of time slots for the scenario with 80% participant percentage, which is on average almost four time slots higher. The effect of the higher capacity is that the average waiting time is almost equal to each other. Also the average numbers of change in time slots for each performed adjustment in capacity are almost identical.

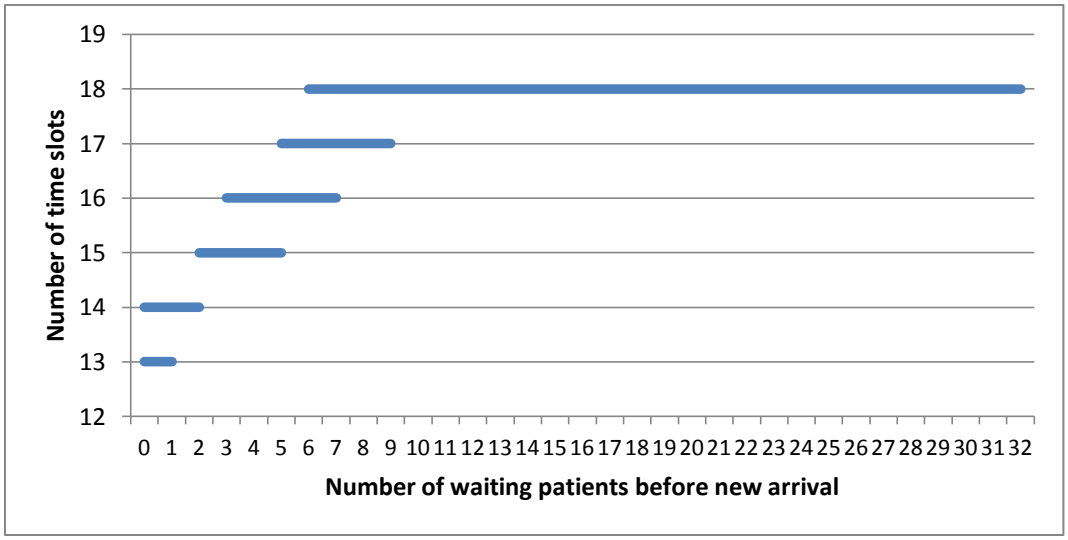

Figure 7-6: Capacity policy for 50-200-50 cost function and 80% participant percentage

In Figure 7-6 the optimal capacity policy when assuming 80% participant percentage is shown. It can be seen that the minimum and maximum capacity are thirteen and eighteen time slots. This is the first difference the scenario with 60% participant percentage, where the minimum capacity is ten time slots. The difference is again the result of more resulting demand for the 80% scenario. This leads also to a higher maximum number of waiting patients.

For this scenario, the points for switching the capacity are determined (Table 7-7). Note that at a current available capacity of fourteen time slots, the policy will not decrease the capacity to thirteen time slots. This means that after once deciding to increasing the capacity from thirteen to fourteen time slots, it will be not profitable to decrease the capacity to thirteen again in any given possible state.

Table 7-7: Points for switching capacity for 50-200-50 cost function and 80% participant percentage

Current capacity	*Decrease one time slot if number of waiting patients is*	*Increase one time slot if number of waiting patients is*
13	N.A.	15
14	N.A.	18
15	16	21
16	18	24
17	21	27
18	23	N.A.

7.3 General conclusions of Markov Decision Process

With the System Dynamics model, the best overall capacity allocation is determined. For this analysis, it was assumed that the capacity is not adjusted during the whole demand period. Naturally, these results showed low capacity utilizations during a large number of weeks. Therefore, in this part, a policy for a weekly capacity planning is developed with a Markov Decision Process.

Based on the analyses with the developed Markov Decision Process, some general conclusions can be drawn. First, like discussed above, the decision makers can use the gained policies as guidelines for deciding on the capacity. Especially the switching points can be used as rules for increasing or decreasing the capacity for the following week, based on the number of patients on the waiting list for a colonoscopy.

Second, by setting higher values for certain cost elements, the hospital can place emphasis on different aspects of the capacity planning. With a high waiting cost, the size of the waiting list becomes most important, while with a high changing cost, the emphasis will be on a stable capacity distribution. The MDP results in different policies for each situation. The hospital can use these policies to determine the one that fits their situation.

If the emphasis is on low access time, the optimal policy results in a high minimum and maximum number of time slots to cope with the demand. The effect is that the maximum number of patients on the waiting list, after the procedures are performed, is low.

If the emphasis lies on stable capacity, i.e. not many variation in capacity within consecutive weeks, the optimal policy results in less needed physician capacity. In turn, less capacity available leads naturally to more patients on the waiting list. On the other hand, the average number of adjustments in capacity is on average negligible.

In case there is no preference for low access time or stable capacity, the costs for these two elements are assumed to be equal. The minimum and maximum capacity for this policy are equal to the minimum of the first scenario and the maximum of the second scenario. The maximum number of waiting patients is also the median of the results of the two other scenarios. The number of adjustments in capacity per capacity change are slightly higher.

Third, when the participant percentage is increased, i.e. when the demand is higher, the results of the optimal capacity policy show a significant higher number of needed capacity. This higher number of capacity is needed in order to keep a low access time.

Fourth, a surprising conclusion is that in none of the above analyzed situations, the minimum number of six time slots is used. For the analysis with the average physician capacity, it turned out that only in case of a waiting cost of 11 Euros or less the minimum capacity was eligible for the policy. On the other hand, the policy often leads to extensive use of eighteen time slots. Since this is the maximum available capacity, the question raises whether the implementation of the screening trial will not lead to extensive capacity problems for the endoscopic department.

8 Conclusions and recommendations

In this report, the effects of implementing a CRC screening trial at an Internal Medicine practice are studied. The effects are analyzed according to two research questions. The first research question and the first part of the report involves analyzing the patient demand pattern resulting from the CRC screening trial. In addition, the second research question involves the effect on the capacity planning of the implementation of the screening trial. Therefore, in the second part of the report an optimal weekly capacity planning policy is created.

The answer of the first research question is found by creating a System Dynamics model with various input parameters with which multiple possible scenarios are simulated. This has led to the following recommendations for the set-up of the screening trial:

- Invite 5500 persons from the target group in a period of eighteen months.
- Phrase the invitations, using a weekly invitation interval, which will lead to inviting approximately 76 persons per week.

Since variability is present in the demand pattern due to uncertainty in participant percentage and in the percentages of a positive test, different demand scenarios are analyzed to gain insight in the consequences of this variability. Next to that, the best overall fitted capacity allocation is given for each demand scenario. However, it must be noted that these conclusions are based on a constant capacity, i.e. the capacity is not adjusted in between demand weeks. The results show low average capacity utilizations. Therefore, to give a more precise answer for the second research question, the capacity planning process is modeled as a Markov Decision Process.

The second part of the report is dedicated to the development and analysis of a Markov Decision Process that is able to generate an optimal weekly capacity planning. The Markov Decision Process determines the optimal number of available time slots for next week, based on the current number of available time slots and the number of patients on the waiting list. So-called switching points are determined which can be used as guidelines for the endoscopic department. These switching points indicate the number of patients on the waiting list after the new arrival of patients when to increase or decrease the available capacity

It is recommended that the hospital takes a decision about the relative importance of each aspect of the capacity planning. In line with the conclusions of Schaefer et al. (2005), it turned out that pinning a cost on waiting patients or on changing the capacity is really difficult. However, by varying the values for the cost elements, emphasis can be placed on keeping the access time as short as possible or on aiming for a stable capacity distribution (that does not change every week).

An important conclusion is that the optimal capacity planning leads to extensive use of the maximum capacity of eighteen colonoscopies in various analyzed situations. Due to this conclusion, it can be questioned whether it is possible to implement the screening trial without overloading the endoscopic department. The currently available capacity of the endoscopic department could be not sufficient to cope with the additional demand resulting from the screening trial. It is highly recommended for the hospital to take stock of the capacity that is really available for the screening trial. It can be concluded that the volume of the capacity needs to be more flexible, as concluded by Rouppe van der Voort et al (2010). Therefore, it is recommended to study the colonoscopy procedure and find ways to improve the performance of the endoscopic department. One can think of redesigning the procedure process, such as changing the sequence of steps or eliminating unnecessary steps. Next to that, it could be studied whether it is really necessary to perform an intake appointment or whether for instance only providing the booklet with information is satisfying enough.

Although not explicitly studied in this report, it might be possible to integrate an invitation feedback system into the weekly capacity planning generated from the optimal policy. In particular when it turns out that the endoscopic department is not capable of performing eighteen colonoscopies per week, it is recommended to implement a system that closes the invitations for a certain number of weeks after the moment that the access time for the colonoscopy becomes too high.

An important extension to this research could be to implement the obtained switching points of the weekly capacity planning into the System Dynamics simulation model. An interesting result of a simulation with this extended model would be the capacity utilizations for the physician. In that way, it could be studied whether the optimal weekly capacity planning really leads to better performance measures of the endoscopic department.

Another extension of the System Dynamics model with the invitation feedback system might be to investigate the effect of increasing the number of invitees per invitation batch after, due to a high access time, the invitations are set back to zero for some time. It turned out that by pausing the invitations for some weeks, the total invitation period extended. In some scenarios, it could happen that the invitation period was doubled. It can be imagined that inviting more persons per invitation batch will lead to a lesser extension of the invitation period. An interesting research question is with how much persons the invitation batch should be increased.

A limitation is that the demand pattern analysis are based on the demand probabilities experienced in other colorectal cancer screening trials. Since the screening trial at the Elkerliek Hospital has not been started yet, the validation of the used values is not possible yet. A recommendation for further research is to validate the used values for the demand possibilities. In addition, after the screening trial has started, the developed models should be updated with the real demand probabilities. In that way, it will be easier for the Elkerliek Hospital to know which results of the models to apply. It is expected that it will be difficult to obtain the real values for the positive test probabilities, however, the participant percentage could be much easier to obtain. Therefore, after the screening trial has started, the hospital could update the participant percentage obtained from the data about numbers of participants.

Finally, it can be interesting to study whether the number of symptomatic patients increases or decreases after the screening trial has started. The available literature is not decisive about the observation. It could also be interesting for the Elkerliek Hospital to research the effects of the implementation of the screening trial for the pathology department.

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Abbreviations

CRC	Colorectal cancer
DD	Demand probabilities scenario
ECR	Eindhoven Cancer Registry
FS	Fixed supply scenario
I/O	input/output
IB	Invitation batch scenario
iFOBT	immunochemical Fecal Occult Blood Test
IKZ	Integraal Kankercentrum Zuid
IP	Invitation period scenario
MDP	Markov Decision Process
NP	Nurse practitioner
OPD	Outpatient department
P	Physician
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
SD	System Dynamics
SR	Stochastic response time scenario
WIP	Work-in-Process

Appendices

Appendix A: Graphical representation of the colonoscopy process

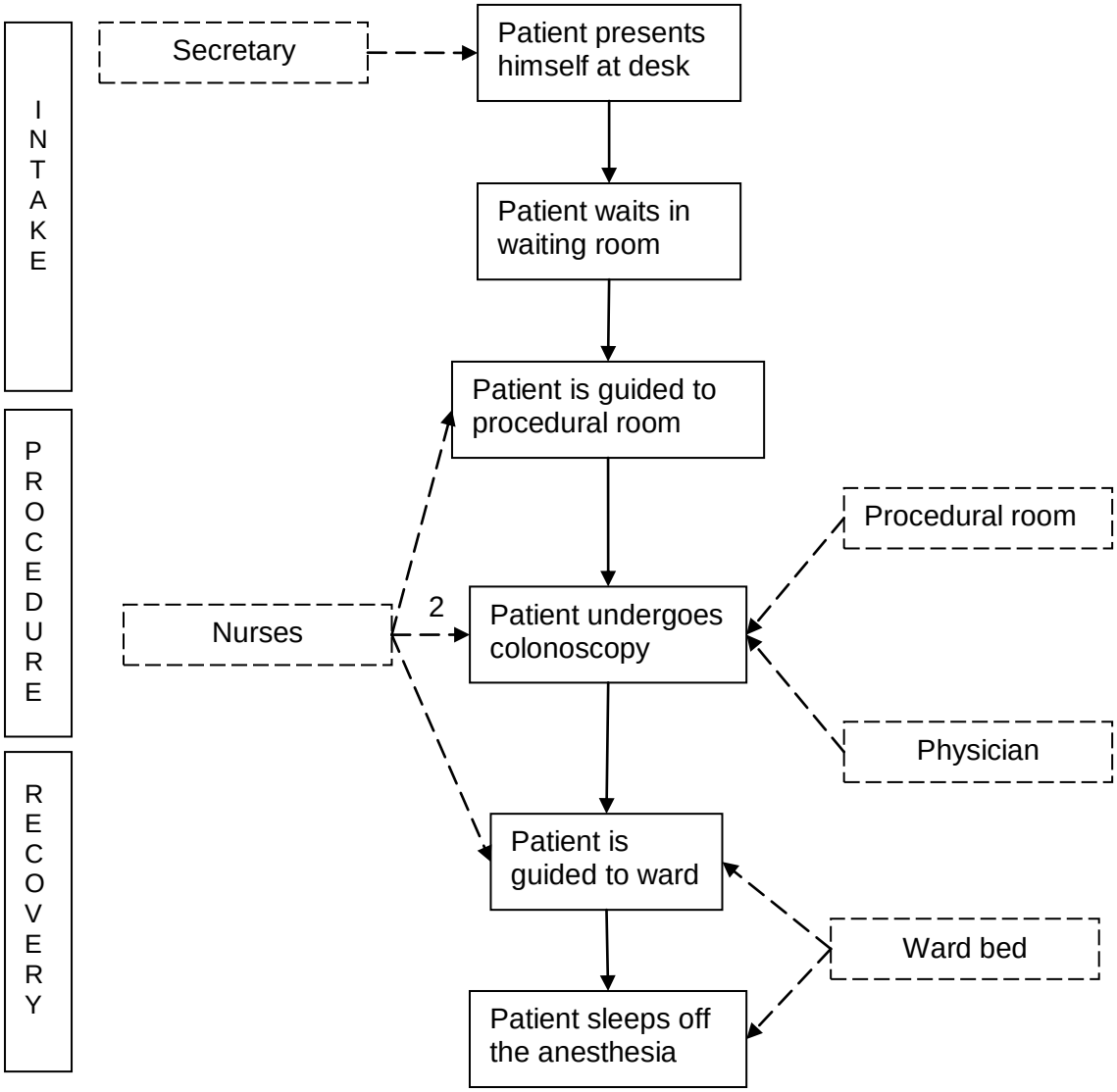


Figure A-1: Simplified graphical representation of the colonoscopy process

The broken boxes indicate resources. Note that for the colonoscopy, two nurses need to be present. The colonoscopy process is divided in three sub processes. First, the patient goes to the intake process, then the procedure takes place and last, the patient goes to the recovery.

Appendix B1: Causal loop diagram

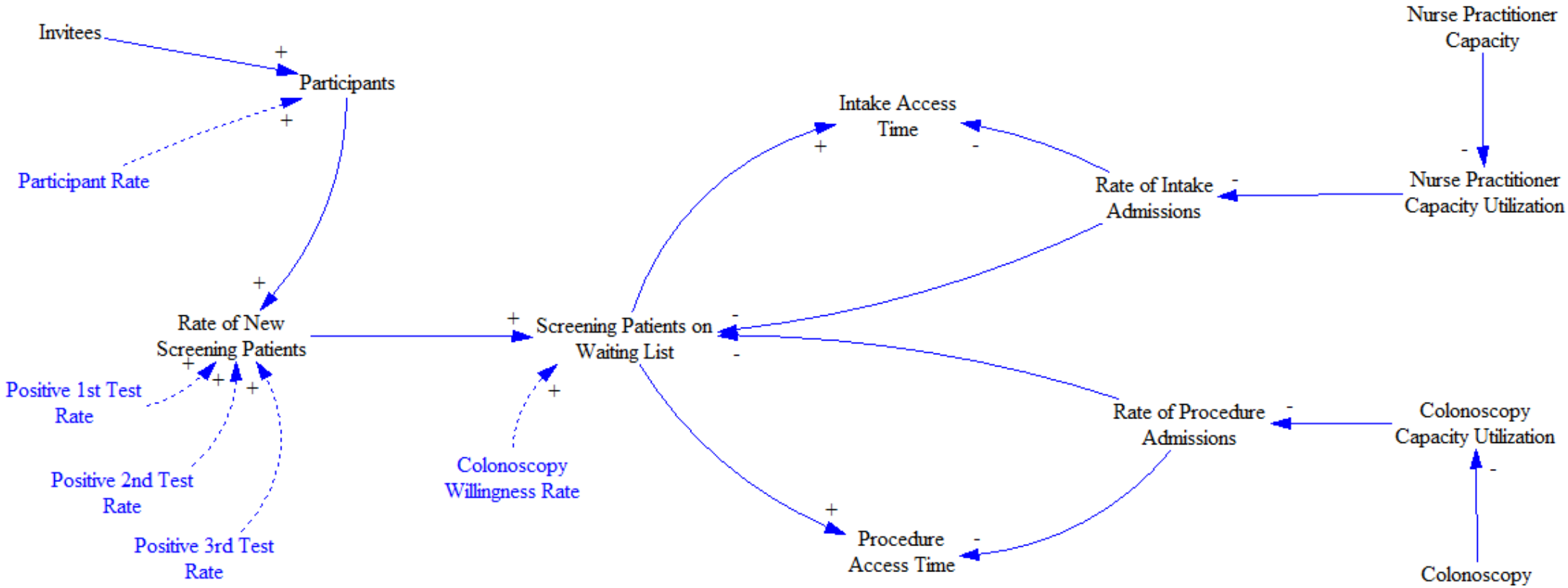


Figure B-1: Causal loop diagram of CRC screening trial process

Appendix B2: Formula basic System Dynamics model

Actual intake access time = IF THEN ELSE((Time>1.75), (Patients on intake waiting list / Intake admission rate), 0)
Units: Week

Actual procedure access time = IF THEN ELSE((Time>1.75), (Patients on procedure waiting list / Procedure admission rate), 0)
Units: Week

False positive first test rate = IF THEN ELSE((Time>2),((((Positive first test rate / (Positive first test rate + Positive second test rate)) * Percentage test false positive) * Finished patients) / Test time pathology),0)
Units: Patients/Week

False positive participants waiting for second test = INTEG (False positive first test rate - Second test for false positive rate, 0)
Units: Patients

False positive participants waiting for third test = INTEG (False positive second test rate - Third test for false positive rate, 0)
Units: Patients

False positive second test rate = IF THEN ELSE((Time>2),((((Positive second test rate / (Positive first test rate + Positive second test rate)) * Percentage test false positive) * Finished patients) / Test time pathology), 0)
Units: Patients/Week

FINAL TIME = 144
Units: Week

Finished participants rate= Finished patients / Test time pathology
Units: Patients/Week

Finished patients= INTEG (Procedure admission rate - False positive first test rate - False positive second test rate - Finished participants rate, 0)
Units: Patients

First test participants= INTEG (Participant rate - Negative first test rate - Positive first test rate, 0)
Units: Patients

INITIAL TIME = 0
Units: Week

Intake admission rate=MIN((Patients on intake waiting list/Target intake access time), Nurse practitioner capacity)
Units: Patients/Week

Invitation rate=305*PULSE TRAIN(1, 0.25 , 1 , 72)
Units: Patients/Week

Invitees= INTEG (Invitation rate-No participant rate-Participant rate,0)
Units: Patients

Negative first test rate=(First test participants*(1-Percentage first test positive))/ Test time first test
Units: Patients/Week

Negative second test rate=(Second test participants*(1-Percentage second test positive))/Test time second test
Units: Patients/Week

Negative third test rate=(Third test participants*(1-Percentage third test positive))/Test time third test
Units: Patients/Week

No participant rate=(Invitees*(1-Percentage that participates))/Reaction time
Units: Patients/Week

Nurse practitioner capacity=10
Units: Patients/Week

Nurse practitioner capacity utilization=Intake admission rate/Nurse practitioner capacity
Units: Dmnl

Participant rate=(Invitees*Percentage that participates)/Reaction time
Units: Patients/Week

Participants waiting for second test= INTEG (Negative first test rate- Second test rate, 0)
Units: Patients

Participants waiting for third test= INTEG (Negative second test rate- Third test rate, 0)
Units: Patients

Patients on intake waiting list= INTEG (Positive first test rate+Positive second test rate+Positive third test rate-Intake admission rate,0)
Units: Patients

Patients on procedure waiting list= INTEG (Intake admission rate-Procedure admission rate, 0)
Units: Patients

Percentage first test positive=0.12
Units: Dmnl

Percentage second test positive = 0.08
Units: Dmnl

Percentage test false positive=0.5
Units: Patients

Percentage that participates=0.6
Units: Dmnl

Percentage third test positive=0.05
Units: Dmnl

Physician capacity=12
Units: Patients/Week

Physician capacity utilization=Procedure admission rate/Physician capacity
Units: Dmnl

Positive first test rate=(First test participants*Percentage first test positive)/Test time first test
Units: Patients/Week

Positive second test rate=(Second test participants*Percentage second test positive)/Test time second test
Units: Patients/Week

Positive third test rate=(Third test participants*Percentage third test positive)/Test time third test
Units: Patients/Week

Procedure admission rate=MIN((Patients on procedure waiting list/Target procedure access time),Physician capacity)
Units: Patients/Week

Reaction time=1
Units: Week

Second test for false positive rate=DELAY FIXED(False positive first test rate, 24,False positive first test rate)
Units: Patients/Week

Second test participants= INTEG (Second test for false positive rate+Second test rate-Negative second test rate- Positive second test rate, 0)
Units: Patients

Second test rate=DELAY FIXED(Negative first test rate, 24, Negative first test rate)
Units: Patients/Week

Target intake access time=1
Units: Week

Target procedure access time=1
Units: Week

Test time first test = 1
Units: Week

Test time pathology=1
Units: Week

Test time second test=1
Units: Week

Test time third test=1
Units: Week

Third test for false positive rate=DELAY FIXED(False positive second test rate, 24, False positive second test rate)
Units: Patients/Week

Third test participants= INTEG (Third test for false positive rate+Third test rate –Negative third test rate-Positive third test rate,0)
Units: Patients

Third test rate=DELAY FIXED(Negative second test rate, 24, Negative second test rate)
Units: Patients/Week

TIME STEP = 0.25
Units: Week [0,?]

Appendix B3: System Dynamics model invitation feedback extension

Intake access time of previous week=DELAY FIXED(Actual intake access time, 1 , 0)
Units: Week

Intake access time of previous week exceeds 1=IF THEN ELSE((Intake access time of previous week>1), 1, 0)
Units: Week

Invitation rate=MIN(IF THEN ELSE((Intake access time of previous week exceeds 1 =1), 0, 305*PULSE TRAIN(1, 0.25 , 1 , 144)),Total invitees)
Units: Patients/Week

Total invitees= INTEG (-Invitation rate,5500)
Units: Patients

Appendix B4: System Dynamics model capacity feedback extension

Adjustment nurse practitioner capacity=IF THEN ELSE(Intake access time of previous week>1, 5, 0)
Units: Patients/Week

Adjustment physician capacity=IF THEN ELSE(Procedure access time of previous week>1, 6, 0)
Units: Patients/Week

Intake access time of previous week=DELAY FIXED(Actual intake access time, 1 , 0)
Units: Week

Nurse practitioner capacity=10+Adjustment nurse practitioner capacity
Units: Patients/Week

Physician capacity=12+Adjustment physician capacity
Units: Patients/Week

Procedure access time of previous week=DELAY FIXED(Actual procedure access time, 1 , 0)
Units: Week

Appendix C1: Invitation period and demand scenarios

Figure C1-1: Patients on waiting list IP2&DD1

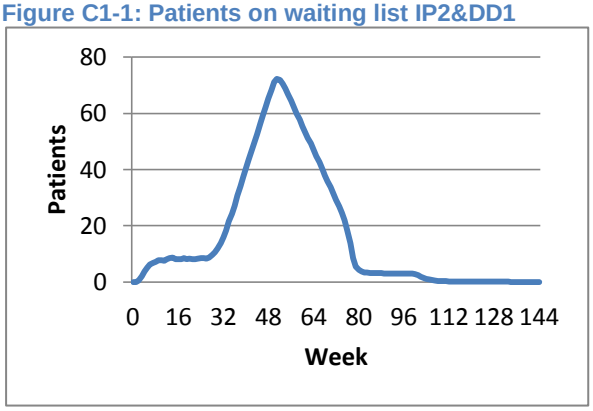


Figure C1-2: Intake access time IP2&DD1

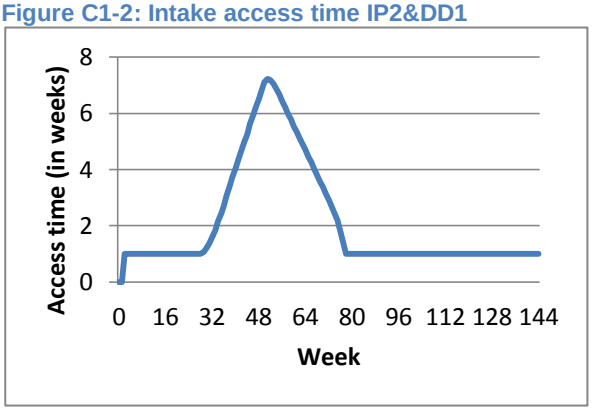


Figure C1-3: Patients on waiting list IP3&DD1

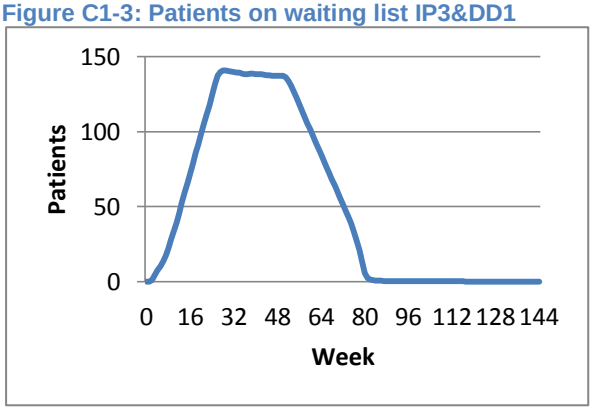
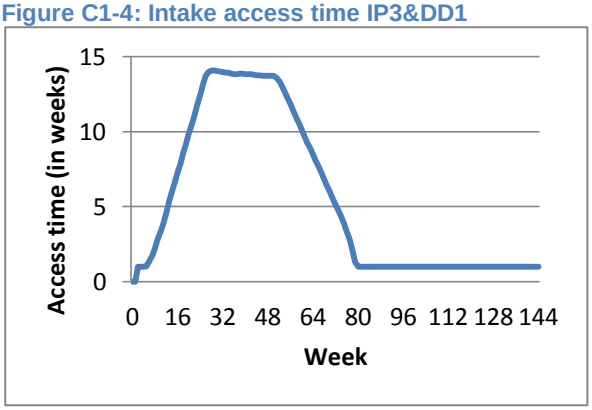


Figure C1-4: Intake access time IP3&DD1



Appendix C2: Invitation period and optimal capacity allocation

Figure C2-1: Intake access time IP2&FS3

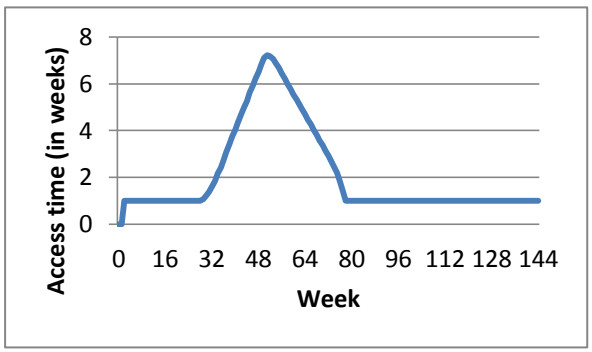


Figure C2-2: Procedure access time IP2&FS3

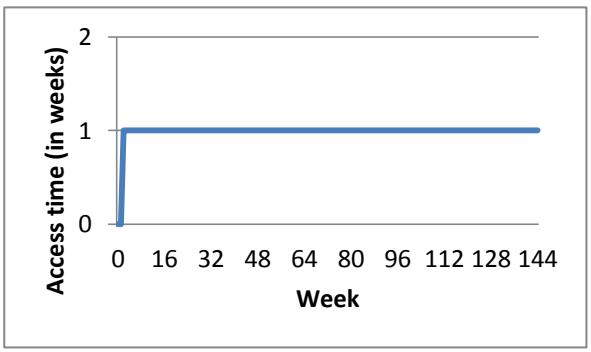


Figure C2-3: NP capacity utilization IP2&FS3

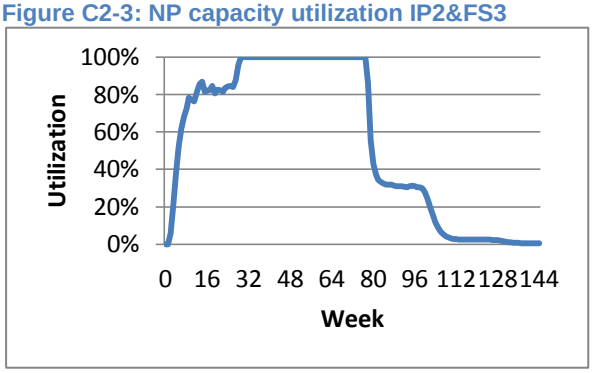


Figure C2-4: P capacity utilization IP2&FS3

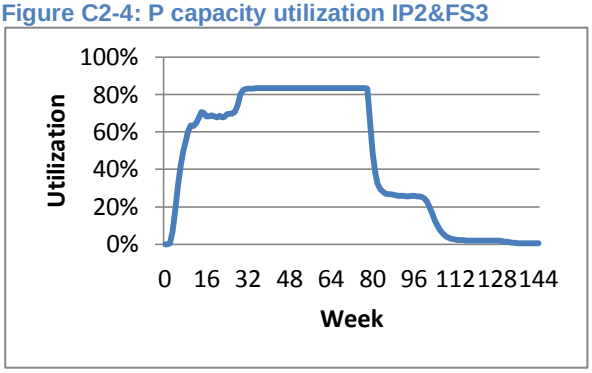


Figure C2-5: Intake access time IP2&FS4

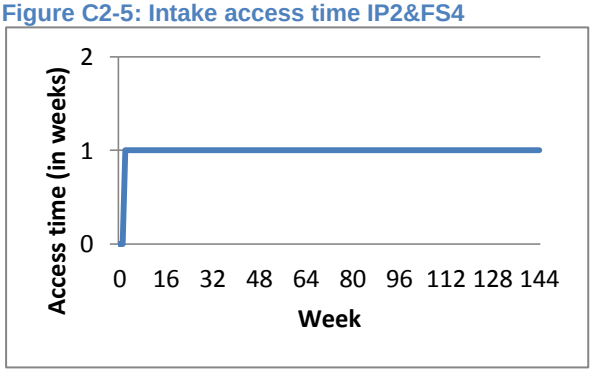


Figure C2-6: Procedure access time IP2&FS4

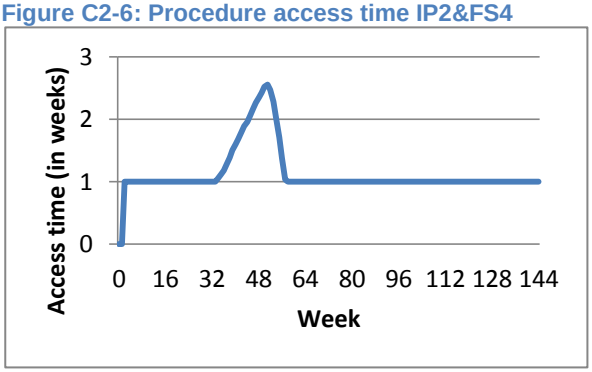


Figure C2-7: NP capacity utilization IP2&FS4

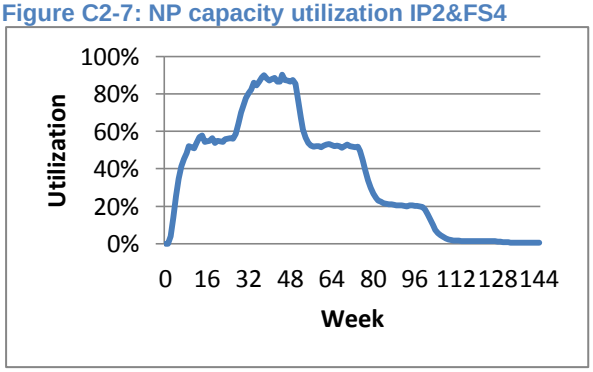
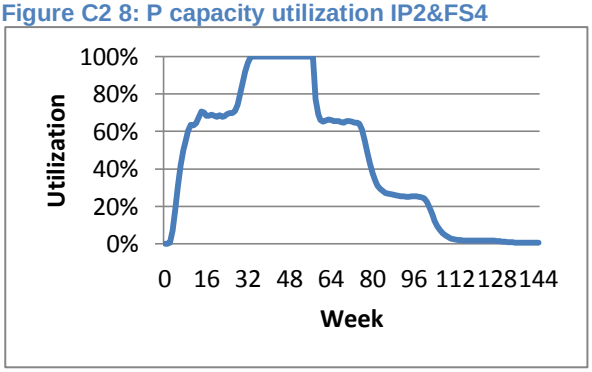
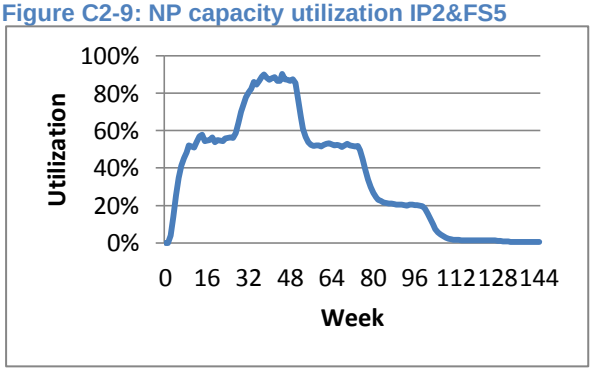


Figure C2 8: P capacity utilization IP2&FS4



Intake access time IP2&FS5:
Constant one week

Figure C2-9: NP capacity utilization IP2&FS5



Procedure access time IP2&FS5:
Constant one week

Figure C2-10: P capacity utilization IP2&FS5

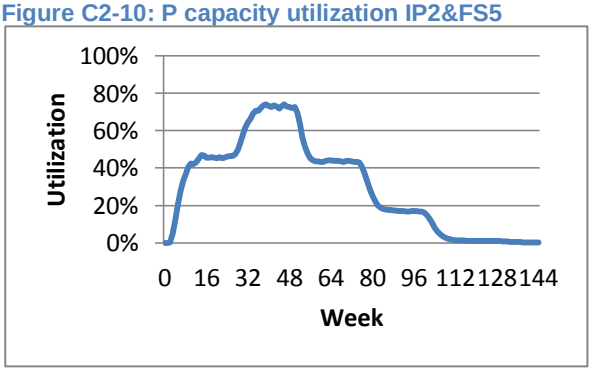


Figure C2-11: Intake access time IP3&FS3

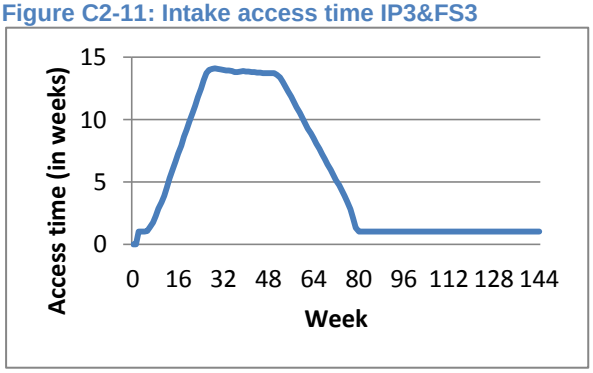


Figure C2-12: Procedure access time IP3&FS3

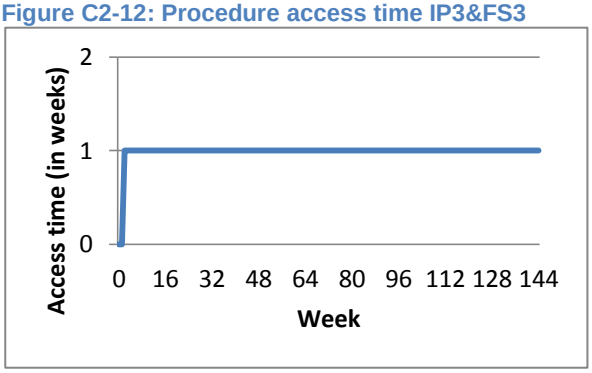


Figure C2-13: NP capacity utilization IP3&FS3

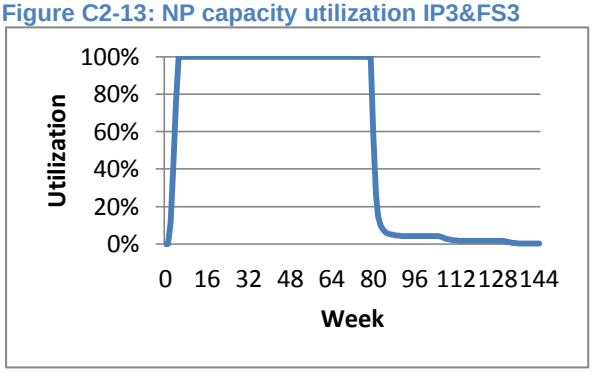


Figure C2-14: P capacity utilization IP3&FS3

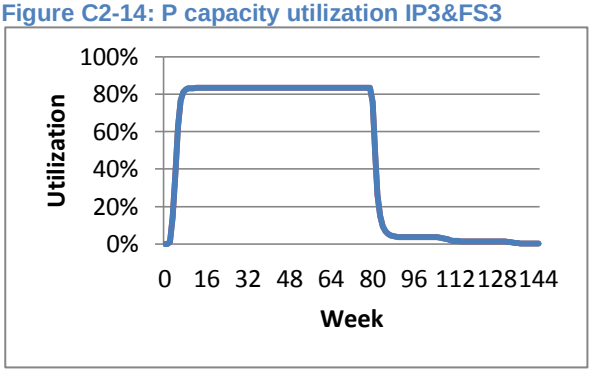


Figure C2-15: Intake access time IP3&FS4

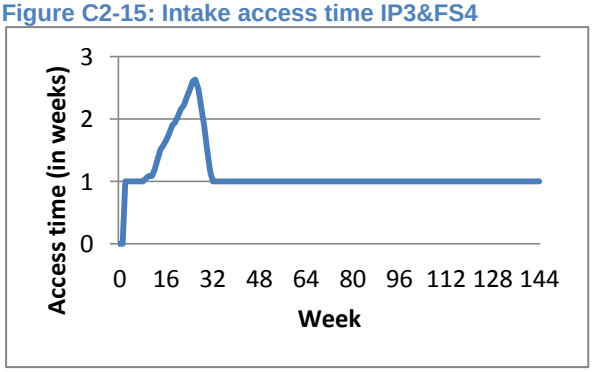


Figure C2-16: Procedure access time IP3&FS4

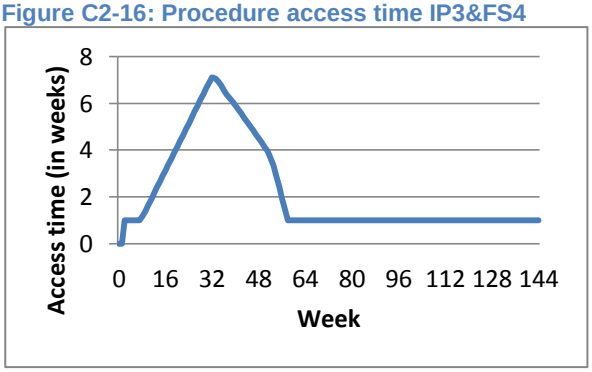


Figure C2-17: NP capacity utilization IP3&FS4

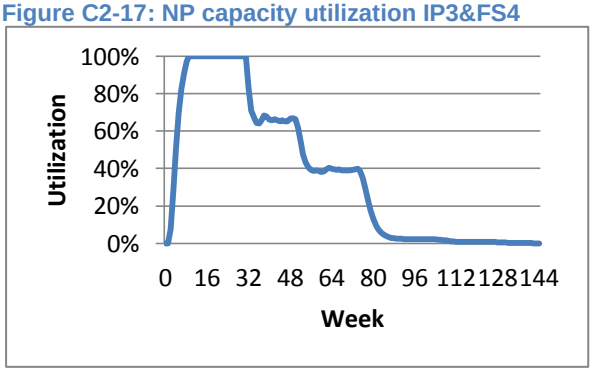


Figure C2-18: P capacity utilization IP3&FS4

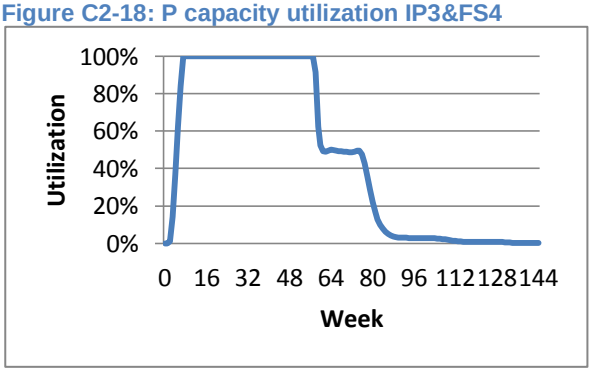


Figure C2-19: Intake access time IP3&FS5

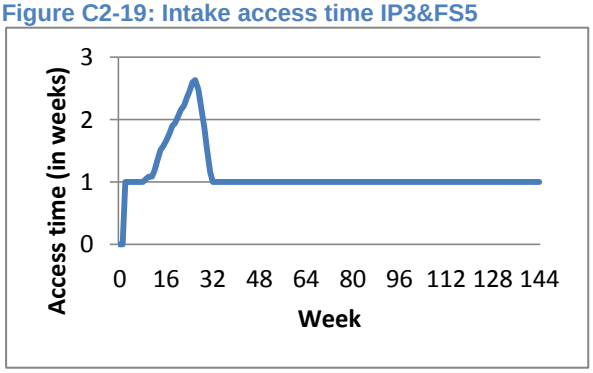


Figure C2-20: Procedure access time IP3&FS5

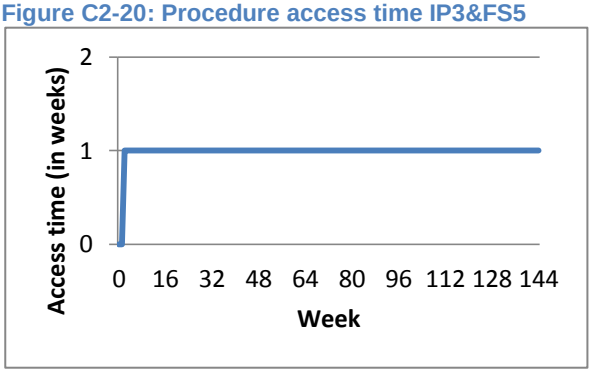


Figure C2-21: NP capacity utilization IP3&FS5

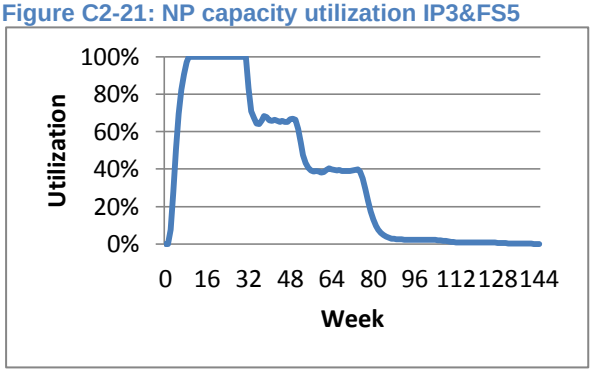
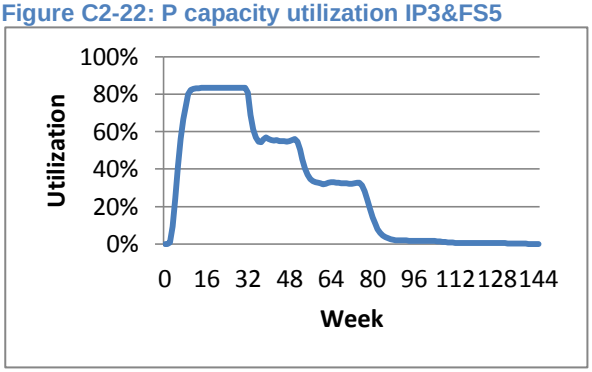
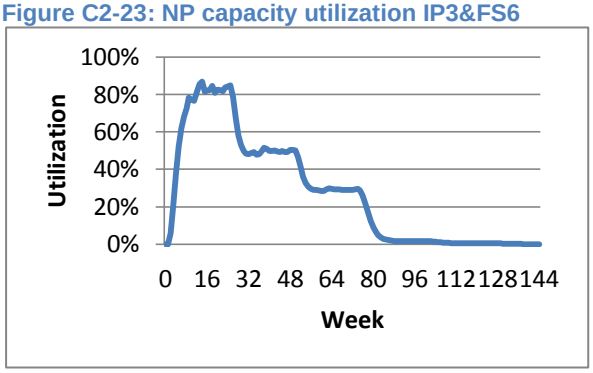


Figure C2-22: P capacity utilization IP3&FS5



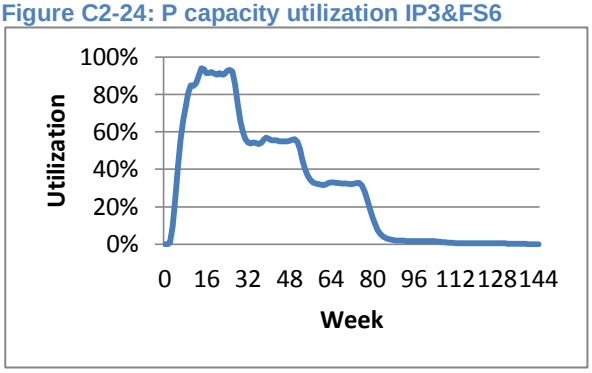
Intake access time IP3&FS6:
Constant one week

Figure C2-23: NP capacity utilization IP3&FS6



Procedure access time IP3&FS6:
Constant one week

Figure C2-24: P capacity utilization IP3&FS6



Appendix C3: Invitation period and feedback regulations

Figure C3-1: Number of invitees progress IP2&FS3 with invitation feedback regulation

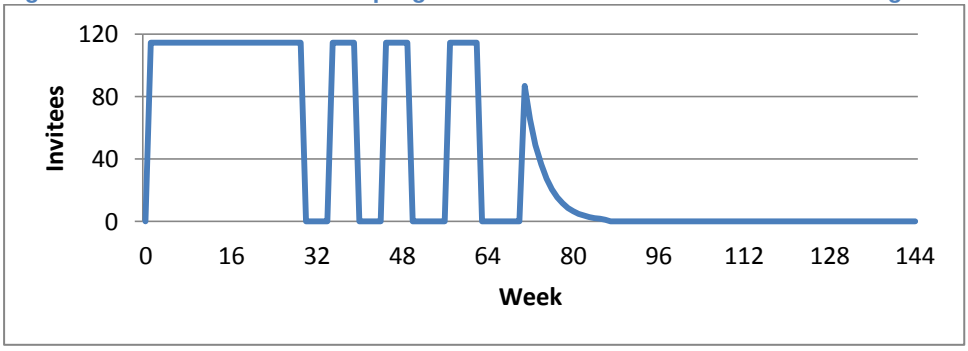


Figure C3-2: Number of invitees progress IP3&FS3 with invitation feedback regulation

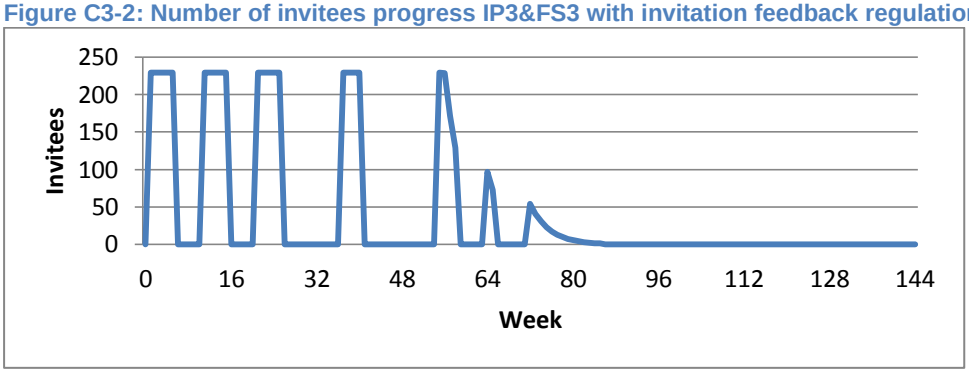


Figure C3-3: Number of invitees progress IP3&FS4 with invitation feedback regulation

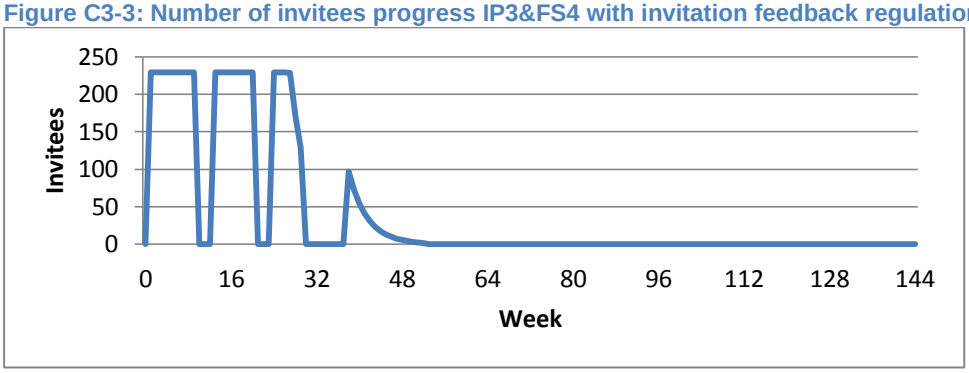


Figure C3-4: NP capacity IP2&FS2 with capacity feedback regulation

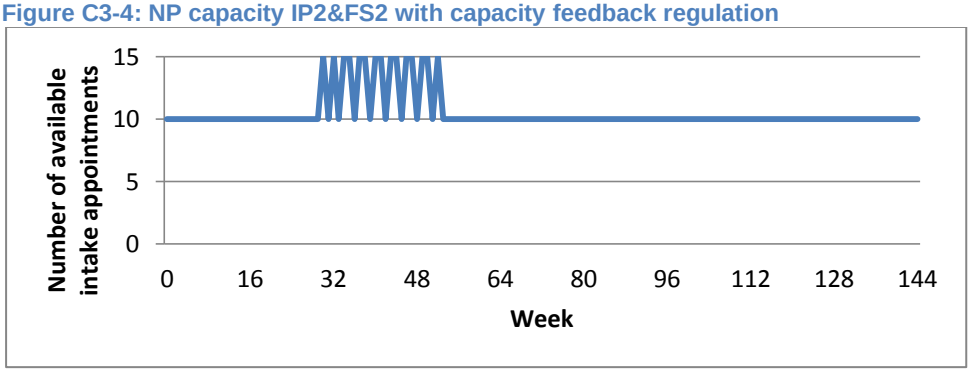


Figure C3-5: P capacity IP2&FS2 with capacity feedback regulation

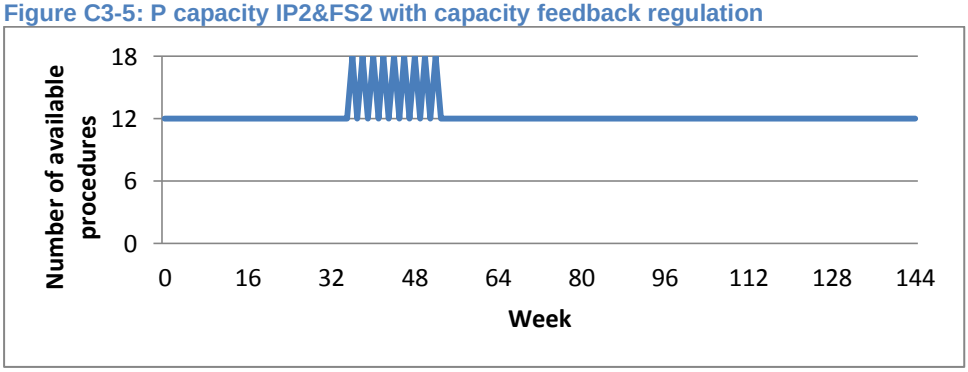


Figure C3-6:'Normal' procedure access time IP2&FS2 with capacity feedback regulation

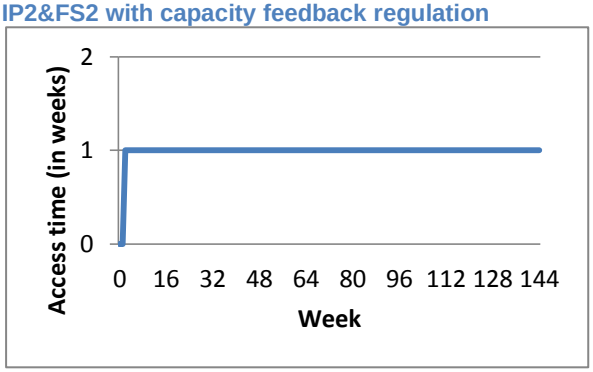


Figure C3-7: Regulated procedure access time IP2&FS2 with capacity feedback regulation

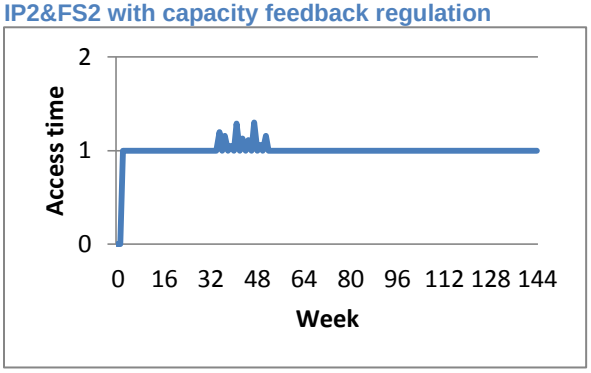


Figure C3-8: NP capacity IP3&FS2 with capacity feedback regulation

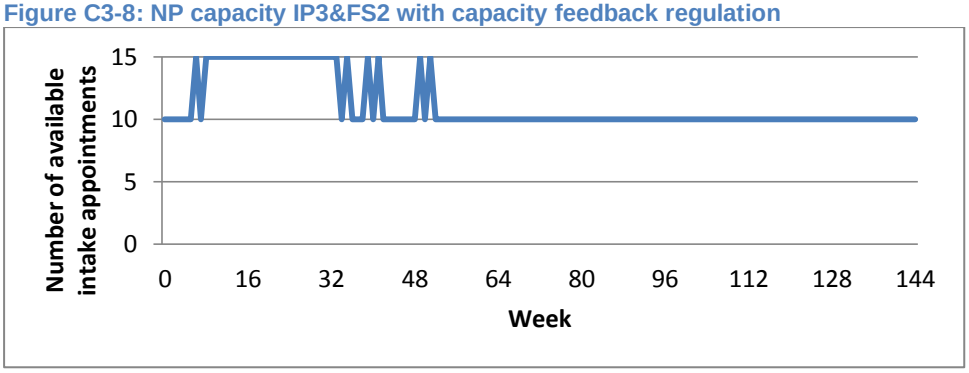


Figure C3-9: P capacity IP3&FS2 with capacity feedback regulation

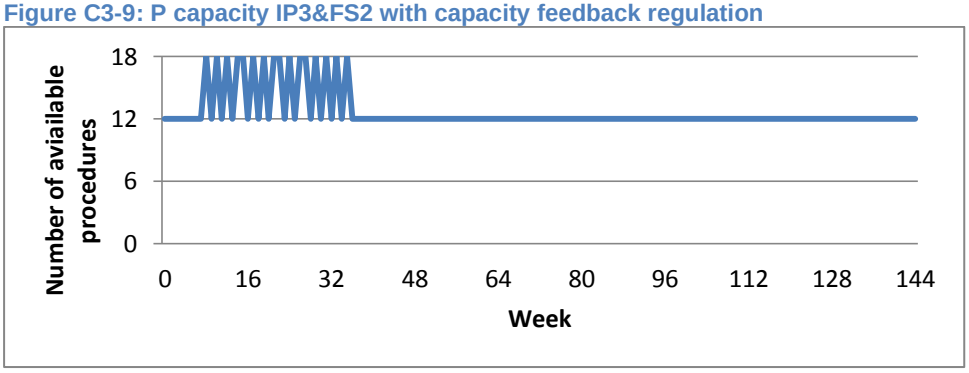


Figure C3-10: 'Normal' procedure access time IP3&FS2 with capacity feedback regulation

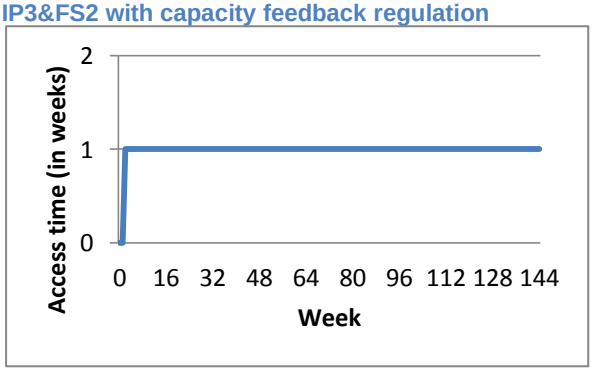
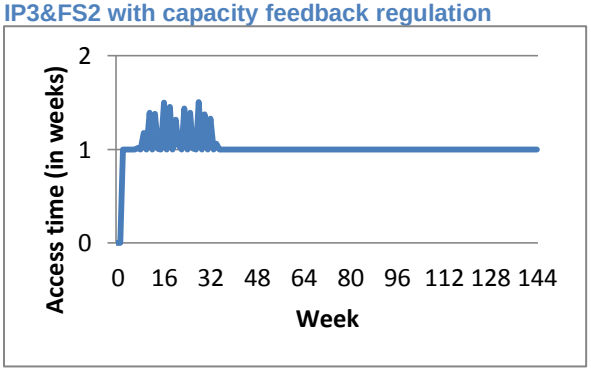


Figure C3-11: Regulated procedure access time IP3&FS2 with capacity feedback regulation



Appendix C4: Stochastic response times

Figure C4-1: Demand SR1

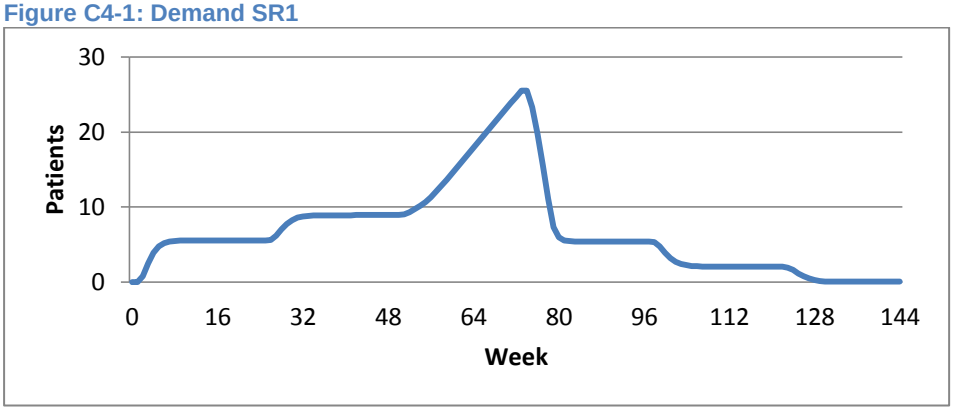


Figure C4-2: Demand SR2

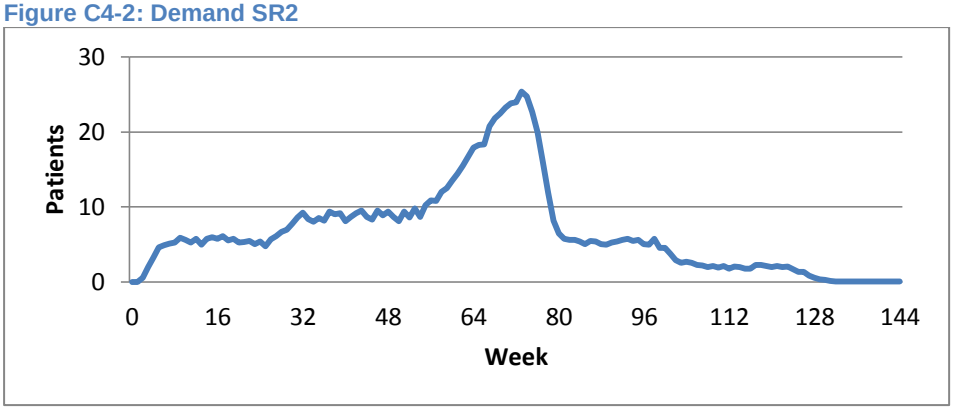


Figure C4-3: Demand SR3

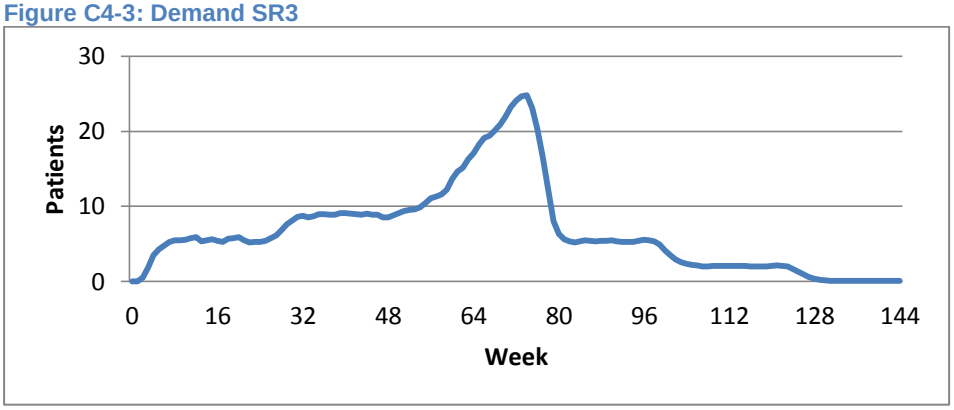
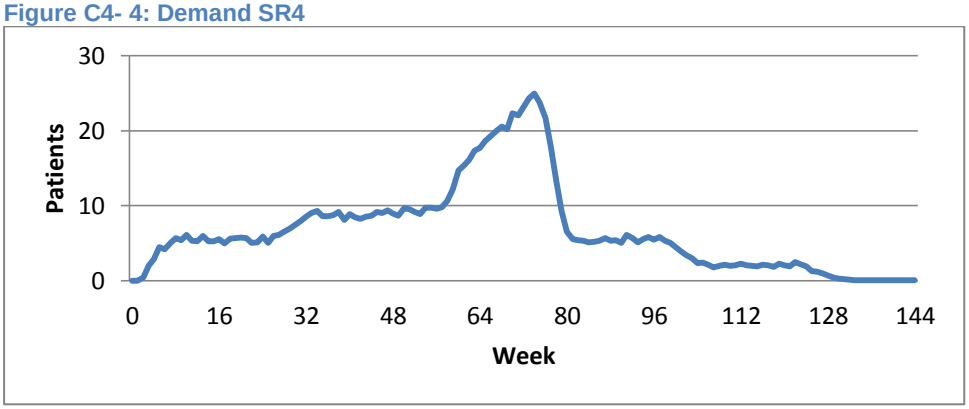


Figure C4- 4: Demand SR4



Appendix C5: Demand scenarios and optimal capacity allocation

Demand scenario	Supply scenario	Average intake access time	Average procedure access time	Average nurse practitioner capacity utilization	Average physician capacity utilization
DD1	*FS3*	1.1 week	1 week	64%	53%
DD1	*FS4*	1 week	1 week	43%	53%
DD2	*FS4*	1.2 week	3 weeks	65%	80%
DD2	*FS5*	1.2 week	1 week	65%	54%
DD2	*FS6*	1 week	1 week	49%	54%
DD3	*FS3*	1 week	1 week	35%	58%
DD3	*FS2*	1 week	1 week	35%	58%
DD3	*FS1*	1 week	1 week	70%	24%
DD4	*FS4*	1 week	2 weeks	67%	82%
DD4	*FS5*	1 week	1 week	67%	55%
DD4	*FS6*	1 week	1 week	50%	55%
DD5	*FS5*	5 weeks	1 week	86%	72%
DD5	*FS6*	1.2 week	1.4 weeks	65%	72%
DD6	*FS3*	1 week	1 week	47%	38%
DD6	*FS2*	1 week	1.2 week	47%	76%
DD6	*FS1*	4 weeks	1 week	91%	76%
DD7	*FS3*	1 week	1 week	43%	70%
DD7	*FS2*	1 week	1.5 week	43%	70%
DD7	*FS1*	5 weeks	1 week	83%	41%
DD8	*FS3*	1.2 weeks	1 week	65%	54%
DD8	*FS4*	1 week	1 week	44%	54%
DD9	*FS3*	1 week	1 week	24%	20%
DD9	*FS2*	1 week	1 week	24%	39%
DD9	*FS1*	1 week	1 week	47%	39%

Figure C5-1: Intake access time DD1&FS3

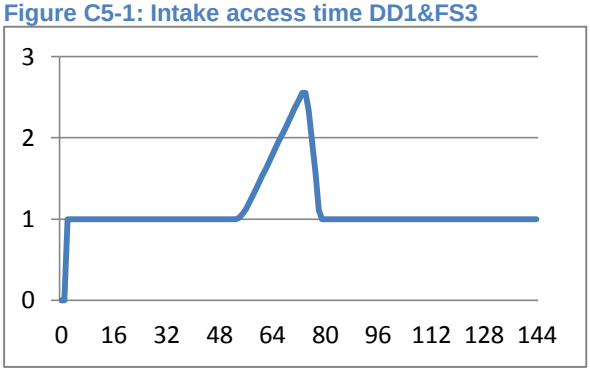


Figure C5-2: Procedure access time DD1&FS3

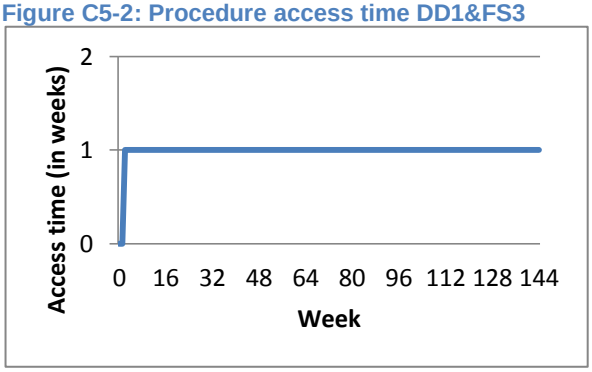


Figure C5-3: NP capacity utilization DD1&FS3

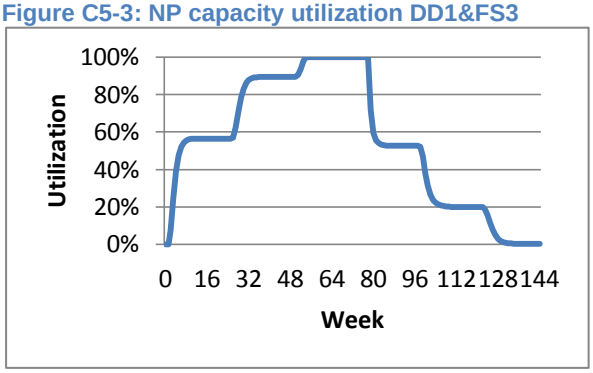
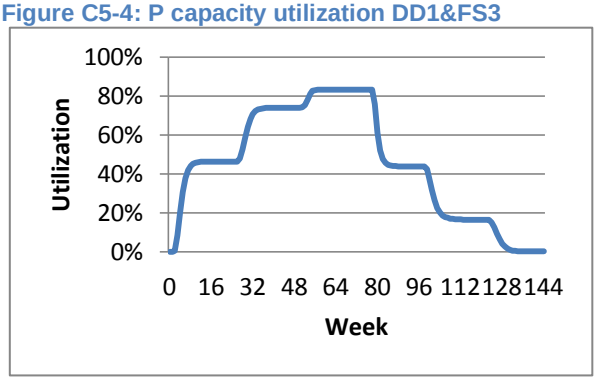
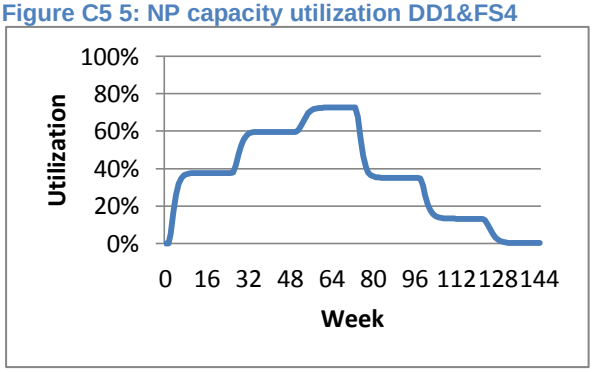


Figure C5-4: P capacity utilization DD1&FS3



Intake access time DD1&FS4:
Constant one week

Figure C5 5: NP capacity utilization DD1&FS4



Procedure access time DD1&FS4:
Constant one week

Figure C5-6: P capacity utilization DD1&FS4

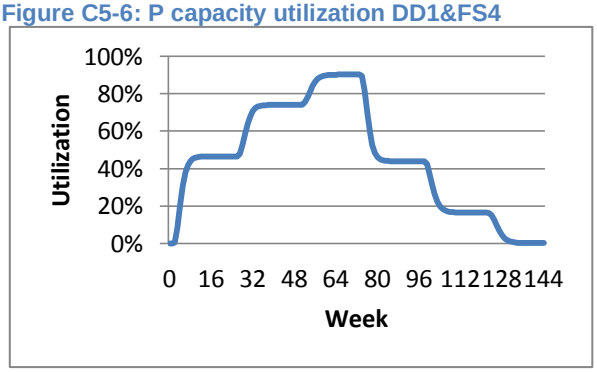


Figure C5-7: Intake access time DD2&FS4

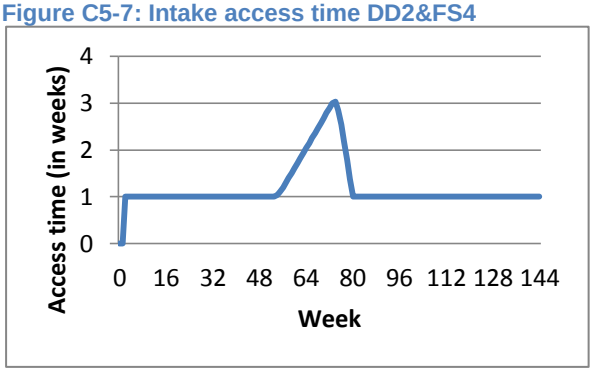


Figure C5-8: Procedure access time DD2&FS4

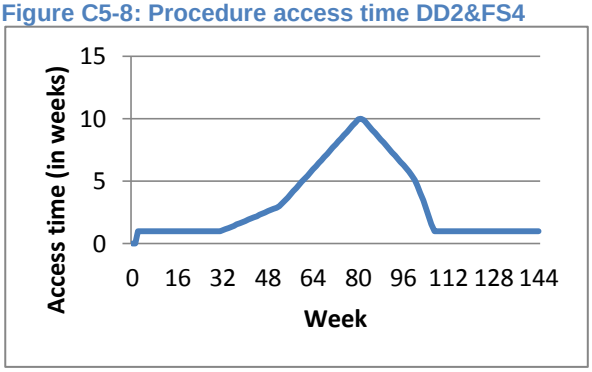


Figure C5-9: NP capacity utilization DD2&FS4

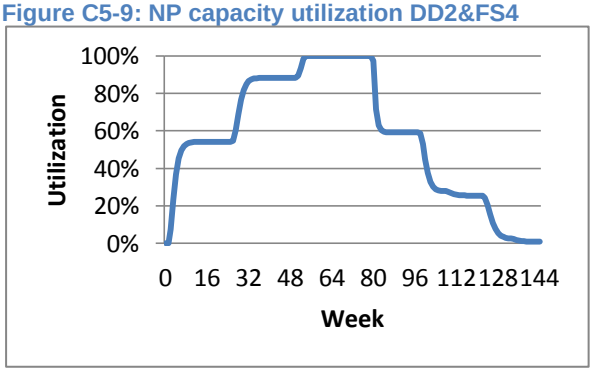


Figure C5-10: P capacity utilization DD2&FS4

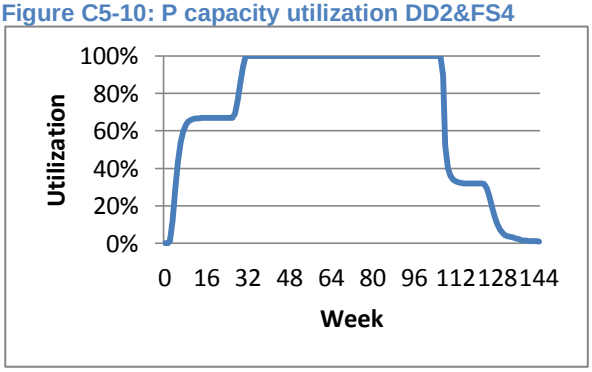


Figure C5-11: Intake access time DD2&FS5

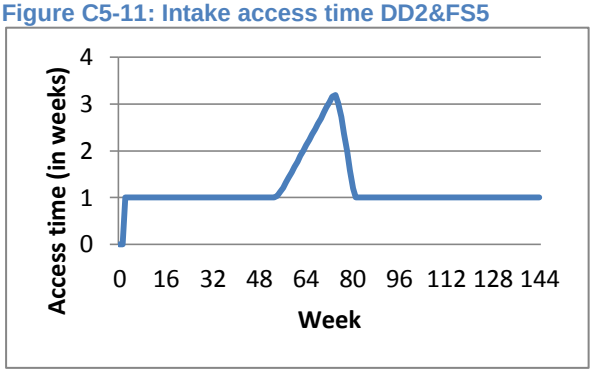


Figure C5-12: Procedure access time DD2&FS5

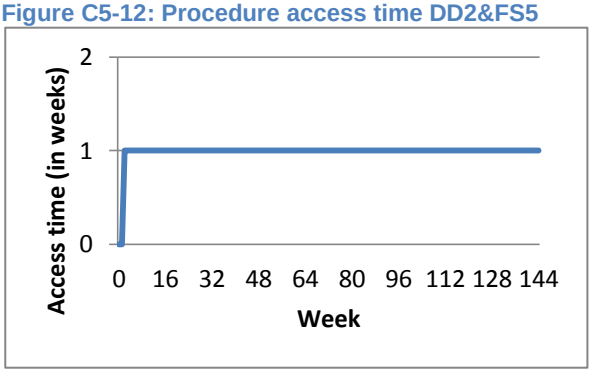


Figure C5-13: NP capacity utilization DD2&FS5

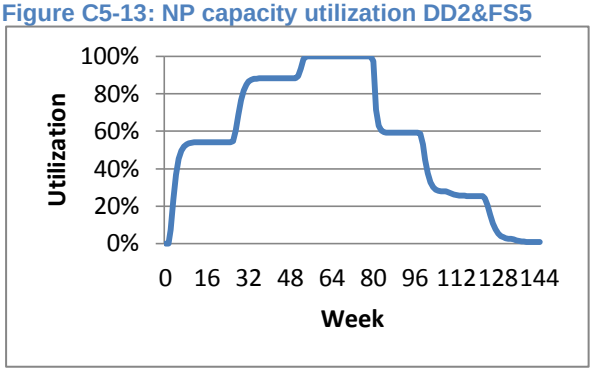
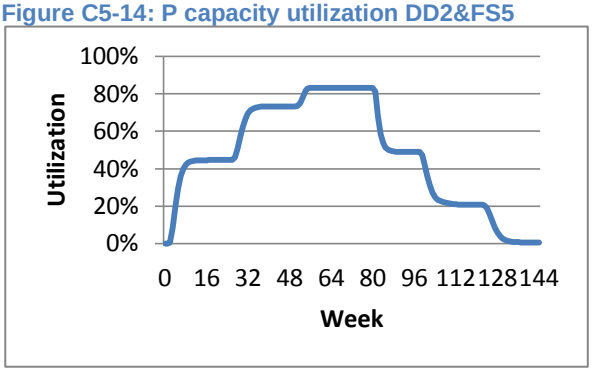


Figure C5-14: P capacity utilization DD2&FS5



Intake access time DD2&FS6:
Constant one week

Procedure access time DD2&FS6:
Constant one week

Figure C5-15: NP capacity utilization DD2&FS6

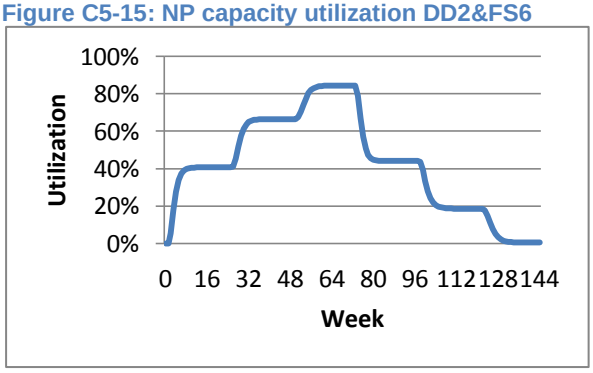
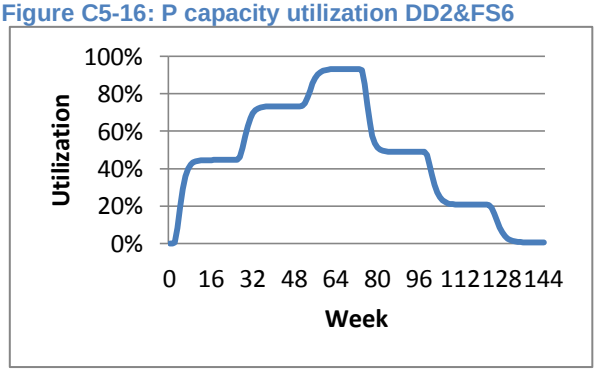


Figure C5-16: P capacity utilization DD2&FS6



Intake access time DD3&FS3:
Constant one week

Procedure access time DD3&FS3:
Constant one week

Figure C5-17: NP capacity utilization DD3&FS3

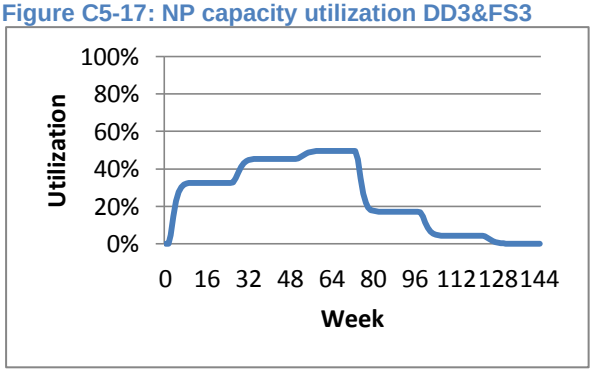
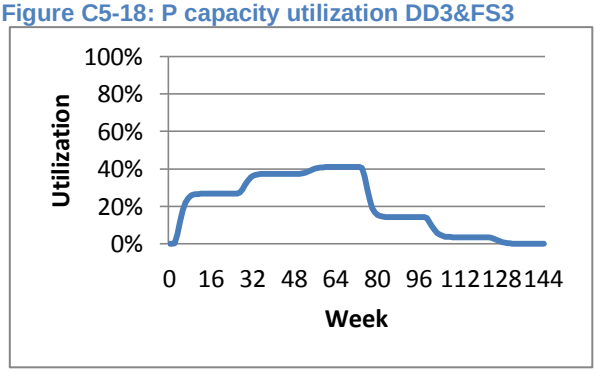


Figure C5-18: P capacity utilization DD3&FS3

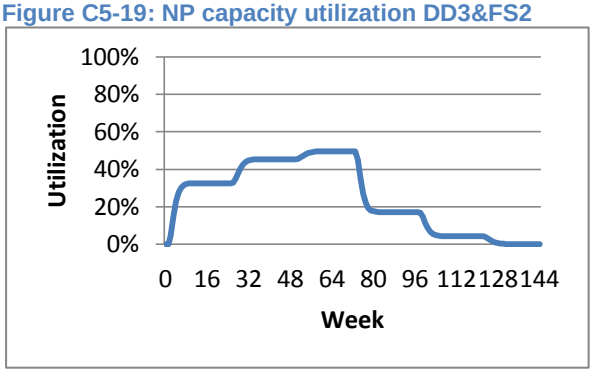


Intake access time DD3&FS2:

Procedure access time DD3&FS2:

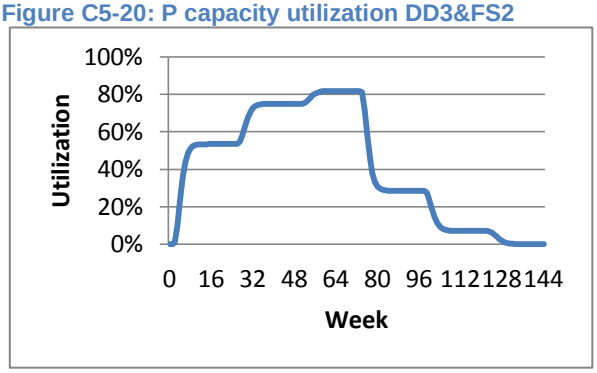
Constant one week

Figure C5-19: NP capacity utilization DD3&FS2



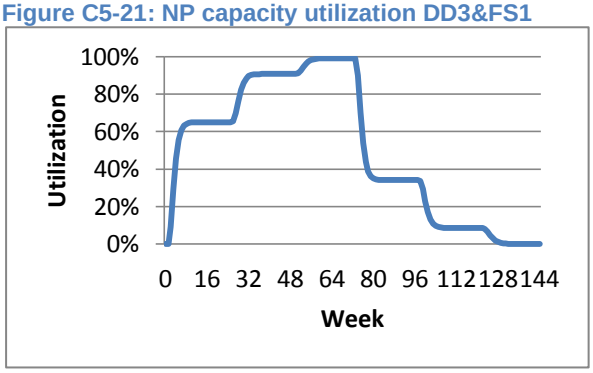
Constant one week

Figure C5-20: P capacity utilization DD3&FS2



Intake access time DD3&FS1:
Constant one week

Figure C5-21: NP capacity utilization DD3&FS1



Procedure access time DD3&FS1:
Constant one week

Figure C5-22: P capacity utilization DD3&FS1

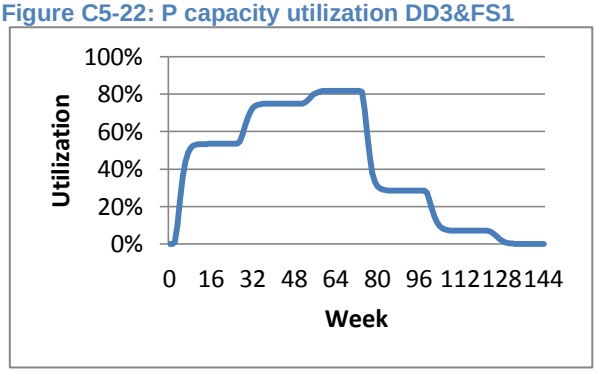


Figure C5-23: Intake access time DD4&FS4

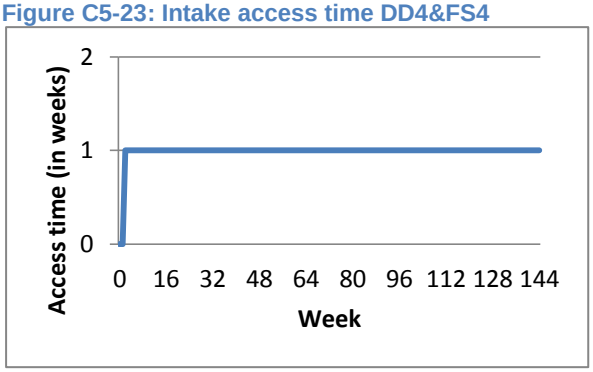


Figure C5-24: Procedure access time DD4&FS4

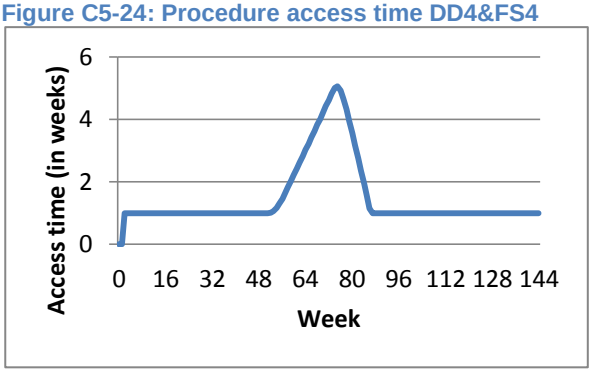


Figure C5-25: NP capacity utilization DD4&FS4

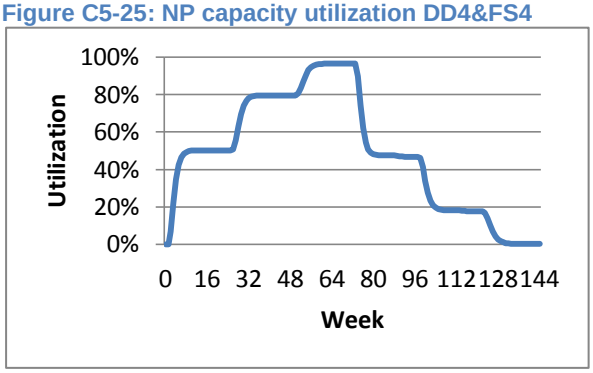
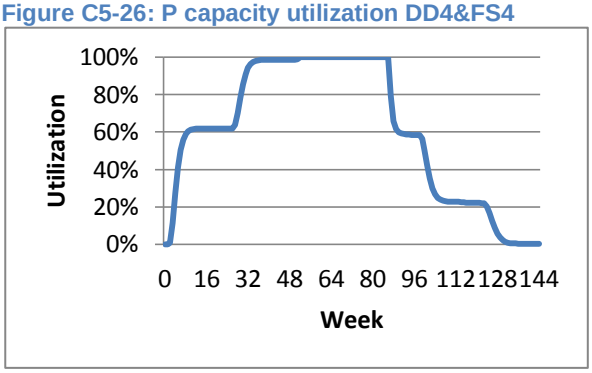


Figure C5-26: P capacity utilization DD4&FS4



Intake access time DD4&FS5:
Constant one week

Procedure access time DD4&FS5:
Constant one week

Figure C5-27: NP capacity utilization DD4&FS5

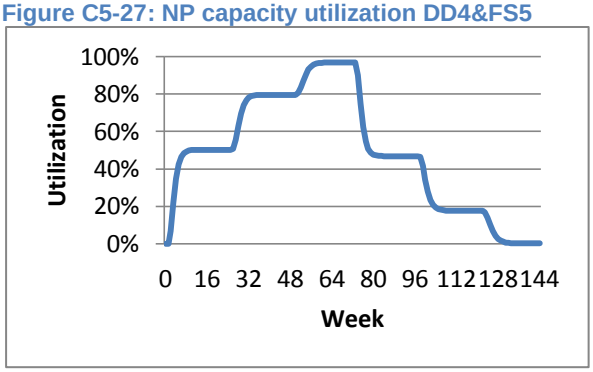
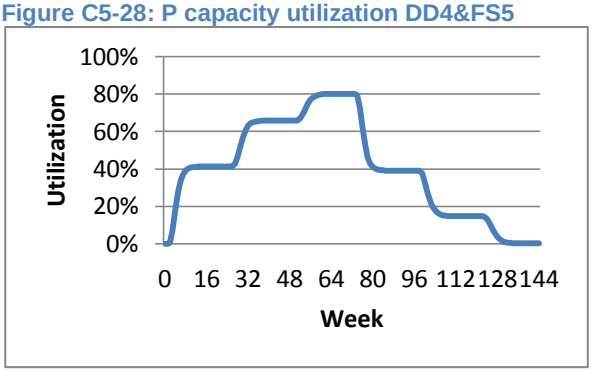


Figure C5-28: P capacity utilization DD4&FS5



Intake access time DD4&FS6:
Constant one week

Procedure access time DD4&FS6:
Constant one week

Figure C5-29: NP capacity utilization DD4&FS6

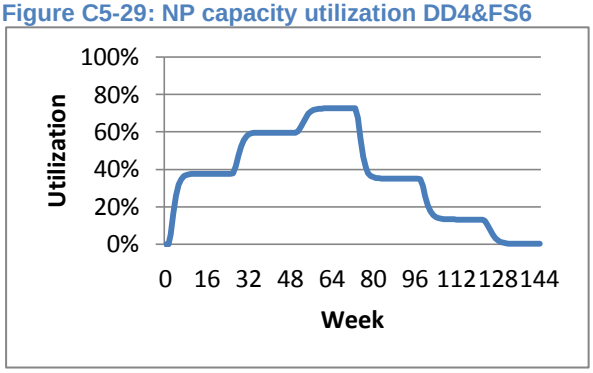


Figure C5-30: P capacity utilization DD4&FS6

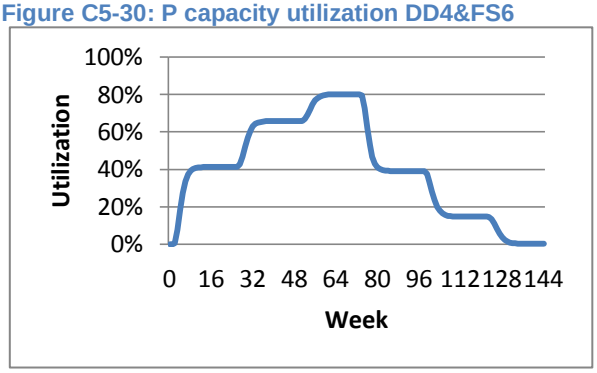


Figure C5-31: Intake access time DD5&FS5

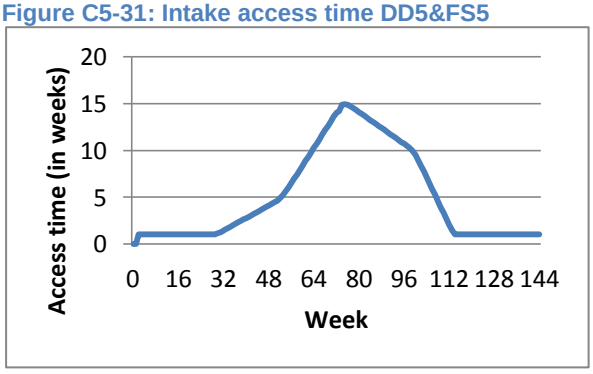


Figure C5-32: Procedure access time DD5&FS5

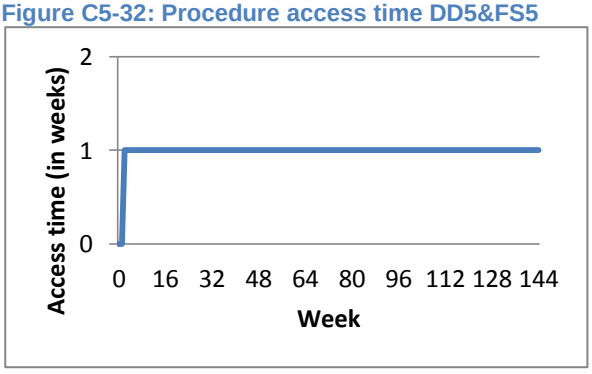


Figure C5-33: NP capacity utilization DD5&FS5

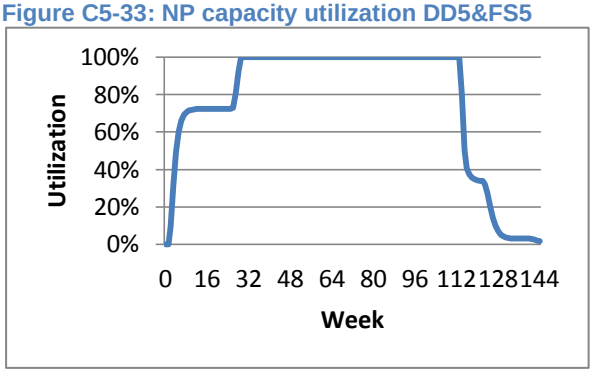


Figure C5-34: P capacity utilization DD5&FS5

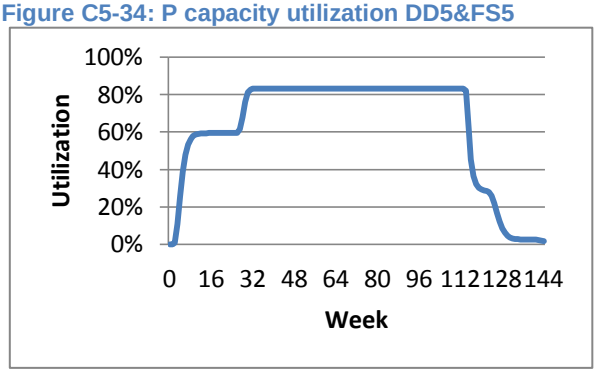


Figure C5-35: Intake access time DD5&FS6

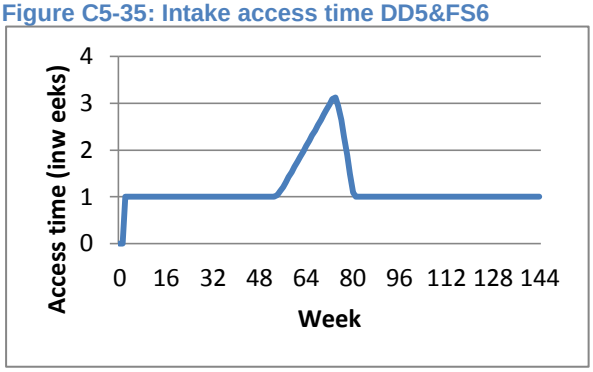


Figure C5-36: Procedure access time DD5&FS6

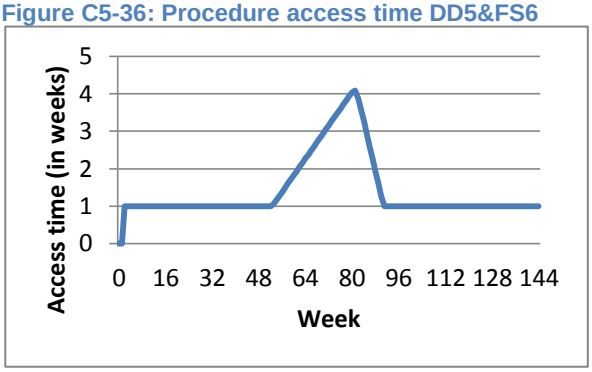


Figure C5-37: NP capacity utilization DD5&FS6

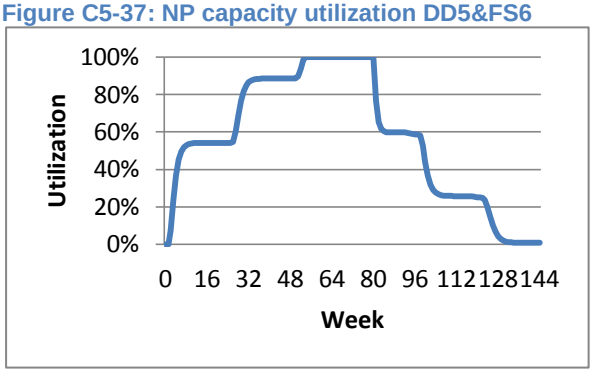
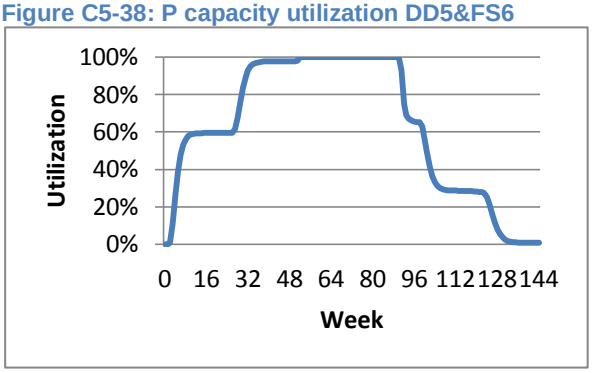


Figure C5-38: P capacity utilization DD5&FS6



Intake access time DD6&FS3:
Constant one week

Procedure access time DD6&FS3:
Constant one week

Figure C5-39: NP capacity utilization DD6&FS3

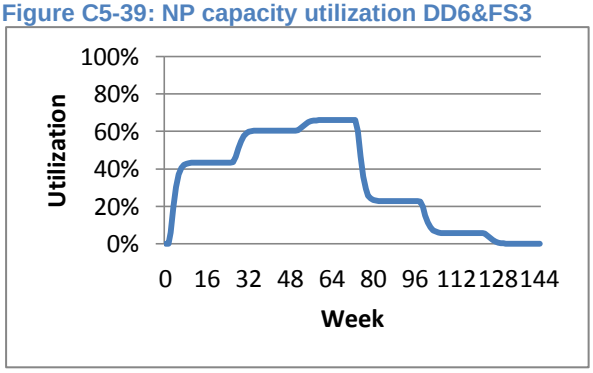


Figure C5-40: P capacity utilization DD6&FS3

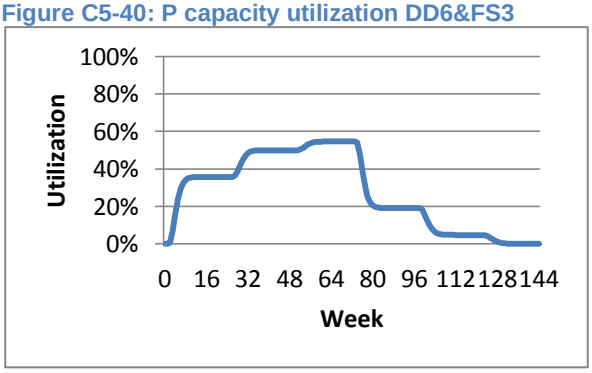


Figure C5-41: Intake access time DD6&FS2

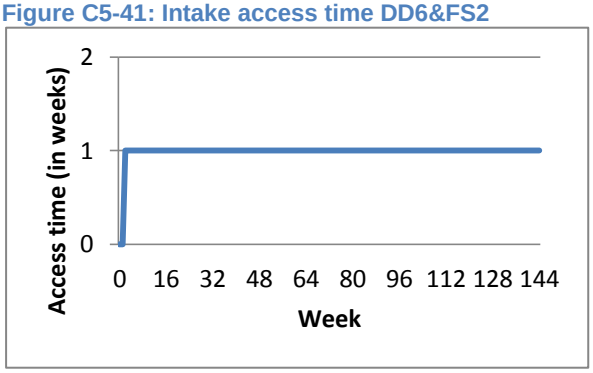


Figure C5-42: Procedure access time DD6&FS2

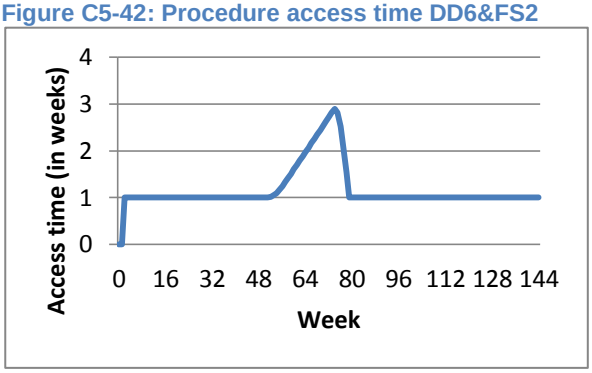


Figure C5-43: NP capacity utilization DD6&FS2

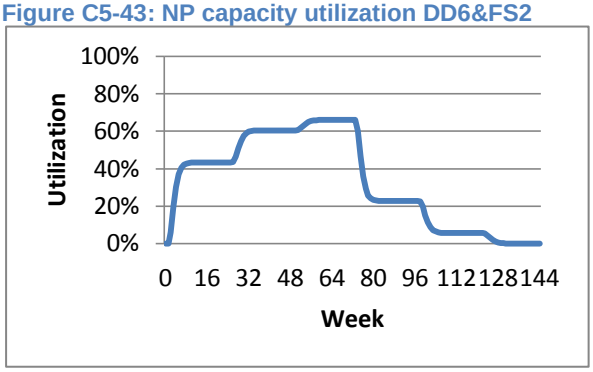


Figure C5-44: P capacity utilization DD6&FS2

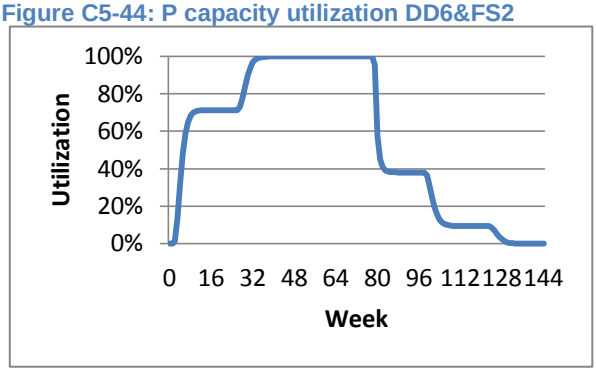


Figure C5-45: Intake access time DD6&FS1

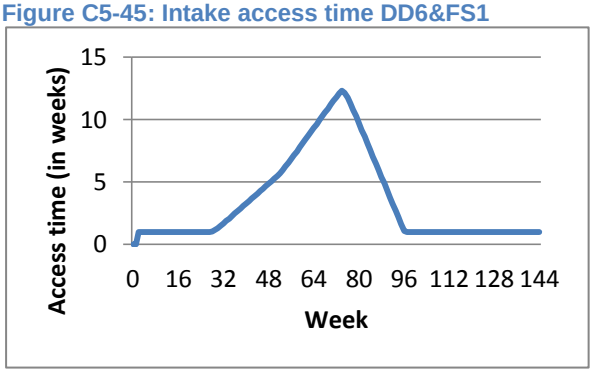


Figure C5-46: Procedure access time DD6&FS1

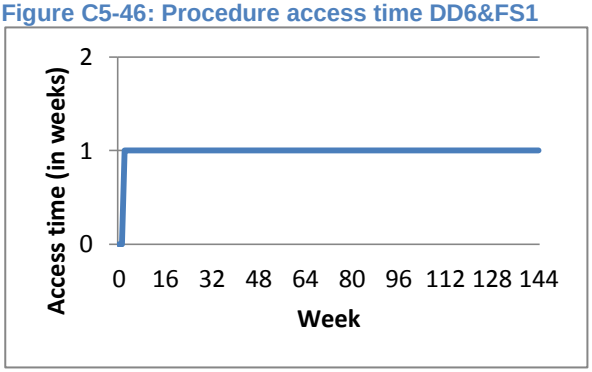


Figure C5-47: NP capacity utilization DD6&FS1

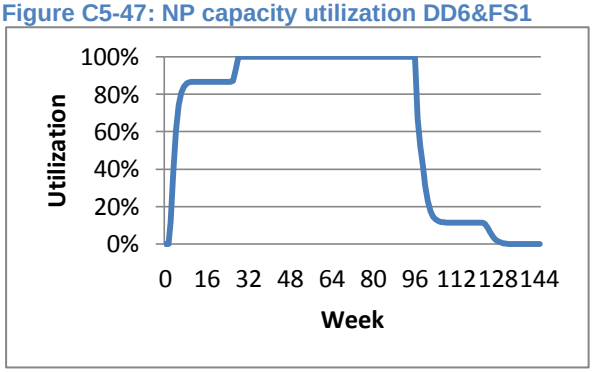
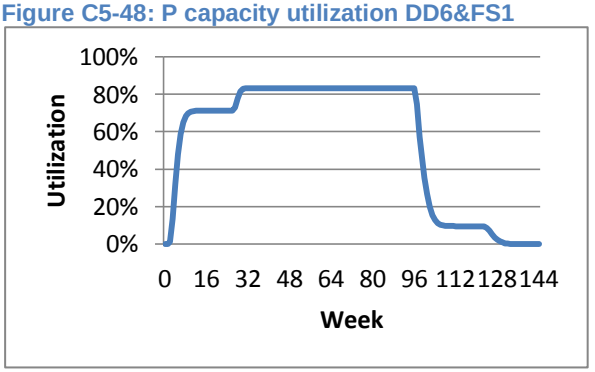


Figure C5-48: P capacity utilization DD6&FS1



Intake access time DD7&FS3:
Constant one week

Procedure access time DD7&FS3:
Constant one week

Figure C5-49: NP capacity utilization DD7&FS3

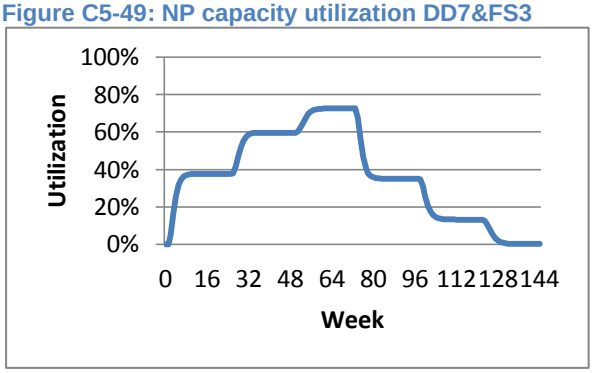


Figure C5-50: P capacity utilization DD7&FS3

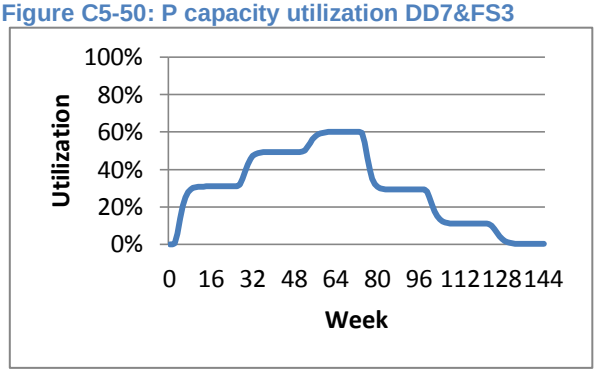


Figure C5-51: Intake access time DD7&FS2

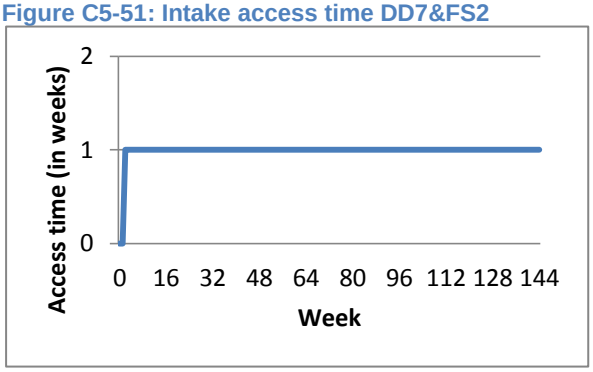


Figure C5-52: Procedure access time DD7&FS2

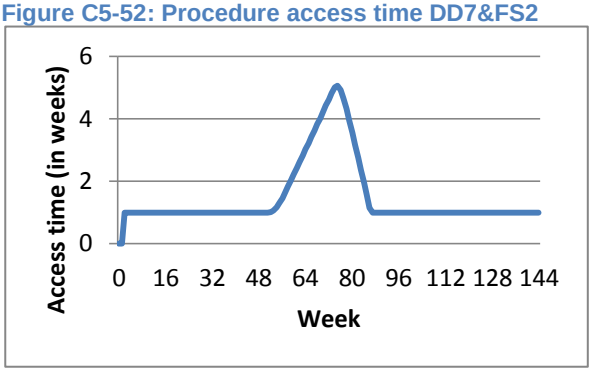


Figure C5-53: NP capacity utilization DD7&FS2

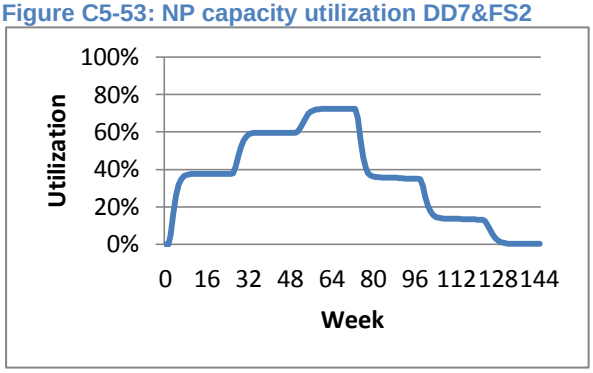


Figure C5-54: P capacity utilization DD7&FS2

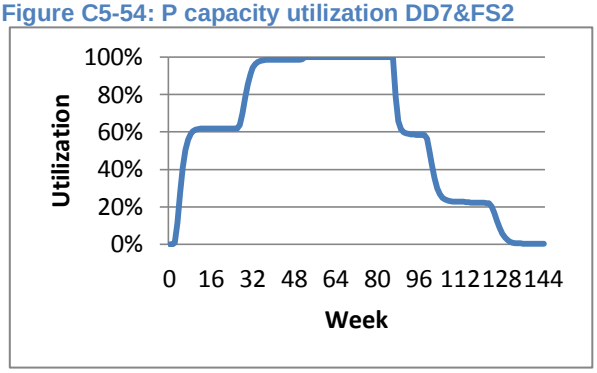


Figure C5-55: Intake access time DD7&FS1

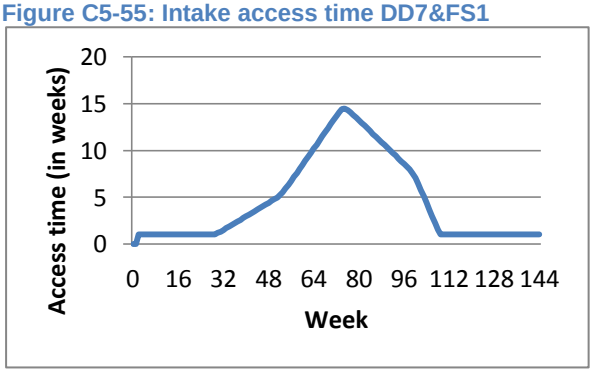


Figure C5-56: Procedure access time DD7&FS1

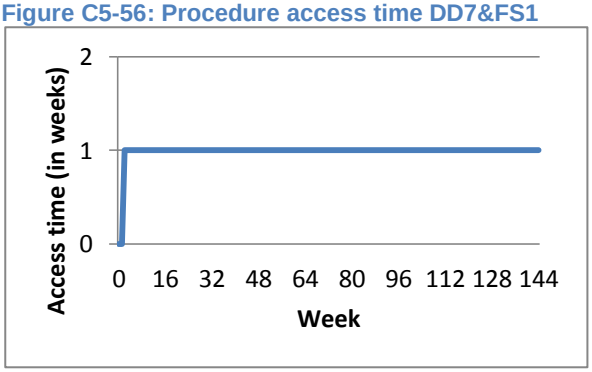


Figure C5-57: NP capacity utilization DD7&FS1

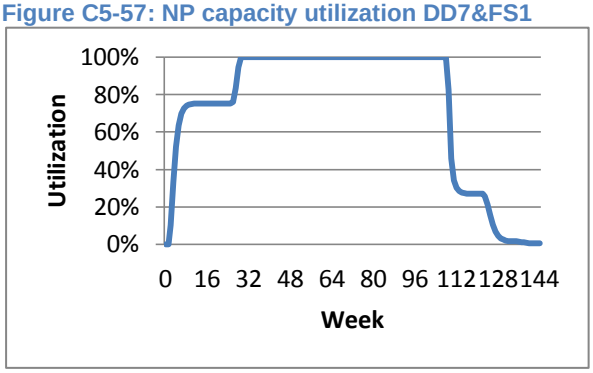


Figure C5-58: P capacity utilization DD7&FS1

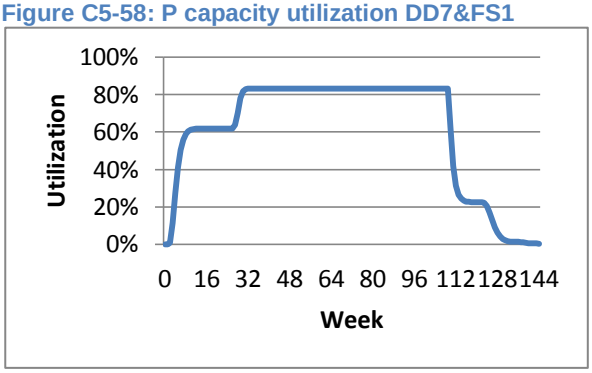


Figure C5-59: Intake access time DD8&FS3

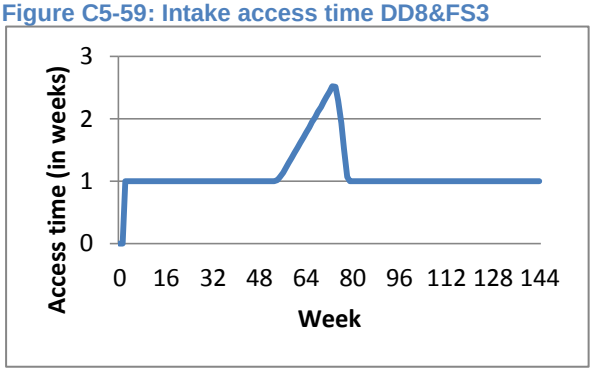


Figure C5-60: Procedure access time DD8&FS3

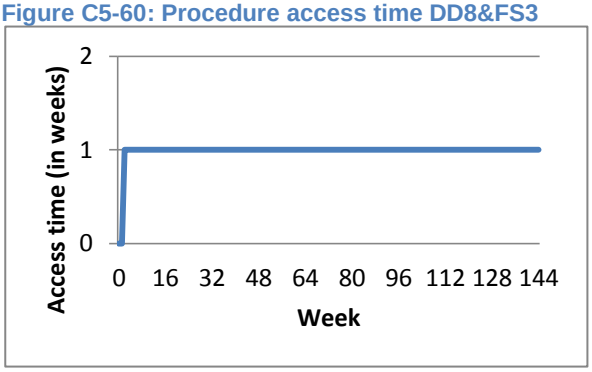


Figure C5-61: NP capacity utilization DD8&FS3

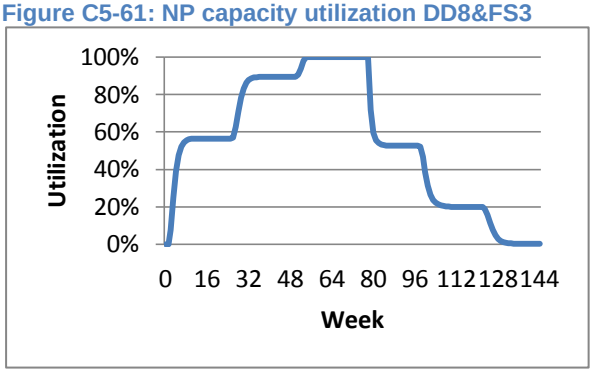
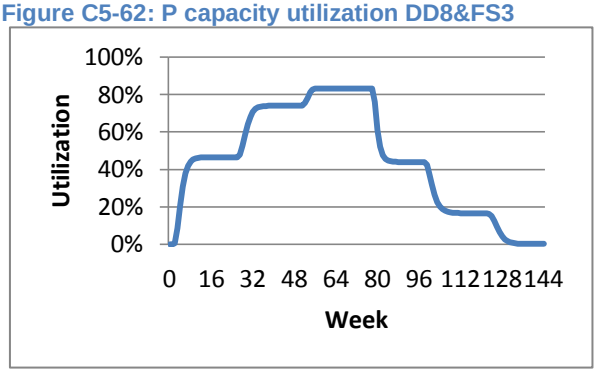


Figure C5-62: P capacity utilization DD8&FS3



Intake access time DD8&FS4:
Constant one week

Procedure access time DD8&FS4:
Constant one week

Figure C5-63: NP capacity utilization DD8&FS4

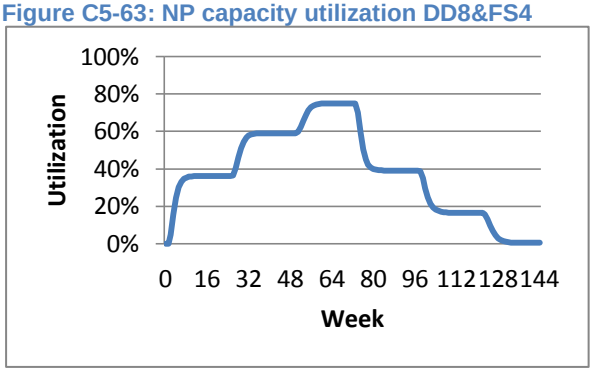
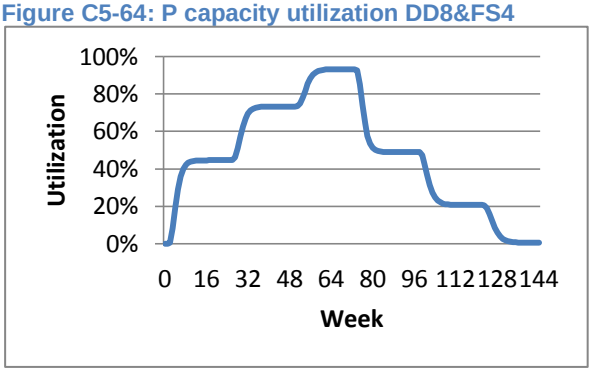


Figure C5-64: P capacity utilization DD8&FS4



Intake access time DD9&FS3:
Constant one week

Procedure access time DD9&FS3:
Constant one week

Figure C5-65: NP capacity utilization DD9&FS3

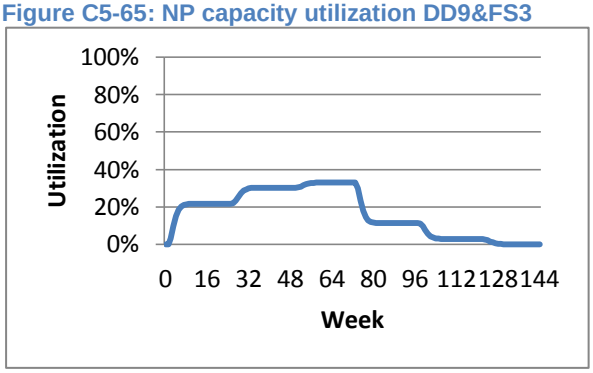
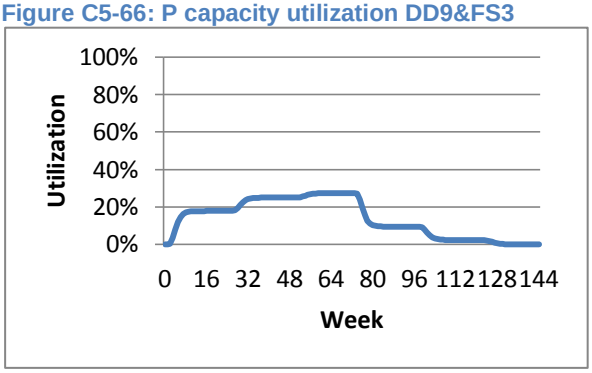


Figure C5-66: P capacity utilization DD9&FS3



Intake access time DD9&FS2:
Constant one week

Procedure access time DD9&FS2:
Constant one week

Figure C5- 67: NP capacity utilization DD9&FS2

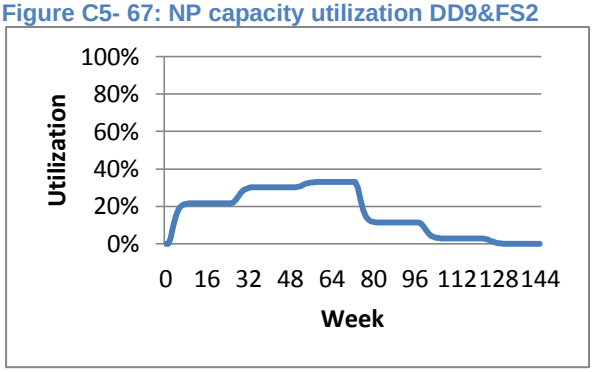
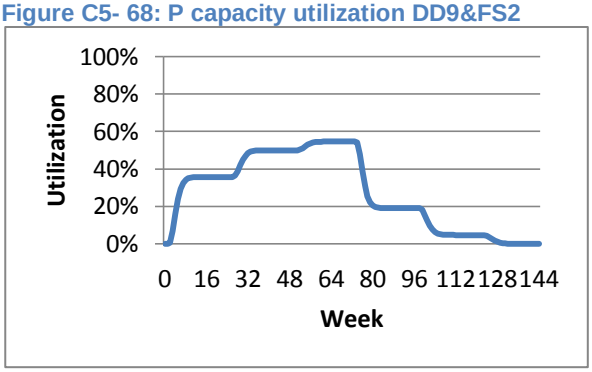
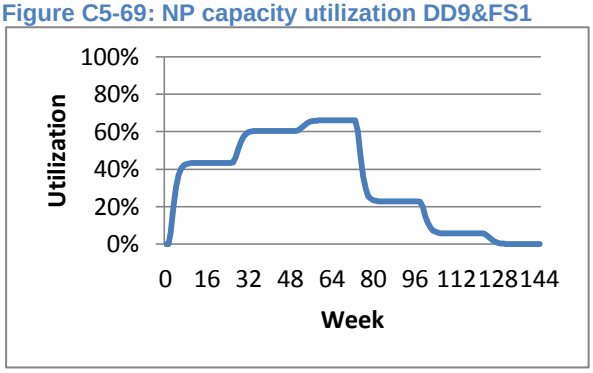


Figure C5- 68: P capacity utilization DD9&FS2



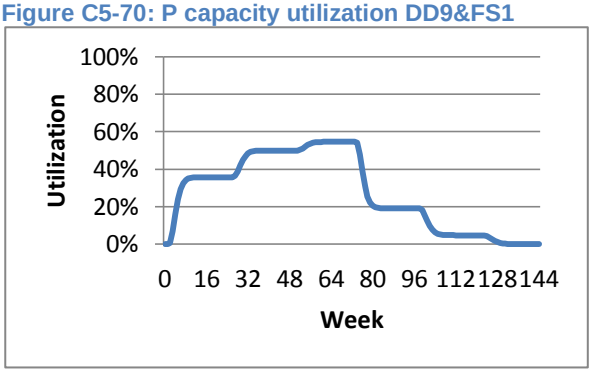
Intake access time DD9&FS1:
Constant one week

Figure C5-69: NP capacity utilization DD9&FS1



Procedure access time DD9&FS1:
Constant one week

Figure C5-70: P capacity utilization DD9&FS1



Appendix C6: Demand scenarios and feedback regulation

Figure C6-1: Number of invitees DD1 with invitation feedback regulation

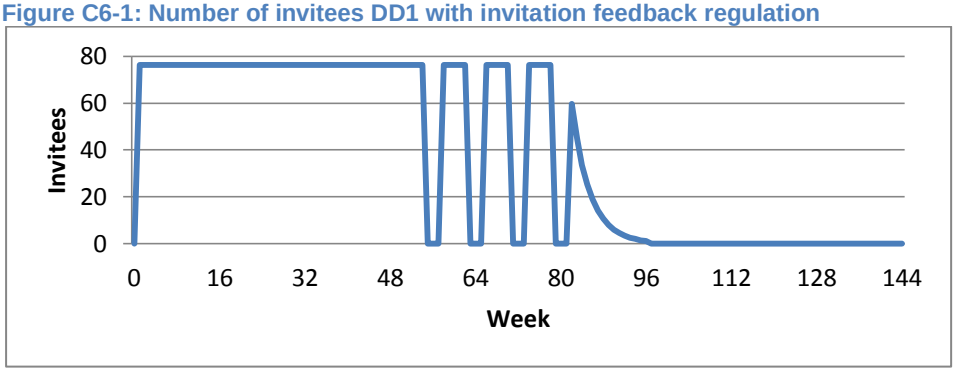


Figure C6-2: Number of invitees DD2 with invitation feedback regulation

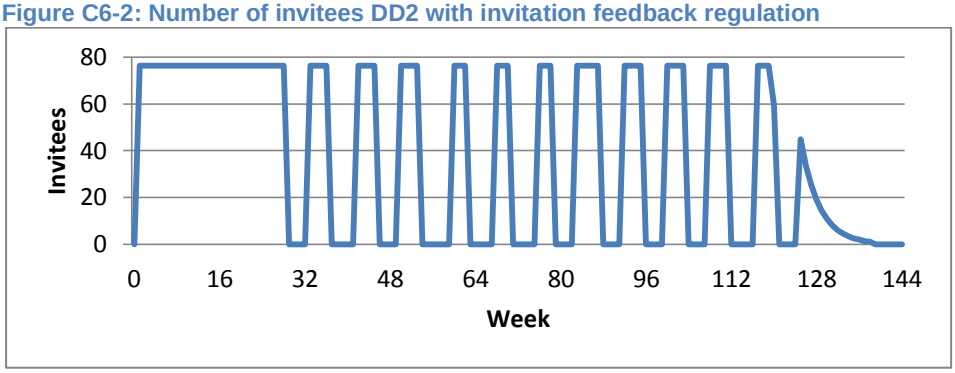


Figure C6-3: Number of invitees DD4 with invitation feedback regulation

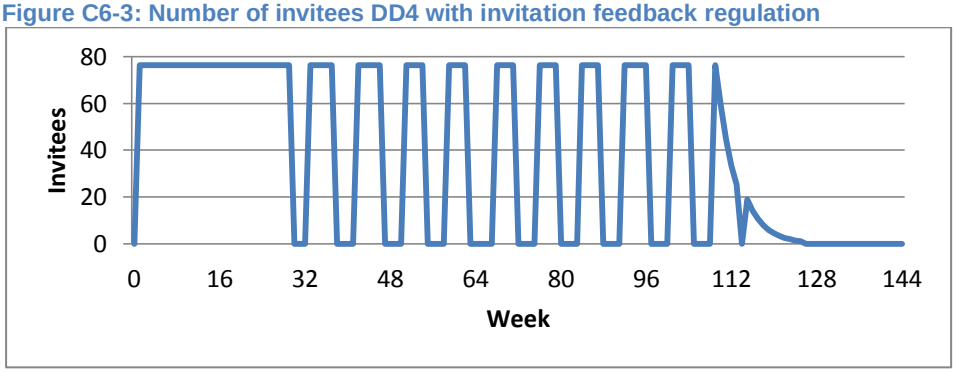


Figure C6-4: Number of invitees DD5 with invitation feedback regulation

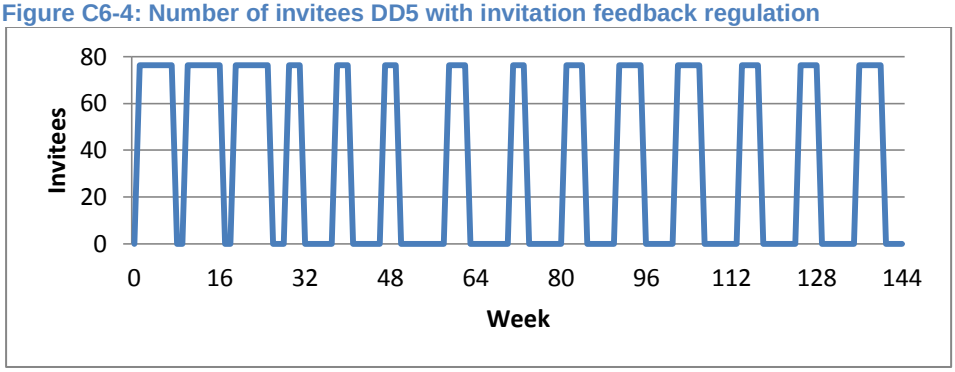
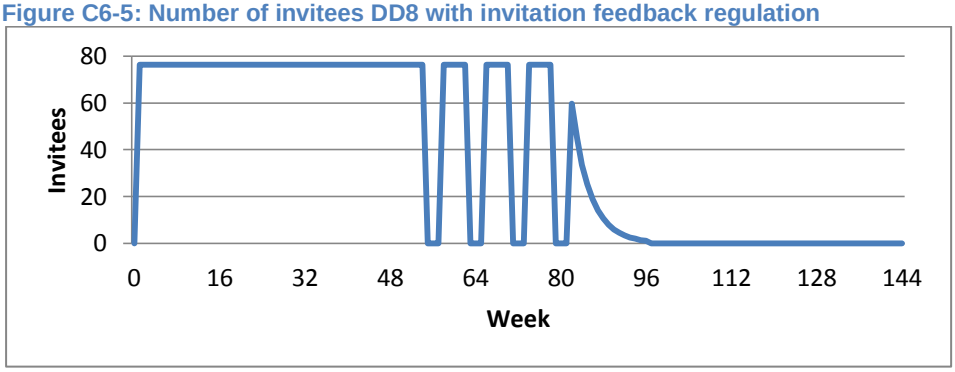


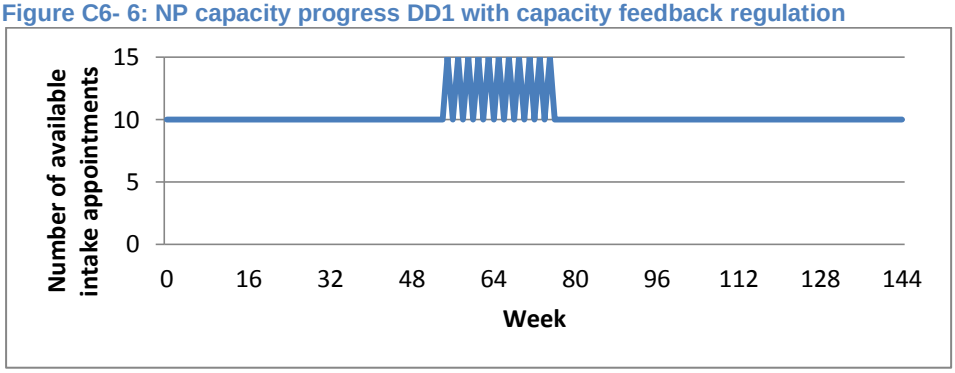
Figure C6-5: Number of invitees DD8 with invitation feedback regulation



Normal procedure access time DD1:
Constant one week

Capacity regulated procedure access time DD1:
Constant one week

Figure C6- 6: NP capacity progress DD1 with capacity feedback regulation



Physician capacity progress DD1 with capacity feedback regulation:
Constant at twelve procedures

Figure C6-7: Normal procedure access time DD2

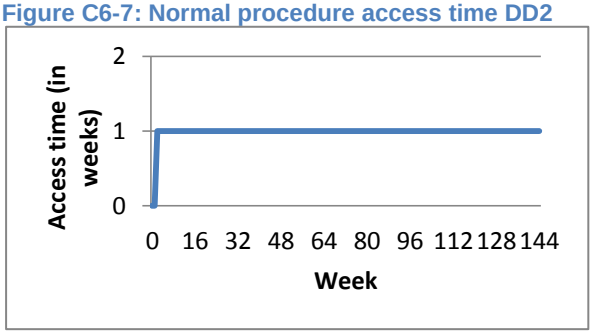


Figure C6-8: Regulated procedure access time DD2

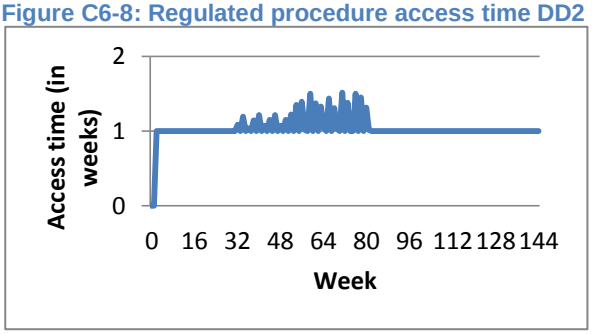


Figure C6- 9: NP capacity progress DD4 with capacity feedback regulation

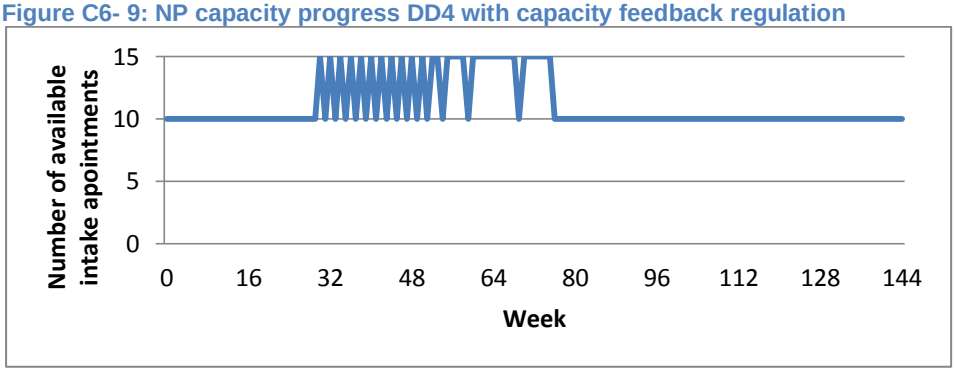


Figure C6- 10: P capacity progress DD4 with capacity feedback regulation

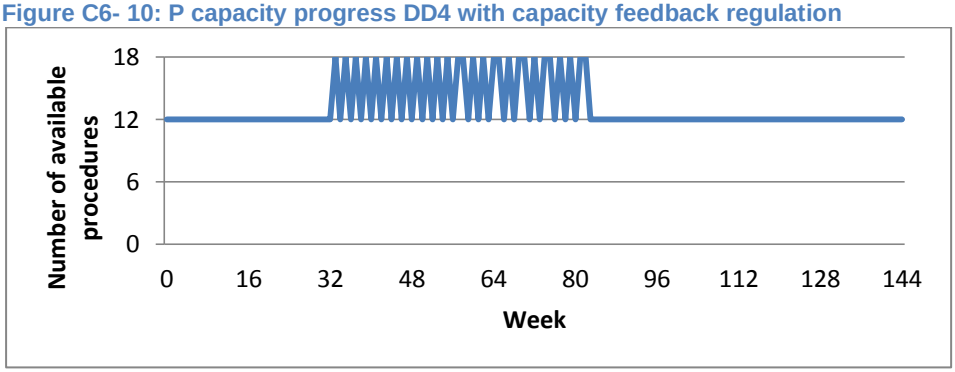


Figure C6-11: Normal procedure access time DD5

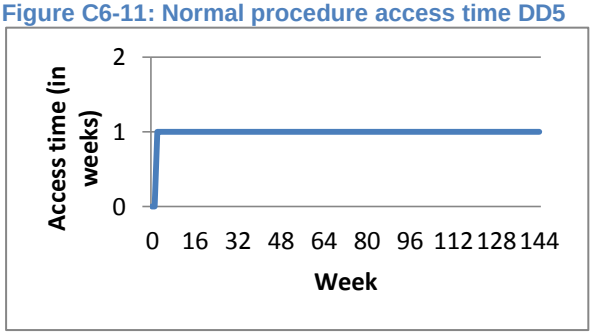


Figure C6-12: Regulated access time DD5

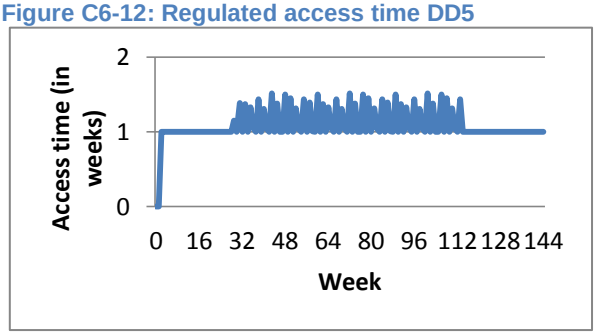


Figure C6- 13: NP capacity progress DD5 with capacity feedback regulation

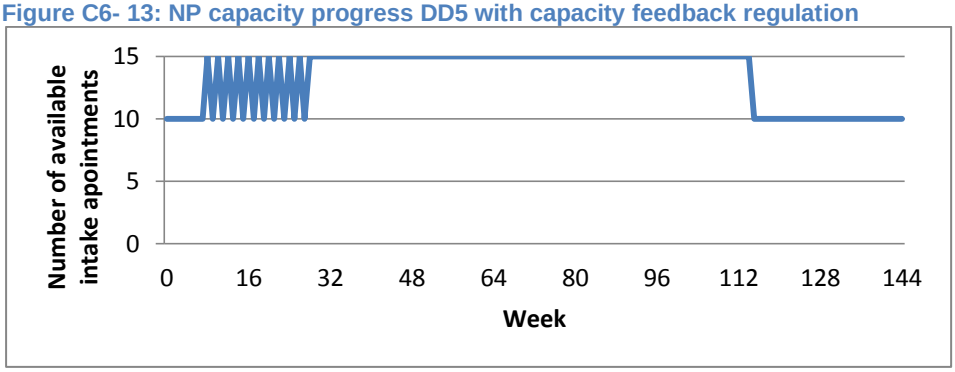
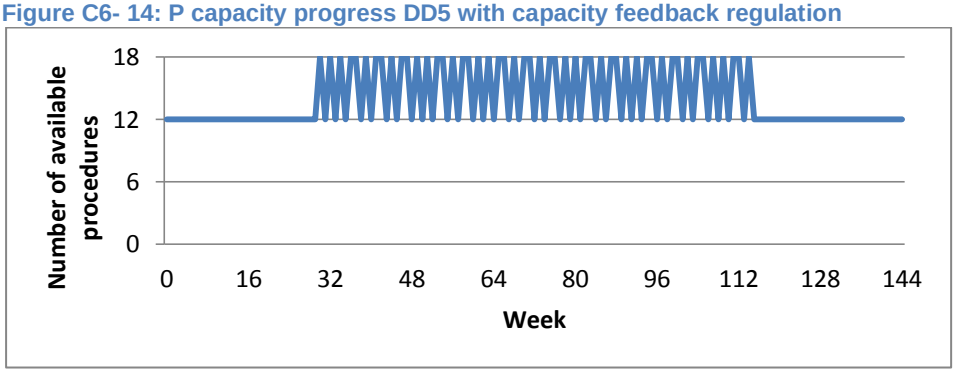


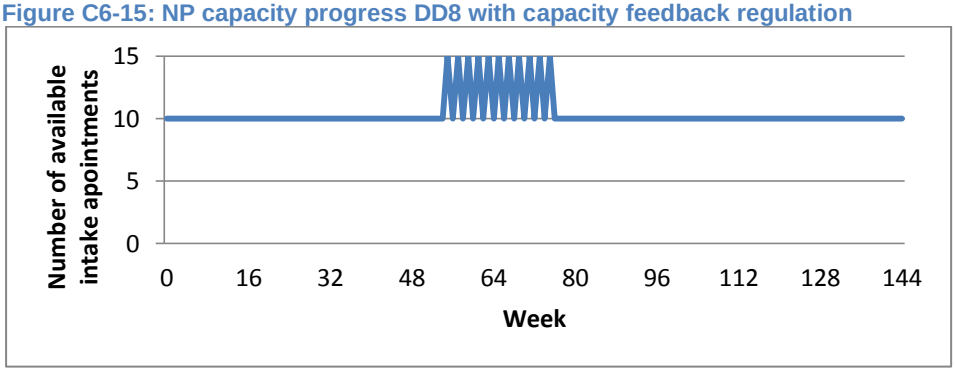
Figure C6- 14: P capacity progress DD5 with capacity feedback regulation



'Normal' procedure access time DD8:
Constant one week

Regulated procedure access time DD8:
Constant one week

Figure C6-15: NP capacity progress DD8 with capacity feedback regulation



Physician capacity progress DD8 with capacity feedback regulation:
Constant at twelve procedures

Figure C6-16: Number of invitees DD5 both regulations situation 1

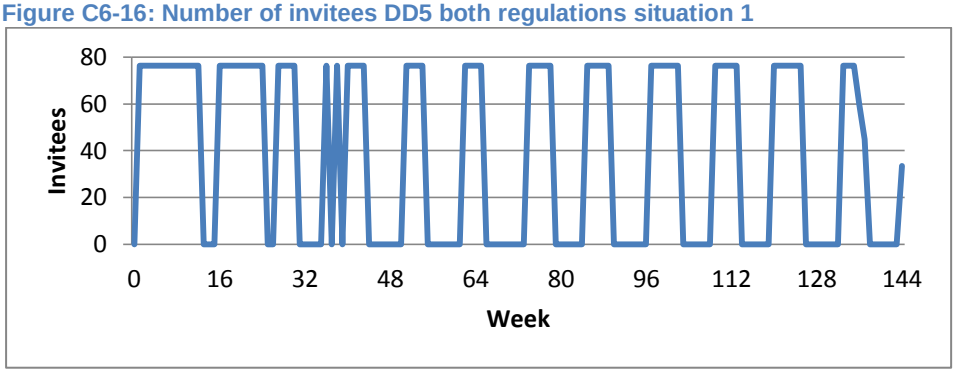


Figure C6-17: NP capacity progress DD5 both regulation situation 1

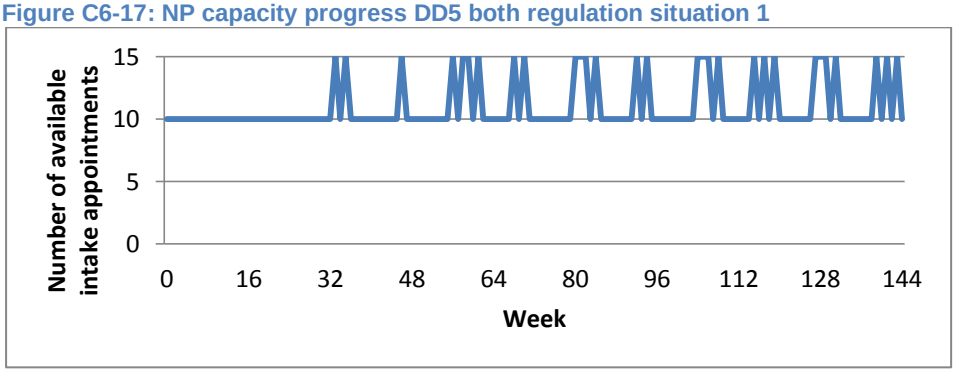


Figure C6-18: P capacity progress DD5 both regulation situation 1

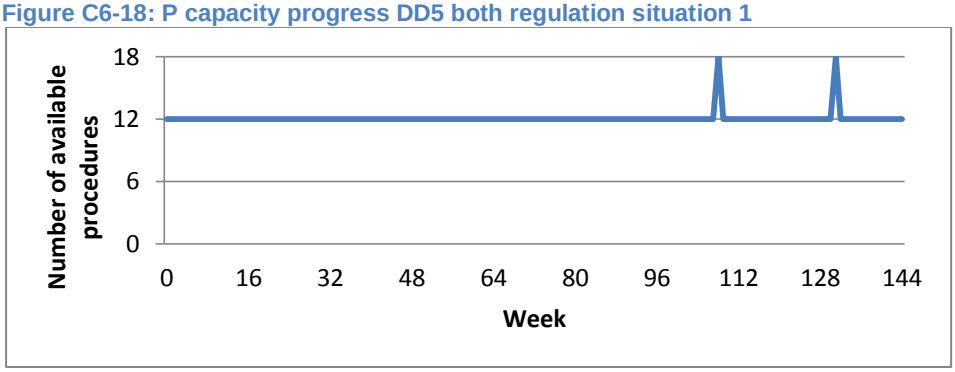


Figure C6-19: Number of invitees DD5 both regulations situation 2

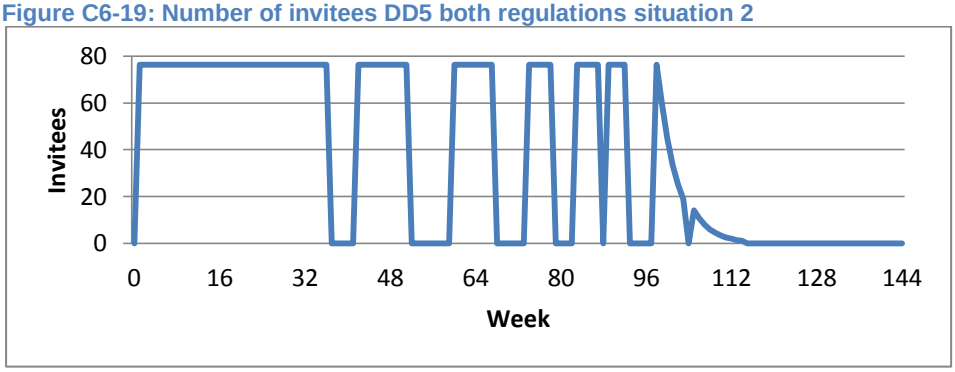


Figure C6-20: NP capacity progress DD5 both regulation situation 2

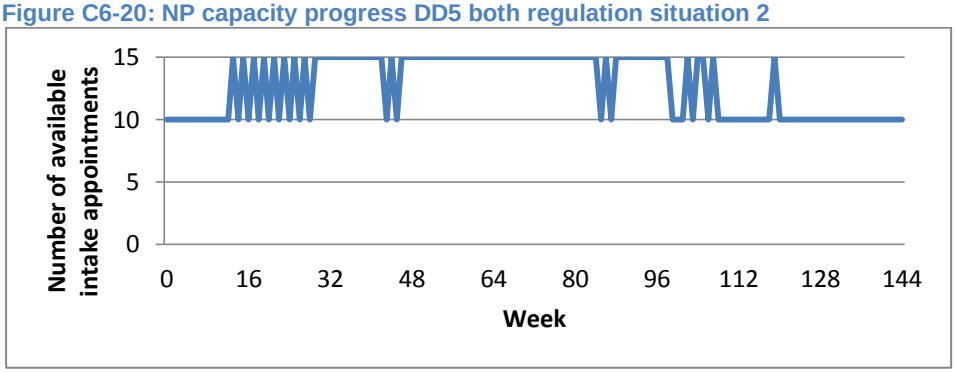
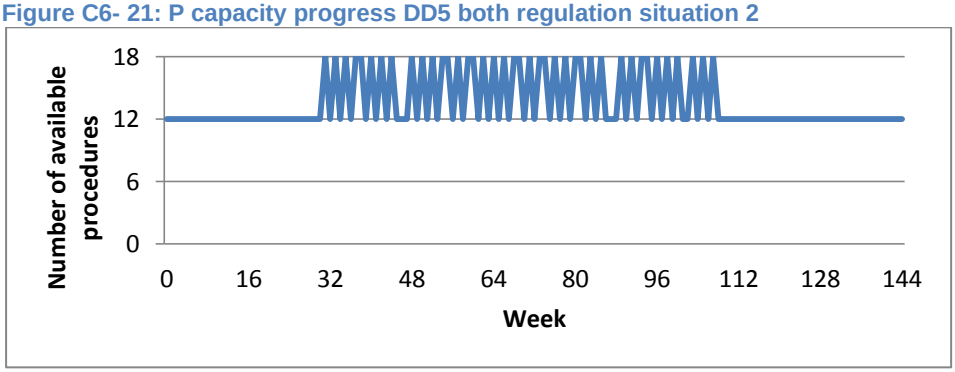


Figure C6- 21: P capacity progress DD5 both regulation situation 2



Appendix C7: Invitation batches and optimal capacity allocation

Figure C7-1: Intake access time IB2&FS3

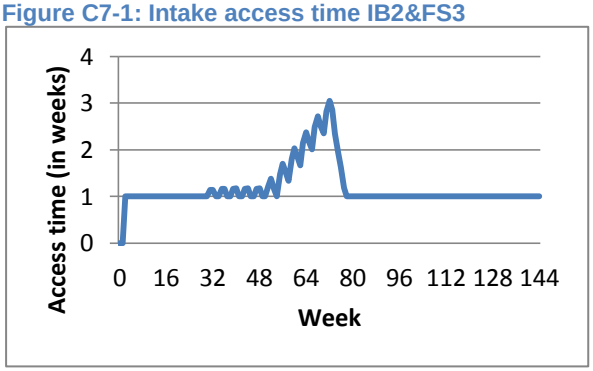


Figure C7-2: Procedure access time IB2&FS3

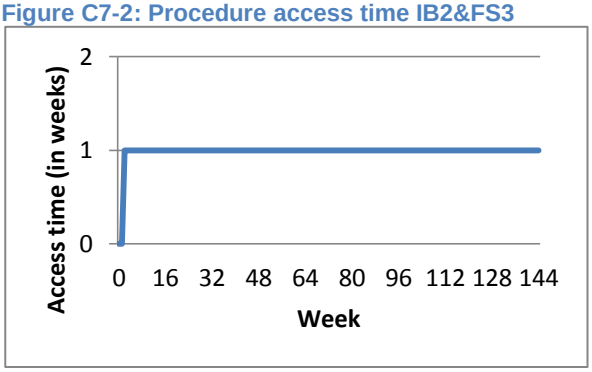


Figure C7-3: NP capacity utilization IB2&FS3

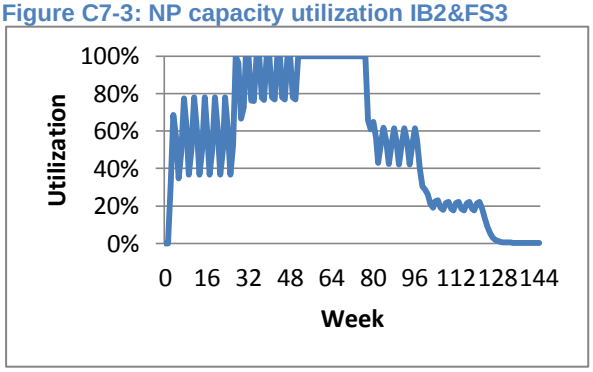


Figure C7-4: P capacity utilization IB2&FS3

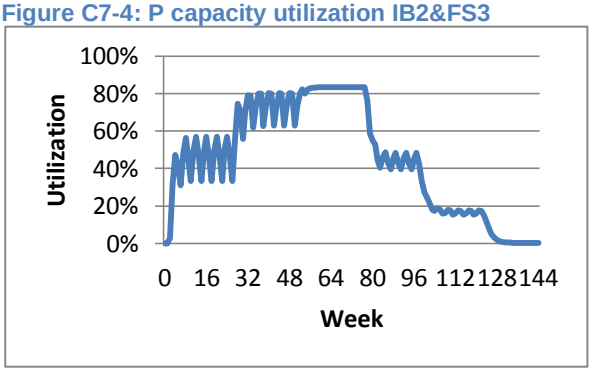


Figure C7-5: Intake access time IB2&FS4

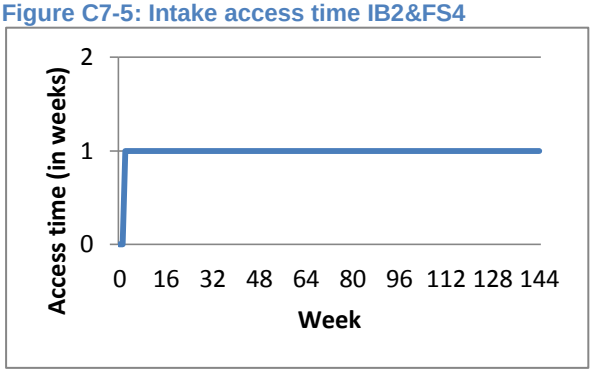


Figure C7-6: Procedure access time IB2&FS4

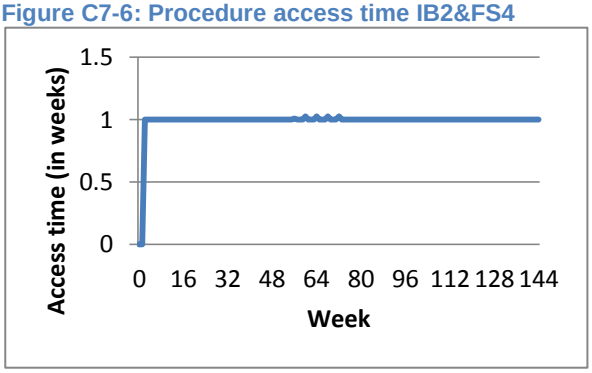


Figure C7-7: NP capacity utilization IB2&FS4

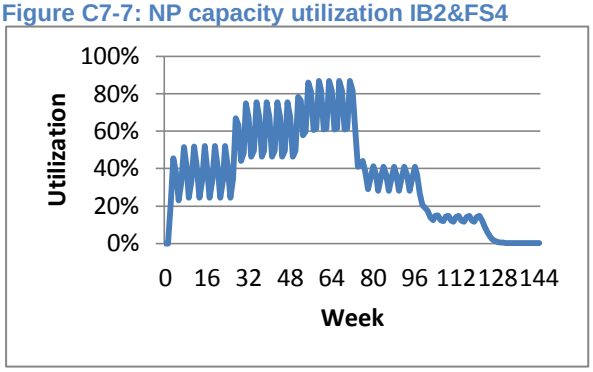
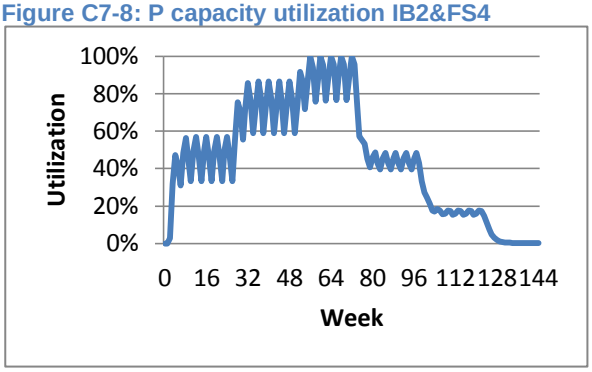


Figure C7-8: P capacity utilization IB2&FS4



Intake access time:
Constant one week

Procedure access time:
Constant one week

Figure C7-9: NP capacity utilization IB2&FS5

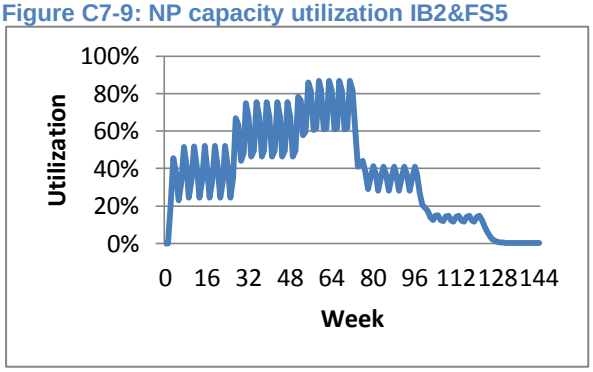


Figure C7-10: P capacity utilization IB2&FS5

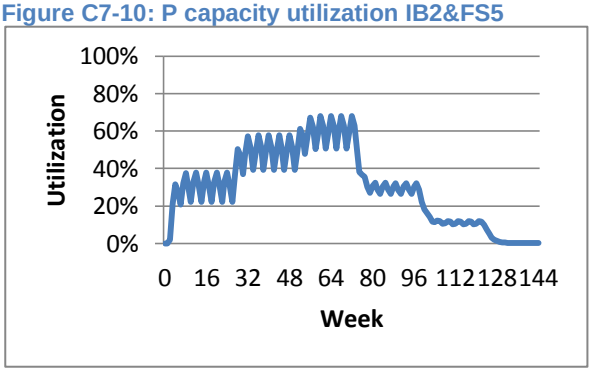


Figure C7-11: Intake access time IB3&FS3

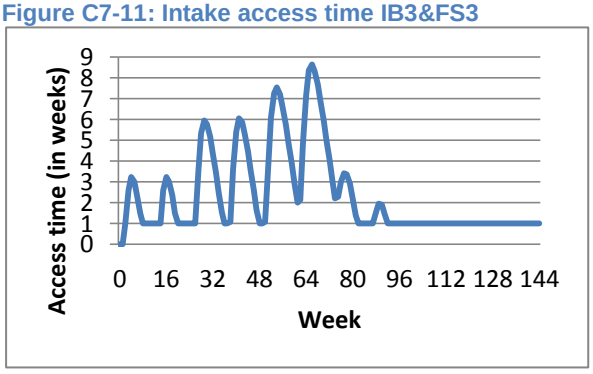


Figure C7-12: Procedure access time IB3&FS3

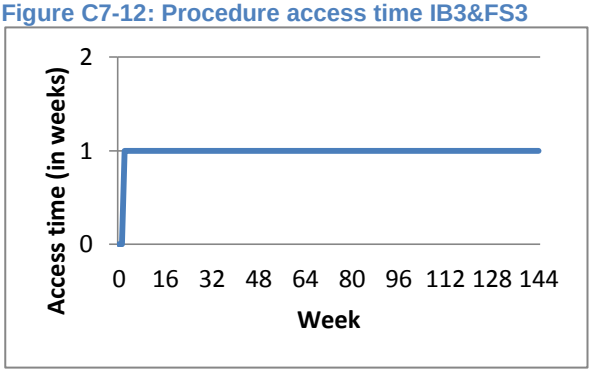


Figure C7- 13: NP capacity utilization IB3&FS3

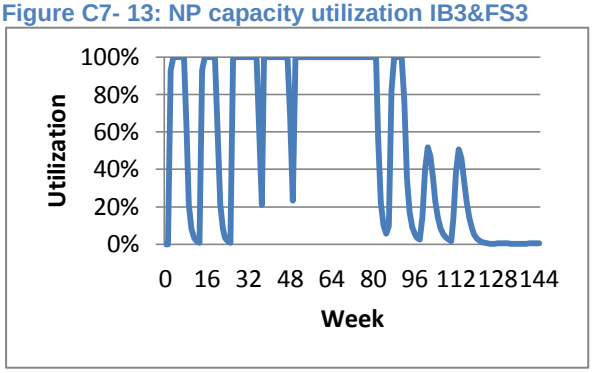


Figure C7- 14: P capacity utilization IB3&FS3

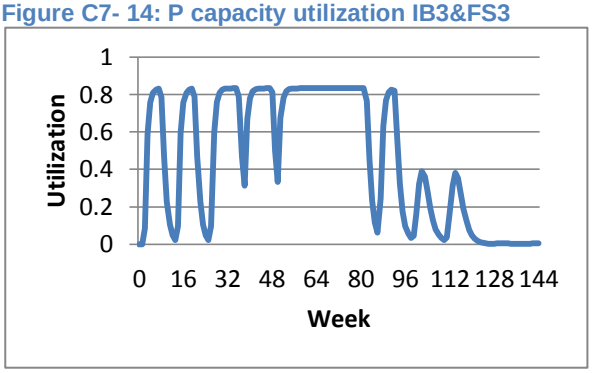


Figure C7-15: Intake access time IB3&FS4

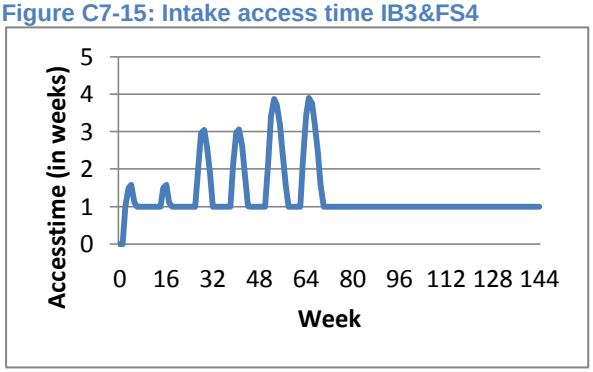


Figure C7-16: Procedure access time IB3&FS4

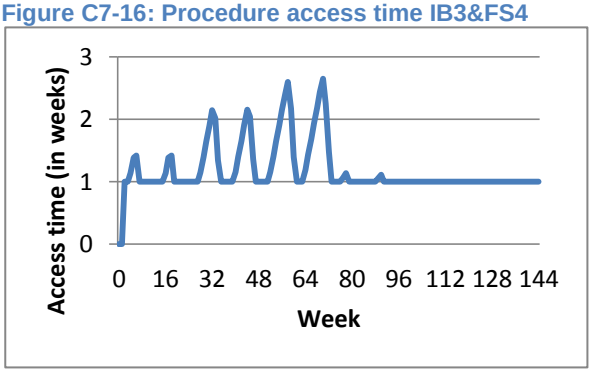


Figure C7-17: NP capacity utilization IB3&FS4

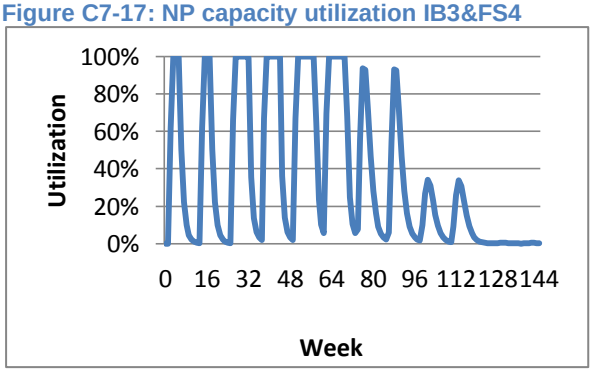


Figure C7-18: P capacity utilization IB3&FS4

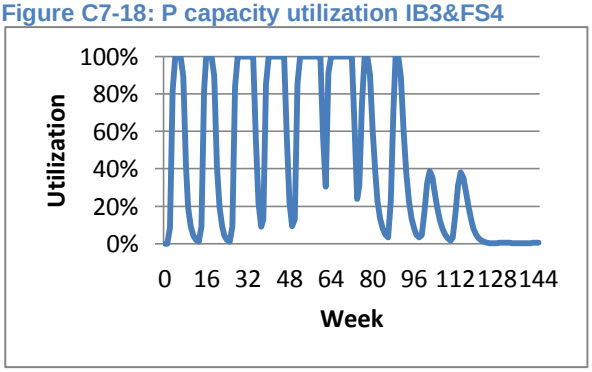


Figure C7-19: Intake access time IB3&FS5

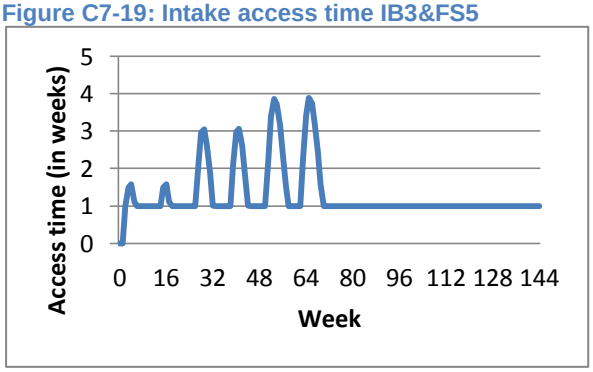


Figure C7-20: Procedure access time IB3&FS5

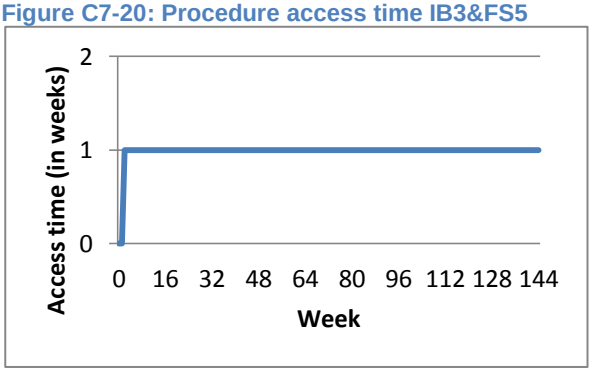


Figure C7-21: NP capacity utilization IB3&FS5

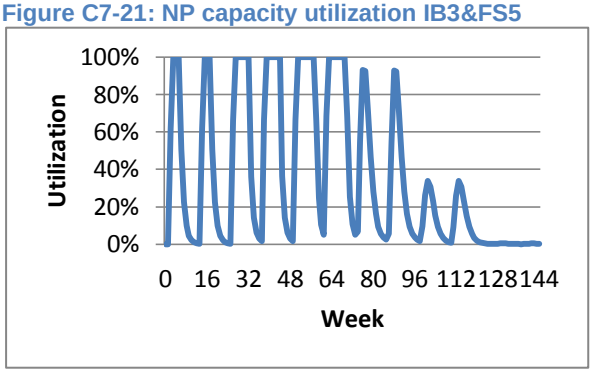


Figure C7-22: P capacity utilization IB3&FS5

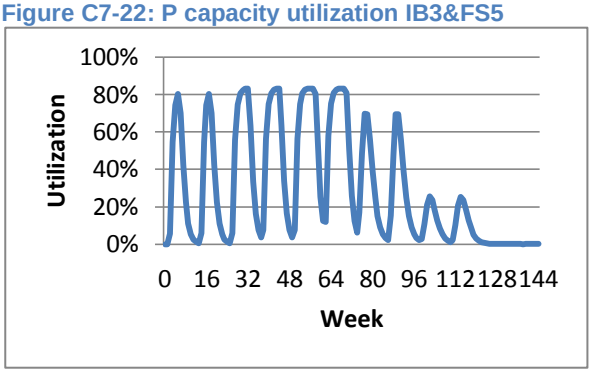


Figure C7-23: Intake access time IB3&FS6

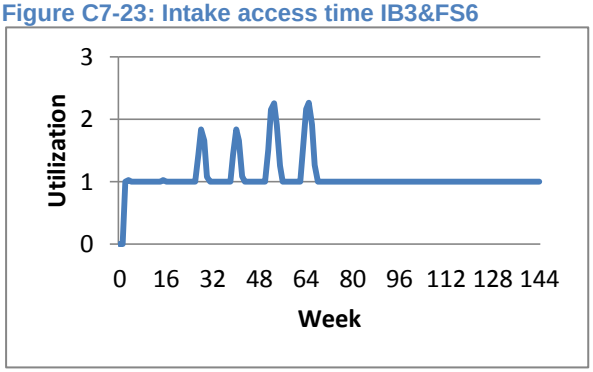


Figure C7-24: Procedure access time IB3&FS6

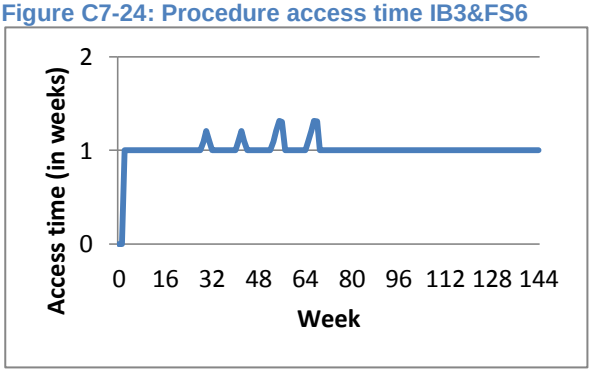


Figure C7-25: NP capacity utilization IB3&FS6

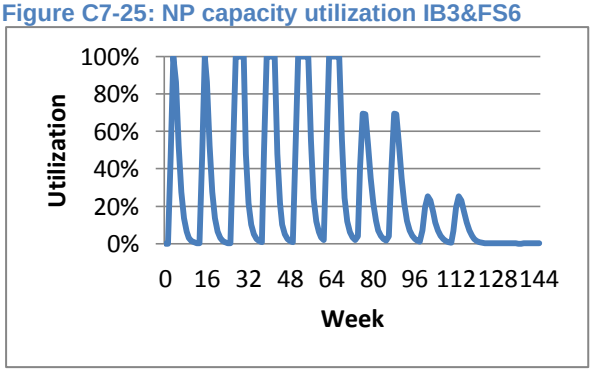
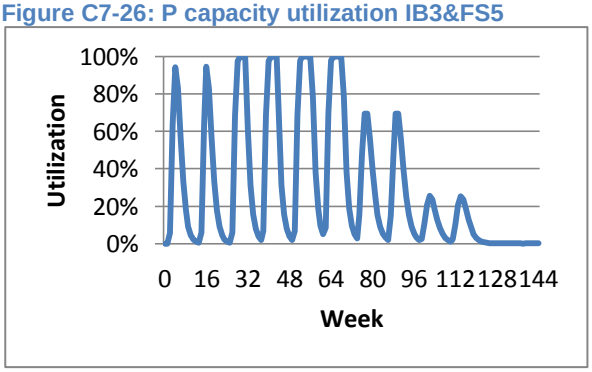


Figure C7-26: P capacity utilization IB3&FS5



Appendix C8: Invitation batches and feedback regulation

Figure C8-1: Normal procedure access time IB2

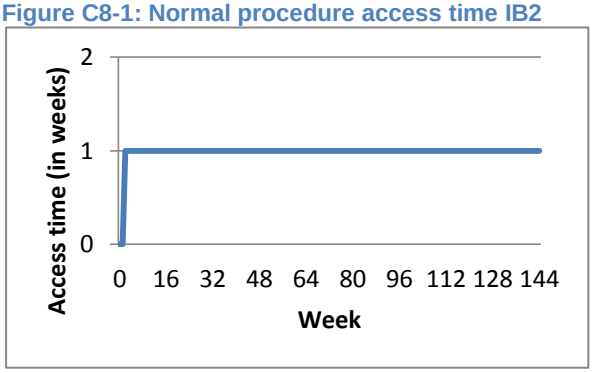


Figure C8-2: Regulated access time IB2

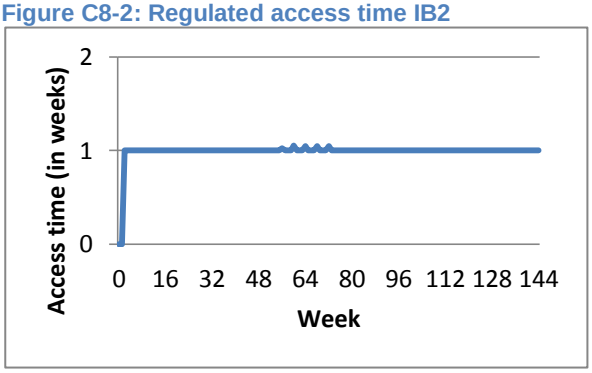


Figure C8-3: NP capacity progress IB2 with capacity feedback regulation

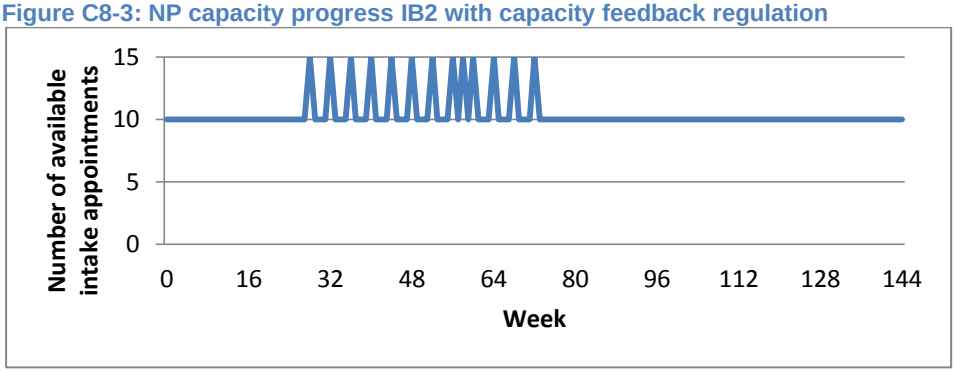


Figure C8-4: P capacity progress IB2 with capacity feedback regulation

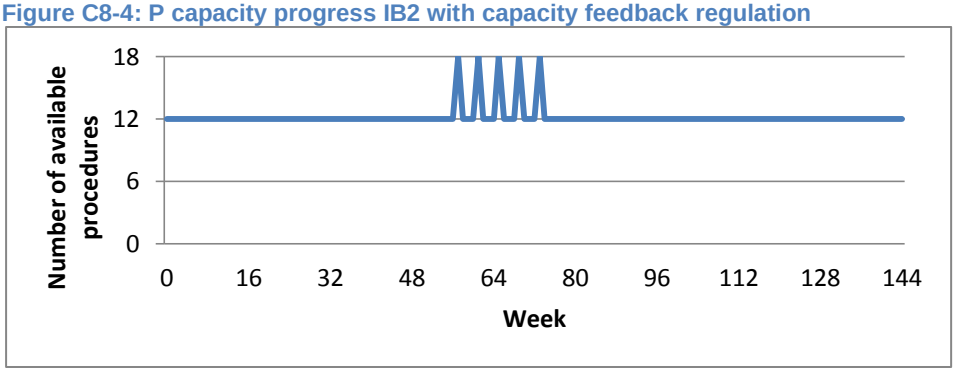


Figure C8-5: Normal intake access time IB3

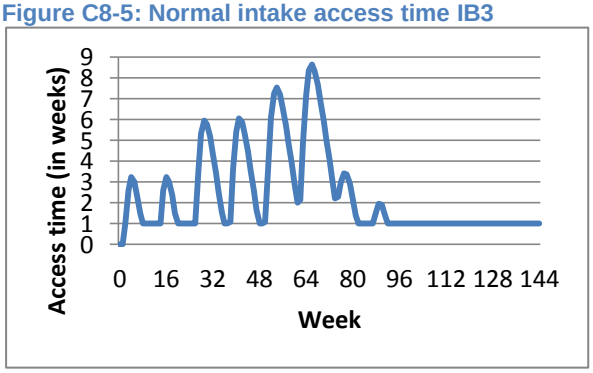


Figure C8-6: Regulated access time IB3

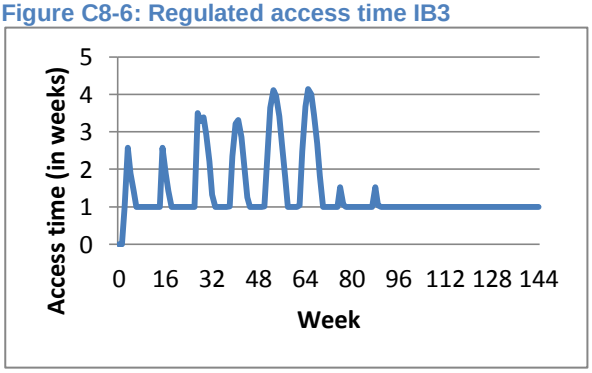


Figure C8- 7: Normal procedure access time IB3

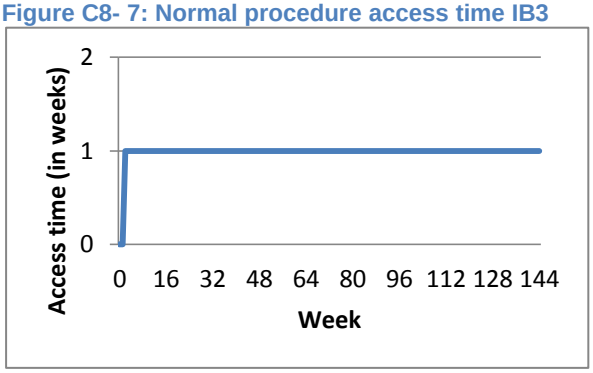


Figure C8- 8: Regulated access time IB3

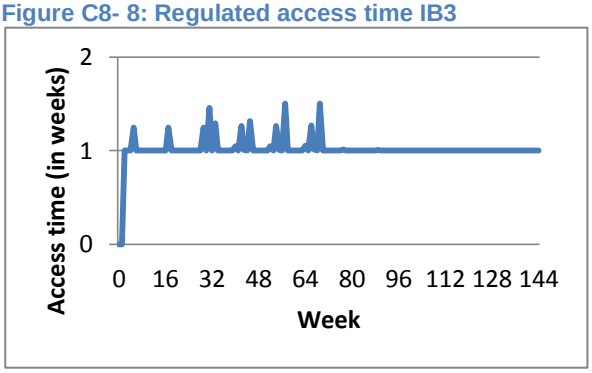


Figure C8- 9: NP capacity progress IB3 with capacity feedback regulation

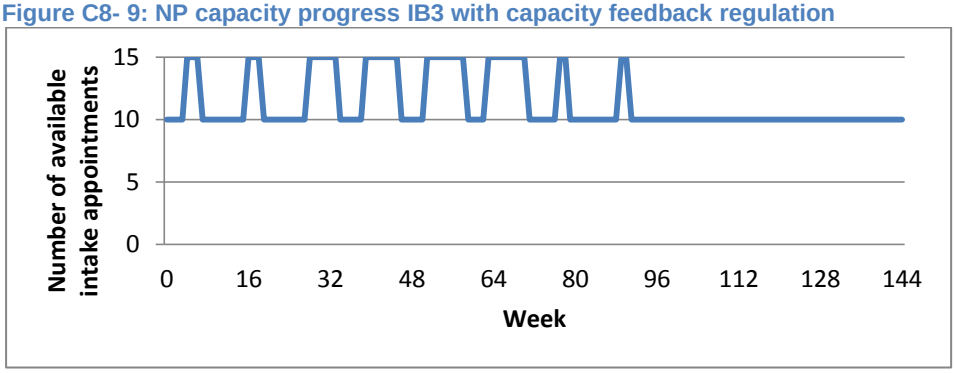


Figure C8- 10: P capacity progress IB3 with capacity feedback regulation