“Optimization of the processing of mammographies within the breast cancer screening program in Flanders”

Word count: 23.044

Sharon Lemagie
Student number: 01300487

Promotor/ Supervisor: Prof. dr. Broos Maenhout
Commissioner: Prof. dr. Koen Van Herck

Master’s Dissertation submitted to obtain the degree of:
Master of Science in Business Engineering

Academic year: 2017 – 2018
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CONFIDENTIALLY AGREEMENT

I declare that the content of this Master’s Dissertation can be consulted and/or reproduced if the sources are mentioned.

Name student: Sharon Lemagie

Signature:
The breast cancer screening program (BCSP) in Flanders is continuously seeking to improve efficiency and patient satisfaction. For this reason, this master’s thesis analyses on the one hand, the organization of the appointments and on the other hand, the processing of mammographies at the Centre for Prevention and Early Detection of Cancer in Ghent. Both aspects of the BCSP are defined in detail as an appointment system, respectively machine scheduling problem. The appointment system of the BCSP is compared to available literature in order to find similar appointment systems or identify opportunities for further research. The main finding is that a lot of studies incorporate (high) no-show rates and to a lesser extent patient heterogeneity and heterogeneity in no-show rates, but no studies were found that consider an appointment system that perfectly integrates services within population screenings and other services provided by the health care facility. Further, the processing of mammographies is modeled as a stochastic linear programming problem. Solving this model will optimize the allocation of radiologists to shifts and ensuring a timely notification of the final diagnosis toward the patient and thus improving patient satisfaction.
ACKNOWLEDGMENTS

This master’s thesis forms the final chapter of 5 years of studying Business Engineering at Ghent University. Writing this master’s thesis has been an intensive period full of learning in the Operations Research field, but also on personal level it has been a remarkable journey. I would like to take this opportunity to thank everyone who supported and helped me through the establishment of this dissertation.

First and foremost, I would like to thank my supervisor Prof. dr. Broos Maenhout for his appropriate guidance and critical view during research and writing. I would also like to thank my commissioner Prof. dr. Koen Van Herck for introducing me into the organization of the breast cancer screening program in Flanders. Furthermore, special thanks go to Svetlana Jidkova, for answering all my questions and giving me valuable insights into the working of the breast cancer screening program. Finally, I would like to thank my friends and family for their kind and uplifting words and supporting me throughout the whole Business Engineering Program.

Sharon Lemanigie,
Ghent, August 2018
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS</td>
<td>Appointment system</td>
</tr>
<tr>
<td>BCSP</td>
<td>Breast Cancer Screening Program</td>
</tr>
</tbody>
</table>
| CvKO         | Centrum voor Kankeropsporing  
               Centre for Prevention and Early Detection of Cancer |
| IT           | Idle time |
| MU           | Mammographic Unit |
| OR           | Operations research |
| OT           | Over time |
| MOO          | Multi-objective optimization |
| WT           | Waiting time |
1. INTRODUCTION

Breast cancer is the most common malignant disease within the female population in Belgium. The Belgian foundation against cancer reports yearly approximately 10 500 diagnoses of breast cancer and every year, it is the cause of death for 2300 women. Furthermore, approximately 1 out of 9 Belgian women will be diagnosed with breast cancer before the age of 75. Not only in Belgium, but also in most other industrialized countries, breast cancer evolved into a serious problem for public health (Renard, Van Eycken, & Arbyn, 2011).

Breast cancer screening programs (BCSP) around the world try to reduce the high burden of breast cancer. The Flemish government organizes a BSCP for women within the age category of 50 to 69 years old in order to detect breast cancer in an early stage, reduce intensive treatments and ultimately, reduce mortality. Just like any other health care organization, the BCSP in Flanders is continuously seeking to find the right balance between efficiency and patient satisfaction. This master’s thesis aims at providing a preliminary analysis of the appointment system (AS) or the way of organizing the appointments at the mammographic units (MU) where the screenings take place. Designing this AS is complicated by two main factors. First, the BCSP in Flanders deals with a rather high no-show rate of 48,1%, which means that almost 50% of the women (or, within this master’s thesis, sometimes called patients) who are invited to participate in the BCSP do not show up at their appointment. This implies that the AS of the BCSP need to be designed such that the detrimental impact of no-show on the efficiency at the MU is mitigated. Secondly, apart from breast cancer screenings, the MU provides several other radiological services to its patients. This implies that the AS of the BCSP needs to be perfectly integrated with the appointments of other radiological services to guarantee efficient working at the MU. This master’s thesis provides a detailed characterization of the organization of appointments within the BCSP in order to have a better insight in the current way of organizing the appointments and to be able to compare it with AS available in literature and eventually, to identify some gaps in literature.

The mammographies that are created during screening at the MU need to be further diagnosed at the Centre for Prevention and Early Detection of Cancer (CvKO - Centrum voor Kankeropsporing) in Ghent. Due to the high no-show rate at the MU, the number of incoming mammographies becomes uncertain and complicates the scheduling of radiologists that need to diagnose these mammographies. To tackle this problem, a stochastic programming model will be constructed that optimizes the allocation of
radiologists to time slots throughout the day while ensuring a timely notification of the final diagnosis towards the patient.

Operations research (OR) forms the foundation of every analysis conducted in this master’s thesis. In other words, this master’s thesis can be considered as a practical application of OR in health care. Although OR receives more and more attention in health care literature (Brailsford & Vissers, 2011), Brandeau (2016) stated that in general, there is a shortage of studies that consider practical implications of OR in the health care industry and thus scholars should be stimulated to focus more on practical issues.

The remainder of this master’s thesis is structured as follows. First, a short introduction about the BCSP in Flanders and Europe is provided. After this introduction, the problem and objective will be explained more in detail whereafter the main concepts related to the design of the AS will be explained and applied on the case of the BCSP. Furthermore, the processing of the mammographies at the CvKO will be defined as a machine scheduling problem. In section 5, a closer look will be given to available literature. Focus will lie on 4 main topics: OR and capacity management in health care, BCSP in general, patient non-attendance and finally, the characteristics of the AS of the BCSP will be compared with the appointment systems studied in recent literature. Several suggestions for further research will be pointed out.

Section 6 of this master’s thesis provides an analysis of the arrival pattern of mammographies at the CvKO. Furthermore, the processing of mammographies at the CvKO will be modelled as a stochastic linear programming problem. This model assigns radiologists to time slots and mammographies to radiologists while making the trade-off between efficiency in capacity allocation and acceleration of the diagnostic process of a mammography.
2. THE BREAST CANCER SCREENING PROGRAM IN FLANDERS: ILLUSTRATION

2.1 Introduction

Since June 2001, the Flemish government organizes and finances a breast cancer population screening program in order to detect breast cancer at an early stage. The BCSP in Flanders offers women the opportunity of conducting a breast screening every two years, free of charge. The organization of BCSP in Flanders is centered at five CvKO’s (Centrum voor Kanker Opsporing) which are located in Antwerp, Ghent, Brussels, Leuven and Bruges. This master’s thesis will focus its analysis on the CvKO in Ghent, but ideally, the results of this case study can be carried over to the 4 other CvKO’s in Flanders. The CvKO of Ghent collaborates with more than 50 mammographic units (MUs) spread over East Flanders. These are radiology centers to which women are invited to conduct a mammography. The tables and figures displayed in this chapter do not solely relate to the CvKO in Ghent, but are the cumulated numbers or averages of the 5 CvKO’s in Flanders, unless otherwise stated.

Women from 50 up to and 69 who live in Flanders and who have a normal risk of breast cancer will be invited to participate in the BCSP. Women who conducted a screening outside the BCSP, will not be invited within the 22 months following the screening outside the BCSP. The invited population receives an invitation letter in which they are encouraged to visit a specific radiology center close to their place of residence. The total number of invited women in 2015 and 2016 in Flanders can be found in Table 1.

<table>
<thead>
<tr>
<th>Age Category</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 – 54 Year</td>
<td>128 766</td>
<td>131 715</td>
</tr>
<tr>
<td>55 – 59 Year</td>
<td>104 228</td>
<td>96 052</td>
</tr>
<tr>
<td>60 – 64 Year</td>
<td>89 729</td>
<td>103 237</td>
</tr>
<tr>
<td>65 – 69 Year</td>
<td>87 477</td>
<td>85 079</td>
</tr>
<tr>
<td>Outside the age category</td>
<td>16</td>
<td>86</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>410 200</strong></td>
<td><strong>416 169</strong></td>
</tr>
</tbody>
</table>

*Table 1: Invited population in Flanders per age category in 2015 and 2016 (Bevolkingsonderzoek, 2017)*
In Table 2 the total number of screenings conducted within the BCSP during the years 2015 and 2016 can be found. The CvKO in Ghent processes more than 56 000 mammographies every year, which comes down to more than one fourth of the total number of screenings conducted in Flanders.

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of screenings</td>
<td>211 658</td>
<td>211 472</td>
</tr>
</tbody>
</table>

*Table 2: Number of women who conducted a screening within the BCSP in 2015 and 2016 (Bevolkingsonderzoek, 2017)*

Through participating in the BCSP, complications and more intensive treatment can be limited and thus, the chance of full recovery increases. The past decades, mortality due to breast cancer has declined in most high-income countries, although the role of mammographic screening in this reduced mortality is hard to quantify (Philippe Autier & Boniol, 2018). Van Hal et al. (2013) argue that the BCSP can substantially reduce breast cancer mortality, provided that the total coverage is adequate. The coverage rate of the BCSP during a specific year can be defined as the number of women who participated in the BCSP during that year together with women who are part of the target population but are not invited because they meet one of the excluding criteria, divided by the total target population. The total coverage in Flanders amounts to 65.3%. This means that 34.7% of women who are eligible for the population screening don’t have a mammography performed.

When only considering the invited population, a rather low attendance rate of 51.9% can be noticed. In other words, 48.1% of the invitees don’t show-up on their appointment, or the overall no-show rate is 48.1%. This high no-show rate has a detrimental impact on the performance of the BCSP, it affects the appointment system heavily and complicates the processing of the mammographies. The no-show rates of the invited population in 2015 and 2016 can be found in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 – 54 Year</td>
<td>55.0%</td>
<td>50.6%</td>
</tr>
<tr>
<td>55 – 59 Year</td>
<td>50.6%</td>
<td>47.1%</td>
</tr>
<tr>
<td>60 – 64 Year</td>
<td>48.2%</td>
<td>45.6%</td>
</tr>
<tr>
<td>65 – 69 Year</td>
<td>50.3%</td>
<td>48.4%</td>
</tr>
<tr>
<td>Average</td>
<td>51.4%</td>
<td>48.1%</td>
</tr>
</tbody>
</table>

*Table 3: Average no-show rates of the invited population per age category in 2015 and 2016 in Flanders (Bevolkingsonderzoek, 2017)*
2.2 Organization of appointments

In Appendix 1 an example of an invitation letter can be found. The patient can find the time, date and MU of the appointment on the invitation letter. Changing the appointment time and date is possible through contacting the CvKO by telephone. If she wishes not to participate in BCSP, she can cancel her appointment through phone or through the website of the screening program. In that way, time slots become available for other participants. It is not obligatory to notify the CvKO in case the patient does not wish to participate. No fee is charged when not showing up at the appointment.

Before the beginning of the year, the CvKO in Ghent divides the population that will receive an invitation letter among the different MUs across the East of Flanders based on the women’s place of residence or based on their preference. After the assignment of women to a MU, each MU lists the weekly preserved time slots available for the BCSP, in such a way that the soon invited population assigned to the MU is spread evenly over the year. When the CvKO receives the time slots the MU sets available, a patient class is assigned to each time slot and a computer algorithm assigns specific women to the slots afterwards. Women are associated with patient classes based on their previous attendance history. To visualize this business process, a BPMN is constructed and displayed in Figure 1. When analyzing the appointment scheduling system of the BCSP, it needs to be taken into account that the main activity of the MUs remains radiologic services outside the screening program. This implies that the appointments at the MU are a combination of appointments within the BCSP and appointments of other radiologic services. It is the task of the MU to ensure that both types of appointments match when passing through the available slots to the CvKO. In Appendix 2 an example of the weekly appointment schedule can be found. The schedule only contains appointments within the BCSP. As can be seen on the figure, not every appointment has the same length. The appointment length at 9AM is 30 minutes, while the appointment length of most other appointments is 15 minutes. This does not mean that in reality the appointment takes twice as long, it may indicate an integration with the other appointments at the MU. Determining the appointment length is again the responsibility of the MU when passing through available slots to the CvKO. Furthermore, it is important to mention that only one patient is assigned to an appointment slot, independent of the appointment length.
2.3 Organization of mammography process flow and diagnosis setting

A screening at the MU can be conducted by a radiologist, a nurse or a laboratory technician. After the screening, the mammography is diagnosed for the first time by a radiologist at the MU. This is called the first reading or first diagnosis and is ideally conducted on the day of screening itself. Every MU is free to plan or schedule the diagnostic sessions (= time span where mammographies are continuously diagnosed), although the diagnostic sessions tend to happen during radiologist idle time or between two appointments. It is estimated that it takes 10sec-3min to diagnose a mammography and to enter it immediately in the database Heracles. The Heracles database contains all the information about invitations together with the screening results and the results of further examinations and treatments.

The first readings and administrative information about the patient are transferred to the responsible CvKO digitally or by post, the latter is hardly used anymore. When first readings are transferred digitally, this happens on the day of first reading at 11PM. In at least 90% of the cases, the mammography should arrive at the CvKO within 7 calendar days, or in other words, the MU has 7 calendar days to process the mammography. The figure in in Appendix 3 points out that in 2016 this target was achieved, although the arrival time had a significant increase compared to the previous years. This is due to the update of Heracles to Heracles 2. It is known that the arrival time evolved positively in 2017 and 2018.

After arrival at the CvKO in Ghent, the breast images are loaded from the FTP server as XML files and the images and information are linked to the patient’s file. After this, a second reading can take place. Radiologists at the CvKO log in into Heracles and they find the complete folder of mammographies that need to be diagnosed. After the second diagnosis is set and the diagnosis is entered in Heracles, the
system automatically compares the first and second diagnosis. When they differ, there is a third diagnosis necessary which is also performed by a radiologist at the CvKO. The system assures that the third reader and the second reader are not the same radiologist. Research pointed out that in case the second diagnosis does not match with the first reading, the third reader tends to set the same diagnosis as the second reader (Bevolkingsonderzoek, 2017).

The diagnostic sessions at the CvKO happen at predefined time slots and during one diagnostic session the reader performs both second and third readings, but the mammographies are separated in different folders. The reader may pay extra attention when assessing the third readings such that the time needed to make a third and final diagnosis may be slightly higher. The diagnosis set by the first and second reader is invisible for the third reader. The total number of third readings performed during the years 2014, 2015 and 2016 in Flanders can be found in Table 4. It can be concluded that the number of third readings remains relatively stable over the years and only 3.4% of screening mammographies need a third reading.

<table>
<thead>
<tr>
<th></th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of screenings within BCSP</td>
<td>197 269</td>
<td>211 658</td>
<td>211 472</td>
</tr>
<tr>
<td>Total number of third readings</td>
<td>6 750</td>
<td>6 948</td>
<td>7 248</td>
</tr>
<tr>
<td>Percentage of third readings on total number of screened women</td>
<td>3.4%</td>
<td>3.3%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

*Table 4: Total number and percentage of third readings (Bevolkingsonderzoek, 2017)*

The total processing time at the CvKO should in 90% of the cases be less than 14 calendar days. From the figure in Appendix 4 can be concluded that this norm is already achieved in 2013, but in 2016 the processing time further improved significantly to 10 calendar days in 90% of the cases, largely thanks to the update to Heracles 2. The last step of the process flow at the CvKO is sending the final diagnosis to the patient and her GP or gynecologist. This happens automatically from Heracles at the end of the day at 11PM. Here there is a distinction made between a deviating diagnosis (when signs of breast cancer are detected) and a desirable diagnosis. In the latter, the results are sent to patient and doctor at the same moment. When the results are deviating, only the patient’s doctor receives an email at 11PM. In The patient receives the diagnosis three days later such that the doctor has time to inform the patient
personally. Following the European norm, 90% of the women who participated need to receive the results of the screening within 21 calendar days. From the figure in Appendix 5 can be seen that the BCSP largely reaches this target. Moreover, in 2016, 90% of diagnoses were already communicated to the patient within 14 calendar days. Nevertheless, the BCSP in Flanders meets the target, efforts should still be taken to reduce this time span in order to accelerate further examinations and reduce the period where the woman can worry about the result. In Figure 2 a Business Process Model and Notation diagram (BPMN diagram) can be found that schematically displays the process flow of a mammography and the workflow of the BCSP in Flanders.
Figure 2: BPMN model of the organization of the BCSP and mammography workflow
2.4 Cancer detection

In Table 5 the percentage of women who are confronted with a deviating result are displayed. A distinction is made between first screenings, when the patient participates to the BCSP for the first time, and subsequent screenings, when the patients already participated in one or more screening rounds. The percentage of first screenings that have a deviating diagnosis relative to the total number of women who have performed a first screening is 4.7% in 2016. As can be seen in Table 5, the number of deviating diagnoses on the total number of subsequent screenings is 2.1% during that same year.

<table>
<thead>
<tr>
<th></th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First screenings</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of screenings</td>
<td>33 918</td>
<td>34 846</td>
<td>35 668</td>
</tr>
<tr>
<td>Number of deviating diagnoses</td>
<td>1 545</td>
<td>1 560</td>
<td>1 677</td>
</tr>
<tr>
<td>Percentage of deviating diagnoses</td>
<td>4.6%</td>
<td>4.5%</td>
<td>4.7%</td>
</tr>
<tr>
<td><strong>Subsequent screenings</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of screenings</td>
<td>163 351</td>
<td>176 812</td>
<td>175 804</td>
</tr>
<tr>
<td>Number of deviating diagnoses</td>
<td>3 448</td>
<td>3 386</td>
<td>3 686</td>
</tr>
<tr>
<td>Percentage of deviating diagnoses</td>
<td>2.1%</td>
<td>1.9%</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

*Table 5: Percentage of women who have been referred to further assessment in 2014, 2015 and 2016 (Bevolkingsonderzoek, 2017)*

4.7%, respectively 2.1%, of the women who conducted a first screening, respectively subsequent screening, are confronted with a deviating diagnosis and are advised to conduct further examinations. If cancer is detected within 24 months after a deviating diagnosis, independent from whether the patient had performed further examinations, the cancer is defined as a cancer detected by screening. The number of cancers detected by screening can be found in Table 6. The numbers are approximations, the final numbers are not known yet. The degree of breast cancer detection is the number of cancers detected by screening divided by the total number of screenings.
The incidence of interval cancers in 2014 is also included in Table 6. Again, the numbers are approximations and no numbers could be derived for 2015 and 2016. An interval cancer is defined as a cancer detected after a desirable diagnosis, or a deviating diagnosis where further examinations excluded the existence of the cancer. The interval cancer needs to be detected before the next screening round or within 24 months if the patient exceeds the maximum age and will thus no longer be invited to participate in the BCSP. The global probability of the occurrence during the years 2010-2014 was 0,03%.

<table>
<thead>
<tr>
<th>Cancer detected by screening</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cancers detected by screening</td>
<td>1 116</td>
<td>1 182</td>
<td>906</td>
</tr>
<tr>
<td>The degree of breast cancer detection (n/1000)</td>
<td>5,7</td>
<td>5,6</td>
<td>5,7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interval cancer</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of interval cancers after a desirable diagnosis</td>
<td>526</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>The degree of interval cancer after desirable diagnosis (n/1000)</td>
<td>2,7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of interval cancers after a deviating diagnosis and following examinations that excluded cancer</td>
<td>60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>The degree of interval cancer after deviating diagnosis and following examinations that excluded cancer (n/1000)</td>
<td>0,3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 6: Breast cancer detection (Cancer detected by screening and interval cancer) (Bevolkingsonderzoek, 2017)*
2.5 BCSP in Europe

Cancer is not only a major public health problem in Belgium, also in Europe the high burden of cancer is recognized. In 2012, the 28 member states of the European union were confronted with five million people who found dead, of which more than a quarter cancer was the main cause of death. Breast cancer is by far the most frequently occurring and the deadliest cancer within the female population. On the 2nd of December 2003, the European Health Ministers adopted a set of recommendations, the Council Recommendation on Cancer Screening, in which the fundamental principles of best practices are defined and by which a shared commitment to implement cancer screening programs was presented by the member states. In 2017, 25 out of 28 member states were organizing or rolling out population-based screening programs. Sweden was the pioneer in initiating a screening program in 1986 (International Agency for Research on Cancer, 2017).

The European Union sets a target age range for women who should be invited to participate in the BCSP of 50 to 69 years. In 2013, 67,5 million European women fell into this age class and thus can be considered as the theoretical target population. Of these 67,5 million women, 95% live in the 25 member states who conduct breast cancer population screenings. During the same year, almost 24 million invitation letters were sent to this target population, while only an average attendance rate of the invitees of 60,2% was registered. This is far below the acceptable level of 70% that was set as standard. Denmark reported the highest attendance rate (83,5%) while Wallonia, with an attendance rate of 6,2%, reported the lowest rate (International Agency for Research on Cancer, 2017). When looking at the attendance rate in Flanders, even in 2016, the attendance rate is situated almost 20% under the European acceptable level. Also in terms of the coverage rate, Flanders stays with its 65,3% under the European target coverage rate (75%) (Bevolkingsonderzoek, 2017).
3. PROBLEM FORMULATION

Within the BCSP, a mammography goes through the following main stages:

This master’s thesis focuses on the one hand on the screening stage at the MU and on the other hand on the second and third reading stage at the CvKO.

Screening at the MU is characterized by a rather high no-show rate of 48.1%. This has a detrimental impact on the efficiency at the MU as it causes radiologist idle time. The appointments of the BCSP need to be organized in such a way that this negative effect of no-shows is mitigated. Furthermore, the AS of the BCSP need to be perfectly aligned with the appointments of other radiological services at the facility. These and several other characteristics make the AS of the BCSP a unique setting in terms of appointment scheduling and question arises if similar AS are studied in literature. This leads to the first research question: To what degree can the AS of the BCSP in Flanders be compared to AS studied in appointment scheduling literature? In other words, are there studies available that consider AS with similar characteristics as the AS of the BCSP or is there an opportunity for further research?

Secondly, the second and third reading stage the CvKO is subject of analysis. The scheduling of radiologists at the CvKO that diagnose mammographies is complicated by the uncertain daily number of mammographies arriving at the CvKO. 3 factors lie on the basis of this uncertain daily number of incoming mammographies: the high no-show rate during screening, the uncertain processing time of the mammographies at the MUs and the possibility of an incomplete patient file arriving at the CvKO (e.g. the breast image may be missing). The daily number of third readings that need to be performed at the CvKO is stochastic as well (a mammography has on average a 3.4% chance of needing a third reading, Table 4) which further complicates the allocation of human resource. Question arises how the 8 radiologists that work with the CvKO can be scheduled such that the time needed to diagnose the mammographies can be significantly shortened while ensuring an efficient allocation of human resources? This leads to the second research question: How can the processing of mammographies at the CvKO be presented as a stochastic
linear programming model that optimizes the allocation of radiologists and improves timely notification towards the patient? Reducing the time needed to process the mammographies, naturally reduces the time a patient needs to wait for her diagnosis. When the patient had a predominantly positive experience during the previous screening round, she may be more inclined to participate again during the next screening round. Although the BCSP attaches a lot of importance to patient satisfaction, it cannot happen at the expense of efficiency at the CvKO. In other words, a trade-off needs to be made between patient satisfaction and efficient scheduling of radiologists.
4. CONCEPTS AND APPLICATION ON THE BCSP CASE

In section 4, some concepts related to appointment scheduling and machine scheduling will be explained and applied on the BCSP case. First, different decision levels that characterize the design of an AS will be described, together with different environmental factors that may affect the performance of an AS. Each decision level and several environmental factors will be applied on the AS of the BCSP in Flanders in order to have a better understanding of the determinants of the AS and to be able to compare it with the AS described in literature. The AS at the MU consists out of both appointments organized for the BCSP and appointment for other radiological services. Focus will lie on the appointments organized for the BCSP by the CvKO in Ghent. Appointment systems set-up by other CvKOs in Flanders may have slightly different characteristics, but the basics remain the same. For every determinant, the policy maker will be mentioned, whether it is the MU, the CvKO or both. An overview of the most important characteristics of the AS of the BCSP are summarized in Table 7.

In the second part of this section, the processing of mammographies will be defined as a machine scheduling problem. Distinction will be made between the overall process from screening to third reading and a smaller scope of this process, the processing of mammographies at the CvKO. Focus will lie on the latter as this is subject of optimization within this master’s thesis.

4.1 Appointment scheduling

An appointment system in health care can be defined as the system for scheduling appointments between medical staff and patients (Cayirli & Veral, 2003) or as a queueing system with scheduled arrivals ((Hassin & Mendel, 2008). An efficient AS leads to better resource utilization and limited waiting times, which in turn affects patient satisfaction (Cayirli & Veral, 2003). Following Ahmadi-Javid et al. (2017), designing outpatient (i.e. patients that visit a clinic for diagnosis or treatment, but do not stay overnight) appointment systems consists out of decision making on a strategical, tactical and operational level. Strategic decisions are known to run over a long time and to design the main structure of the appointment system. In most models studied in literature, decisions on the strategic level are not subject of optimization but can be considered as input data. Tactical decisions, on the other hand, are medium-term decisions and determine how groups of patients or patients as a whole are scheduled. They define the AS characteristics so that resources are used efficiently and access to medical care is guaranteed. Operational decisions are known to be decisions on the individual patient level that deal with the execution of the schedule. Besides these strategic, tactical and operational decisions, an appointment system needs to
consider external environmental factors like no-shows and walk-ins and find ways to mitigate the negative effects of these factors (Ahmadi-Javid et al., 2017). For a complete literature review of appointment scheduling decisions, see Ahmadi-Javid et al. (2017).

4.1.1 Strategic level

In what follows the access policy, the type of scheduling, the number of servers and the policy on acceptance of walk-in patients will shortly be described.

Access policy

In literature, 3 main access policies can be distinguished (Ahmadi-Javid et al., 2017). The first one is the traditional policy where all women are scheduled in advance of the appointment day. All capacity is reserved for pre-scheduled women, while in the case of the second access policy, the open access policy, the schedule is filled with same-day appointments, this means that patients make a call for an appointment for the same day. When scheduling according to an open access policy, the no-show rates tend to be lower. The third policy is the hybrid access, which is a mix of the traditional and the open access policy. The traditional access policy has as advantage that the physician’s workday can be fully booked in advance, however, this policy often deals with a high probability that patients do not show up at their appointments. The open access reduces or even eliminates no-shows, but introduces significantly more variability into the daily workload (Ahmadi-Javid et al., 2017; Robinson & Chen, 2010).

Type of scheduling

Ahmadi-Javid et al. (2017) define 2 major types of scheduling: online scheduling and offline scheduling. In offline scheduling, the set of women that needs to be invited and their characteristics are known in advance. Online scheduling is the opposite approach where the appointments are scheduled immediately after the request has arrived. In practice, more online scheduling systems are implemented, while offline scheduling is relatively more studied in literature (Ahmadi-Javid et al., 2017).

Number of servers or resources

The servers and resources that are the most frequently considered in AS literature are clinic staff, medical equipment and beds. The number of servers or resources implemented to meet demand is known to be a determinant for the profit of the clinic (Ahmadi-Javid et al., 2017).

Walk-in patients
Walk-in patients are patients who arrive at the clinic without an appointment. Two categories within walk-in patients can be distinguished: urgent and regular walk-in patients.

4.1.2 Tactical level

Tactical decisions that will be described in this section are panel size, capacity allocation to different patient categories, scheduling window, the appointment interval, the number of appointments per consultation session and block size.

Panel size
The panel size is defined as the number of patients the clinic provides care for, or in other words, the total number of potential patients of the clinic or physician. The calling population is a fraction of the panel size that actually go to the clinic during a period. In many cases, the clinic cannot control the panel size such that the panel size cannot be subject of optimization (Ahmadi-Javid et al., 2017).

Capacity allocation to patient categories
When designing the appointment system, capacity can be allocated to different patient groups in advance. How much capacity will be reserved for patients visiting the doctor for the first time, how much capacity for returning patients? In case of a hybrid access policy, how many slots are available for prescheduled appointments and how many slots are available for same-day appointments?

Scheduling window
The scheduling window, appointment delay or scheduling horizon denotes the time span between the day of reservation and the appointment day itself or how far into the future appointments can be booked (Liu, 2016). The no-show rate is highly affected by the scheduling window. Appointments with a higher scheduling window tend to have a higher no-show rate.

Appointment interval
The appointment interval or slot is defined as the time span between two successive appointments and can be set constant or variable (Cayirli & Veral, 2003). The appointment interval has a major impact on the efficiency of the appointment system. However, most appointment scheduling literature sets the appointment interval equal to the mean service time. Proportionally adjusting the appointment interval is a well-known tool for mitigating the negative effects of no-shows. Vissers (1979) found that this approach may perform slightly better than overbooking (see block size) thanks to its sustained impact
through the clinic. In general, for homogeneous patients several patterns exist for adjusting the appointment interval. A dome-shaped structure is characterized by increasing appointment intervals towards the middle of the clinic session, while during the second half of the session, appointment interval gradually decreases. A plateau-dome pattern is a dome-shaped structure where the appointments in the middle of the session have the same length. Finally, an increasing structure is a structure where later in the session, the appointment interval is higher than at the beginning. This is especially beneficial when the physician is frequently interrupted (Ahmadi-Javid et al., 2017).

**Number of appointments per consultation session**

A clinic or consultation session is defined by Cao & Tang (2014) as a time span during which the facility is continuously operating, and after which the operation is temporarily on hold, (e.g. lunch break or end of the day) until the next clinic session is launched. External factors impact the optimal number of patients seen. For example, the provider may schedule more patients than the actual available capacity in order to compensate for no-shows. This is called overbooking. Liu, Ziya, & Kulkarni (2010) argue that overbooking is especially interesting when the patient load or the number of patients is low. However, several authors stress that overbooking needs to be implemented carefully as it can lead to considerably more patient waiting time and provider over time (Samorani & LaGanga, 2015; Zeng, Turkcan, Lin, & Lawley, 2010).

**Block size**

A consultation session is divided in several blocks. A block consists of patients that are given the same appointment time and block size is the number of patients in the block or in other words, the number of patients that are scheduled at the beginning of an appointment slot. Ahmadi-Javid et al. (2017) distinguish four main rules described in literature in terms of block size. The simplest is the single-block system where only one patient is assigned per block. Bailey (1952) was the first to introduce a single-block system with two patients assigned to the initial block. This the second rule and later recognized as the Bailey’s rule. Further there are the multiple block rule where a fixed number of patients are assigned to a slot and variable block rule where the number of patients assigned to a block varies within the consultation session.

4.1.3 Operational level
The appointment specifics or the appointment day and time form the most important decisions at the operational level. When different patient classes can be distinguished, the patient sequence can also be determined.

**Appointment day and time**
Clinics working with a traditional or hybrid access policy need to assign patients to a day that is conform the appointment window. Also, patient priority levels can be considered when assigning patients to working days. Together with the day, the appointment time needs to be determined, this is the specific time that a patient is scheduled to start receiving care (Ahmadi-Javid et al., 2017).

**Patient sequence**
Some studies attempt to determine the optimal order in which patients are scheduled. These studies often combine the patient sequencing problem with determining the appointment day and time. Ahmadi-Javid et al. (2017) argue that in most studies the patient sequence is given or is determined by using simple heuristic rules. Zacharias & Pinedo (2014) come up with a sequencing rule based on the weights and no-show probabilities of patients.

### 4.1.4 External environmental factors

**Patient and physician unpunctuality**
Patient and physician unpunctuality are a measure for the earliness or lateness of a physician or patient at the appointment or the difference between the appointment time and the actual arrival time at the appointment. Incorporating patient or physician unpunctuality into the model complicates the model severely (Ahmadi-Javid et al., 2017).

**Patient non-attendance**
Non-attendance or no-show refers to the situation where a patient fails to attend the appointment. No-shows deteriorate the efficiency of an outpatient clinic considerably and the AS needs to be designed in such a way that the negative effects of no-shows can be mitigated (Ahmadi-Javid et al., 2017).

**Cancellation**
Within cancellation, a distinction can be made between last-minute cancellation and cancellation far enough in advance. When patients cancel their appointment far enough in advance, the appointment slot can become free again and available for booking new patient requests. Most studies in literature however
only consider last-minute cancellation as operationally it comes down to a no-show (Ahmadi-Javid et al., 2017).

**Service time**

Service time or consultation time is defined by Bailey (1952) as the time span devoted to one patient wherein a medical examination or a treatment can be conducted and wherein an advice can be formulated. During this time span, no other patients can be seen. Service times can either be stochastic or deterministic (Gupta & Denton, 2008). Most appointment scheduling studies consider independent and identical distributed (i.i.d) service times for all scheduled patients. Ahmadi-Javid et al., (2017) point to a relatively new research trend where service times are independently and distinctly distributed (i.d.d), service time distributions are dependent on patient characteristics or service type. Another widely implemented assumption is the independency between the service times and arrival pattern of the patients. According to Cayirli & Veral (2003), the latter may be questionable as physicians tend to shorten the service times during peak moments in order to limit patient waiting times.

To measure the variability of service times, a frequently used measure is the coefficient of variation or the standard deviation of the service times divided by the mean service time (Cayirli & Veral, 2003).

\[ CV = \frac{\sigma}{\mu} \]

Several stochastic distributions are eligible for describing uncertain service times and a wide variety is implemented in literature (see Table 8 and Cayirli & Veral (2003)). Cayirli & Veral (2003) conclude that the unimodal, right skewed distributions have the closest fit with doctor’s service time.

**Patient heterogeneity**

Most studies assume that patients are homogeneous for scheduling purposes. When different patient classes can be composed based on distinct patient characteristics, the question arises whether the AS could benefit from incorporating these different patient classes when designing appointment systems. A common way of improving appointment schedules is by grouping patients according to similar characteristics and then providing the different groups with different appointment intervals (Cayirli & Veral, 2003). Some of the classification methods which have been considered in the literature include inpatient vs. outpatient (Sickinger & Kolisch, 2009), new vs. return patients, service time variability, type of medical procedure (Cayirli & Veral, 2003) and different no-show rates(...). Studies with different patient classes differ from the studies that consider homogeneous patients such that in the latter case only the time interval between 2 arrivals throughout the consultation session needs to be determined, or in other words, an appointment time needs to be assigned to each patient. When scheduling heterogeneous patients also the sequencing of different patient classes is of interest (Zacharias & Pinedo, 2014). Cayirli,
Veral, & Rosen (2006) found that the choice of the sequencing rule for sequencing different patient classes has a higher impact on the performance of the AS than the choice of the appointment rule.

4.1.5 Performance measures

When measuring the performance of an AS, the (often conflicting) objectives of 3 main stakeholders need to be incorporated: system owners, staff and patients (Ahmadi-Javid et al., 2017). Most studies focus on the mean patient’s waiting time, mean system’s overtime or mean doctor’s idle time when measuring the system’s performance. Frequently, different weights are assigned to these measures so that minimizing the weighted sum of these costs becomes the objective (Cayirli & Veral, 2003). Sometimes also the number of patients seen is included to measure the productivity of the doctor. For a complete overview of most common performance measures in literature, see Cayirli et al. (2003).

Bar-dayan (2002) and McCarthy, McGee, & O’Boyle (2000) prove that waiting time in the medical facility is a major factor affecting patient satisfaction. The psychological cost of waiting is defined by Osuna (1985) as the accumulated stress and anxiety the patient experiences when waiting for service due to the sense of waste and uncertainty. Empirical studies point out that the waiting cost grows exponentially with the waiting time. Furthermore, increased waiting times combined with reduced time spent with the physician leads to the smallest patient satisfaction (Anderson, Camacho, & Balkrishnan, 2007; Camacho, Anderson, Safrit, & Hoffmann, 2006). Goossens et al. (2014) and Camacho et al. (2006) pointed out that long waiting times can negatively affect the willingness to return.

4.1.6 Application on the BCSP case

4.1.6.1 Strategic level

Within the BCSP, all women are scheduled well in advance of the appointment day, no same-day appointments are scheduled. Also the complete list of women who need to be invited is known before the beginning of the year. The BCSP implements a traditional access policy with offline scheduling, both inherent to the BCSP. The number of servers refers in this case to the number of medical imaging devices. Every MU opens only one medical imaging device for the BCSP. A device registered as server in the BCSP is subject to daily quality control, which turns to be very costly for the MU. This explains why MUs are equipped with a single server for the BCSP. When considering walk-in patients, the distinction can be made between walk-in patients within the population screening and walk-ins outside the population
screening. The former are invited women who show up at the MU at a time other than the time on their invitation letter, the latter are patients, not invited within the BCSP, who show up at the MU without appointment, e.g. emergency patients. Each MU has full responsibility for buffering walk-in patients, i.e. it is supposed that possible walk-ins are already buffered when passing through available time slots to the CvKO.

4.1.6.2 Tactical level

The panel size the MU provides care for during a specific year is the total number of women that are invited to visit that specific MU during that year. Women are assigned to the MU that lies geographically the closest or based on the women’s preferences. For example, if during the previous screening round, the woman changed the location of the appointment to another MU, she will be invited to the latter MU during the next screening round. Spreading the invited population over the MU across Flanders is done at the CvKO. As already mentioned in the case introduction, at the end of the year women that will be invited during the following year are divided into patient classes based on their probability of (not) showing up. In terms of the capacity allocation decision, there is no restriction in the number of patients of a specific patient group that can be assigned to a specific MU. This means that one MU may have a higher percentage of women who have the highest probability of not showing up, compared to another MU. The appointment scheduling window for BCSP appointment is 2-3 weeks as women receive the invitation letter 2-3 weeks before the actual appointment. Not only increasing the appointment scheduling window could have a negative impact on the no-show rate (Liu, 2016), when shortening the window, women may not be free anymore during the appointment which will increase the no-show rate. The appointment scheduling window is the decision of the CvKO.

The appointment interval is a responsibility of the MU. When passing through the available slots for the next year, the appointment interval is implicitly incorporated. In the weekly schedule example in Appendix 2, the appointment interval varies across the day from 15 minutes to 30 minutes. The varying appointment interval is not dependent on the patient class as the appointment interval is determined before the assignment of the patient classes. It has more to do with merging the BCSP appointments and appointments of other radiological services. A longer appointment interval may for example mean that within this interval other appointments are scheduled at the MU, appointments outside the BCSP. The length of a consultation session is different for each MU and not known by the CvKO. The CvKO is not informed about the appointments outside the BCSP, so the total number of appointments during a consultation session is determined by the MU. The total number of appointments within the BCSP per
consultation session is known by the CvKO but set by the MU at the beginning of the year. For every appointment within the BCSP, the block size is one. This is a policy set by the CvKO in Ghent, the block size policy may differ across the other CvKO’s in Flanders. The actual block size at the MU may be more than one as the MU is free to book another appointment outside the BCSP at the same time. In other words, the CvKO does not allow overbooking of BCSP appointments, but the MU itself can overbook it with appointments of other radiological services or by setting the appointment interval between two appointments short enough so that in reality overbooking is indirectly incorporated into the AS.

4.1.6.3 Operational level

At the end of the year, when the CvKO receives the weekly available time slots of the MU, the CvKO starts with assigning a patient class to each time slot, or in other words, the CvKO is sequencing the patient classes. Afterwards a computer algorithm assigns individual woman to a time slot that matches her patient class. All the decisions at operational level are taken by the CvKO, however, the preferences of the MU need to be incorporated.

4.1.6.4 External environmental factors

As patient and physician unpunctuality lead to an enormous complexity when scheduling patients, it is expected that the MU does not incorporate this factor when passing through the available time slots to the CvKO at the beginning of the year. Patient non-attendance forms a serious problem for the BCSP with an average no-show rate of 48,1% in 2016 and measures need to be taken to moderate its negative impact on the efficiency at the MU and the total coverage of the BCSP. On the one hand, the appointment system needs to be designed in such a way that negative effects are mitigated (in this case overbooking is indirectly incorporated in the AS, on the other hand the question arises if measures taken to encourage more women to participate in the BCSP would be more effective in increasing the efficiency of the MU and the effectiveness of the BCSP.

Women are free to change the appointment to another time or another day. Special time slots are incorporated into the AS that remain available for these women. Women can also notify the CvKO if they wish to cancel their appointment such that the appointment can become available for women who wish to change their appointment. Little is known about the service time of a screening. It is estimated that a screening at the MU can take 3 to 15 minutes. The high difference in time is dependent on the mobility
of the patient, the characteristics of the breast and the fact if the patient is still in doubt of participating in the BCSP and needs to be informed again about the (dis-)advantages of participating.

The AS of the CvKO implements patient heterogeneity based on the attendance behavior of the women during the previous screening rounds or the related no-show probability. The CvKO distinguishes 5 patient classes:

- Women who have a regular attendance behavior. These women always attended the previous appointments for which they were invited for and thus, these women have the highest probability of show up at their next appointment.

- Women who are invited to participate for the first time. These are the women who are 50 or will become 50 during that year or women who immigrated to Flanders. Their attendance behavior is hard to predict.

- Women who are characterized by a unregular attendance behavior. They did not attend their appointment during the last screening round two years ago, but they showed up at their appointment at least once during other previous screening rounds.

- Women who have been invited to participate in the BCSP, but who failed to show up every time. These women have the highest no-show probability.

The MU notifies the CvKO about its preferences and suggestions regarding the allocation of patient categories to available slots before the beginning of the year, after which the CvKO allocates the categories to the slots. The average no-show probabilities of each patient category are not known. Regarding changes and cancellations of the appointments, only time slots of women with a regular attendance behavior become available for other women after cancellation or shifting to another appointment time.

4.1.6.5 Performance measures

An ideal AS within the BCSP units the objectives of the three main stakeholders. The patient expects minimal waiting times before the screening, while the radiologists at the MU strive for maximal efficiency or minimization of idle time and over time. The CvKO can be considered as the third stakeholder. They
attach a lot of importance to patient satisfaction while they also strive for a good cooperation with the MU.
<table>
<thead>
<tr>
<th>Access policy</th>
<th>Type of scheduling</th>
<th>Number of servers</th>
<th>Service time distribution</th>
<th>No-show</th>
<th>Patient heterogeneity</th>
<th>Adjusted appointment interval</th>
<th>Overbooking</th>
<th>Patient unpunctuality</th>
<th>Walk-in patients</th>
<th>Cancellation &amp; changing time and day</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCSP Flanders</td>
<td>Traditional</td>
<td>Offline</td>
<td>Single</td>
<td>Unknown</td>
<td>+</td>
<td>+ Based on previous attendance behavior</td>
<td>+ Independent on patient class</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 7: Summary of main characteristics of the AS of the BCSP in Flanders (with +: incorporated in the AS & -: not incorporated in the AS)
4.2 Machine scheduling

Machine scheduling problems in general exist in many areas (e.g. production planning, logistics, communication etc.) and the variations are endless (Šeda, 2007). Scheduling in general is known as optimizing an objective function by allocating scarce resources to tasks or activities (Leung, 2004). Machine scheduling problems often take place in a manufacturing environment and consist out of scheduling jobs on one or more machines while optimizing one or more performance measures. Based on job characteristics, constraints on the process and objectives, different types of machine scheduling problems can be defined (Machine Scheduling, n.d.). Similarly, Conway et al. (2003) classify scheduling problems based on four types of information: (1) The jobs or tasks that need to be processed, (2) the number of machines and the type of machines, (3) constraints inherent to the machine scheduling environment (4) the performance measures that need to be optimized.

The mammography flow at the CvKO (i.e. second and third reading) is a practical example of machine scheduling problem in the health care industry. The machine scheduling problem deals with assigning mammographies to the available capacity. Jobs can take many forms, but in the case of the BCSP the term job refers to a mammography that needs to be diagnosed. Processing the mammographies is done by machines, here again machine is an abstract term for the means by which the mammographies are processed, in this case it refers to manpower or radiologists. Some restrictions in the scheduling of jobs are inherent to BCSP scheduling environment. For example, the second reader and third reader cannot be the same person. For each machine scheduling problem performance measures need to be defined that will be optimized when solving the problem. As the BCSP attaches a lot of importance to the timely notification of the diagnosis towards the patient, thus one objective is minimizing the processing time of a mammography. While ensuring patient satisfaction, increased efficiency at the stages at the CvKO is a second objective.

In what follows the mammography flow from screening to final diagnosis will shortly be described and characterized. Focus of this master’s thesis, however, is a smaller part of this mammography flow, more specifically: the optimization of the processing of the mammographies at the CvKO. General job data will be defined and this process will be profoundly described using the $\alpha/\beta/\gamma$ - notation proposed by Graham et al. (1979).
4.2.1 Complete mammography flow

The complete mammography flow is displayed as a BPMN model in Figure 2. The first two stages of the process (i.e. screening and first reading) take place at the MUs while the last 2 stages (i.e. second reading and third reading) take place at the CvKO. All four stages are composed out of parallel machines/servers. During the first two stages, the term machines represents the different MUs that can perform screenings and first readings simultaneously. Naturally, the first reading of a mammography happens at the MU where the patient conducted the screening. At the CvKO, there is currently room for 2 radiologists to conduct second and third readings simultaneously. During a diagnostic session, the radiologist conducts both second and third readings. A diagnostic session is the time span or shift in which a radiologist is continuously diagnosing mammographies. All the mammographies go through the stages in the same order. However, only mammographies with a discrepancy between the first and second reading are processed in the third reading workstation, the other mammographies skip this stage. In 2016, an average of only 3.4% of all mammographies needed a third reading (Bevolkingsonderzoek, 2017).

As the mammographies go through multiple stages, the machine scheduling problem is called a multi-stage machine scheduling problem. Chen, B., Potts, C. N., & Woeginger, G. J. (1998) define three main multi-stage systems: the flow shop, the open shop and the job shop. In a job shop and in a flow shop, all the jobs have a fixed routing through all the stages, while in an open shop, the routing is part of the decision process. In the case of a flow shop, all jobs follow the same routing, while in a job shop, jobs may have different routings. The machine configuration of the complete mammography flow can be defined in two different ways:

**Hybrid flow shop**

A hybrid flow shop is also known as a flexible flow shop, a compound flow shop, a multi-processor flow shop (Pinedo, 2012). Ruiz & Vázquez-Rodríguez (2010) define the hybrid flow shop as follows:

1. The machine configuration is composed out of at least two stages
2. At least one stage is composed out of at least 2 machines in parallel.
3. All the jobs have the same fixed routing.
4. A job can skip any number of stages, as long as it goes through at least one stage
5. \( p_{jk} \) is the processing time of job j at stage k
These statements match the description of the mammography flow described above. The hybrid flow shop allows that mammographies that do not need a third reading skip the last stage. Mathematically, these mammographies can be modelled by setting their processing time for that last stage equal to zero. The representation of the complete mammography flow as a hybrid flow shop is displayed in Figure 4.

![Diagram of Hybrid Flow Shop](image)

**Figure 4: Representation of the complete mammography flow as a hybrid flow shop**

**Re-entrant flow shop**

As during a diagnostic session a radiologist conducts both second and third readings, the radiologist combines these two stages. That is why it is justified to merge the last two stages into one stage. Mammographies that need a third reading will go through this combined station twice. Jing, Huang, & Tang (2011) define this characteristic of jobs that go through a certain machine (or set of machine) more than once as job re-entrance. Again, not all the mammographies re-enter the flow, only the mammographies that need a third reading. The representation of the complete mammography flow as a re-entrant flow shop is displayed in Figure 5.
4.2.2 Diagnosing mammographies at the CvKO

In this section the machine scheduling problem is narrowed down to the operations at the CvKO: the second and third reading. The problem is described more in detail by first specifying job data and then implementing the classification scheme of Graham et al. (1979).

4.2.2.1 Job data and characteristics

In every machine scheduling environment some data can be associated with the jobs that need to be processed. These data have a major impact solving the machine scheduling problem. The total number of mammographies that needs to be diagnosed every week is denoted by $n$ and the subscript $m$ refers to a specific mammography. The CvKO works together with in total 8 radiologists and a specific radiologist is denoted by the subscript $r$. Following (Parker, 1996) and (Pinedo, 2012) the job data are defined and described for the BCSP in Flanders.

*Processing times ($p_2$ & $p_3$)*

The processing time of a job refers to the time needed to process a job at a specific machine. In the case of the BCSP in Flanders the exact processing times are unknown and depend on several factors. For
example, when the image is of bad quality it may be harder and it may take longer to diagnose the mammography. Furthermore, the radiologists may adjust the processing time according to the number of mammographies that are still waiting to be diagnosed. Up till now, no information is available about the processing times or their distribution. To reduce complexity, it is assumed that processing times are deterministic. Moreover, they are the same for every mammography and independent from which radiologist diagnosed the mammography. However, a distinction is made between second reading and third reading. When a radiologist is conducting a third reading, he or she knows that there was a discrepancy between the first diagnosis and the second diagnosis and may pay extra attention assessing the mammography. In other words, the time needed to diagnose a mammography for the third time \( p_3 \) may be slightly higher than the time needed to diagnose a mammography for the second time \( p_2 \). When talking to a radiologist at the CvKO, he estimated that it takes between 10 seconds to 1.5 minutes to diagnose a mammography. Within this master’s thesis, the processing times will arbitrary be set to:

\[
\begin{align*}
p_2 &= 1 \text{ minute} \\
p_3 &= 1.5 \text{ minute}
\end{align*}
\]

**Release date or arrival date**

The release date of a job is the date the job becomes available for processing or the date at which the jobs arrives at the system. Applied on the BCSP, the arrival date of a mammography at the CvKO is unknown or stochastic. The day at which the mammography is created is equal to the date the patient’s appointment is scheduled at the MU and is known. But several factors make the release date of the mammographies at the second reading station stochastic. The time needed to process the mammography at the MU is uncertain and variable, so it is unknown when the mammography will arrive at the CvKO. Furthermore, there is a chance that the patient file received by the CvKO is incomplete (e.g. the images are missing) and so that the mammographies cannot be diagnosed immediately. In section 6.1 an analysis of the incoming mammographies is conducted.

**Due date**

The due date of a job refers to the date at which a job is committed to be completed. The mammographies at the CvKO do not have a fixed due date. However, the European guidelines state that in 90% of the cases the processing time at the CvKO cannot be longer than 14 calendar days. When looking at the complete mammography flow (from screening to notification of the diagnosis towards the patient) 90% of the women need to be notified about their diagnosis within 21 calendar days after the day of screening. The BCSP in Flanders meet both European targets (Appendix 4 & Appendix 5).
**Weight**
In machine scheduling problems, jobs tend to have a weight or a priority factor assigned to them that denotes the importance of a job relative to the other jobs. Mammographies in the BCSP do not have different weights assigned to them, all the mammographies have the same priority.

**Sequence dependent set-up times**
The time needed to switch over a machine from one job to another, is called the setup time. This setup time may be dependent on the sequence of jobs. During diagnostic sessions at the CvKO, no (sequence dependent) setup times occur between two mammographies. Only at the beginning of a diagnostic session, there is set-up time which includes starting the computer and logging in into Heracles, but this setup time is relatively small and can be neglected.

**4.2.2.2 α/β/γ notation**
Within the $\alpha/\beta/\gamma$ – notation proposed by Graham et al. (1979), the $\alpha$-field stands for the number of machines and the configuration, the $\beta$-field for the assumptions and constraints inherent to the machine scheduling environment and the $\gamma$-field represents the performance measures that need to be optimized.

**$\alpha$ – Field**
The machine configuration of the process of diagnosing the mammographies at the CvKO can be represented in two ways. If the second reading workstation and the third reading workstation are assumed to be two distinct stages, the system behaves like multi-stage machine environment, more specifically: hybrid flow shop with in both stages at most 2 parallel radiologists. The intermediate storage of mammographies between the stages is unlimited. An important feature is that radiologist 1 in the second reading stage is the same person as radiologist 1 in the third reading stage. More concrete, this means that radiologist 1 of the third reading stage and radiologist 1 of the third reading stage cannot diagnose mammographies simultaneously. Mammographies which do not need a third reading, skip the last stage and processing times at the last stage are thus equal to zero for these mammographies.
When the second and third reading stage are combined to one single stage, the machine configuration becomes a single stage environment with at most 2 radiologists diagnosing mammographies in parallel. Mammographies that need a third reading re-enter the stage and pass through that stage twice.

**$\beta$ – Field**
Pinedo (2012) summarizes the most common restrictions in machine scheduling problems. The restrictions that apply on the machine environment at the CvKO are described below.

- **Release date**: The start time of a job is restricted to its release date. This means that no mammography can get a second reading before its arrival date at the CvKO.

- **Recirculation**: In case of a single stage parallel machine environment, the mammographies that need a third reading may re-enter the system and visit the stage two times.

- **Machine eligibility restriction**: For every mammography, the second and third reader cannot be the same radiologist.

- **Processing times**: The time needed to diagnose a mammography during second reading, respectively third reading, is assumed to be the same for all the mammographies.

**γ - Field**

In general, the BCSP in Flanders endeavors to accelerate the notification of the diagnosis towards the patient. This means that the time span between screening and the consignment of the letters with the results towards the patients should be limited. The processing time of the mammographies at the CvKO covers a large part of this time span, so limiting the time that jobs spend at the CvKO is of great importance. Next to timely notification of the diagnosis and thus patient satisfaction, the CvKO strives for efficient capacity allocation or in other words an optimal assignment of radiologists to shifts across the week. Like in most real life scheduling environments, not one but two objectives need to be optimized and the problem becomes a multi-objective optimization problem (MOO). (Marler & Arora, 2004) define MOO as the process of systematically and simultaneously optimizing a set of objective functions. Typically, these objectives are inconsistent with each other and often it is impossible to find a solution that simultaneously optimizes all the objectives. (Marler & Arora, 2004) provide an extensive overview of methods to solve MOO problems. These methods are classified in three main groups based on the preference functions of the problem:

- A priori articulation of preferences: The preferences can be specified or the relative importance of the different objectives can be quantified.
• A posteriori articulation of preferences: An explicit expression of the preferences is hard for problems that implement these methods. The user benefits from developing a set of optimal solutions (Pareto optimal set) and finally choosing one of these solutions as final decision. The Pareto optimal set is composed out of solutions that lie at the boundaries of the feasible space. For each Pareto optimal solution, no other solution exists that improves any objective without deteriorating the other objectives.

• No articulation of preferences: The user is not able to concretely specify his preferences.

An example of a method that incorporates an a priori articulation of preferences is goal programming (Marler & Arora, 2004). Goals are specified for each objective function and the sum of the deviations from each goal is minimized. The preemptive or lexicographic goal programming approach is a subclass of goal programming methods. The deviations are prioritized for each objective and are minimized one at a time, in descending order of priorities or the objective with the highest priority first. The preemptive goal programming method will become clearer when applied on the machine scheduling case of the CvKO in section 6.2.3.

Question arises if in the BCSP case, it is possible to specify goals for each individual objective and to set priorities to each objective. That is why setting up a set of optimal solutions and comparing the solutions would lead to a more thoughtful and effective decision. More specifically, the decision maker can consider both strengths and weaknesses of each solution and integrate this information when taking the final decision. The mathematical model serves more as decision support tool and less as a tool that provides a concrete answer (Erol & Ferrell, 2003). A common way of providing the Pareto optimal set is implementing weighted methods. These methods incorporate parameters, for example coefficients, that represent the user’s preferences and that will be continuously variated to construct the Pareto optimal solution set. The weighted sum approach is the most common approach among the weighted methods. One composite objective function is constructed that is composed out of the weighted sum of the objectives, the MOO problem is thus converted in a single objective optimization problem. Although this method is relatively easy to implement, constructing the relative preference vector may remain a highly subjective issue. The representation of the weighted objective function can also be found in section 6.2.3.
This literature study focuses on four main topics. First the role of operations research in the health care sector will be shortly described, followed by a short analysis on BCSP literature that focuses on the one hand on the screening guidelines and more specifically on the starting age and on the other hand, the benefit-harm balance of BCSP in general. Further, as the BCSP in Flanders deals with a rather high no-show rate, literature on no-show in both general outpatient appointment systems and BCSPs are considered. The last section will focus on outpatient appointment scheduling. This is a widely described subject in literature for several reasons. First of all, efficiency in outpatient health care systems became increasingly important the last decades mainly due to the continuous growth in expenditures in the health care sector, the increase in demand for health services and patients who became more and more demanding in terms of quality of the provided service (Ahmadi-Javid et al., 2017). Moreover, outpatient departments form an important cost driver for medical institutions and when the facility fails in making outpatient departments cost-effective, they often find themselves in financially unfavorable situations. As the AS of the BCSP is a unique setting, question arises if similar AS are considered in literature or if there are opportunities for further research. A distinction will be made between optimization studies and simulation studies. The former are characterized by finding a solution to an objective (usually a minimization or maximization) while solutions need to meet a set of restrictions. These studies tend to focus on a rather basic appointment system with limited incorporation of environmental factors and make use of queuing theory, mathematical programming or dynamic programming. Simulation studies in contrast, implement more detailed AS in a complex environment (Muthuraman & Lawley, 2008). This literature review focuses mainly on optimization studies as within this studies the characteristics of the AS are elaborated more precisely compared to simulation studies and the comparison with the AS of the BCSP becomes more accurate.

5.1 Operations research & capacity management in health care

Operations research receives more and more attention in health care literature. Brailsford & Vissers (2011) report several reasons. First, more and more people are involved in the health care industry either as employees or they stand at the receiving end as patients. Demographic trends such as the ageing population and the expansion of new technologies lead to increased health care expenditures, also reported by Ahmadi-Javid, Jalali, & Klassen (2017). The past decennia, patients became more demanding and services are now increasingly organized from patient’s perspective. Health care optimization is more and more about finding the right balance between provider’s efficiency and patient satisfaction. Lubicz
(2017) investigated what were the most discussed topics in OR health care studies. Bai, Fügener, Schoenfelder, & Brunner (2018) also present a literature review of OR studies, focusing on the emergency unit within the health care system. Brandeau, Sainfort, & Pierskalla (2004) synthesize the applications of OR in the health care industry in an extensive handbook. One of the first chapters covers capacity planning and management in hospitals (Green, 2005). The main goal of capacity management is limiting patient waiting times and avoiding idle capacity while meeting demand in time and as efficient as possible (Adenso-Díaz, González-Torre, & García, 2002). Green (2005) distinguishes four major measures of hospital capacity. The most fundamental measure is the number of inpatient beds, followed by personnel planning (particularly nurses), operating rooms and diagnostic equipment.

This master’s thesis will focus on the capacity management at the CvKO in Ghent, as will be elaborated on in section 6. More specifically, it constructs a linear programing model to optimize the second component of capacity management, i.e. personnel planning, or in this case, radiologist planning. Oddoye, Jones, Tamiz, & Schmidt (2009) analyze a similar problem in the medical assessment unit of a hospital in the UK where optimal staffing requirements need to be determined and the system’s bottlenecks need to be minimized such that patient flow is optimized. The authors combine simulation with goal programming, more specifically, data obtained through simulation can serve as input data for the goal programming model. Implementing a simulation model allows to capture and model the patient flow while goal programming allows to meet different targets over a set of conflicting objectives. Kwak & Lee (1997) only make use of goal programming for modelling and solving a human resource allocation problem in health care facilities. This study aims at assigning personnel to shifts while minimizing the salaries and ensuring patient satisfaction.

5.2 Breast cancer screening programs

In general, controversy concerning screening guidelines can be noticed in research that focuses on breast cancer population screenings. One of the most discussed topics is lowering the starting age of the screening program. Screening efficacy of the screening age 50 up to 69 is proven and is also recommended by the European Union. In section 5.2.1, the most recent studies that investigate the efficacy of lowering the starting age are listed. Next to lowering the starting age, the benefit-harm balance of cancer population is receiving increased attention in literature. Further in Section 5.2.2 the major benefits and potential harms are listed and applied on the BCSP in Flanders.
5.2.1 Starting age

The BCSP in Flanders and most BCSPs in Europe invite women starting from age 50, as screening starting at that age is assumed to be effective. However, several studies argue that the starting age of 50 should be lowered. Koleva-Kolarova et al. (2018) evaluate potential benefits, harms and cost-effectiveness of lowering this starting age as between the age of 45 and 50. The authors conclude that introducing two extra screening rounds is justified as there is additional reduction in mortality from breast cancer, it is cost-effective and the harms are relatively small. Destounis & Santacroce (2018) and Ray, Price, & Joe (2017) also argue that screening beginning at the age of 40 has a significant impact on mortality reduction and that annually screening is more effective because younger women deal with more rapid cancer growth rates. Van den Ende, Oordt-Speets, Vroling, & van Agt (2017) however, argue that the age range should not be extended to woman younger than 50 as they state that the effectiveness of screening younger women has not been proven up till now. When looking at the situation in population screenings across Europe 9 member states adopt a wider age rage than the recommended age range (Austria, Czech Republic, France, Greece, Hungary, Italy, Netherlands, Portugal and Sweden). Estonia on the other hand, narrowed down the age range to 50-64 years.

Further implications of extending the age range for the organization of the BCSP remain unclear. When widening the age range, more invitations are sent and more appointments need to be scheduled. Question arises if MU have enough available capacity and what is the cost of the capacity expansion. Like most other BCSPs in Europe, the BCSP in Flanders is financed by the Flemish government. No studies were found that investigated what is the financial impact of widening the age range.

5.2.2 The benefit-harm balance

The benefit-harm balance of BCSPs is becoming more and more subject of research. Marmot et al. (2013) investigate this benefit-harm balance in the UK. The major benefit is early diagnosis of breast cancer so that early intervention can take place, more aggressive and toxic treatments can be averted and ultimately mortality is reduced (Marmot et al., 2013; Ray et al., 2017). One of the first studies that investigated the mortality reduction after mass screening is Tabár et al., (1985). The authors based their study on Swedish women aged 40-74 and found a 31% reduction in mortality. More recently, van Luijt, Heijndsijk, & de Koning (2017) analyzed the Norwegian female population between 55 and 80 years old and found a mortality reduction of 16% and predicted a maximal reduction of 30% in 2022. Similarly, Sankatsing et al. (2017) tracked down the mortality reduction of Dutch women 20 years after the
introduction of the BCSP in the Netherlands. A 30% reduction was found for women within the age category from 55 to 74 years. Tan, van Oortmarssen, de Koning, Boer, & Habbema (2006) analyze the impact on mortality of breast cancer screening and adjuvant treatment (i.e. treatment that is conducted after initial treatments mainly to suppress the formation of secondary tumors) in the US between 1975 and 2000. To quantify the impact, the authors make use of the MISCAN-Fadia model. They found a 15% reduction of mortality thanks to screening and a 21% reduction thanks to adjuvant treatment in the year 2000. In contrast to these authors who estimated significant reductions in mortality, Autier, Boniol, Gavin, & Vatten (2011) compared BCSPs of neighboring European countries (including Flanders) with different levels of screening and compared it with the decrease in mortality. The authors argue that the mortality reduction cannot be completely ascribed to BCSPs as between the countries, the differences between the timing of the implementation of the BCSP were significant while a similar reduction in mortality was not noticed. The authors suggest that the reduction can be rather explained by increased efficiency in health care systems and more effective treatments.

Estimations of the impact of the BCSP on the mortality of the female population in Flanders are not yet available. However, from the annual report of the cancer screening programs in Flanders (2017) can be concluded that currently they are taking initiative to quantify the impact. At that moment, the CvKO was negotiating with both MISCAN (Tan et al., 2006) and SIMRISC (Greuter et al., 2010) model to determine which model will be followed.

The past decade, next to the potential benefits and especially the reduction in mortality, more and more authors analyze and stress the negative side-effect of BCSPs. The most recognized side-effect is overdiagnosis, i.e. the detection of cancers diagnosed by screening, which would not be clinically apparent in the patient’s life without screening (Marmot et al., 2013). In case of overdiagnosis, patients undergo unnecessary treatments like surgery, radiation and chemotherapy resulting in a decrease of life quality (van den Ende et al., 2017). According to Carter & Barratt (2017), overdiagnosis arises largely from the fact that screening mammographies are more likely to detect slowly growing cancers which are generally less harmful than the rapidly growing, more aggressive cancers. The more overdiagnosis occurs within the population screening, the less likely the BCSPs are able to reach the ultimate goal of reducing illness and premature death (Carter & Barratt, 2017). Marmot et al. (2013) estimated that overdiagnosis amounted to 11% as a percentage of breast cancer incidence. However, Nehmat & Nehmat (2017) argue that up till now, the risk and impact of overdiagnosis remains an unresolved issue due to heterogeneity in methodologies. There are different possible methodologies to quantify the magnitude of overdiagnosis and scientific and political elements may affect the interpretation of evidence.
Next to overdiagnosis, researchers mention other negative side effects like pain and radiation exposure during mammography screening, false-negative results and false-positive recalls. (van den Ende et al., 2017). False negative results mean that an interval cancer is diagnosed within 24 months after the last screening. A common misunderstanding is the difference between overdiagnosis and false-positive recall where in the latter, the patient is incorrectly told that they risk having cancer, which leads to unnecessary testing. Overdiagnosis however is a cancer that is correctly diagnosed, but without the screening, the cancer would never be detected as it had no impact on the patient’s wellbeing and perceived health (Nehmat & Nehmat, 2017; Carter & Barratt, 2017).

As already mentioned, the BCSP deals with a further assessment rate of 4.7% for first screenings and a 2.1% for subsequent screenings. The CvKO can lower the number of false-positive diagnoses by lowering the further assessment rates. However, in that case, the probability of interval cancer would increase. Thus, the trade-off between those two side-effects needs to be made. In terms of overdiagnosis, no concrete estimations have been made yet for the BCSP in Flanders. A negative side effect not mentioned in literature is that some mammographies need to be retaken when the quality of the original mammography is not sufficient to set a correct diagnosis. In that case the patient is recalled to the MU for a second screening which leads to increased uncertainty and stress for the patient and ultimately a decrease in patient satisfaction. The number of recalls because of bad mammography quality for the BCSP in Flanders are displayed in Appendix 6. The numbers apply on the years 2015 and 2016. It can be concluded that the number of recalls is relatively low but should ideally go to zero.

In general, the benefits of a breast cancer population screening outweigh the potential harms. However, efforts need to be made to reduce the potential harms and participants need to be informed about them. Ray et al. (2017) argue that too often the potential harms are overemphasized relative to the life-saving benefits. They state that for most women, the benefit of early detection outweighs the potential harms and are therefore willing to take the risk of overdiagnosis.

5.3 Patient non-attendance

Marmot et al. (2013) stated that the greater the participation rate in the BCSP, the greater the benefits for public health. Therefore, policy makers should attach importance to encouraging women to accept the invitation in order to enhance participation. Currently the BCSP in Flanders deals with a 48.1% no-show rate and does not meet the European coverage target rate of 75%. No-shows are widely described
in appointment scheduling literature, mainly because of their detrimental effect on the performance of the appointment system. More specifically, no-shows lead to a reduction in the clinic’s revenue and productivity and limit the patient access as effective capacity is reduced (LaGanga & Lawrence, 2012). Berg et al. (2013) estimated the cost of no-shows and the effect of no-show mitigating strategies in an endoscopy suite. They found that non-attendance leads to 16.4% net loss per day and that mitigation strategies may reduce the loss due to no-show behavior to 3.8%-10.5%.

Norris et al. (2014) present 4 main predictors of patient attendance in outpatient clinics. The main predictor was call-appointment interval (or lead time), followed by prior attendance history, financial payer (mostly insurance provider) and the age of the patient. The longer the lead time, the more likely the patient is going to miss the appointment and moreover, the less likely other factors matter. Kaplan-Lewis & Percac-Lima (2013) investigated reasons for no-shows in a predominantly non-English, low-income population in the US. They reported forgetting and miscommunication as main causes of no-shows. Lacy (2004) investigates no-show behavior from the perspective of patients. Main reasons included are anxiety or fear, a feeling of being disrespected and not fully understanding the appointment system.

It is important that GPs and gynecologists support the BCSP as they can play a crucial role in motivating women to participate in a cancer population screening program and so rising the participation rate (Wouters, Vleminckx, & Van Hal, 2006). Schoofs, Krijger, Vandevoorde, & Devroey (2017) found a strong association between having diabetes and participate in the BCSP. As diabetic patients visit their GP regularly, physicians can play a crucial role in motivating these women to participate. Van Hal et al. (2013) found that a personal invitation letter was a strong communication channel to motivate women to participate and that women found the mobile screening unit very accessible. Participation in BCSPs can be related to several factors, one of them is socioeconomic status (Schoofs et al., 2017). (P. Autier et al., 2011) Dierckx et al. (2006) investigated the relationship between participation in the BCSP and the socioeconomic status of the neighborhood the invited women live in. The authors found a significant lower participation rate of women living in underprivileged areas, while areas with a high percentage of women older than 65 and couples with children tend towards a higher participation rate. Van Hal et al. (2013) argue that it is a matter of equity to incorporate deprived populations for cancer prevention and propose a tailored strategy to stimulate these woman to the BCSP. It is important to have a similar participation in lower and higher socioeconomic classes in order to reduce the inequalities in survival of breast cancer (Puliti et al., 2012). Uy et al. (2017) found that text message interventions can have a positive impact on the screening rates and that also resource-poor populations may benefit from it.
Brett & Austoker (2001) found that when the patient received a false-positive in the previous screening round and thus underwent further examinations, she experiences higher adverse psychological consequences shortly before being re-invited for a routine screening compared to woman who had a negative result. Goossens et al. (2014) also found that by lowering the number of false positives, the participation within the BCSP in Flanders may be enhanced. Also limiting the time span between two invitations to 25 months or less and reducing the waiting times at the MU positively impact the rescreening rates. Whelehan, Evans, Wells, & MacGillivray (2013) provide evidence that pain during a previous screening mammography contributes to lower rescreening rates.

5.4 The appointment system of the BCSP compared to available literature

In the following section the AS of some optimization studies will be characterized. Focus will lie on studies that consider AS with similar characteristics as the AS of the BCSP. The summary of the characteristics of the AS of the BCSP can be found in Table 7 in section 4.1.6. Several characteristics lie at the basis of the unique setting in terms of outpatient scheduling.

First, the AS at the MU is a combination of appointments within and outside the BCSP. To guarantee an efficient working at the MU, both the appointments within the BCSP and other radiological services need to be perfectly integrated. When looking at the available literature, almost no studies were found that consider designing AS specifically for population screenings, whether they are integrated with other appointments at the facility or not. Tinkler, Pegington, & Baldwin (2001) analyzed patient scheduling within BCSP, however the authors only focused on previous non-attenders of the screening. They found that concentrating previous non-attenders in dedicated screening sessions, increases the efficiency in mobile screening units considerably and reduces the average reserved time for screening this type of women. Qu, Peng, Kong, & Shi (2013) construct a template for a weekly schedule in an outpatient clinic that provides different services. Each type of service has its own forecasted demand, average patient no-show rate and average service time. This is very similar to a MU that can be considered as a medical facility that provides different services including screenings within the BCSP. The difference with the AS of the MU is that a set-up time occurs between 2 service types and during each consultation session only one type of service can be conducted, while at the MU the set-up times between two different services are relatively small or zero and within each consultation session both appointments within the BCSP and other radiological services are scheduled. Instead of assigning the services to different consultation
sessions, the objective of the AS of the BCSP is to construct an AS that efficiently integrates both the services.

Secondly, patients are classified in different patient classes based on their attendance during previous screening rounds which is an indicator for the no-show probability for the next appointment. Incorporating patient heterogeneity only started to receive more attention in literature the past decade, nevertheless, the number of studies that consider patient heterogeneity is still limited. Dividing patients in different classes based on differences in no-show rate is a common classification scheme in literature. Some studies only incorporate two classes (Cayirli, Veral, & Rosen, 2008; Deceuninck, Fiems, & De Vuyst, 2018; Lee, Heim, Sriskandarajah, & Zhu, 2018; Liu, 2016; Zacharias & Pinedo, 2014). Zacharias & Pinedo (2014) for example, make the distinction between patients with a 100% chance of showing up and patients that may not show up. Other studies consider several patient classes based on individual patient dependent no-show probabilities (Berg, Denton, Ayca Erdogan, Rohleder, & Huschka, 2014; Daggy et al., 2010; Huang & Zuniga, 2012; Muthuraman & Lawley, 2008; Zeng et al., 2010). Berg et al. (2014) found that it is better to schedule patients with higher no-show probabilities later during the day as it reduces the cost of waiting time, idle time and overtime.

Other common classification schemes are new versus returning patients (Cayirli et al., 2008; Deceuninck et al., 2018; Lee et al., 2018) or classifying patients based on the level of emergency. For example, Patrick, Puterman, & Queyranne (2008) divide patients in different priority classes based on the medical acceptable waiting time, while the objective is to minimize the number of patients whose waiting time exceeds the acceptable waiting time. By use of simulation, Cayirli, Veral, & Rosen (2008) introduce two approaches towards patient classification: using patient classification only for sequencing patients and using classification both for sequencing patients and adjusting the appointment interval accordingly. The authors found that adjusting the appointment interval performs slightly better than a fixed interval.

Samorani & LaGanga (2015) does not incorporate patient heterogeneity, however they do implement heterogeneity in no-show probabilities. The no-show rate for every appointment is predicted based on the lead time between day of reservation and the day of the appointment. Parizi & Ghate (2016) also implement different no-how probabilities based on the lead time (and on the type of job). LaGanga & Lawrence (2012) argue that no-shows rates vary across the day. The authors extend their overbooking model and solution procedure to patient no-show rates that vary across the day and argue that when using such slot-by-slot show rates, significantly better schedules can be constructed.
A third determinant of the AS of the BCSP is that patients can cancel or modify the appointment. A modification can be considered as a cancellation of the existing appointment combines with a new appointment request. Only three studies were found that consider cancellation (Liu et al., 2010; Parizi & Ghate, 2016; Schütz & Kolisch, 2013). Liu et al. (2010) implements no-show and cancellation probabilities that increase with the appointment lead time. Similarly, Parizi & Ghate (2016) allow no-show probabilities and cancellation probabilities to vary across job-types and how long ago the appointment was booked. Schütz & Kolisch (2013) extend the model of Parizi & Ghate (2016) by also incorporating no-show and cancellation probabilities that are dependent on the patient type.

The AS of the BCSP is characterized by a traditional offline scheduling policy. Compared to online scheduling, offline scheduling is implemented more frequently in literature than online scheduling, while in reality, most outpatient medical facilities schedule their patients right after appointment request and thus implement online scheduling (Ahmadi-Javid et al., 2017). Some studies are rather theoretical, while other studies reflect on a real life case. The AS of radiology departments are a popular subject in literature (Kolisch & Sickinger, 2008; Patrick et al., 2008; Schütz & Kolisch, 2013).

Finally, an efficient AS within the BCSP minimizes patient waiting time, system overtime and radiologist idle time. Also in literature, these are the most common performance measures that need to be optimized (Ahmadi-Javid et al., 2017). Often in online scheduling, patients can be denied and thus not incorporated into the model and the objective of the model includes finding the best accept/deny decision. That is why in online scheduling, often the revenue of patients seen or the cost of rejecting a patient is incorporated as a performance measure (Kolisch & Sickinger, 2008; Liu, 2016; Patrick et al., 2008).
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<th>Adjusted appointm. interval</th>
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<td>Single</td>
<td>Deterministic</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>2 patient classes: New patients and follow-up patients (differ in mean service times and no-show probabilities)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Liu (2016)</td>
<td>Hybrid</td>
<td>On</td>
<td>Single</td>
<td>Exponential</td>
<td>+</td>
<td>+ 2 patient classes based on different no-show probabilities</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Maximize revenue of patients seen + revenue of ancillary task - patient rejection cost</td>
</tr>
<tr>
<td>Liu et al. (2010)</td>
<td>Hybrid Offline</td>
<td>Single</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>Maximize Revenue of patients seen - Cost of booking a patient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muthuraman &amp; Lawley (2008)</td>
<td>Open access</td>
<td>On</td>
<td>Single</td>
<td>Exponential</td>
<td>+</td>
<td>+ Several patient classes based on: patient attributes and prior attendance history</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Maximize revenue of patients seen - WT - OT</td>
</tr>
<tr>
<td>Reference</td>
<td>Methodology</td>
<td>Online</td>
<td>Multi-Class</td>
<td>Hybrid</td>
<td>OT</td>
<td>WT</td>
<td>Patient Rejection Cost</td>
<td>Objective</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Parizi &amp; Ghate (2016)</td>
<td>Hybrid</td>
<td>Online</td>
<td>Multi</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>Maximize Revenue of patients seen - OT – WT - patient rejection cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qu, Peng, Kong, &amp; Shi, (2013)</td>
<td>Trad</td>
<td>Offline</td>
<td>Multi</td>
<td>Lognormal</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>Balance workload between clinical sessions Minimize</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>Strategy</td>
<td>Status</td>
<td>Class Type</td>
<td>Constraints</td>
<td>Objective</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Schütz &amp; Kolisch, (2013)</td>
<td>Trad</td>
<td>On</td>
<td>Single</td>
<td>Deterministic + + Several patient classes based on the service time, probability of cancellation and no-show probabilities</td>
<td>Maximize Revenue of patients seen -OT -patient rejection cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zacharias &amp; Pinedo, (2014)</td>
<td>Trad</td>
<td>Off</td>
<td>Single</td>
<td>- + + 2 classes: Patients who have a 100% chance of showing up and patients with a no-show probability &amp;</td>
<td>Minimize WT + OT+ IT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Access policy</td>
<td>Type of Sched.</td>
<td># Servers</td>
<td>Service time distr.</td>
<td>No-show</td>
<td>Patient heterogeneity</td>
<td>Adjusted appointm. interval</td>
<td>Overbooking</td>
<td>Patient unpunctuality</td>
<td>Walk-in</td>
<td>Cancellation</td>
<td>Performance</td>
</tr>
<tr>
<td>--------------------</td>
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<td>-------------</td>
</tr>
<tr>
<td>Zeng, Turkcan, Lin &amp; Lawley (2010)</td>
<td>Trad</td>
<td>Off</td>
<td>Single</td>
<td>Exponential</td>
<td>+</td>
<td>+</td>
<td>Several patient classes based on no-show probabilities</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8: Summary of the AS characteristics of optimization studies (with + incorporated in the AS, – not incorporated in the model, \(WT\) = patient waiting time, \(IT\) = Provider idle time, \(OT\) = Provider/System over time)
6 THE PROCESSING OF MAMMOGRAPHIES AS A MACHINE SCHEDULING PROBLEM

The BCSP in Flanders is continuously seeking to increase patient satisfaction. One aspect of patient satisfaction is a timely notification of the final diagnosis towards the patient. In that way, the period of uncertainty and stress is reduced and further examinations can start earlier. To be able to shorten this period of uncertainty, a good understanding of the process of diagnose setting and notification towards the patient is necessary. In Figure 6, this process or the complete mammography flow is displayed as a BPMN model, this is a simplified model of the one in Figure 2 in section 2.3, but with special attention attached to waiting times or delays. Several fixed or arbitrary delays occur and are represented as intermediate timer events in the model. For example, mammographies are only sent from the MU to the CvKO at 11PM the day of first reading. Some variable delays in the process are represented as well. Firstly, the time the patient spends in the waiting room of the MU, can be optimized by more accurate appointment scheduling. The time between screening and first reading is a delay that needs to be optimized by the MU. The MU is responsible for organizing the first reading session and in the ideal situation, the first reading happens at the day of screening. If not, the processing time of a mammography immediately increases with one day and this means that the patient is waiting one day extra for her final diagnosis. The CvKO is not responsible for scheduling the first reading session at the MU, most MUs do not schedule first reading sessions, they happen in a moment of radiologist’s idle time. The CvKO can only encourage the MUs to diagnose the mammography on the day of screening by for example charging a fee when mammographies are not sent to the CvKO on the day of screening. The time between the arrival of a mammography at the CvKO and the second reading is under control of the CvKO, together with, if a third reading is necessary, the delay between the second reading and the third reading.
Figure 6: BPMN model of the mammography flow, WT = waiting time
The scheduling of radiologists at the CvKO is complicated by the high uncertainty in the number of incoming mammographies or the incoming demand. This high uncertainty can be contributed to three factors: the high no-show rate, the uncertain processing time of the mammographies at the CvKO and the possibility of an incomplete patient file arriving at the CvKO. When not enough radiologists are available, the second or third reading of some mammographies are postponed to the next day, the total processing time of a mammography increases with one day and the time of uncertainty for the patient in question increases with one day which ultimately leads to decreased patient satisfaction.

This master’s thesis will focus on the processing of the mammographies at the CvKO. The screening at the MU is described earlier in this master’s thesis and the first reading sessions are differently organized for every MU. Screening and first reading are organized by the MU itself and lie outside the scope of control of the CvKO, that is why this master’s thesis focuses on the stages taking place at the CvKO.

In this section a stochastic linear programming model will be constructed that captures the processing of mammographies at the CvKO in Ghent as a single stage re-entrant machine scheduling environment. Linear programming is a technique that allows finding a solution to a linear optimization problem (maximization or minimization) within a framework of restrictions. These restrictions or constraints are function of the decision variables and other parameters. In many real-life problems, these parameters are uncertain and can be characterized by a probability distribution. The CvKO in Ghent deals with uncertainty in the total incoming mammographies. First in this section, a short analysis on the incoming mammographies will be conducted. Secondly, some assumptions made to construct the model are explained, followed by a definition of the variables. Finally, the objective function and constraints are constructed.

6.1 Demand analysis

To analyze the arrival pattern of mammographies at the CvKO, the actual arrival dates of the mammographies were not available. The number of mammographies diagnosed per day and per radiologist during the months January till October in 2017 were available. Currently, most incoming mammographies receive their second reading on the same day of arrival at the CvKO, thus, the number of second readings per day can be a reasonable estimation of the total number of incoming mammographies per day. When accumulating the daily numbers of second and third readings, the monthly number of readings are found that are displayed in Table 9. Similar to the findings of the
Bevolkingsonderzoek (2017) who found that on average 3.4% of the mammographies need a third reading, the demand data pointed out that a mammography has a 3.6% chance of requiring a third reading.

<table>
<thead>
<tr>
<th></th>
<th># Second readings</th>
<th># Third readings</th>
<th>% Third readings</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>4 991</td>
<td>140</td>
<td>2.81%</td>
</tr>
<tr>
<td>February</td>
<td>4 567</td>
<td>192</td>
<td>4.20%</td>
</tr>
<tr>
<td>March</td>
<td>6 135</td>
<td>193</td>
<td>3.15%</td>
</tr>
<tr>
<td>April</td>
<td>5 302</td>
<td>230</td>
<td>4.34%</td>
</tr>
<tr>
<td>May</td>
<td>7 277</td>
<td>187</td>
<td>2.57%</td>
</tr>
<tr>
<td>June</td>
<td>6 427</td>
<td>248</td>
<td>3.86%</td>
</tr>
<tr>
<td>July</td>
<td>3 174</td>
<td>177</td>
<td>5.58%</td>
</tr>
<tr>
<td>August</td>
<td>3 718</td>
<td>130</td>
<td>3.50%</td>
</tr>
<tr>
<td>September</td>
<td>5 782</td>
<td>226</td>
<td>3.91%</td>
</tr>
<tr>
<td>October</td>
<td>6 691</td>
<td>218</td>
<td>3.26%</td>
</tr>
<tr>
<td>Total</td>
<td>54 064</td>
<td>1 941</td>
<td>3.59%</td>
</tr>
</tbody>
</table>

Table 9: Monthly number of second and third readings at the CvKO in 2017

In Table 10, the average number of mammographies that are diagnosed per diagnostic session can be found. The averages vary highly across the months. On average 74 mammographies are diagnosed per diagnostic session.

<table>
<thead>
<tr>
<th></th>
<th>Average number of mammographies/diagnostic session</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>75</td>
</tr>
<tr>
<td>February</td>
<td>67</td>
</tr>
<tr>
<td>March</td>
<td>81</td>
</tr>
<tr>
<td>April</td>
<td>71</td>
</tr>
<tr>
<td>May</td>
<td>82</td>
</tr>
<tr>
<td>June</td>
<td>79</td>
</tr>
<tr>
<td>July</td>
<td>61</td>
</tr>
<tr>
<td>August</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>September</td>
<td>86</td>
</tr>
<tr>
<td>October</td>
<td>110</td>
</tr>
<tr>
<td>Total average</td>
<td>78</td>
</tr>
</tbody>
</table>

*Table 10: The average number of mammographies (both second and third readings) diagnosed per diagnostic session at the CvKO in 2017*

The probability distribution of the daily incoming mammographies or the daily demand for second readings can be estimated based on historical data available. In Appendix 7, the tests results can be found for the Kolmogorov-Smirnov test for the Poisson, normal, exponential and uniform distribution. There is not enough evidence to reject the null hypothesis that the daily demand is normally distributed on the 5% significance level, while the null hypothesizes that the daily demand is Poisson, exponential or uniform distributed can be rejected on the 5% significance level. So concluded, the daily demand for third readings is normally distributed on the 5% significance level with a mean of 242 and a rather high standard deviation of 99 mammographies.

6.2 Mathematical model

6.2.1 Assumptions and reality

To be able to understand the model below, some assumptions need to be understood. For every assumption, the comparison with the reality will be made.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Reality</th>
</tr>
</thead>
<tbody>
<tr>
<td>There are 5 regular working days.</td>
<td>Sometimes mammographies are diagnosed during weekends as well.</td>
</tr>
<tr>
<td>Every day, 4 shifts can be scheduled starting at 9AM, 11AM, 1PM, 3PM.</td>
<td>Shifts do not have a fixed starting hour.</td>
</tr>
<tr>
<td>The shift length is fixed, namely 2 hours.</td>
<td>No fixed shift length, but an average shift length of 2 hours is plausible.</td>
</tr>
<tr>
<td>There exist shifts without a radiologist assigned to them.</td>
<td>The radiologists of the CvKO are not continuously diagnosing mammographies, diagnostic sessions do not cover the whole day.</td>
</tr>
<tr>
<td>During a shift, a radiologist diagnoses at least 50 mammographies. Radiologists would not be</td>
<td>From demand data could be concluded that the average number of mammographies diagnosed</td>
</tr>
</tbody>
</table>
pleased if they need to go to the CvKO to diagnose only a few minor mammographies. during a diagnostic session amounts to 78 (Table 10).

The maximum number of radiologists assigned to a shift is 2. Currently, the CvKO in Ghent has 2 rooms at its disposal where diagnostic sessions can be conducted. Normally, one radiologist can be diagnosing in each room, but if necessary, extra capacity can be implemented.

The third reading of a mammography cannot happen during the same shift as the second reading. The second and third reading of the same mammography can happen during the same shift, although diagnosed by two different radiologists.

The total number of incoming mammographies each day is stochastic. The total number of incoming mammographies each day is also stochastic in reality.

Processing times are deterministic. Processing times are stochastic. There is no information about the probability distribution of the processing times.

There is a fixed cost associated with assigning a radiologist to a shift. Radiologists are payed according to the number of mammographies they have diagnosed.

A second reading needs to be conducted on the day of arrival at the CvKO or the day after. A second reading can be postponed by more than one day.

A third reading needs to be conducted on the day of the second screening or the day after. A third reading can be postponed by more than one day.

All incoming mammographies of the week need to be processed before the weekend. Second and third readings of mammographies can be postponed to the week after.

The set of possible incoming mammographies of a specific day can be composed out of mammographies that were screened maximum 5 working days before. An example is displayed in Figure 7 for the set of possible incoming mammographies at Monday. Following the European guidelines, 90% of the mammographies should arrive at the CvKO within 7 calendar days after screening. In other words, the MU has 7 days to process the mammography.

Table 11: The assumptions made to construct the stochastic linear programming model compared to reality
6.2.2 Variables

- **Sets**
  - \( R = \{1,2,3,4,5,6,7,8\} \) Set of radiologists
    - \( \text{with } r \in R \) The CvKO works together with 8 radiologists that can be scheduled through the week.

  - \( S = \{1,2,3,4\} \) Set of shifts: 1 stands for the shift starting at 8AM till 10AM
    - \( \text{with } s \in S \) ....
    - 4 stands for the shift starting at 2PM till 4PM

  - \( D = \{1,2,3,4,5\} \) Set of working days: 1 stands for Monday, 2 stands for Tuesday, ....
    - \( \text{with } d \in D \)

  - \( M = \{1,2,3, \ldots N\} \) Set of mammographies that can possibly arrive at the CvKO during one week. As it is assumed that the MU has maximum 5 working days after screening to send the mammography to the CvKO, the possible incoming mammographies of a specific day are all the mammographies created maximum 5 working days ago. In other words, this set is composed of all the women scheduled the week before and the week itself except for Friday.
    - \( \text{with } m \in M \)

- **Decision variables:**
  - The values of the decision variables need to be determined in order to solve the problem and optimize the objective function. \( X_{rsd} \) assigns capacity or radiologists to shifts. \( Y_{2mrzd} \) and \( Y_{3mrzd} \) assign mammographies to the scarce resource (= radiologists) for a second, respectively third reading.

  - \( X_{rsd} \)
    - 1 if radiologist \( r \) is assigned to shift \( s \) on day \( d \),
    - 0, otherwise
\( Y_{2 \text{mr}sd} \) 1 if mammography \( m \) is assigned to radiologist \( r \) on shift \( s \) on day \( d \) for a second reading
0, otherwise

\( Y_{3 \text{mr}sd} \) 1 if mammography \( m \) is assigned to radiologist \( r \) on shift \( s \) on day \( d \) for a third reading
0, otherwise

- **Parameters**

The values of the parameters are known or stochastic.

\( I_{md} \) Not every mammography \( m \in M \) will arrive at the CvKO. For women who don’t show up at their appointments, no mammography will be created and the mammography will thus never arrive at the CvKO. If a woman arrives at her appointment, the mammography is created and the MU has 5 days to process the mammography and send it to the CvKO. \( I_{md} \) is 1, if mammography is part of the incoming mammographies at day \( d \) 0, otherwise

In section 6.1 was found that the sum follows a normal distribution.

\[
\sum_m I_{md} \sim N(242,99^2) \quad \forall d \in D
\]

\( c_1 \) Fixed cost of opening a shift

\( c_2 \) Fixed cost of postponing a second reading to the next day

\( c_3 \) Fixed cost of postponing a third reading to the next day

\( Z_m \) 1, if mammography \( m \) needs a third reading
0, otherwise

\( t_2 \) Time needed to diagnose a mammography during second reading (in minutes)

\( t_3 \) Time needed to diagnose a mammography during third reading (in minutes)

\( L \) Shift length (120 minutes)

\( T_{2md} \) \( T_{2md} \) describes the ‘tardiness’ of the second reading of a mammography \( m \).
1, if the second reading of a mammography \( m \) with arrival date \( d \), does not happen at day \( d \), but the second reading is planned for the next day \((d+1)\). In that way, the processing time of a mammography increases unnecessarily with one day 0, if the mammography is diagnosed at the arrival day \( d \).

\( T_{3md} \) describes the ‘tardiness’ of the third reading of a mammography \( m \).

1, if the third reading of a mammography \( m \) is not conducted at the same day as the second reading, given that the mammography needs a third reading and the day of second reading is \( d \). The day of third reading becomes \( d+1 \). In that way, the processing time of a mammography increases unnecessarily with one day.

0, if the mammography gets its third diagnosis on the same day as the second reading.

6.2.3 Objective function

**Preemptive goal programming**

The CvKO needs to minimize three conflicting objectives simultaneously. The first objective function \( F_1(X_{rsd}) \) is the minimization of the number of activated shifts and the assigned radiologists to the shifts. This objective aims for an efficient human resource allocation at the CvKO in Ghent. The second and the third objective function \((F_2(T_{2md}) & F_3(T_{3md}))\) aim at shortening the processing time of a mammography by minimizing the number of second, respectively third readings, that are postponed to the next day. When implementing preemptive goal programming, the scheduler needs to be able to assign different priorities to the objective functions. For now, it is assumed that \( F_1(X_{rsd}) \) has the highest priority, followed by \( F_2(T_{2md}) \) and finally \( F_3(T_{3md}) \).

\[
F_1(X_{rsd}) = \sum_r \sum_s \sum_d X_{rsd}
\]

\[
F_2(T_{2md}) = \sum_m \sum_d T_{2md}
\]

\[
F_3(T_{3md}) = \sum_m \sum_d T_{3md}
\]

In order to be able to implement goal programming, a goal needs to be set for each objective function. More specifically, \( b_1 \) becomes the specific goal for \( F_1(X_{rsd}) \), \( b_2 \) for \( F_2(T_{2md}) \) and \( b_3 \) for \( F_3(T_{3md}) \). \( d_1 \) is the deviation of the first objective from the goal \( b_1 \) and similarly \( d_2 \) and \( d_3 \) can be defined for the second and third objective function. The deviations are a measure for to what degree the objective
function is exceeding the goal. In general, three extra constraints need to be added that define $d_1$, $d_2$ & $d_3$ as the deviation of the objective of its goal value.

$$
F_1(X_{rsd}) - d_1 \leq b_1 \\
F_2(T_{2md}) - d_2 \leq b_2 \\
F_3(T_{3ma}) - d_3 \leq b_3
$$

The problem is solved in several iterations. For every iteration, a different objective is minimized and different constraints are added. During the first iteration, the deviation of the objective with the highest priority is minimized, followed by the objective with the second highest priority and so on. In the following, the objective function minimized during each iteration will be described together with the extra constraints added to the general constraints that will be defined in section 6.2.4.

**Iteration 1**

Minimize $d_1$

Subject to

- Constraints defined in section 6.2.4
- $d_1, d_2 \& d_3 \geq 0$ and integer

**Iteration 2**

Minimize $d_2$

Subject to

- Constraints defined in section 6.2.4
- $d_1 \leq$ the value found for the variables during the first iteration
- $d_1, d_2 \& d_3 \geq 0$ and integer

**Iteration 3**

Minimize $d_3$

Subject to

- Constraints defined in section 6.2.4
- $d_1 \leq$ the value found for the variables during the first iteration
- $d_2 \leq$ the value found for the variables during the second iteration
- $d_1, d_2 \& d_3 \geq 0$ and integer

**Weighted sum method**
Minimize

\[ c_1 \sum_{r} \sum_{s} \sum_{d} X_{r,s,d} + c_2 \sum_{m} \sum_{d} T_{2md} + c_3 \sum_{m} \sum_{d} T_{3md} \]

The three objectives combined in this composite objective function are the same as the ones described above. By constructing the objective function as a composite function of three objective functions and assigning weights \((c_1, c_2, c_3)\) to the objectives, the objective becomes minimizing the weighted sum of the objectives. Assigning values to the parameters is a \(c_1, c_2\) and \(c_3\) is a highly subjective issue and is hard to define for the BCSP. That is why an a posteriori articulation of preferences fits better. The values for the weights are then altered to find the Pareto optimal set and thus the optimal trade-off between efficiency and patient satisfaction can be constructed.

6.2.4 Constraints

The constraints define limitations and restrictions on the assignment of radiologists and mammographies to shifts. First, the constraints will be listed followed by their explanation.

1. \(Y_{2mrsd} \leq X_{r,s,d}\) \(\forall m \in M, \forall r \in R, \forall s \in S, \forall d \in D\)

2. \(Y_{3mrsd} \leq X_{r,s,d}\) \(\forall m \in M, \forall r \in R, \forall s \in S, \forall d \in D\)

3. \(\sum_{r} X_{r,s,d} \leq 2\) \(\forall s \in S, \forall d \in D\)

4. \(\sum_{d} \sum_{s} X_{r,s,d} \geq 1\) \(\forall r \in R\)

5. \(\sum_{s} X_{r,s,d} \leq 1\) \(\forall r \in R, \forall d \in D\)

6. \(\sum_{m} Y_{2mrsd} + \sum_{m} Y_{3mrsd} \geq 50 \times X_{r,s,d}\) \(\forall r \in R, \forall s \in S, \forall d \in D\)
\[
\sum_{s} \sum_{d} Y_{2, mrsd} + \sum_{s} \sum_{d} Y_{3, mrsd} \leq 1 \quad \forall m \in M \\
\forall r \in R
\]

\[
\sum_{r} \sum_{s} Y_{2, mrsd} + \sum_{r} \sum_{s} Y_{2, mrs(d+1)} \geq I_{md}(\xi) \quad \forall m \in M \\
\forall d \in \{1,2,3,4\}
\]

\[
\sum_{r} \sum_{s} Y_{3, mrsd} + \sum_{r} \sum_{s} Y_{3, mrs(d+1)} \geq Z_{m}(\xi) \cdot Y_{2, mrsd} \quad \forall m \in M \\
\forall d \in \{1,2,3,4\}
\]

\[
\sum_{r} \sum_{s} Y_{2, mrs5} \geq I_{m5}(\xi) \quad \forall m \in M \\
\forall d = 5
\]

\[
\sum_{r} \sum_{s} Y_{3, mrs5} \geq Y_{2, mrs5} \cdot Z_{m}(\xi) \quad \forall m \in M \\
\forall d = 5
\]

\[
T_{2md} \geq I_{md}(\xi) + \sum_{r} \sum_{s} Y_{2, mrs(d+1)} - 1 \quad \forall m \in M \\
\forall d \in \{1,2,3,4\}
\]

\[
T_{3md} \geq \sum_{r} \sum_{s} Y_{2, mrsd} + \sum_{r} \sum_{s} Y_{3, mrs(d+1)} - 1 \quad \forall m \in M \\
\forall d \in \{1,2,3,4\}
\]

\[
\sum_{m} t_{2m} \cdot Y_{2, mrsd} + \sum_{m} t_{3m} \cdot Y_{3, mrsd} \leq L \quad \forall r \in R, \\
\forall s \in S, \\
\forall d \in D
\]

\[
\sum_{r} Y_{2, mrsd} + \sum_{r} Y_{3, mrsd} \leq 1 \quad \forall m \in M, \\
\forall r \in R, \\
\forall s \in S \\
\forall d \in \{1,2,3,4\}
\]

\[
\sum_{r} Y_{2, mrsd} + \sum_{r} Y_{3, mrsd} \leq 1 \quad \forall m \in M \\
\forall r \in R, \\
\forall s \in \{1,2,3\} \\
\forall d = 5
\]
(1) A mammography can only get a second reading during a specific shift by a specific radiologist if this radiologist is assigned to that specific shift.

(2) A mammography can only get a third reading during a specific shift by a specific radiologist if this radiologist is assigned to that specific shift.

(3) Maximum 2 radiologists can diagnose the mammographies simultaneously.

(4) Each radiologist conducts at least one diagnostic session per week.

(5) Each radiologist conducts at most one diagnostic session per day.

(6) During a shift, a radiologist diagnoses at least 50 mammographies.

(7) Second and third reader cannot be the same radiologist.

(8) Each incoming mammography needs to be diagnosed during the day of arrival or the day after and need thus be assigned to a shift on one of these days.

(9) If after a second reading a third reading is necessary, the third reading need to be scheduled on the day of the second reading or the next day.

(10) All the incoming mammographies on Friday need receive their second reading the same day.

(11) All the mammographies that received their second reading on Friday and need a third reading, will receive this third reading the same day.

(12) If the mammography \( m \) does not get a second reading at the day of its arrival at the CvKO, the second reading is postponed to the next day and \( T_{2md} \) becomes 1 (with \( d \) the day of arrival at the CvKO).
(13) If a mammography needs a third reading, and the third reading is scheduled for the day after the second reading, $T_{3d}$ becomes 1 (with $d$ the day where the second reading is conducted).

(14) The time needed to diagnose all the mammographies that are assigned to a shift, cannot exceed the shift length which is fixed to 120 minutes.

(15) Except for the last shift on Friday, the second reading and third reading cannot happen during the same shift. When during the last shift on Friday a second reading is conducted for which a third reading is necessary, this third reading cannot be transferred to the next week (see constraint 11), thus a relaxation of the constraint is necessary.

(17) $X_{rsd}$, $Y_{2rsd}$, $Y_{3rsd}$ are binary variables.
7 DISCUSSION

7.1 Summary

The goal of this master’s thesis is twofold. On the one hand, a literature review of optimization studies that consider AS with similar characteristics as the AS of the BCSP is provided; on the other hand, a stochastic linear programming model will be constructed that optimizes the allocation of radiologists at the CvKO while ensuring timely notification of the final diagnosis towards the patients.

To be able to provide an accurate comparison of the AS of the BCSP and the AS studied in literature, the AS of the BCSP need to be characterized in detail. A summary of the characteristics can be found Table 7. The main characteristics that distinguish the AS of the BCSP from other, more general appointment systems are the high no-show rate of on average 48.1%, the classification of patients or patient heterogeneity based on previous attendance behavior and thirdly, the possibility that a patient cancels the appointment. Another important characteristic is the fact that the MU conducts, apart from screenings within the BCSP, also other radiological services. This implies that only optimizing the AS of the BCSP would not lead to any efficiency gains when the AS is not perfectly aligned with the appointments of the other radiological services. To accomplish this perfect integration, a good cooperation between the MU and CvKO is necessary.

The detrimental impact of no-shows on the efficiency of the health care facility is widely recognized in literature. The most common tools incorporated in AS to overcome the negative impact of no-shows are overbooking and adjusting the appointment interval. Patient heterogeneity only started to receive attention in literature in the past decade, thus the available literature is still limited. Several patient classification schemes are common of which classification based on no-show probabilities is one of them. Almost no studies were found that consider appointment cancellation or modification, which is another opportunity for future research. The integration of different AS in one health care facility received also limited attention in literature. However, the composite AS can be characterized as a single or multi-server scheduling environment with the following patient classification: patients outside the BCSP and patients within the BCSP, which can be further classified by differences in no-show rate. This appointment scheduling environment is more common in literature. In general, the number of practical studies that considered the AS of a population screening is very limited. No study investigated the integration of population screening appointments with other radiological services which is the final opportunity of future research.
Before constructing the stochastic linear programming model, the processing of mammographies at the CvKO is defined as a machine scheduling problem to get better insight in the scheduling environment. This environment can be defined as on the one hand, a two-stage hybrid flow shop; on the other hand; a single stage environment with certain jobs re-entering the system. The stochastic linear programming model was constructed based on the latter approach where mammographies that need a third reading re-enter the system. The machine scheduling environment at the CvKO is characterized by a stochastic demand, the total daily incoming mammographies is uncertain. The results of the demand analysis in this master’s thesis shows that it can be assumed that the total number of mammographies is normally distributed on 5% significance level. Not only, the total demand of second readings is uncertain, also the daily number of necessary third reading is uncertain. No data were available to estimate the probability distribution of this variable.

The stochastic linear programming model aims at minimizing the number of shifts activated and the number of radiologists assigned to these shifts while minimizing the processing time of the mammography. A trade-off thus needs to be made between patient satisfaction and efficiency in allocation of human resources. Currently, the BCSP in Flanders already meets the European guidelines in terms of timely notification towards the patient (Bevolkingsonderzoek, 2017), but it strives for continuous improvement and increasing patient satisfaction. This linear programming model may support the policy makers of the BCSP in taking more accurate decisions.

7.2 Research contribution

In terms of scheduling of population screening appointments, almost no theoretical, nor practical studies can be found. This master’s thesis is one of the few practical studies that analyzes an appointment system of a population screening.

7.3 Limitations

The comparison of the appointment system of the BCSP with other AS available in literature focuses mainly on optimization literature. It may be of interest to also incorporate simulation studies in the analysis. Furthermore, some arbitrary assumptions are made when constructing the linear
programming model which fades the representation of the reality. Another limitation is that there is no analysis incorporated that considers solving the stochastic model.
REFERENCES


Bar-dayan, Y. (2002). Waiting time is a major predictor of patient satisfaction in a primary military clinic. *Military Medicine, 167*(10), 842


Lubicz, M. (2017). *Applications of operations research and intelligent techniques in the health systems: A bibliometric analysis*10.1007/978-3-319-46589-0_8


APPENDIX

1. THE BREAST CANCER SCREENING PROGRAM IN FLANDERS: ILLUSTRATION

Appendix 1: Example of an invitation letter

Beste

We nodigen je uit om deelnemend te zijn aan het Bevolkingsonderzoek Borstkanker voor vrouwen van 50 tot en met 69 jaar. Met een screeningsmammografie om de twee jaar kunnen afwijkingen in een borst vroegtijdig worden opgespoord. Je beslist zelf of je al dan niet deelnemt. Maar hoe sneller je erbij bent, hoe groter de kans om te genezen. De behandeling is dan ook minder zwaar.

HOE NEEM JE DEEL?

Ga naar de afspraak die we hier voorstellen.
Datum en uur:
Mammografische eenheid:

Hou deze brief bij en neem hem mee naar je nieuwe afspraak. De brief geldt als voorschrift. Je ontvangt geen nieuwe brief met de gewijzigde afspraak.

Will je meer informatie over dit bevolkingsonderzoek?

Lees de bijgevoegde folder.

Helpt je persoonlijke vragen of twijfels je om deel te nemen?

Neem contact op met je huisarts.

Surf naar www.bevolkingsonderzoek.be

Kies je ervoor om niet deel te nemen?

Laat het ons weten. Zo help je ons om nieuwe afspraken voor anderen te regelen.


Met vriendelijke groeten,

Dr. Patrick Martens
Director Centrum voor Kankeropsporing

Je persoonlijke code:

De screeningsmammografie is gratis als je bij een Belgisch ziekenfonds bent aangesloten.
Appendix 2: Example of weekly schedule of appointments within the BCSP at a specific MU
Appendix 3: Processing time of the mammographies at the MU (Bevolkingsonderzoek, 2017)
Appendix 4: Processing time of the mammographies at the CvKO (Bevolkingsonderzoek, 2017)
Appendix 5: Total processing time of a mammography (Bevolkingsonderzoek, 2017)
<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
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<tbody>
<tr>
<td>Number of screenings</td>
<td>211,658</td>
<td>211,472</td>
</tr>
<tr>
<td>Number of recalls</td>
<td>78</td>
<td>105</td>
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Appendix 6: Number of recalls within the BCSP in Flanders because of bad quality of the original mammography in 2015 and 2016 (Bevolkingsonderzoek, 2017)

2. THE PROCESSING OF MAMMOGRAPHIES AS A MACHINE SCHEDULING PROBLEM – DEMAND ANALYSIS

One-Sample Kolmogorov-Smirnov Test

\[ V_5 \]

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<tr>
<td>Negative</td>
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<tr>
<td>Test Statistic</td>
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<tr>
<td>Asymp. Sig. (2-tailed)</td>
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a. Test distribution is Normal.
b. Calculated from data.
c. Lilliefors Significance Correction.

One-Sample Kolmogorov-Smirnov Test

\[ V_5 \]

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<td>Asymp. Sig. (2-tailed)</td>
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</table>

a. Test distribution is Uniform.
b. Calculated from data.
### One-Sample Kolmogorov-Smirnov Test

#### 3

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<tr>
<td><strong>Positive</strong></td>
<td>.368</td>
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<tr>
<td><strong>Negative</strong></td>
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<td><strong>Kolmogorov-Smirnov Z</strong></td>
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a. Test distribution is Poisson.
b. Calculated from data.

#### 4

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a. Test Distribution is Exponential.
b. Calculated from data.

*Appendix 7: Tests for probability distributions of daily incoming mammographies at the CvKO*