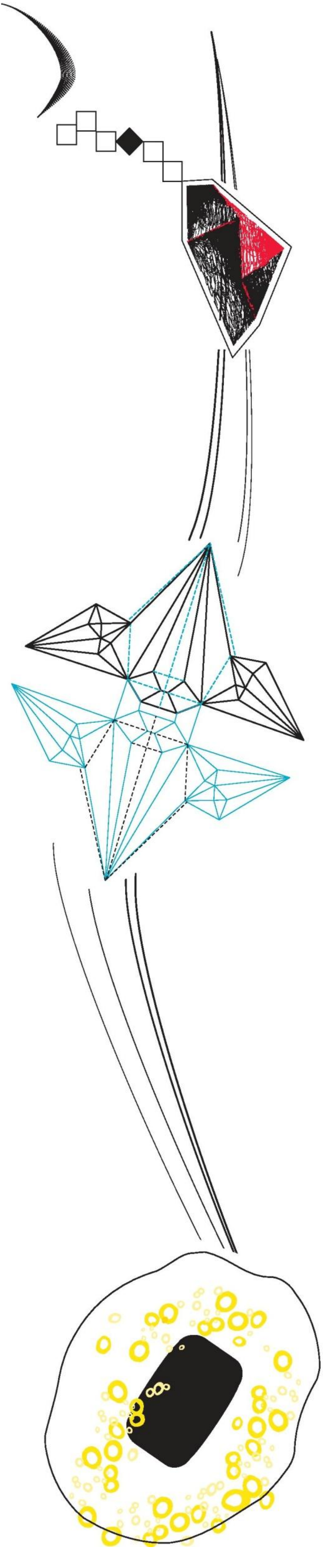

MASTER THESIS

PUBLIC VERSION

OPTIMIZING THE NUMBER OF MEDICAL DEVICES BASED ON THE TOTAL COST OF OWNERHSIP

A case study at Siemens Healthcare Nederland B.V.

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Management summary

In times when there is a lot of financial pressure on Dutch hospitals, it is very important that hospitals look critically at the number of installed medical devices to process their patients. Siemens Healthcare Nederland B.V. (Siemens) would like to support their customers in this changing environment, by offering them a contract which includes the equipment, maintenance and other services like training and consulting, further referred to as a MES contract. In the Netherlands, MES contracts last for approximately fifteen years. During these years, the hospital yearly pays a leveled fee which includes all costs for the acquisition, the maintenance and extra services, resulting in a stable cash flow for the partnering hospital. As part of the consulting component, Siemens suggested our research which is focused on finding the optimal number of devices in a hospital's fleet in every period of the MES contract, that would still be able to process all expected demand. We base our decision on the number of devices on the minimal Total Costs of Ownership (TCO) of Siemens plus the hospital, over all devices together. TCO takes not just the purchasing price into account but all costs associated with the acquisition, the use, and maintenance of an item (Ellram & Siferd, 1993). The main research question that we will answer in this research is therefore:

How to determine the optimal number of devices in a hospital's portfolio of equipment over a multiple period time horizon, when taking the total costs of owning the equipment into account, and how will the optimization influence the number of devices in the portfolio of equipment and the associated total costs of ownership, of a Dutch hospital that has a MES contract with Siemens?

Based on the available literature on TCO and the input of experts from a Dutch hospital (Hospital A) and Siemens, we designed a model to determine the TCO of the total portfolio of devices of a hospital. We included the cost elements of the MES contract, labour, disposables, operating supplies, downtime and floor/space, and described the dependencies of these costs to the expected demand, the number of devices and opening hours. The goal of the model is to minimize the Total Cost of Ownership by changing on the number of devices and opening hours. The values of the two variables are both restricted. At first since there should always be enough capacity to process the expected demand and secondly since there is a maximal number of hours that a department can be opened on a day. The result of the model is the optimal number of devices with the associated number of opening hours in every period to meet the expected demand.

We implemented the developed model into a Microsoft Excel tool in order to use it in practice. The tool is used to examine two experiments; a theoretical case and the practical case of Hospital A. In the theoretical case, a middle size hospital with only Bucky's and MRI scanners at two locations, the TCO of the optimal solution over 15 years was approximately € 40.885.000,-. We found that a reduction of 0,28% of this amount can be realized by combining the two locations of the theoretical case, since less devices are needed to process the expected demand and thus the risks in fluctuating demand is pooled. Since this amount is not significant, we advice to perform extra research on the potential benefits of a merger of the hospital, before executing it. If we remove the restriction on the moment of removal and thus the device could be removed anytime, it is possible to decrease the costs of the optimal solution for two separated locations with just 0,01%. If the expected yearly growth percentage of the demand is estimated wrongly, and appears to be the additive inverse for all categories and locations (e.g. 1,5% becomes -1,5%), a decrease in TCO is visible of 15,96%. Therefore we strongly advice to make sure that the demand is forecasted well.

We've put all settings of the current MES contract of Hospital A into the developed tool in order to evaluate the current solution. As a result we found that the value of the TCO would approximately be € 42.700.000,-, which is 8,31% higher than in the optimal case for Hospital A. In order to realize this reduction in costs of approximately eight percent, we advice that the number of Angio's, C-Arms and SPECT-scanners should be reduced from two or three to one, and the number of Ultrasound systems should be reduced from five till two. Besides that, the addition of the MRI scanner should be delayed with seven years. This last change is advised since we found out that it will always be cheaper to extend the MRI scanner's opening hours till its maximum instead of adding another device to increase the capacity. This is even the case when owning very many MRI scanners. For cheaper devices, like Ultrasounds, there does exist a trade off between adding a device and extending opening hours.

The parameters in the TCO model have influence on the total value of the TCO and the threshold values, which tell at which number of patients it is better to add or remove a device. Therefore, when the parameters are estimated wrong or when operations change, it changes the final solution as well. From the sensitivity analysis we conclude that changes in the treatment times, the costs for labour outside regular hours, and the forecasted demand account for the most significant changes in the value of the TCO and threshold values. Therefore, we advice that the values of these three parameters are critically reviewed when the model is used.

Besides optimizing the number of devices, the developed tool provides also insight in points for improvement. For example, the effect of a more efficient planning, which results in shorter average treatment times could be calculated. Moreover, we made it possible to see the shares of each cost element to the TCO. Based on the shares of the cost elements, opportunities for cost reductions could be determined.

Since the model is constructed with the help of just one hospital and since the operating costs could not be validated, we recommend to perform more research on the validity of the developed model. Besides that, a major limitation for the use of the model is that the parameters that influence the final decision most, the costs for labour outside regular hours and the expected demand, are the ones that are hardest to estimate according to the hospital. Therefore we suggest to do extra research on forecasting the demand and the costs of labour outside regular hours.

Samenvatting (Dutch)

In tijden van veel financiële druk op de Nederlandse ziekenhuizen, is het erg belangrijk dat het aantal apparaten waarop patiënten worden onderzocht kritisch wordt bekeken. Siemens Healthcare Nederland B.V. (Siemens) wil graag haar klanten bijstaan in deze veranderende omgeving door contracten aan te bieden waar de aanschaf van apparaten, het onderhoud en overige diensten, zoals trainingen en advies, onder vallen. Deze contracten worden MES contracten genoemd en gelden over het algemeen voor een periode van ongeveer vijftien jaar in Nederland. Tijdens de contractduur betaalt het ziekenhuis een jaarlijks constant bedrag aan Siemens, waarbij de kosten van alle drie de componenten in zijn opgenomen. Dit resulteert in een stabiele cash flow voor het samenwerkende ziekenhuis en voorkomt grote pieken bij nieuwe investeringen. Als onderdeel van de adviserende component van een MES contract stelt Siemens dit onderzoek voor naar het vinden van het optimale aantal apparaten in het wagenpark van een ziekenhuis over alle periodes van het MES contract, waarbij het belangrijk is dat er altijd voldoende capaciteit is om aan de verwachte vraag te voldoen. We nemen de beslissing over het aantal apparaten op basis van de minimale Total Cost of Ownership (TCO) van alle apparaten samen. TCO is een manier om verder te kijken dan enkel de aanschafwaarde van een apparaat door ook de kosten die komen kijken bij het gebruik en onderhoud ervan over de hele levensduur mee te nemen in een overweging (Ellram & Siferd, 1993). Hieruit volgt de hoofdvraag wij beantwoorden in dit onderzoek:

Hoe kan het optimale aantal apparaten in het totale porfolio van een ziekenhuis over meerdere periodes worden bepaald, wanneer de totale kosten voor het bezitten van de apparatuur worden meegenomen in de beslissing, en wat is de invloed van de optimalisatie op het aantal apparaten in de apparatuur portfolio en de bijbehorende Total Cost of Ownership, van een Nederlands ziekenhuis dat al een MES contract met Siemens heeft?

Op basis van de beschikbare literatuur over TCO en input van experts vanuit een Nederlands ziekenhuis (Ziekenhuis A) en Siemens, hebben wij een model ontwikkeld om de TCO van het totale porfolio van apparaten in een ziekenhuis te bepalen. In de ontwikkeling van het model hebben we de volgende kosten mee genomen: MES contract, arbeid, disposables, operating supplies, downtime en de exploitatie van de ruimte. We hebben van al deze kostelementen bepaald hoe de kosten afhangen van de openingstijden, het aantal apparaten en het verwachtte aantal patiënten. De waarde van de TCO kunnen we in het model beïnvloeden door het veranderen van het aantal apparaten en de dagelijkse openingstijden, welke beiden begrensd zijn doordat er altijd voldoende capaciteit aanwezig moet zijn om aan de verwachtte vraag te voldoen en doordat er een maximaal aantal uur is dat een afdeling open kan zijn op een dag.

We hebben het model geïmplementeerd in een Microsoft Excel tool zodat het model gemakkelijk in praktijk kan worden gebruikt. De ontwikkelde tool wordt gebruikt om twee experimenten uit te voeren; namelijk een theoretische casus en een praktische casus van Ziekenhuis A. De theoretische casus bestaat uit een middelgroot ziekenhuis met enkel Bucky en MRI scanners op twee verschillende locaties. Voor deze casus geeft de optimale situatie een TCO over vijftien jaar van ongeveer € 40.885.000,-. We realiseren een besparing van 0,28% wanneer de twee locaties van de casus worden gecombineerd doordat er dan minder apparaten nodig zijn om de verwachtte patiënten te scannen doordat de risico's in fluctuerende patiëntenaantallen zijn gedeeld over de apparaten. Wanneer we de beperking op het moment van het verwijderen van apparaten negeren, is het maar mogelijk om de kosten met 0,01% te verlagen. Wanneer het verwachtte jaarlijkse groeipercentage van de vraag verkeerd wordt geschat en zelfs het tegenovergestelde blijkt te zijn

(bijvoorbeeld 1,5% wordt -1,5%), verlaagt de TCO met 15,96%. Daarom adviseren wij dat er goed wordt gekeken naar de correctheid van de voorspelde vraag.

Door het invoeren van de gegevens van het huidige MES contract van Ziekenhuis A in de ontwikkelde tool, hebben we de huidige situatie beoordeeld. De waarde van de TCO van de huidige situatie is ongeveer € 42.700.000,- , wat 8,31% hoger is dan de optimale situatie voor Ziekenhuis A. We kunnen deze reductie van kosten realiseren doordat het aantal apparaten wat nodig is in elke periode gelijk is aan, of minder is dan, het aantal apparaten in de huidige situatie. Wij adviseren daarom dat het aantal Angio, C-Boog en SPECT systemen wordt gereduceerd van twee of drie naar één apparaat en dat er maar twee in plaats van vijf Echo's moeten worden gebruikt. Bovendien zal het toevoegen van een extra MRI scanner worden verlaat met zeven jaar. Wij adviseren deze laatste verandering doordat het altijd goedkoper is om de openingstijden op de MRI scanner te verruimen tot een maximum van 16 uur per dag, dan het toevoegen van een extra apparaat om de capaciteit te vergroten. Dit is zelfs nog het geval wanneer er wordt gekeken naar het toevoegen van een vijfde apparaat. Voor goedkopere apparaten, zoals een echo, is er wel een trade-off tussen extra apparaten en openingstijden.

De parameters in het TCO model hebben invloed op de waarde van de TCO en op de breakeven points, dus als deze parameters verkeerd worden geschat of wanneer operations veranderen, heeft dit effect op de uiteindelijke oplossing van het model. Uit de gevoeligheidsanalyse concluderen wij dat de meest significante veranderingen in de TCO en de breakeven point te zien zijn wanneer de behandeltijd verandert, wanneer de kosten voor arbeid buiten openingstijden niet klopt, en wanneer de verwachte vraag anders is. Daarom adviseren wij dat de waardes van deze drie parameters kritisch worden als het model wordt gebruikt.

Naast het optimaliseren van het aantal apparaten, biedt de ontwikkelde tool nog extra mogelijkheden. Bijvoorbeeld het effect kan worden gekwantificeerd van een efficiëntere planning waardoor de behandeltijden verminderen. Daarnaast hebben wij het mogelijk gemaakt om het aandeel van elk kostenelement in de TCO te bekijken, wat input levert voor mogelijk kost reducties.

Aangezien het model enkel ontwikkeld is met de hulp van één ziekenhuis en doordat het niet mogelijk was om de operationele kosten te valideren, bevelen wij aan dat er meer onderzoek wordt gedaan naar de validiteit van het ontwikkelde model. Daarnaast, een belangrijke bedreiging van het model is dat de parameters die de oplossing het meest beïnvloeden, namelijk de kosten voor arbeid buiten openingstijden en de verwachtte vraag, het lastigst zijn om te bepalen. Daarom raden wij aan dat er extra onderzoek wordt gedaan in het bepalen van een goede voorspelling van de vraag en in het bepalen van de arbeidskosten.

Preface

All good things come to an end. Just like my great student life. During six years I've had the opportunity to gain a lot of new knowledge and the experiences. This fantastic time is closed by writing my master thesis, which is lying in front of you.

I am very grateful for the opportunity to perform my research at Siemens Healthcare B.V. The nice ambiance and kind and helpful colleagues, made working on my thesis way easier. Special thanks go to Pasquelle for giving me all the freedom I desired and for helping me wherever I needed it.

From the university, a lot of help was provided by Ingrid Vliegen. I had the mathematical knowledge present, however writing a thesis is more than just doing calculations. Therefore, I really needed some help in giving my research a good structure. Ingrid was always willing to help and the meetings were pleasant and therefore, I would like to thank Ingrid for the support during the past six months.

Besides my first supervisor Ingrid Vliegen, I would like to thank Ahmad Al Hanbali in his role as second supervisor from the university, for helping me to improve the quality of my research in the final phase of my graduation project. Furthermore, I appreciate the effort of Leo van der Wegen for attending my colloquium as a substitute of Mr Al Hanbali. My thanks go out to him as well.

Furthermore, I would like to thank my friends and family for all support, especially in times when I was constantly talking about my graduation project. At those moments, they were always there to listen to me and to give me good distractions.

Even though it is sad that the wonderful time of being a student is coming to an end, I think that it will give a lot of new opportunities. I'm looking forward to everything that is going to happen after graduation!

I hope you will enjoy reading my master thesis, since a lot of effort, joy and love is put into it!

Kind regards,

Liza Fredriks
Den Haag, July 2015

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List of abbreviations

HES	Healthcare Enterprise Solutions
LCC	Life Cycle Costing
MES	Managed Equipment Service
NPV	Net Present Value
NBV	Net Book Value
TCO	Total Cost of Ownership
US	Ultrasound

List of notations

Indices:

i	Item
k	Cost element
ON, OFF	Indices for status of equipment; respectively equipment is on and off
p	Period
s	Equipment category / department
REG, EXT, IRR, TOT	Indices for type of time units; respectively regular, extra, irregular, total time units
v	Location

Sets:

I	Set of all items
K	Set of all cost elements
P	Set of all periods $1...T$
S	Set of all equipment categories
$R_{s,v}$	Subset of set I
V	Set of all locations

Variables:

$B_{i,p} \in \{0,1\}$	Indicates whether an item i is installed at period p (from Siemens or another supplier)
C_p	Total costs of all cost elements of all items at period p
C_p^k	Total costs for cost element k, at period p
C_p^{Do}	Costs for cost element *Downtime,* at period p
C_p^{Ex}	Costs for cost element *Extra MES Service,* at period p
C_p^{Fl}	Costs for cost element *Floor/space*, at period p
C_p^{La}	Costs for cost element *Labour,* at period p
C_p^{MES}	Costs for the MES contract, at period p; (fee per period)
C_p^{Op}	Costs for cost element *Operating supplies,* at period p
$C_{i,p}^k$	Costs for cost element k, for item i, at period p
$C_{i,p}^{Aq}$	Costs for cost element *Acquisition*, for item i, at period p
$C_{i,p}^{Ma}$	Costs for cost element *Maintenance*, for item i, at period p

$C_{i,p}^{Op}$	Costs for cost element *Operating supplies* for item i, at period p
$D_{p,s,v}$	Number of devices at period p, in category s, and location v
$E_{D,D+1}$	Threshold value of number of patients where the TCO of having D devices is equal to $(D+1)$ devices
$F_{p,s,v}$	Number of patients at department s that could be scanned during the chosen opening hours at period p of location v
$G_{i,p} \in \{0,1\}$	Indicates at which periods p, an item i gets installed/replaced
$H_{p,s,v}$	Time units of all items in category s, during period p at location v together
$J_{i,p} \in \{0,1\}$	Indicates whether Siemens' item i is installed at period p
L_i	Moment of removal of item i
M_i	Moment of first install of item i
N_i	Number of installs during T of item i
$O_{p,s,v}$	Number of time units one item of department/equipment category s is open in period p at location v
$O_{p,s,v}^{REG}$	Number of regular time units one item of department/equipment category s is open in period p at location v
$O_{p,s,v}^{EXT}$	Number of extra time units one item of department/equipment category s is open in period p at location v
$O_{p,s,v}^{IRR}$	Number of irregular time units one item of department/equipment category s is open in period p at location v
$pa_{R,D}$	Number of patients that could maximally be scanned in regular time units at D devices
$pa_{R,D+1}$	Number of patients that could maximally be scanned in regular time units at $D+1$ devices
$pa_{E,D}$	Number of patients that could maximally be scanned in extra time units at D devices
$pa_{E,D+1}$	Number of patients that could maximally be scanned in extra time units at $D+1$ devices
$pa_{M,D}$	Number of patients that could maximally be scanned at D devices
$pa_{M,D+1}$	Number of patients that could maximally be scanned at $D+1$ devices
$Q_i \in \{0,1\}$	Equipment installed before first install, $Yes = 1, No = 0$
T	Number of periods in MES contract; horizon for TCO calculations

Parameter:

a	Margin for profit of cash flow out
b_s	Costs of missing one examination at category s
c	Compensation for irregular hours (percentage of normal wages)

d	Discount rate
e_s	Number of employees needed to run one item at department s
$f_{p,s,v}$	Expected demand of equipment category s at period p at location v
g_s	Average price for disposables per examination on
h_s^{MAX}	Maximal number of time units that department s may be opened in any period
h^{REG}	Maximal number of regular time units in a period
h^{EXT}	Maximal number of extra time units in a period
h^{IRR}	Maximal number of irregular time units in a period
h^{TOT}	Total number of time units in a full period
j	Indexation of the maintenance per period
l	Indexation of cash flow MES contract yearly fee
m_i	Maintenance percentage Siemens equipment per period, of item i
o_s	Operating supplies costs per time unit of equipment category s
pr_i	Price of item i
$\overline{pr_s}$	Average price of an item in category s
pu_s	Number of time units of preventive maintenance and updates of one item in category s
q	Extra costs per hour for extra (EXT) hours
r_i	Replacement interval of item i
$\overline{r_s}$	Average replacement interval of an item in category s
$t_{s,v}$	Treatment time of product category s at location v
u_s	Total costs for one square meter of usage for department s
ut_s	Average uptime guarantee in a MES contract for category s
w_s	Wages per person, per time unit, per equipment category s
x	Extra MES service percentage of total acquisition costs of equipment in a contract
y_s	Utilization percentage
z_s	Number of square meters needed for item in category s

1. Introduction

The purchase of new technical equipment, for example a production machine or a medical system, is a big investment for a company or a hospital. However, this investment does not only contain the price to buy the equipment, but also a lot of other costs are involved which will be visible during the lifetime of the purchased product. After the equipment is bought, it has to operate. When operating, there are expenses like energy and labour costs. Furthermore, technical devices require maintenance and this will bring along extra costs as well. Within the Dutch Healthcare sector the expenses on medical equipment (without all extra costs) account just for approximately 1% of the total expenses of a hospital (ING Economisch Bureau, 2012). Since an investment is more than just the price of equipment, a well-founded purchasing decision is important. This is especially the case when buying capital goods, since these goods are a big investment which will not be replaced in a short notice. A wrong choice will have long lasting consequences. In order to make a good investment decision, a clear overview of costs involved during the lifetime of a product is needed.

A consideration of making an investment for replacing a device or adding a device, might arise if the demand of a company is changing. When this happens, the company could choose to add or remove a device to be able to meet the expected demand. A decision could be based on the costs of owning the added or removed device individually. However, that approach neglects the interaction of the device on the total portfolio of devices. A change to the total number of devices could, for example, influence the hours that all other devices are running and therefore, it might have consequences on the operating costs of all devices and thus on the total costs. With this consideration in mind, a purchasing decision needs to be based on the total cost of owning all devices in the portfolio. Alternative solutions to meet the changes in demand, like changing the opening hours, could be reviewed based on these total costs of all devices in the portfolio and be compared with the total costs of a purchase or a removal of a device.

This research focuses on developing a model to help with the purchasing decision when considering the portfolio of products a company has. A company could be a hospital but might also be a manufacturer for example. The model is developed for Siemens Healthcare Nederland B.V. (henceforth Siemens), and therefore this study focuses on the purchase of medical equipment.

1.1. Research motivation

Siemens would like to give hospitals well founded advice on the purchase of their medical equipment. Since 2010, Siemens Netherlands offers hospitals Managed Equipment Service (MES) contracts which offers technical equipment to the hospital and provides the necessary support. MES contracts worldwide could last for 15 till 40 years, but in the Netherlands the longest contract at this moment lasts 15 for years. Within these contracts all different combinations of medical equipment and services are possible. At the beginning of the contract, the (re)placement of equipment is determined for the rest of the contract. The equipment is described in functionality and characteristics of the equipment, since the equipment at the moment of contracting may not exist anymore a few years later due to technological improvements. At this moment, a hospital asks Siemens to install specific devices in certain years at their hospital. Besides that, the replacement period for the devices, which is mostly between seven till ten years, is taken into account. Based on these two conditions a roadmap is constructed. The roadmap is a table that visualizes the product portfolio over time and shows when equipment is replaced, added or removed. The construction of the roadmap is based on common sense, or rough estimates of Siemens and the customer. What the effect is on the total costs, and which alternatives there are for adding another machine, are not always taken into account. Due to changes in the healthcare system in the Netherlands (see Section 2.2), it becomes more and more important that hospitals take a good look at their finances. Siemens would like to be a trusted partner by not just selling their medical systems, but also by giving well-founded and objective advice in the pre-sales phase to help hospitals in the changing environment of the healthcare sector.

The concept of taking all costs associated with the acquisition, use and maintenance of a purchased item is called total cost of ownership (TCO) in literature (Ellram & Siferd, 1993). TCO analysis does not only look at the purchasing costs but it examines the explicit and hidden costs during the lifetime of a product as well. The literature about TCO is mostly focused on the supplier selection and monitoring supplier's performance (Ellram, 1995b; Ellram & Siferd, 1993). By means of calculating the total costs involved over the whole lifetime, a company could decide which supplier they want to make the purchase from. This decision is made for a given item and selects one supplier. This research looks at the purchasing decision as well, but the supplier is already known. The contribution of this research is that the interaction effect on the total costs of ownership when having multiple machines is added. The use of TCO makes it possible to give an objective view on the purchasing decision. After taking the interaction effect into account, it becomes possible to find a mathematical optimization over the possible purchasing options. Just a few articles focus on finding the optimal investment by using mathematical optimizations (Degraeve, Labro, & Roodhooft, 2005; Degraeve & Roodhooft, 1999).

1.2. Research objective

The objective of this research is to develop a multi-period model which helps to make a well founded decision on multiple alternative product portfolios over time, by taking the total costs of owning the products into account. 'Multi-period' denotes that the purchasing decision is made at every period of a finite horizon. This indicates that a purchase or removal can be made in every year of the lifetime of the contract and not just at the beginning. The roadmap, which shows the changes of equipment, is made at the beginning of the contract, and thus the model helps to make decisions on future purchases.

The model is implemented at Siemens and constructed with the help of a Dutch MES-contracted hospital. This way, it is possible to see how the optimization of the portfolio would influence the current situation of the cooperating hospital. The implementation is worked out in a spreadsheet which could be used by Siemens in the pre-sales phase. It will be possible to change data in the spreadsheet to apply the model for different hospitals, when Siemens gets in contact with potential customers.

1.3. Research question

This study is based on a design problem suggested by Siemens. The main question which is answered in this research is:

How to determine the optimal number of devices in a hospital's portfolio of equipment over a multiple period time horizon, when taking the total costs of owning the equipment into account, and how will the optimization influence the number of devices in the portfolio of equipment and the associated total costs of ownership, of a Dutch hospital that has a MES contract with Siemens?

The main question can be answered after several steps are performed. Every step denotes a midterm goal in the research. The different steps that are taken in this study are listed below.

At first, extra background information on the main question is needed. This helps to place this research in context and to understand the urgency of the recommendations in practice.

1. *Gain insight into the context where the research question arose.*

The overall goal of the research is to determine the optimal number of devices. Since solutions get evaluated based on the TCO, a model to calculate the TCO of the whole portfolio of devices is needed. For the construction of a valid TCO model, some background information is needed. Therefore literature in the field of interest is reviewed. The goal of this literature study is stated in step two.

2. *Know which models are present in literature to determine the total costs involved over the lifetime of a product. Find out which cost elements can be used to construct a model and know how to decide on which costs are relevant in case of the purchase of capital goods.*

After the second part, the actual cost elements for the model need to be determined. This is done by combining the knowledge found in the literature, the knowledge of Siemens and input from the collaborating hospital. Because some possible cost elements are part of the MES contract between the hospital and Siemens, knowledge about the pricing of a MES contract needs to be gained as well. The third phase is the basis of this part of the research.

3. *Determine relevant cost elements for owning medical equipment at Siemens' customers and know which costs are taken into account when pricing a MES contract at Siemens.*

When all costs are clear, the restrictions on suitable solutions need to be set. This is necessary to get a realistic solution for the mathematical optimization. The next question focuses on that.

4. *Determine the solution space of a portfolio of medical equipment, know what the variables are that could form new alternatives, and have insight in the interaction effect of the variables on the different cost elements of the TCO model.*

Step four is the last step where knowledge needs to be gained. After this fourth step, the construction of the model begins.

5. *Design and develop a model that optimizes the roadmap of medical equipment based on the total costs of the whole portfolio for a hospital.*

When the model is developed, it can be implemented in a tool. In the implemented tool two cases are examined, namely one experiment based on a fictive data and one on data from a cooperating hospital. When that is done, the model can be verified and validated. This last step is performed to ensure the model is doing what it should do and to see whether the model represents reality well.

6. *Implement the model into a tool and describe the experiments.*
7. *Verify and validate the developed model.*

The last step of this research is to generate results with the developed model for the two cases described in the implementation. This way, the effect of applying the developed model is determined. The last step contains also the sensitivity analysis.

8. *Generate results for the theoretical and practical case and determine the sensitivity of the outcomes to changes in the values of the parameters.*

These eight steps shape this research and together guide to the answer on the main research question.

1.4. Data gathering

This research considers the case of the supply chain of medical equipment. The manufacturer of these technical devices, Siemens, is collaborating with Dutch hospitals. For this study, data from Siemens and a Dutch hospital is used. The data is gathered through several interviews with employees and managers from both supply chain actors. This is done to gain good insight in all costs involved from both parties. Different files and figures are provided by the interviewees.

The assisting hospital in the development phase will be named Hospital A. This is done because there is a lot of confidential information needed to create the model. Publication of this data could have a bad influence on the competitiveness of the hospitals.

1.5. Outline of document

Eight steps are performed in this research to find an answer to the main research question. These steps form not only the framework of the research but also the structure of this document. The first step which gives insight in the context of the research is documented in Chapter 2. Background information on the company Siemens and the healthcare sector is given in that chapter. Besides that, Chapter 2 gives additional information on the MES contract which is a partnership between a hospital and Siemens and is the area where Siemens wants to apply the model on.

In the third chapter, relevant literature is reviewed based on the second step proposed in Section 1.3. A summary and analyses of several articles are combined to gain the required knowledge on different models and the possible cost elements within these models.

Chapter 4 consists of several steps. At first, the model that calculates the TCO of a proposed solution is described in Section 4.1. That section describes the conceptual model, which contains a global description of a TCO calculation and the reasoning on the different cost elements that are taken into account in this research. Section 4.2 continues the TCO model design but it goes more in depth than the previous section. After the first two sections of Chapter 4, the TCO model that evaluates a solution is done. The chapter is continued with a description of the constraints for a valid solution in Section 4.3. The final goal of the research, finding the optimal solution, is described in the fourth part, Section 4.4. In order to use the developed model in practice, some adjustments need to be made to the model. These adjustments are described in Section 4.5. Section 4.6 shows the implementation of the model into a tool for Siemens.

The model will used to determine the optimal number of devices for two different cases. The implemented cases are described in the Section 5. The first case is a small theoretical case and is explained in Section 5.1, where after the practical case of Hospital A is described in Section 5.2.

The 6Th Chapter verifies and validates the model to check whether it is implemented well and whether it is representative for the reality. In Chapter 7 the results from step 8 of this research are shown. This is done for the theoretical and the practical case. To see the influence of changes in parameters on the found solution, a sensitivity analysis is performed at the final part of this chapter.

The conclusions, limitations, practical and theoretical recommendations can be found in Chapter 8. The last pages of this research show the appendixes which can be read when having extra interest in certain topics. The appendixes can be found at the end of this document.

2. Context analyses

To have a clear understanding of the background of the design problem investigated in this thesis, the upcoming paragraphs provides extra information about the organization of Siemens, the sector Siemens Healthcare operates in and the MES contracts.

Siemens is a multinational and operates in several sectors. Therefore it has many different departments. Section 2.1 describes which department requested the development of the model and how this department is related to the rest of the company. The Dutch healthcare sector is illustrated in Section 2.2 and gives extra understanding of the relevance of this research. The model that is developed in this research is applied to a specific type of contract, a MES contract. Section 2.3 describes what this term means.

2.1. Siemens Healthcare

Siemens was founded as a company specialized in telegraphing in 1847 and was named Siemens & Halske (Siemens, 2015). In more than 165 years, a lot of things changed within the company. They went from 10 employees in only Germany to having 343.000 employees spread out all over the world in 2014. At the end of the 19th century, Siemens opened their first office in the Netherlands in The Hague, which is later named Siemens Nederland N.V. .

Technological development did not stood still. Currently, Siemens is specialized in several technical sectors; e.g. energy, healthcare and building technologies. This research is performed in the department Siemens Healthcare Nederland B.V.. At this department Siemens is developing imaging and therapy systems which help with early diagnosis and intervention, more effective prevention and therapy. Examples of imaging systems are CT-scans and MRI scans. Besides these imaging systems, clinical products and diagnostic systems are developed within Siemens Healthcare. To support the use of this medical equipment in the hospitals, there is a division focused on customer services. This division manages customer relations, works as a consulting partner for the hospitals, and makes trainings possible for employees who have to work with the medical devices. The MES contracts are developed within customer services division in the business unit Healthcare Enterprise Solutions (HES).

2.2. The healthcare sector

Siemens Healthcare Nederland is operating in a market which is has changed over the past years and which will only face new challenges in the future. One of Europe's major challenges for the upcoming years is the demographical change. The population is ageing, which comes together with a higher total morbidity (European Research Area Board, 2009). This transformation asks for a higher quality of healthcare which can be accomplished by new innovations in this sector. In the previous years, a lot of new technologies for diagnosis, prevention, treatment and rehabilitation are implemented in hospitals and these medical devices account today for a significant amount of public health expenses (European Alliance for Personalised Medicine, 2011). With all new current research this amount will only grow. Expectations for the period 2012-2015 were that the total expenses on medical equipment will yearly grow with 4% (ING Economisch Bureau, 2012).

Besides the demographical changes, also the environment where Dutch hospitals operate in is changing. The economical situation in the Netherlands has changed due to the economical crisis. Costs for healthcare have grown faster than the income of the average Dutch inhabitant (Raad voor de Volksgezondheid en Zorg, 2011). For this reason patients have started to become critical not only on quality but also on costs (ING Economisch Bureau, 2014). Besides that, due to political changes, the risks in the healthcare sector increased, which caused that hospitals are nowadays more and more seen like a company, which has to be financial healthy, makes profit and needs to have a good solvability. ING Economisch Bureau (2014) mentioned that hospitals are not always rescued anymore by stakeholders or government when they are in financial troubles. These influences on the healthcare sector make the introduction of technological changes harder. Because hospitals still strive to give their patients the most advanced care possible, they have to think of smart ways to finance it. One major problem in this is that, because of the economical crisis, banks are less willing to give big loans. So, investments in medical equipment need to be carefully planned. Next to that, hospitals have to strive to use their equipment as efficient as possible, by for example increasing the productivity (Meijer, Douven, & Berg, 2010).

To cover all these sector changes, Siemens Healthcare Nederland has introduced MES contracts. In Section 2.3, the MES contracts and its benefits are explained more in depth.

2.3. Managed Equipment Service contract

It has become more and more important for companies to deliver not just goods or just services (Vandermerwe & Rada, 1988). Already in 1988, Vandermerwe and Rada mentioned that a lot of industries were “Servitizating”. Companies were changing from delivering only a good or a service to complete bundles that consist of goods, services, support, knowledge and self service. Within these bundles there were different modules which customers could combine to make their own suitable package. Years after the introduction of service and goods contracts in several other businesses, this concept also reached the healthcare sector at the beginning of the 21th century. This happened for the first time in the United Kingdom and was named a MES contract (BeBright, 2013). It started as a request from the hospitals because of benefits in their tax payments. In 2009 Dutch hospitals also started with contracting MES contracts, even though there is no fiscal benefit in the Netherlands. In 2013, there were over 10 Dutch hospitals that made use of these contracts with Siemens or other suppliers (BeBright, 2013). Within Siemens, the Netherlands is together with the United Kingdom, Canada and Australia leading in the development of these special contracts.

A MES is a contract between a hospital and a private sector service provider, which states that the installation, management, maintenance and disposal of medical equipment, as well as training and reporting during the full lifetime of the contract, is the responsibility of the supplier (Siemens Healthcare UK, 2015). Siemens offers MES contracts in the area of medical imaging and laboratory solutions, healthcare IT and third party medical technology. No MES contract is the same. Dependent on the wishes of the hospitals the contracts can be adjusted.

Figure 1 shows the different services possible in a MES contract. Generally it could be divided into three categories, namely: Medical equipment, Extended services, and Planning and financing. As part of consulting under the header of Planning and financing, Siemens would like to give hospitals an objective recommendation about the optimal number of devices in their fleet, which will become possible with the outcomes of this research.

Even though there are no fiscal benefits in the Netherlands, there are other advantages for hospitals when they choose for a MES contract (Siemens Healthcare NL, 2015). At first, budgetary certainty is possible since all annual fees are fixed at the start of the project. Since the fee is levelled over the lifetime of the contract, there is no big peek in the cash flow when an investment has to be made. Levelled fees over the years make it possible for hospitals to have a good solvability. Moreover, it is easier to get loans from banks when a hospital shows that it has a good solvability. In times of economical change, this is an important advantage for hospitals. In return for the invested money, Siemens manages all key risks so that the uncertainties are reduced for the hospital and thus for their patients. Risks are for example covered because Siemens takes the responsibility for the maintenance of the delivered medical systems. And above all, a main advantage is that the hospital can make use of the newest technologies and the most up to date technical knowledge. This is accomplished by always implementing advanced systems at the hospitals and by the up to date knowledge of the application specialists which teach the hospital to use the equipment optimally. Moreover, when the installed base of equipment is big enough, there is the possibility to have a Man On Site (MOS) who is able to fix (small) malfunctions. Besides that, a hospital gets priority when failures of the equipment occur and with the help of the MOS the hospital is able to have direct contact with service managers when there are major malfunctions. This results in shorter response times when there are small defects and Siemens is able to act quick and adequate with bigger ones.

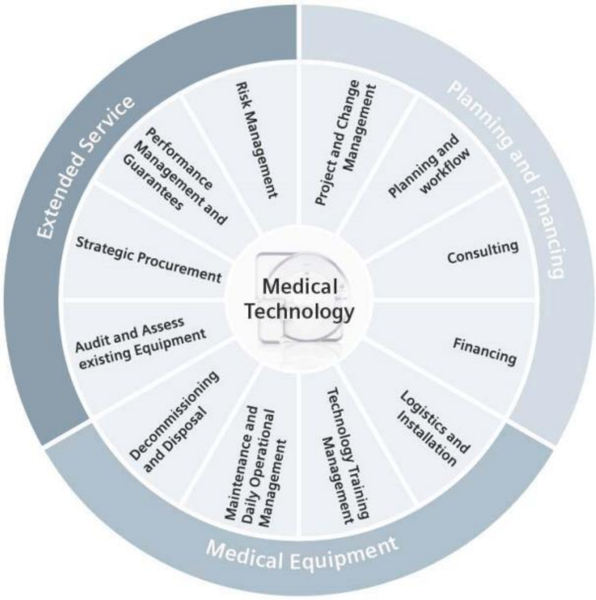

Figure 1: Managed Equipment Services

Now the history and benefits of MES contracts are known, it is time to look more closely at how the process of making a MES contract look like and at how the contracts generally work.

The development of a MES contract consists of three different phases; acquisition, commissioning, and execution. In the first phase, Siemens needs to make general calculations to present a first offer to the potential customer. The customer gets offers from multiple companies that want to have the job. The acquisition phase takes around 12 months. When the hospital has chosen to work with Siemens, the second phase starts and will take 3-6 moths. In this phase the real contract and exact calculations based on all preferences of the customer are made. Besides the MES contract, contracts with third parties are closed in this phase. These contracts are made to cover the service of already installed equipment from a third party. These contracts last until the equipment is replaced by Siemens equipment. The final phase of the MES contract is the execution, which takes, dependent on the contract, 15 till 40 years. During the execution of the contract, Siemens has to make yearly forecasts of maintenance to make sure they stay within budget.

The main part of the MES contract consists of the equipment, because without installed equipment, no maintenance and extra services, and thus no MES contract, are needed. The decisions of which functionalities of systems will be purchased at what moment during the MES contract are made at the beginning of the contract. The exact equipment that will be installed may differ in time because of technological changes. These decisions are visualized in a roadmap. Some changes to this roadmap are allowed during the contract, but this might have influence on the flat fee. An example of a roadmap is shown in Table 1.

Item	Year of first replacement	Replacement period (years)	Years														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CT	1	8	X								X						
MRI	4	7				X							X				

Table 1: Example of a roadmap

A first replacement could occur in the first period of the contract, as well as in a later period when there is already an existing medical device installed from Siemens or another company and it is still working properly. In that case, service on the existing equipment during the years prior to the first installation is also the responsibility of Siemens. Another option to have a first installation later in the contract is when the hospital expects growth and a device is added.

The replacement period of equipment denotes after how many years the systems need to be replaced. This period is determined by Siemens and its customer and is based on the technological improvements and the wear out time of certain equipment. Most of the times this period is 7 till 14 years, but in case of a very innovative hospital it could be decided by Siemens and the hospital to have a shorter interval between the replacements.

During the MES contract, the newly installed equipment is in general Siemens equipment, even when current medical devices are from a different manufacturer. There is a possibility in some contracts that a hospital keeps the freedom of choice in medical equipment for a certain percentage of the contract value. This means that a hospital is allowed to choose for a device from another supplier. A hospital could chose for this possibility when for example another manufacturer offers a more advanced technology. When a hospital wants to have a device from a third party, Siemens will arrange the installation and will still offer the maintenance. Besides the option of all kinds of equipment, different kinds of services could be added to the contract. During the contract lifetime, the systems stay owned by Siemens.

The cash flow associated with the installation of the equipment from the roadmap of Table 1 can be visualized in a graph. When this hospital has a MES contract, it could level the costs of purchasing the equipment over the duration of the contract. Without a MES contract, every purchase requires a new big investment. The cash flows of both options are shown in Figure 2. The prices of the equipment are fictional.

The yearly fee for a hospital when having a MES contract is not just determined by the installation of equipment. Several extra services, like education and consultancy are made in the contract as well. Besides that, maintenance is included in the contract. In consultation with the customer, Siemens describes in its contracts how much uptime they guarantee per year per device. Besides that, they decide on the service windows. These service windows denote at what moments Siemens provides service to the customer. Crucial equipment could for example have a 24/7 service window, whereas less important devices are serviced only on weekdays and normal working hours. When this service level is not achieved, Siemens has to pay a penalty to the customers. Customers could also choose for extra options like upgrades, virus protection, and flat panel detectors.

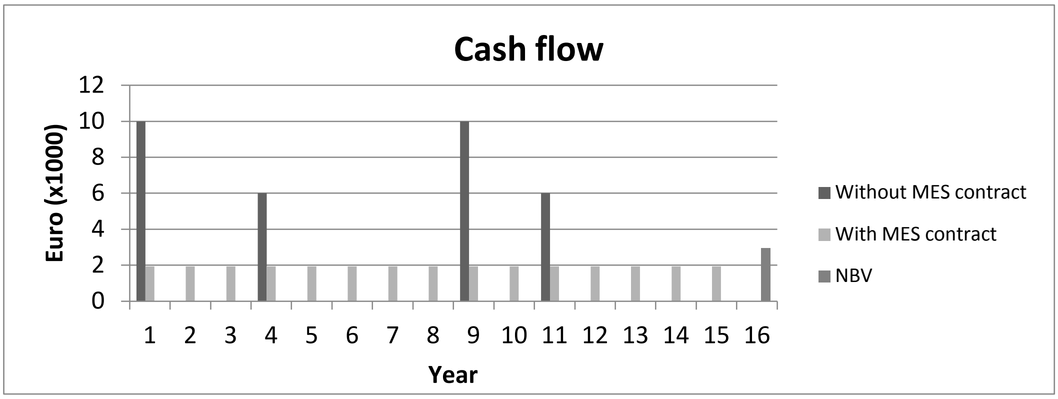

Figure 2: Example of the cash flow with and without a MES contract

2.4. Summary

In the context analysis we found that the healthcare sector has changed over the past years and that it will keep changing in the future. The main reasons for these changes are the demographical pressure and financial pressure on the market where Siemens Healthcare Nederland B.V. is operating in. At first since there is more and more demand for technological solutions in the healthcare due to an ageing population and the associated higher total morbidity. Secondly, we see that the economical crisis made patients to be more critical on the costs of care and it made banks less keen on providing loans for investments. In order to support hospitals in the changing environment, Siemens Healthcare Nederland B.V. offers MES contracts which contain equipment, maintenance and extra services. Siemens' customers with these contracts pay a levelled yearly fee to prevent peaks in the hospital's cash flow when new equipment needs to be purchased.

3. Literature review

This chapter contains a review of available literature of the subject TCO. The goal of the review is to gain knowledge about different models and cost elements within these models. Insight in the TCO makes it possible to create the model that evaluates possible solutions in order to decide on the number of devices with minimal total costs. Relevant articles in this field of interest are summarized in order to form a theoretical framework for the development of the model.

Section 3.1 investigates the origin of TCO, the concept of TCO, and it concludes with the benefits of making use of TCO. After the introduction of the concept, practical applications and roadblocks for implementing a TCO approach are studied. The second section, Section 3.2, describes the literature that is currently available about models that calculate the TCO. It is possible to use different cost elements in a TCO model to make it applicable for specific cases. Section 3.3 discusses these cost elements. This chapter concludes in Section 3.4 with a summary of the findings of the literature review.

3.1. Total cost of ownership

The cost of a product is more than just the purchase price. Besides the price, there is the possibility that a lot of other expenses are included in the purchase of a product. The product could, for example, break down early or maintenance is needed. Besides that, it might be possible that extra trainings and services have to be paid to be able to make use of the purchased product. A study shows that only less than 15% of a company's total costs is the actual purchase price (Snelgrove, 2012). Therefore a purchasing decision should not be only based on the price of the product.

The foundation of the TCO research is built by L.M. Ellram, an American assistant professor of Purchasing and Logistics Management. Alone and together with S.P. Siferd, she did a lot of research in defining the concept, benefits, barriers and the possible applications of TCO.

3.1.1. History

Before 1980, a lot of American firms based their purchasing decision on the bottom line of a supply contract or on the lowest bid of a company (Ellram & Siferd, 1993). Inventory costs or de costs of poor quality were not taken into account in this decision. Since the 80s the view on purchasing changed dramatically. Companies started realizing that they could not just trade the price and still keep good quality. Cavinato (1992) found evidence that the change towards total costs and value instead of individual costs was also visible in practice. Big companies, like Ford and Boeing, showed this new orientation. According to Ellram and Siferd (1993), literature around 1930 already mentioned the broader vision on purchasing, but it lacked a systematic way of determining all relevant costs involved in a purchase. The lack of a procedure for cost calculations that take more than just the price into account, might be the reason that it took years for companies to change their purchasing behaviour.

The first time the phrase "total cost of ownership" was used, was in 1987 by Bill Kirwin from Gartner consulting group (Snelgrove, 2012; Uyar, 2014). It was applied in the information technology field and helped to calculate the costs of owning a desktop device including technical support, maintenance, training and development, administration, capital and end-user costs. From that moment on, a lot of research is done on the concept of TCO.

3.1.2. The concept

TCO is defined as follows: "TCO is a purchasing tool and philosophy aimed at understanding the relevant cost of buying a particular good or service from a particular supplier" (Ellram & Siferd, 1998). A TCO approach takes into account all costs associated with the acquisition, use and maintenance of an item (Ellram & Siferd, 1993). This makes sure the company does not only focus on the moment of purchase, but it forces the company to look at the whole life-cycle of a product. The firm needs to consider the activities they perform that cause costs in all points of time. Overall, it could be said that TCO looks at the 'true' costs of a purchase from a supplier (Ellram & Siferd, 1993).

Even though it might look like that TCO is the highest level of making strategic purchasing decisions. Cavinato (1992) placed it in a theoretical framework which showed to different stages of development of a company (Cavinato, 1992). The framework examined the whole evaluation of a firm towards the use of total costs for supply chain competitiveness, which contains five steps:

I. Lowest price
II. Lowest landed cost
III. Lowest total cost to the firm
IV. Lowest total cost to the final firm in the entire supply chain
V. Highest total value to the ultimate customer of the final firm in the supply chain.

At the lowest level of development, companies' purchases are just based on the lowest price. Scientific articles on budgeting and control systems before 1920 were all making use of this principle (Cavinato, 1992). The highest level of development is a view on the total value for the ultimate customer. By maximizing this total value, every part of the supply chain will have the responsibility for their portion of the value-added. The development towards the use of TCO, level three and four, is thus not even the highest level of development, because maximizing the total value for the end customer goes even beyond it.

3.1.3. Benefits of TCO

Even though TCO is a complex way of getting a better understanding of the costs involved when purchasing goods, it could have a lot of benefits for a firm (Ellram, 1993). Ellram categorized the benefits under five different headings.

- Performance measurement
- Decision making
- Communication
- Insight/Understanding
- Support Continuous improvement

At first, the application of TCO helps with measuring the performance of the firm. It is a concrete way of measuring and therefore excellent for benchmarking. Secondly, when the TCO is known, it could help with decision making. Based on quantitative data, a better informed purchasing decision can be made. TCO calculations contain information and data from different departments of a company, therefore communication within the company will improve. Also the external communication between supplier and the firm improves when using TCO because of the required transparency of the supplier. The fourth benefit is the most obvious one. TCO provides excellent insight and data for comparing supplier performance and negotiations. It also gives insight in the long term vision, the 'big picture'. The new gained insights from a TCO analysis show opportunities for cost savings and therefore, the TCO helps to improve continuously. Considering all these benefits, it could be said that TCO is an important instrument for purchasing management and supports a more strategic focus by including the long term costs (Wouters, Anderson, & Wynstra, 2005).

3.1.4. Application

TCO is a good tool to use in purchasing management, since it takes all costs incurred with the purchase and use of a product into account in a systematic way. Many researches are done on the role TCO could play in different purchasing processes. There is a lot of difference between the purchases of different products. Therefore many case studies are available in literature. This literature review will only focus on major changes in applications of the TCO concept in purchasing management.

In the nineties research is mainly focused on the selection of one item from one supplier at one time period (Ellram, 1995b; Ellram & Siferd, 1993). This one product could be a service, MRO, a component, capital for production, capital for support or raw materials. When a firm needs to purchase a new product, it could calculate the TCO of the offers of every supplier. As a result, a company is able to select the supplier with the lowest TCO for the selected item at that moment.

Degraeve and Roodhooft (1999) extended the use of TCO to be able to select multiple suppliers when being able to select different order sizes for multiple time periods (Degraeve & Roodhooft, 1999). This is useful in the situation where the ordering costs and batch costs play a significant role in the TCO and when there is a big difference for those costs between the suppliers. They created an optimization by using mathematical programming for the specific case of a Belgian multinational steel producer. Because the model was validated by using just a small case, further research was needed. A few years after the development of the mathematical optimization model in 1999, an extension of the model was made (Degraeve et al., 2005). By the implementation of the model at another company than the steel producer of the research from 1999, the researchers validated the extended model and thus as well the old model.

Besides the application of TCO to purchase one or multiple products, the concept can be used for other goals. In the framework of Cavinato (1992), which is described in Section 3.1.2, the author mentioned that the fourth level is reached when companies are able to minimize the total costs for the final firm in the entire supply chain (Cavinato, 1992). This view is broader than just selecting the best supplier for one company. Minimization of the total costs for the final firm in the entire supply chain is only possible when looking inside each firm of the supply chain. The result of this approach is that companies enjoy greater sales and they have competitiveness gains compared to other chains. Even though the usefulness of calculating the total cost over the entire supply chain was already mentioned in 1992, little research is done on using TCO on more than just one part of the chain. Caniato, Ronchi, Luzzini, and Brivio (2014) develop a model that calculates the TCO in the tinting industry for a machine manufacturer, the paint producer and the final retailer and thus the entire supply chain (Caniato et al., 2014). The authors find, in line with the literature, that the use of TCO is a good tool to evaluate suppliers. Besides that, they see that it is also relevant for sales support or as a marketing tool. When the vendor has insight in the issues of its customer, the vendor could select the right product to sell. Finally, internal insight highlights possibilities of cost reduction. Even though Caniato et al. (2014) look at the interaction effect, they do not quantify it. They offer just suggestions on interesting effects, but without mathematically optimizing it. The research by Caniato et al. (2014) shows that there is potential for further research on the influences of the costs of one part of the supply chain on the whole supply chain.

The highest level of development stated by Cavinato (1992) is the view on the total value to the ultimate customer of the final firm in the supply chain. This goes even beyond just looking at the total costs involved. Snelgrove (2012) states that the customer is willing to pay if the vendor is able to quantify the benefits of buying the product (Snelgrove, 2012). Therefore his view on the future is that TCO calculations will not just be about the costs but also about the total value created for the customer. This is in line with what Cavinato (1992) saw as the ultimate development for a strategically oriented firm. It is remarkable that this is still seen as a future perspective in practice, even though it was already mentioned in literature twenty years earlier.

In general TCO computations can be used, besides the selection of one or multiple suppliers, as a way to measure the consequences of performance improvements and to evaluate alternative policies of a company with respect to the number of suppliers, the number of orders and the minimum or maximum quantities in an order (Degraeve, Labro, & Roodhooft, 2000). Caniato et al. (2014) add to this list the possibility of improving the total costs of the supply chain.

3.1.5. TCO in practice

Section 3.1.3 has shown a lot of benefits for companies to make use of TCO. However, there are some roadblocks that make the application of TCO harder. The effect of the barriers was visible in practice trough the years, because a lot of companies had a hard time to implement the TCO concept in their purchasing decisions (Ellram & Siferd, 1993; Ferrin & Plank, 2002; Milligan, 1999).

Researchers through the years defined possible roadblocks for the implementation. Ellram (1994) shows several major roadblocks that might occur when a company implements TCO. She categorizes the barriers under three different headings (Ellram, 1994). At first there are cultural issues. Companies might feel resistance to changing their behaviour and therefore it is hard to move away from the price orientation. Secondly, education might be a road block when implementing TCO. Without the right knowledge, it is hard to identify relevant costs. Besides that, employees could think the TCO is too inflexible and theoretical. Because of lack of experience, companies are not confident enough to rely on the outcomes of the TCO calculations. This little experience is still mentioned in 2005 under purchasing managers (Wouters et al., 2005). The last factor that makes the implementation of TCO harder is the availability of resources. The lack of data is a major point under this heading. Without the right data, representative calculations cannot be made. Also resources in manpower to develop, implement, and maintain the TCO calculations could form a barrier.

In 1995, Ellram adds some extra points that slow down the implementation of TCO analyses to this list (Ellram, 1995b). She mentions that there is no standard approach available in literature or practice for TCO. This makes it very hard for companies to start with the implementation of the concept. To help a company to develop a unique TCO model, education is needed.

Geissdoerfer, Gleich, Wald, and Motwani (2009) find as a result of a survey under 59 German, 30 U.S, and 9 other companies that the main reasons why companies do not use TCO are resource dependent (Geissdoerfer et al., 2009). Most of the time there are not enough resources available which is related to the fact that companies think TCO modelling is too time consuming. The lack of standard models might be the reason why it takes too much time to develop and use a TCO approach. Besides that, the customers do not require from a company that they have calculated their TCO when it acts as a vendor.

3.2. TCO models

Geissdoerfer et al. (2009) mentioned in 2009 still a lack of a standardized model, even though there has been quite some research done in the past. From the moment TCO got introduced, people have tried to determine whether it is possible to make a standardized TCO model that is applicable in all cases. A standard model would indicate that basically the same cost elements are considered for each buy with a standard format (Ellram, 1995b). Therefore it can be used for a variety of purchases

(Ellram, 1994). The model is 'ready to go' when a new purchase has to be examined. In a study performed by Ellram (1995b) under eleven manufacturing companies, most of the organizations used unique models and thus they made a new TCO model for every new purchase. There were some factors, such as quality, delivery, and service, which were shared by some of the models, but the specific costs in these categories differ between all models. Companies mentioned that standard models are not possible because purchases vary a lot. Besides that, the TCO using firm wants to be flexible in cost modelling by being able to adapt it to their needs, to adapt it to various buys and to react on changes in internal focus. On the other hand, there is a desire to have a user friendly and easy to use standard TCO model which can be computerized. The sample size in this study might not be completely representative, but there was little research done until 1995 on TCO and the research gives a broad but limited picture of TCO practices.

The vision that there is no standard TCO model possible is shared by the research of Ferrin and Plank (2002). A single-wave mail survey was send to members of the Institute for Supply Management to gain information about the use of TCO (Ferrin & Plank, 2002). The goal of the survey was to find whether there is a standard TCO model possible, and if there is not, whether it is possible to determine a core set of cost drivers that can be used in most of the models. One hundred forty-six people replied on the information request. The researchers suggest that there will not exist a standard TCO model, but there are some cost drivers that are more universal than others.

Besides the opinion of the users of TCO models, which was shown in literature of Ellram (1995b) and Ferrin and Plank (2002), the lack of standard models is also visible in literature. A lot of case studies are performed in literature to determine the TCO of a purchase. These case studies are mainly unique and there is little potential to generalize the models. Some authors accomplished to make a more generic model, but these are most of the times still specific for a branch, company or specific goal.

It could be concluded that there is no standard model available which can be easily implemented in different cases. Geissdoerfer et al. (2009) state that a standardization of the TCO model is needed to increase the usage of it among companies (Geissdoerfer et al., 2009). A standard model will save a lot of time and it will become easier to compare the calculated values (Geissdoerfer et al., 2012). Moreover, the buyer-supplier relation will be more efficient when using a standard model. The supplier knows when he uses the same model what the purchaser's criteria are, and can therefore give a better offer to its customer.

To make the development of a standardized model more realistic in the future, Geissdoerfer et al. (2012) gathered seven general requirements for a standard TCO model from existing research (Geissdoerfer et al., 2012). This list is an adjustment of their list made in 2009 (Geissdoerfer et al., 2009). The requirements are listed below:

- Enable the integration of qualitative factors
- Period for consideration
- Overall equipment efficiency
- Cost categories and cost drivers
- Transaction costs
- Accuracy of the models
- Activity-based costing as a basis

Based on the requirements of a standardized model, Geissdoerfer et al. (2012) propose a modular structure that forms a basis for the standardized model, which is shown in Figure 3. The modules refer to some of the requirements of a standardized model. As can be seen in the in Figure 3, all TCO models should have in common that they calculate the NPV. This is in line with the statement of Humphries and McCaleb (2004). Costs in TCO are calculated over a long time period or over the whole lifetime of a product. The value of money changes over time and therefore using a discount rate makes sure that the calculations give a good representation. Including qualitative factors, transaction costs and equipment performance into the TCO model is optional (Geissdoerfer et al., 2012). The choice of including these factors may be influenced by contextual factors like country, sector, company size and organisational units. Transaction costs for capital goods account for example for less than 5% of the total cost. Therefore, these costs are hardly used in TCO models for that objective.

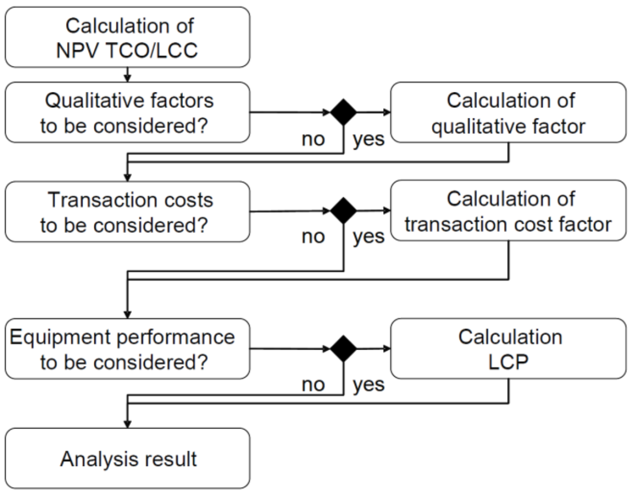

Figure 3: A standardised model with a modular structure (Geissdoerfer, Gleich, Wald, & Motwani, 2012)

After determining the modular structure of a standardized model, Geissdoerfer et al. (2012) constructed several very general, high level mathematical equations describing the TCO calculations. At first, they say that the object that is examined needs to be clear. This could be a capital good, or a sub assembly, raw materials etc. The overall objective of the calculation is to calculate the total costs C, which can be derived from the sum of all the cost categories Cc_i where i denotes the cost categories. This is the second step described by Geissdoerfer et al. (2012).

$$C = \sum_{i} Cc_i \tag{1}$$

The third step is the calculation of the Net Present Value. From every category the NPV needs to be taken by discounting the costs of each period *p* by the discount rate *r*. The C_p denotes in this case the net cash flow of a period.

$$NPV\ C = \sum_{p=0}^{n-1} \frac{C_p}{(1+r)^p} \tag{2}$$

The article of Geissdoerfer et al. (2012) gives also formulas on how to include the three optional requirements. The developed Equations 1 and 2 are general and therefore the model does not say how all cost elements can be calculated.

Even though the model of Geissdoerfer et al. (2012) is nearest by a standardization of a TCO model, there is no ‘ready to go’ model available in literature. Therefore it can be questioned whether there will ever be a standard model for a TCO calculation.

3.3. Cost elements

One of the most important factors of a TCO calculation is that the right costs are included. When a major element is missing, wrong conclusions are drawn from the model. As stated before, the TCO calculation should include all costs associated with the acquisition, use and maintenance of an item. Each of these three areas include many different cost elements that could be included into a model. Ellram and Siferd (1993) defined six main purchasing activities which contribute to the TCO. These activities are: management, delivery, service, communications, price and quality. But still all of these activities contain several cost elements. The selection of which costs need to be included in the model can be described by the Pareto Law; you choose 20% of all factors that account for 80% of the total costs (Ellram, 1994).

As mentioned before, Ferrin and Plank (2002) did a survey to find out whether there are some core cost elements that are used in almost all TCO calculations in practice (Ferrin and Plank, 2002). The majority of the people answered the question on the existence of a core set of cost drivers that apply to every commodity or commodity category. The result of the questionnaire indicates that most of the surveyed members think this core set exists. Besides that, the majority agreed with the statement that there is a set of cost drivers relevant only to specific commodities or commodity categories. The existence of a core set does not exclude the existence of the set of case specific drivers. In an open question of the research of Ferrin and Plank, the responders were able to suggest key cost drivers for TCO purchasing. A set of 237 drivers was collected by the authors. The authors categorized the core drivers in 13 different categories, which are listed below.

- Operations cost
- Quality
- Logistics
- Technological Advantage
- Supplier Reliability and Capability
- Maintenance
- Inventory Cost
- Transaction Cost
- Life Cycle
- Initial Price
- Customer-Related Costs
- Opportunity cost
- Miscellaneous

Geissdoerfer et al. (2009) acknowledged that the core cost categories are dependent on the object of interest of the TCO calculation (Geissdoerfer et al., 2009). They investigated which cost groups are mostly used in TCO calculations for purchasing a capital good, or raw materials, services etc. This research was done based on information of 98 different companies, mostly from Germany and the United States of America. They investigated, based on the thirteen categories mentioned in the research of Ferrin and Plank (2002), how many companies consider each cost category/cost driver in their application of the TCO model. The result of this research is shown in Table 32 in Appendix A. The information provided by the assisting companies suggests that some of the core cost categories are more often generally applied than others. Big differences are visible between the different objects of interest (capital goods, raw materials, MRO etc.). For example, the initial costs are used in 81% of the times when purchasing a capital good, where only 38% of the companies used that category when purchasing a service.

The authors selected from the thirteen core cost categories five that are used most often to analyze more in depth. The five chosen categories are: Initial costs, Operating costs, quality costs, logistic costs and maintenance costs. Even though the category capabilities/reliability of suppliers should be part of this group based on the sum of the percentages, the authors chose the maintenance costs instead. The difference in total percentage of those two categories is minimal. Geissdoerfer et al. (2009) specify cost elements in the five categories for all objects of TCO analysis and analyze how often these cost elements are used in practice in a model. Because this research is focused on capital goods, just the findings for the purchase of these items are shown in Table 2. The whole table is presented in Appendix A.

Initial costs	
Price (incl. spare parts & warranty)	82%
Reconstruction costs	32%
Setup/installation customer/supplier	18%
Operating costs	
Labour	46%
Tooling/consumables	39%
Operating supplies (Energy, gas, etc.)	32%
Floor/space costs	18%
Quality costs	
Failure costs	18%
Inspection costs	14%

Logistic costs	
Freight/transport costs	18%
Duties and taxes	7%
Packaging	4%
Maintenance costs	
Labour	32%
Spare parts	46%
Special tools/measurement devices	18%
Service costs	25%
Downtime costs	39%

Table 2: Use of cost categories and cost drivers of capital goods in practice (Geissdoerfer et al., 2009)

Remarkable is that neither Geissdoerfer et al. (2009) nor Ferrin and Plank (2002) specified what they understand under the defined cost elements. Both researches just mention the names of the elements. Therefore it is unclear why the spare parts are mentioned twice and what is included in the service costs which is part of the maintenance costs.

When creating a TCO model, the cost categories and drivers mentioned in Table 2 with a threshold of 25% could be used, according to the authors. Most of the cost elements that will be used for capital goods are within the category of the initial costs, operating costs and maintenance costs. In the end, the user of a TCO model should always decide on whether the cost elements are relevant to its specific case. Missing elements should be used and the proposed elements to include in the model should be critically reviewed.

The conclusion for cost elements in a TCO calculation for capital goods, by Geissdoerfer et al. (2009), is in line with research performed by Öner, Franssen, Kiesmüller, and Van Houtum (2007). Öner et al. (2007) perform a Life Cycle Cost Measurement (LCCM) for an Engineer-To-Order company which delivers capital goods. Life Cycle Cost measurements are a subset of TCO calculations, because they take only take transaction and post-transaction cost factors into account (Ellram, 1995a). Based on a Cost Breakdown Structure (CBS) analysis, Öner et al. (2007) determined five 'cost buckets' that cover the main costs for the purchase of technical systems. These cost categories are: acquisition costs (price, installation, spare parts, etc.), maintenance costs, operating costs, downtime costs, and disposal costs. Where Geissdoerfer et al. (2009) put downtime costs under the heading maintenance, Öner et al. (2007) make a different category. However, when they implement their model, they ignore these costs based on expert opinions. This is in line with the research of Geissdoerfer et al. (2009), where the authors find that disposal costs are barely used in practice for capital goods TCO models.

The information from Table 32 and Table 2 is based on how often companies used a cost element in their calculations. Ellram (1994) stated that the cost elements should be included according to the Pareto Law. This means that 20% of the cost elements included in the model should account for 80% of the total costs. Geissdoerfer et al. (2009) quantify the costs of each element compared to the overall costs in percentages. This was done based on information of just 1 till 4 companies, which does not give a representative value. The authors state that it could only be used for companies that have no clue about the distribution of their total costs over the cost elements. So, besides the test on how often cost elements are used, no validated information is available that tells the size of the share on a cost element in the total costs.

More information on the size of every cost category in TCO calculations for capital goods can be found in some implementations of TCO in the literature. The results of three TCO/LCC calculations are visible in Table 3. In the research of Öner et al. (2007) development costs are not taken into account, whereas Meutstege (2007) neglects the costs of running the equipment. The research of Gupta (1983) does not specifically distinguish maintenance costs, but covers support costs by the operations costs.

	Öner et al. (2007) *Engineer-To-Order systems*	**Meutstege (2007)** *Analytical instrumentation equipment*	**Gupta (1983)** *Weapon systems*
Development costs	N/A	2,6%	2%
Acquisition costs / Production costs	23%	64,9%	21%
Maintenance costs	27%	32,5%	77%
Operations costs	2%	N/A	
Downtime costs	48%	N/A	N/A

Table 3: Share of different cost categories in TCO

Conclusions that can be drawn from Table 3 are that it is very dependent of the scope of the TCO calculation which cost elements are relevant to take into account since the shares differ a lot between different researches. However acquisition costs/production costs have a significant influence on all calculations. Besides that, maintenance costs play a major role in the total costs over the lifetime of a product.

3.4. Summary

To calculate the total costs involved over the lifetime of a product we can use the concept of TCO. This concept takes into account all costs associated with the acquisition, use and maintenance of an item (Ellram & Siferd, 1993). We see that TCO is mainly used in literature to select a supplier or monitor the performance of a supplier (Ellram, 1995b; Ellram & Siferd, 1993). Even though there are a lot of benefits for the use of a TCO model, the concept is not generally applied in practice (Ellram & Siferd, 1993; Ferrin & Plank, 2002; Milligan, 1999). Roadblocks are found in cultural issues, education/training issues, and resource issues (Ellram, 1994). We found several studies on the question whether or not there exists a standard model for TCO calculations (Ellram, 1995b; Ferrin & Plank, 2002). Overall, we can conclude that models will always have some unique elements, so besides a very general representation of a TCO model by Geissdoerfer et al. (2012), no standard model is available. Researchers agree on the fact that there is a core set of drivers which make up most of the models (Ferrin & Plank, 2002; Geissdoerfer et al., 2009). Geissdoerfer et al. (2009) investigated whether the choice of objective, for example raw materials or capital goods, influences which cost drivers are relevant to use in a model. From this research we conclude that for capital goods, and thus for medical equipment, the initial costs, operating costs and maintenance costs are advised to be included into a TCO model. When we looked at some implementations of TCO or LCC, we found that mainly the price and maintenance costs are responsible for a big part of the total costs over the lifetime of a product. However, these examples were not only on capital goods. Our last important finding is that Geissdoerfer et al. (2009) mention that it is important to stay critical on including their determined cost elements into a model, because no capital good is the same.

4. Model design

In order to be able to decide on the optimal number of devices in the portfolio of a hospital, based on minimal costs of owning all devices, a model is designed. The model determines for every period the number of devices and associated opening hours that are needed to meet the expected demand of those periods. A decision on the number of equipment is made based on the minimal total cost of ownership of all devices together, so alternative solutions are evaluated by the calculation of the TCO. Chapter 3 provided information about the TCO models described in literature and possible cost elements that can be used in a TCO model. In order to find the optimal number of devices at all periods, a model to calculate the TCO of medical equipment is developed. The design of our model is described in this chapter and is done by combining the literature review with input from Siemens and the hospital.

The conceptual TCO model is described in Section 4.1. That section provides the global calculations for determining the total costs when knowing the costs of all cost elements. Besides that, Section 4.1 provides the cost elements used for our model which are determined by the input of literature, Siemens and Hospital A. Once the basics of the TCO model are explained, the model is described in more detail in Section 4.2. That second section shows how every cost element is calculated. The third section, Section 4.3, describes the constraints for a possible solution of the model. Section 4.4 shows the last part of the model, the optimization model that determines the number of devices and the associated opening hours to minimize the TCO. The last two sections of Chapter 4 look at the use of the model in practice. In order to implement the model for Siemens, adjustments to the model are made in Section 4.5. The implementation is finally given in Section 4.6.

4.1. Conceptual TCO model

The construction of the conceptual model of the TCO calculations consists of several steps. At first, in Section 4.1.1, the general model to calculate the total cost of ownership of medical equipment at a hospital is determined. This model is very global and does not yet include the specific cost elements that are relevant to this case study. Therefore, the second step is to determine which cost elements are important to take into account in the TCO calculations, which is shown in Section 4.1.2. Since this research is based on a on the specific case of a MES contract, which covers, among other things, the purchasing price and the maintenance costs, the pricing of a MES contract is examined in Section 4.1.3. The last part, Section 4.1.4, summarizes all cost elements used in the TCO model.

4.1.1. Global TCO model

TCO calculations take into account all costs that occur during the lifetime of a product. MES contracts have finite endings and therefore it is possible that the medical equipment is not at the end of its lifetime when the contract is finished. Because Siemens assumes that the contract will be continued, an infinite time horizon is assumed. Therefore, the basic principle of TCO is still applicable in the case of the medical equipment of Siemens and its customers.

There is just one general standard model for a TCO calculation found in the literature. Geissdoerfer et al. (2012) proposed that a model could consist of different modules, shown in Figure 3. The model is build up by four different modules namely: the Net Present Value, qualitative factors, transaction costs and equipment performance. Including qualitative factors, transaction costs or equipment performance in a model is optional, and depends on the specific application, while all TCO models should use the NPV of the costs. These modules does not say anything about the quantitative cost elements, which are discussed in Section 4.1.2.

This research will only take quantitative factors into account. Qualitative factors like delivery performance, supplier support etc. are not relevant in this case because there is just one supplier and the performance will be the same for all alternative solutions. Transaction costs account for less than 5% of the TCO when purchasing capital goods (Geissdoerfer et al., 2012). Furthermore, the transaction costs of Siemens are mostly included in the price of the MES contract, and those for the hospital are hardly comprehensible. So, for our model, the transaction costs are neglected. The last module, equipment performance, is also not applicable to our model. All possible purchasing options are assumed to have the same equipment and thus there is no difference in performance. This leaves the standardized model of Geissdoerfer et al. (2012) to just taking the NPV of the sum of all cost elements of every period.

Once decided on the different modules proposed by Geissdoerfer et al. (2012), the design of the TCO model for medical equipment could start. In order to calculate the TCO, several steps need to be taken. At first, the cost elements that play a significant role in the total costs have to be determined. The decision on these costs is made in the Section 4.1.2. Once these elements are known, the costs (C_p^k) of a cost element $k \in K$ at every period $p \in P = \{1 \dots T\}$ over all equipment needs to be calculated. In Section 4.2, the calculations for every cost element are described.

When the costs of every cost element are known at every period, the second step can be taken. The second step calculates the total costs for a period (C_p). This is done by summing the costs of all cost elements in that period (C_p^k).

$$C_p = \sum_{k \in K} C_p^k \qquad \forall p \in P \tag{3}$$

The third step is to take the NPV of the costs of every period (C_p) over the whole horizon; the cash flow. Taking the NPV makes sure a good representation of the TCO is given. The value of payments may differ in every period, and therefore paying the same amount in two different years, may influence the TCO value. Calculating the NPV of the cash flow is done by discounting every period with the discount rate d. Even though the moment of payment might differ between contracts, it is assumed that it takes place at the beginning of a period since this happens most of the times. The end result of this calculation is the TCO of Equation 4.

$$TCO = NPV\ C = \sum_{p \in P} \frac{C_p}{(1+d)^{p-1}} \tag{4}$$

Keep in mind that the indices from this model differ from the indices of the model of Geissdoerfer et al. (2012). A list of indices, variables and parameters can be found at page XI .

Equation 3 and 4, do not say anything about the calculation of the value of the cost elements. A decision on which cost elements k to use in the model should be taken first. This is done by combining literature with the information provided by Siemens and the cooperating hospital.

4.1.2. TCO cost elements for medical equipment

In Chapter 3, literature has shown that there is no standard model for cost elements available to determine the TCO of a product. However, several authors agreed on the existence of a core set of cost elements where a model could be based on (Ferrin & Plank, 2002; Geissdoerfer et al., 2009). The thirteen categories of costs which could be included into a model are given in Section 3.3. Geissdoerfer et al. (2009) suggest to select the cost elements based on a threshold value of 25% of the most often used elements by the surveyed companies. The cost elements for capital goods based on this threshold value are shown in Table 4.

Mentioned by:	Geissdoerfer et al. (2009)	Siemens and Hospital A
Initial costs	Price (incl. spare parts & warranty)	Acquisition (warranty and disposal)
	Reconstruction costs	
Operating costs	Labour	Labour
	Tooling/consumables	Tooling/consumables
	Operating supplies (Energy, gas, etc.)	Operating supplies (Energy, gas, etc.)
		Floor/space
Maintenance costs	Labour	Labour
	Spare parts	Spare parts
	Service	Service
	Downtime	Direct downtime

Table 4: Cost elements mentioned by literature (left) and by Siemens and Hospital A (right)

Besides the three cost categories of Geissdoerfer et al. (2009), two other cost groups are considered in literature. Öner et al. (2007) suggest to take disposal costs into account, but experts in the scope of research of Öner et al. (2007) mention already that these costs are negligable. This result is in line with the research of Geissdoerfer et al. (2009). After talking to experts within Siemens, there is decided that the disposal costs can be neglected as well in the case of medical equipment. This is done since these costs are already included in the purchase price of equipment. Meutstege (2007) takes the development costs into account as well. In the TCO for the customers of Siemens, these costs are not taken into account either, because they are included in the price of the equipment.

The definite cost elements used in the model are not just decided based on literature. The expertise from Siemens and the cooperating hospital are taken into account as well. The cost elements mentioned by these two parties are given in Table 4 as well. There are a lot of similarities and just some differences between the expertise from literature and from Siemens and its customer.

At first, the ‘reconstruction costs’ of the replacement are too hard to take into account because it is completely dependent on the hospital and the equipment and therefore unknown in the acquisition phase. That is why these costs are not included in the model. Secondly, un the category of tooling/consumables both parties highlighted that they want the focus on the consumables which are named disposables in the healthcare. Tools for the use of equipment are mostly included in the purchase price or can be neglected for this research. A cost element mentioned by both parties, that did not make it on the list of important cost elements for capital goods by Geissdoerfer et al. (2009), are the floor/space costs. This cost element is independent of the opening hours, but it will change when new equipment is added. Because Siemens and the hospital expect that the floor/space costs will play a significant role in the TCO, these costs are included in the model. Since it is not possible to quantify the effect of downtime on, for example, the patients health or on the competitiveness among other hospitals in this research, it is only possible to take the direct costs made by the hospital during downtime into account. This contains of the costs made for disposables etc. which are already prepared for the examination and cannot be used twice. The last important difference between the Siemens case and the literature, is the way of pricing the MES contract. Therefore the pricing process is explained in more detail in the Section 4.1.3.

4.1.3. MES contract pricing

In the special case of the purchase of medical equipment from Siemens by having a MES contract, several costs for a hospital are combined and levelled through the years, see Section 2.3. The decision of having more or less equipment installed will change the price of the MES contract and will thus have influence on the TCO. To optimize the purchase of the equipment, the pricing of a MES contract needs to be examined. Insight in the effect of changes in the portfolio on the price of the contract is needed to calculate the effect of it on the TCO.

A MES contract covers the acquisition costs and the maintenance of the equipment.. Besides these two expenses, a MES contract consists of several more expenses. Examples of these costs are training of end users and consultancy. These costs, named Extra MES costs, will be taken into account in the model because they influence the price of the MES contract and the extra costs give a more representative view of the total cost of owning the equipment. The operating costs are still the responsibility of a hospital

The maintenance costs of a MES contract cover all the labour that is needed to repair or maintain the installed equipment. Besides that, the spare parts are owned by Siemens. This is beneficial for a hospital, since Siemens owns with all MES contracts together many more devices than one hospital does and therefore better inventory management is possible which results in lower inventory levels due to the risk pooling effect. The service costs, which are the expenses associated with external companies performing maintenance, are included in the partnership as well. The hospital does not have to contact external companies, because Siemens is responsible for all maintenance. This is even the case for equipment installed by other parties. Within a MES contract the labour for maintenance, spare parts, and service costs are covered under the name maintenance. Only the direct downtime which is also part of the maintenance costs, is the responsibility of the equipment owner.

4.1.4. Summary

The literature study combined with the expertise of Hospital A and Siemens, and the elements of a MES contract result in the list of Table 5 that contains the cost elements that are included in the model. The table shows as well where the data could be retrieved from.

MES (Siemens)	C^{MES}
Acquisition	C^{Aq}
Maintenance (Labour, spare parts & service costs)	C^{Ma}
Extra MES Service (Training, consultancy, etc.)	C^{Ex}

Hospital	
Labour (Operating)	C^{La}
Disposables	C^{Di}
Operating supplies (Energy, gas, etc.)	C^{Op}
Direct downtime	C^{Do}
Floor/Space (Exploitation)	C^{Fl}

Table 5: Cost elements in model, including distinction of the MES contract and hospital costs

4.2. Detailed model for calculating cost elements

Eight cost elements are included in the TCO model and are shown in Table 5. In order to calculate the TCO of medical equipment, more detail is needed on how to calculate the different cost elements. The way of calculating the costs that are included in the pricing of a MES contract, are determined first. This is done with the help of several Siemens employees. The second part of Section 4.2 describes the model of the hospital dependent cost elements.

There are several indices that are used throughout the whole model. These indices, the ones of the location, the equipment category and the items, are explained prior to the details of the different cost elements.

A MES contract with a hospital could cover multiple locations of that same hospital. This happens for example when two hospitals are merged in the past. The different locations should be distinguished in the model because the patients of one location are not interchangeable with those of another location. Therefore, every location should be able to process its own demand. A location is denoted by v ($\in V$).

There are several types of equipment in a hospital that all perform different types of screenings. For example, there are categories/departments like: MRI-scanners, CT-scanners, and Ultrasound-devices. It is named a category from Siemens' perspective and is identical to a department in a hospital and therefore these terms are used for the same thing. All categories/departments s together form the set S. Within every equipment category there are multiple models, for example the MRI MAGNETOM Amira or MRI MAGNETOM Skyra. Our model assumes that all devices within a category have the same cost parameters, except for the price of a device. These category parameters are for example the expenses for one hour of labour or the costs of energy for one hour. The cost parameters might differ between the cost categories. The use of the parameters is described when the associated cost elements are discussed.

An item i represents one installed device at the hospital. Every device is part of a set of devices. A set is described by a category (s) – location (v) combination and is for example the group of MRI-scanners at location one. These sets are needed because every group has their own demand of patients and has different cost parameters for cost elements like, for example, labour costs.

A set of items is denoted by $R_{s,v}$ ($s \in S, v \in V$). As mentioned before, an item i represents one installed device. Two installed devices of the same model have a different item number. All i's together in the whole hospital, form the set I. Every item is part of a set $R_{s,v}$, ($R_{n,l} \cap R_{m,k} = \emptyset \quad \forall n,m \in S; \ \forall l,k \in V \ \ when \ (n,l) \neq (m,k)$) and all sets cover together the whole set of items ($\bigcup_{s \in S, v \in V} R_{s,v} = I$). Besides that, it is impossible that an item is part of two different categories.

4.2.1. MES contract costs

The model that is developed in this research will be used in the acquisition phase of the MES contract. In this phase some detailed information is unknown. Due to the lack of information, the model will include some costs that are estimates of the definite costs.

Acquisition

The cost element a*cquisition* changes when there are changes in the portfolio of the hospital. Changes in the portfolio could occur in three different circumstances:

- When the replacement interval of an installed device is over and is thus considered as 'old', it gets replaced by a new device. The replacement period and the equipment is described in Section 2.3.
- The hospital grows and the current installed equipment is not enough to cover the demand. Therefore the hospital decides to add an extra device to their portfolio. This could happen at any period.
- The demand of patients for the hospital decreases and therefore the portfolio of equipment could shrink. A device is removed once it passed the replacement interval. A removal is not

allowed in the meanwhile, when the replacement interval is not over yet. However, during the replacement interval the hospital is able to adjust its opening hours to the decreasing demand.

The costs associated with the installed items and its changes, are expressed as acquisition costs. The acquisition costs of the equipment in a MES contract are determined by the depreciations of the equipment in the contract lifetime. The depreciation in a year is equal to the price of one piece of equipment divided by its replacement period.

Every item i has its own price p_i which is constant during the years. Items that are of the same type might have different prices because of different settings. The purchase prizes of the equipment are given from the business unit and are constant over time. So an installation of equipment at year 6 of the contract has the same price as an installation of the same functionality at period 8.

As mentioned before, the hospital pays only the depreciation of Siemens equipment during the contract, so not for the equipment installed prior to the start of the contract if there was no MES contract before. So the depreciation is taken from the moment that an item i is installed for the first time in the contract M_i (which does not have to be the first period of the contract), till the moment of removal L_i or till the end of the contract T. Where the moment of removal is dependent on the replacement interval. Whether a Siemens item i is installed within the contract, at a certain period p, is defined as $J_{i,p}$ which is equal to 1 if it is installed and 0 if it is not.

$$J_{i,p} = \begin{cases} 1 & If \quad M_i \leq p < \min(L_i \, ; \, T+1) \\ 0 & Otherwise \end{cases} \qquad \forall \, p \in P, i \in I \tag{5}$$

The replacement interval r_i of item i is determined by Siemens together with its customer. The parameter r_i determines that equipment is replaced after a few years because of technological improvements or wear out. For example, when $r_i = 5$, item i is replaced every five years from the first install on. The replacement will happen until the model determines that less devices are required to fulfil the demand and thus a device needs to be removed.

The costs ($C_{i,p}^{Aq}$) for the cost element a*cquisition* for item i at period *p* is equal to the depreciation, as mentioned before, and can thus be calculated by dividing pr_i, the price of the equipment, by the replacement period r_i. This value is only assigned to that variable when Siemens equipment is installed, and thus when $J_{i,p}$ equals 1.

$$C_{i,p}^{Aq} = \begin{cases} \dfrac{pr_i}{r_i} & If \;\; J_{i,p} = 1 \\ 0 & Otherwise \end{cases} \qquad \forall \, p \in P, i \in I \tag{6}$$

Maintenance

The preferences for the maintenance are more or less known in the acquisition phase, but it may still change over time during the acquisition and execution phase. A lot of calculations are needed to determine the exact value for the cost element *maintenance*. A factor of influence of the maintenance costs is for example the age of the equipment. Siemens mentions that especially in the early and in the end years, more maintenance is needed. Other possibilities that influence the maintenance costs are service levels and service windows. Because of the changing requirements and the complexity of the maintenance calculations, an assumption is made. The model assumes that the maintenance of the equipment can be expressed in a total percentage of the equipment price. Every year the same percentage of the equipment price is used as the value of the maintenance costs for that medical item.

Besides maintenance on its own equipment, Siemens is also responsible for the maintenance of equipment from a third party that is part of the MES contract. If an item i is already installed before the first install M_i in the contract, Q_i equals 1, otherwise it has the value 0. The costs for maintenance of a third party are included in the price of maintenance for the customer. The value of the maintenance of the equipment from another supplier is determined based on the assumption that the installed functionality has the same price as Siemens' equipment. The maintenance of the equipment is calculated by taking a percentage m_i of the installed equipment price. Based on Siemens experts' opinion, this percentage for third party maintenance is approximately the same as the percentage of equipment from Siemens. Therefore it is assumed that the costs for third party maintenance could be estimated by the same percentage m_i.

The costs for maintenance are assigned to all periods where an item is installed, even when this equipment is not from Siemens. The previously defined variable $J_{i,p}$ shows just the moments where Siemens' equipment is installed in the contract and it neglects the periods where equipment from a third party is installed. Because Siemens is also responsible for the maintenance of others, a new variable $B_{i,p}$ is introduced. This new variable will also be used later on to determine the number of items to meet the demand, since the demand could be processed by all available items and not just Siemens devices. The variable $B_{i,p}$ equals 1 when item i is installed at period p, and 0 when item is not. Periods where $B_{i,p}$ equals 1, are those where $J_{i,p}$ equals one, as well as to the periods where third party equipment is installed.

$$B_{i,p} = \begin{cases} 1 & If\ (J_{i,p} = 1)\ OR\ \ (p < M_i\ AND\ Q_i = 1) \\ 0 & Otherwise \end{cases} \qquad \forall\, p \in P, i \in I \tag{7}$$

The costs associated with the cost element *maintenance* for item i at period p ($C_{i,p}^{Ma}$) are calculated by multiplying the purchase price by the maintenance percentage. It is possible that the hospital and Siemens agree on an indexation of the maintenance to cover future inflation. This indexation adds to every period an extra percentage of maintenance costs j.

$$C_{i,p}^{Ma} = \begin{cases} (1+j)^{p-1} \cdot m_i \cdot pr_i & If\ \ B_{i,p} = 1 \\ 0 & Otherwise \end{cases} \qquad \forall\, p \in P, i \in I \tag{8}$$

The total costs of maintenance per period (C_p^{Ma}) turn out to be the sum of the maintenance of all items in period p:

$$C_p^{Ma} = \sum_{i \in I} C_{i,p}^{Ma} \qquad \forall\, p \in P \tag{9}$$

Extra MES Service

Within a MES contract there are several extra services to add to the contract. Extra services consist for example of extra user trainings and consulting. In the acquisition phase, there is no accurate information available on the extra services the customers chooses, so no exact number could be used in the model. However, the expenses for the extra options are mostly dependent on the number of equipment installed. Therefore, these extra costs are expressed as a percentage x of the total acquisition value of the equipment. The percentage of extra MES service costs x can be determined by experts that make use of the model. The total cost of the acquisition of the equipment is equal to the sum over all items i and all periods p of the depreciation of an item in a period. When taking the product of the extra MES service percentage x and the total acquisition value, the costs for the cost element *extra MES service* costs of a period (C_p^{Ex}) are known.

$$C_p^{Ex} = x \cdot \sum_{i \in I} \sum_{p \in P} C_{i,p}^{Aq} \qquad \forall p \in P \tag{10}$$

Total MES costs

The customer of Siemens pays a yearly fee which is build up by the costs for the installed equipment, (the acquisition costs), the maintenance and the Extra MES Service costs.

Confidential

At the end of the contract, the hospital needs to pay the Net Book Value (NBV), which is the difference of the value of the equipment installed in the contract and the amount paid for it during the contract. In order to calculate the NBV the number of installs of an item (N_i) during the contract is needed. The number of installs is calculated by ceiling the difference between the removal (L_i) and the first install at M_i. Ceiling the number is needed for cases where the contract length or removal is not equal to a multiply of the replacement interval plus the moment of the first install.

$$N_i = \left\lceil \frac{(L_i - M_i)}{R_i} \right\rceil \qquad \forall i \in I \tag{11}$$

$$NBV = \sum_{i \in I} (pr_i \cdot N_i) - \sum_{i \in I} \sum_{p \in P} C_{i,p}^{Aq} \tag{12}$$

Confidential

The yearly fee is determined once the Total MES costs are known. The Total MES costs are equal to the sum of the indexations of the fee of the first period. Siemens chooses to index the fee of every period by l.

$$Total\ MES\ turnover = \sum_{p \in P} C_p^{MES} = C_1^{MES} \cdot \sum_{p \in P} \left((1+l)^{(p-1)} \right) \tag{14}$$

From Equation 14, the fee of the first period can be derived.

$$First\ period\ fee = C_1^{MES} = \frac{Total\ MES\ turnover \ \cdot l}{(1+l)^p - 1} \tag{15}$$

Once the fee of the first year is known, the cash flow of the MES contract price can be calculated for every period.

$$C_p^{MES} = C_1^{MES} \cdot (1+l)^{(p-1)} \qquad \forall p \in P \tag{16}$$

4.2.2. Hospital costs

The costs that occur at the hospital during the partnership are most of the time dependent on the number of patients the hospital has to examine. When the number of patients for a department increases, the hospital could choose to broaden its opening hours and therefore the hospital needs to pay extra costs for labour and energy. Besides these two cost elements, there are in some categories costs associated with an examination when for example the hospital has to pay for the disposable contrast that is injected in the patient before the patient could go into the scanner. Once the number of patients increases, the costs of disposables will increase as well. Because most of the hospital costs depend on the number of hours or on the number of examinations, the dependency between these two numbers is explained first.

Number of hours versus number of patients

Every equipment category - location combination (s, v) has its own treatment time $t_{s,v}$, and thus a different number of patients can be scanned in every category in the same amount of time. The treatment time consists of the time from the moment employees start preparing the examination until the patient walks out of the room.

Within an equipment category there might be different models. A constant and average treatment time is used, even though some models are more advanced than others and are therefore able to scan faster than others. However, the difference between the scan times is according to Siemens nowadays very small between more advanced and a bit older devices. So, the treatment time stays the same value, even when a more advanced item is added. The treatment time at a department at a certain location should be obtained from hospital data, since every hospital has a different way of working.

The number of patients ($F_{p,s,v}$) at a department s that could be scanned during the opening hours of a whole period p at a location v is not just equal to the number of hours divided by the treatment time. The model assumes that the hospital is open during corrective and preventive maintenance, but it is unable to scan patients during those moments. The hospital costs, that are dependent of the number of hours that a hospital is opened, are calculated over the total hours it is open and not just the effective hours where patients could be scanned in. When corrective maintenance is needed, this is unplanned and therefore the employees are already planned and have to be paid. During preventive maintenance, which could be planned, there are also employees scheduled whether or not to assist or to do side tasks associated with the equipment. Besides that, it is assumed that the equipment is still consuming energy during those moments. This assumption is made because several tests need to be performed by the technical staff during maintenance.

The maximal percentage of corrective downtime is an agreement between Siemens and its customer. As a result, the hospital could use ut_s, the average uptime, percent of the available hours to scan patients, for example 95%. The average is used because there is not enough information available in the early acquisition phase on the exact details of the maintenance contracts.

The number of time units for preventive maintenance and updates are given by Siemens. This number is not dependent on the agreement between Siemens and its customer and it falls outside the uptime guarantee. The number of time units is independent on the number of hours equipment is in use and thus every item in a category s has, no matter the location, the same amount of time units (pu_s) of preventive maintenance and updates. Therefore the number of hours pu_s should be multiplied by the number of items ($D_{p,s,v}$) in that category s at location v at period p. The value of $D_{p,s,v}$ is determined with the help of the previously defined variable $B_{i,p}$.

$$D_{p,s,v} = \sum_{i \in R_{s,v}} B_{i,p} \qquad \forall p \in P, s \in S, v \in V \tag{17}$$

Now all the variables are known, the number of patients ($F_{p,s,v}$) that could be scanned during the opening hours of a whole period p, at category s and location v could be modelled. This is done by correcting the total number of time units in a certain department at a specific period at location v ($H_{p,s,v}$) for maintenance and dividing that by the treatment time.

$$F_{p,s,v} = \frac{\left(H_{p,s,v} - pu_s \cdot D_{p,s,v}\right) \cdot ut_s}{t_{s,v}} \qquad \forall p \in P, s \in S, v \in V \tag{18}$$

Labour (Operating)

In order to operate medical equipment, several employees are necessary. Employees are for example responsible for guiding the patients through the examination and they have to adjust the settings for every new test. The hospital has to pay its employees, which form the costs for the cost element *labour*.

Every employee that operates equipment earns a certain wage. Besides the amount of money an employee receives, the hospital makes extra costs, like taxes, in order to pay their employees. The total costs a hospital spends on one time unit of labour is expressed as w_s. These costs w_s are dependent on de department where they are working. No inflation factor is taken into account on the wages and therefore the costs for one time unit of labour are assumed to be constant over time. The assumption is made that the costs for one time unit of labour are the same across the different locations of a hospital.

The working hours on a day could be distinguished in three different categories. These three categories are shown in an example that is visualized in Figure 4 on a timeline of one day of work. The first category contains the regular working hours (REG) within the opening hours of a hospital. Within this category there are normal wages and no extra specialties. In the second category of hours are the hours that are outside the opening hours but the wages of the employees that operate the equipment is still normal. Outside the opening hours the hospital needs besides the normal employees, extra labour for managing the department and hospital, so the expenses on labour are higher in these hours than on regular hours. These extra hours have the index EXT. The third category of hours includes the hours where extra labour and higher wages are applied to. Those hours are the irregular working hours (IRR). The change of the wages is determined by the legislations in the healthcare sector.

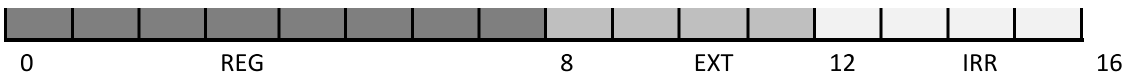

Figure 4: Example of different types of hours on a day

There is a maximum amount of time units that a hospital could open a department per day. The maximum number of time units in the whole period of one device in department s is denoted by h_s^{MAX}. This number is for example equal to the maximum number of hours on a day times the number of days the department is open in a period. It is also possible to calculate with time units of 15 minutes or one minute. In those cases h_s^{MAX} is a higher number.

The parameter h^{REG} gives the maximal number of time units of one device in regular working hours. For example when the hospital is standard open from 8 till 16.00 o'clock, 250 days a year, the parameter has the value 2000 (hours). This number is independent of the department. The maximal number of extra hours of an item in the hospital over the whole period is denoted by h^{EXT}. The last parameter is h^{IRR} and gives the maximum for the irregular hours in a period. The maximal number of hours allowed in a period at department s (h_s^{MAX}) should always be smaller than or equal to the sum of the maximal hours of regular, extra and irregular time. It is thus possible that the hospital chooses the maximum number of hours in a period to be smaller. This is for example the case when a hospital decides that the CT-scans could only be opened during the normal opening hours of a hospital.

$$h_s^{MAX} \leq h^{REG} + h^{EXT} + h^{IRR} \qquad \forall s \in S \tag{19}$$

The next variable, denoted by $O_{p,s,v}$, describes what the optimal number of time units is on one device to meet the demand with a given number of devices in a period p in a certain department s at location v. This number is an output of the model. The number of time units a department is open might differ between locations, but the assumption is made that at a certain location all equipment of one category ($i \in R_{s,v}$) has the same opening hours. This means that the hours are levelled over all items. Because every type ($REG, EXT\ and\ IRR$) has its own associated costs, there should be determined how many time units of $O_{p,s,v}$ are regular, extra and irregular ones.

The first time units of $O_{p,s,v}$ until h^{REG} are regular hours, denoted by $O_{p,s,v}^{REG}$. When the number of time units in a period of a device in category s exceeds h^{REG}, there are also extra units ($O_{p,s,v}^{EXT}$). There are irregular hours $O_{p,s,v}^{IRR}$ if there are more time units than h^{REG} plus h^{EXT}. The three equations describing the calculation of the number of hours account for all periods, categories/departments and locations.

$$O_{p,s,v}^{REG} = \min\left(O_{p,s,v}\ , h^{REG}\right) \tag{20}$$

$$O_{p,s,v}^{EXT} = \min\ \left(\max\left(O_{p,s,v} - O_{p,s,v}^{REG}\ , 0\right), h^{EXT}\right) \tag{21}$$

$$O_{p,s,v}^{IRR} = \min\ \left(\max\left(O_{p,s,v} - \left(O_{p,s,v}^{REG} + O_{p,s,v}^{EXT}\right), 0\right), h^{IRR}\right) \tag{22}$$

The total number of hours in a certain department s of all items of that department together at a specific period at location v ($H_{p,s,v}$) is determined by the number of devices ($D_{p,s,v}$) times the number of hours that one item in that category is opened during that period $\left(O_{p,s,v}\right)$. For example, there are three MRI-scanners at location one during the first period and the department is opened 100 hours a year, the value of $H_{p,s,v}$ becomes then 300. In the end, this number, $H_{p,s,v}$, should be able to cover all the demand of that period – department – location combination. The same way as the total time units is calculated, are the total number of hours per type of hours determined.

$$H_{p,s,v} = O_{p,s,v} \cdot D_{p,s,v} \qquad \forall p \in P, s \in S, v \in V \tag{23}$$

$$H_{p,s,v}^{x} = O_{p,s,v}^{x} \cdot D_{p,s,v} \qquad \forall p \in P, s \in S, v \in V, x \in \{REG, EXT, IRR\} \tag{24}$$

Now all different types of hours are defined, the value of the costs per type are needed in order to calculate the costs for the cost element *labour* (C_p^{La}) at period p. As mentioned before, every type of time units ($REG, EXT\ and\ IRR$) have their own associated costs. During the regular hours, the hospital spends w_s on one time unit of labour. For the extra hours, the hospital pays q extra above the normal spending of w_s. During irregular hours, the spending of $w_s$is increased by a factor c. The extra costs per hour q are also applicable on the irregular hours.

The last step is to model the costs at period p for the cost element *labour* C_p^{La} . This is done by multiplying all types of hours by its costs and taking the sum of those values. This value does not directly give all costs, because for some types of equipment there is more than one employee needed to run the equipment. The number of operators for one item at category s is denoted by e_s. So, in order to get the costs of C_p^{La}, the sum is multiplied by e_s. However, the standard extra costs for time units outside the opening hours (q) are independent of this number of employees. This is done for all combinations of a location and category.

$$C_p^{La} = \sum_{v \in V} \sum_{s \in S} \left(\left(H_{p,s,v}^{REG} + H_{p,s,v}^{EXT} + (1+c) \cdot H_{p,s,v}^{IRR} \right) \cdot w_s \cdot e_s + \left(H_{p,s,v}^{EXT} + H_{p,s,v}^{IRR} \right) \cdot q \right) \quad \forall\, p \in P \tag{25}$$

Disposables

Disposables are needed for several types of examinations. Common disposables for the use of Siemens equipment are: paper for under the patient's body, needles, or contrast liquids. The costs for disposals need to be determined per category since there are large differences between categories. Data on the average costs (g_s) per examination on equipment from every category s is needed to calculate the total costs for this cost element. By multiplying the number of examinations per period of every category times the average costs per examination on disposables, the total costs $\left(C_p^{Di}\right)$ for *disposables* of that period is known. The expected number of examinations per period p of a category s is calculated by the sum over all locations of the expected demand $\left(f_{p,s,v}\right)$ per period, category and location combination.

$$C_p^{Di} = \sum_{s \in S} \left(g_s \cdot \sum_{v \in V} f_{p,s,v} \right) \qquad \forall\, p \in P \tag{26}$$

Operating supplies

Operating supplies are dependent of the number of time units a department is open. The price of one unit of operating supply is independent of the period and the location of the hospital. An example of operating supplies is the energy consumption of the equipment. The longer the systems are running (ON), the higher the costs. However, even when systems are off (OFF), they consume power as well. In order to calculate the total costs for the cost element *operating supplies* $\left(C_{p,s}^{Op}\right)$ at period p, the number of time units equipment in category s over all locations at that period is running $\left(H_{p,s}\right)$, is multiplied by the costs (o_s^{ON}) per time unit of one item. It is assumed that the equipment uses operating supplies, like energy, as well during downtime. Therefore the previously defined variable $H_{p,s}$ could be used for the operating supplies costs. This is also done for the time that the system is off $\left(H_{p,s}^{OFF}\right)$, which is equal to the total (TOT) number of possible time units in a period $(H_{p,s}^{TOT})$ minus the time the equipment is running. The total number of time units is equal to the maximal number of units for one device (h^{TOT}) times the number of devices. The value of h^{TOT} is for example 8760, when looking at a period of a year of 365 days, with hours being the time units. The costs associated with having the equipment off for one time unit is denoted by o_s^{OFF}. The costs of running equipment and the costs for the time they are off are added. By summing the calculated values over all categories, the cost of the cost element *operating supplies* is known per period $\left(C_p^{Op}\right)$.

$$C_p^{Op} = \sum_{v \in V} \sum_{s \in S} \left(H_{p,s,v} \cdot o_s^{ON} + H_{p,s,v}^{OFF} \cdot o_s^{OFF} \right) \qquad \forall p \in P \tag{27}$$

Where,

$$H_{p,s,v}^{OFF} = h^{TOT} \cdot D_{p,s,v} - H_{p,s,v} \qquad \forall p \in P, s \in S, v \in V. \tag{28}$$

Direct downtime

A hospital cannot take corrective maintenance into account in their daily planning because it is unpredictable. The updates and preventive maintenance on the other hand, are planned and therefore no patients are scheduled at those moments. So, in $(1 - ut_s)$ percent (for example 5%) of the total opening hours minus the hours of preventive maintenance and updates the equipment is down and patients cannot be examined. By dividing this number of downtime hours by the treatment time $t_{s,v}$, the total number of missed examinations is known for that location at that category of devices. Missing one examination gives the hospital b_s of extra expenses. These costs are for expenses which are already made for the missed examinations, which is described in Section 4.1.3. Therefore the total number of missed examinations should be multiplied by these costs. This calculation is summed over every location-equipment category combination. Once that is done, the costs of *downtime* at period p $\left(C_p^{Do}\right)$ are known.

$$C_p^{Do} = \sum_{s \in S} \sum_{v \in V} \frac{b_s \cdot (1 - ut_s) \cdot (H_{p,s,v} - pu_s \cdot D_{p,s,v})}{t_{s,v}} \qquad \forall p \in P \tag{29}$$

Floor/space

The total space required for medical equipment contains not just the area around the devices but there is also a control room and space for technical equipment needed. All this space should be internally paid. The price per square meter is assumed to be independent of the location. Besides the floor costs, there are other costs associated with the exploitation of a room. These costs, like the energy and service, are dependent on the number of square meters that is in use and differ from previously mentioned energy and service costs since these costs are independent of the use of the equipment.

The costs associated with the cost element *floor/space* per period $\left(C_p^{Fl}\right)$ are calculated by taking all the costs together for one square meter of room u_s and multiplying those costs by the total number of square meters in use. The amount of used space per category is calculated by the multiplication of the number of meters needed for one device of equipment from category s (z_s), times the number of devices there is in that category. The sum of the square meters over all categories is equal to the total number of square meters in use.

$$C_p^{Fl} = u_s \cdot \sum_{s \in S} \left(z_s \cdot \sum_{v \in V} D_{p,s,v} \right) \qquad \forall p \in P \tag{30}$$

4.3. Constraints on the solution

Sections 4.1 and 4.2 described the model that could be used to evaluate a solution. The evaluation is done based on the Total Cost of Ownership of the examined solution. A solution is the combination of the number of devices and opening hours. There are constraints to the solution of the minimization of the TCO, so not every solution is suitable. This paragraph describes the constraint for the model.

The overall requirement of the hospital is to be able to meet the demand in every category at every moment at all locations. Demand is expressed in number of patients ($f_{p,s,v}$) of a certain category s, per period p of location v. This number is a forecast for the upcoming periods. All items i in a category s at location v are assumed to be able to process the patients from the demand $f_{p,s,v}$ of a period.

A hundred percent utilization of the capacity is not realistic, because the demand is not evenly spread over the whole period. Therefore there should be room in the capacity for peaks in demand. Besides that, it is not ideal for employees. In order to be cover this all, a utilization percentage y_s for every category should be chosen by the hospital.

The equipment installed in the hospital should have the capacity to examine all the patients including the utilization percentage. Therefore, a valid solution is created when the capacity expressed in number of patients ($F_{p,s,v}$) at every period and at all departments for all locations times the utilization percentage exceeds the number of expected patients for that period. The calculation of $F_{p,s,v}$ is already defined in Equation 18.

$$F_{p,s,v} \cdot y_s \geq f_{p,s,v} \qquad \forall p \in P, s \in S, v \in V \tag{31}$$

The second constraint limits the number of opening hours in a period. It is not preferable to have a department open for 24/7. Besides that, patients are not always willing to undergo an examination at any time a day. Therefore the number of hours one device is opened during the whole period of any location, department and period $\left(O_{p,s,v}\right)$ is limited by a maximum h_s^{MAX}.

$$O_{p,s,v} \leq h_s^{MAX} \qquad \forall p \in P, s \in S, v \in V \tag{32}$$

The final constraint is based on the restriction that devices could only be removed when a full replacement period has passed. Therefore the variable L_i, which denotes at which period item i is removed, should always be the first period (M_i) plus a multiply of the replacement intervals (r_i). This constraint is given in Equation 33.

$$L_i = M_i + int * r_i \qquad \forall i \in I \mid int \in \mathbb{N} \tag{33}$$

4.4. Optimization

Sections 4.2 and 4.3 described a model that is able to calculate all costs associated with the ownership of medical equipment, as well as the constraints for a suitable solution. These two parts form the basis of the optimization model. The model that determines which solution gives the best TCO value is described in this section.

The goal of the optimization of the portfolio of medical equipment is to minimize the TCO. The minimization is restricted by the demand per category and location in every time period. This means that the capacity should be enough to cover this demand. The available capacity can be changed by two different decisions. The first option is to extend (to a predefined maximum) or narrow down the opening hours. The second option is to add an item to or to remove an item from the portfolio of equipment. Both of these options change the TCO in a different way, which is further explained in Section 4.4.2.

Mathematically, the optimization could be described as follows:

$$
\begin{gathered}
Minimize\ TCO \\
s.t. \\
F_{p,s,v} \cdot y_s \geq f_{p,s,v} \quad \forall p \in P, s \in S, v \in V \\
O_{p,s,v} \leq h_s^{MAX} \quad \forall p \in P, s \in S, v \in V
\end{gathered} \tag{34}
$$

The main goal of the optimization is to minimize the TCO over all eight cost elements. Where the TCO is calculated by Equation 3 and 4. The dependency between $D_{p,s,v}$ and $O_{p,s,v}$ is shown in Equation 35, which is derived from Equation 18 and 23.

$$
F_{p,s,v} = \frac{(O_{p,s,v} - pu_s) \cdot ut_s \cdot D_{p,s,v}}{t_{s,v}} \quad \forall p \in P, s \in S, v \in V \tag{35}
$$

The calculation of every cost element C_p^k is described in the Section 4.2 and the constraints are defined in Section 4.3.

4.4.1. Concept and assumptions

The demand is given per period, category and location combination as described in Section 4.3. It is assumed that patients are not interchangeable between the departments and locations. Besides that, the costs associated with the change of the capacity of a department at a certain department and location does not influence the costs of the other departments. Therefore, every department - location combination could be optimized separately which results in multiple minimization problems.

The optimization starts with determining the threshold value which tells at which number of patients it is cheaper to change the number of devices instead of just changing the number of opening hours. An example is given in Figure 5, where it is better to have two devices instead of one when the demand is more than 5025 and less than the next breakeven point. Based on the demand of patients and the choice of number of devices, the minimal opening hours to meet the demand could be calculated for the department and location of interest. Once this is known, the TCO of the combination of number of devices and opening hours is determined with the input of the parameters of department s and location v. An example of the value of the TCO is visible in Figure 5 for the choice of one till three devices. The constraint on the maximal opening hours is visible in the graphs at the end of every line.

When determining the threshold value, no period specific information, like the indexation of maintenance in that period, will be used. This assumption is supported by Siemens, since they are not sure what the future indexations will be in the acquisition phase. Therefore the threshold values will be constant over time.

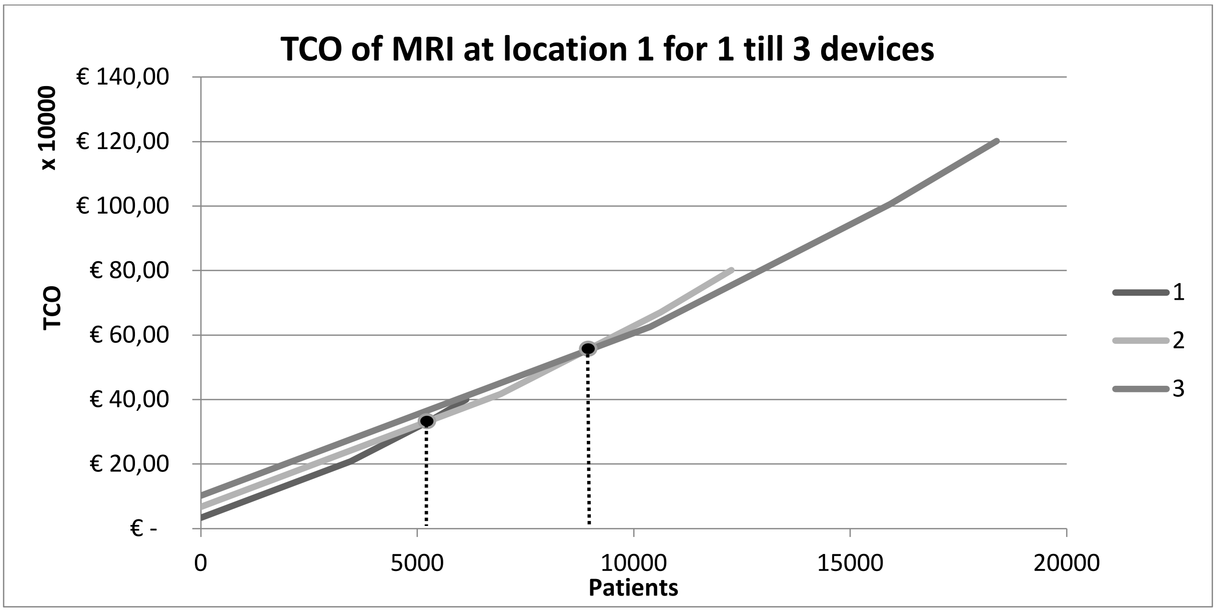

Figure 5: Example of the TCO value versus the number of patients for 1 till 3 devices

The second assumption is that the contract will be infinitely lasting. In reality MES contracts have a finite contract length. In the Netherlands these contracts last approximately 10 till 15 years. After these years, the hospital has to pay the NBV of the equipment that is installed at the hospital. Siemens assumes that the hospital will continue the contract after it is finished. This way, the NBV could be included in the new contract. When this continues, the horizon of the optimization becomes infinite.

Once the break even points are known, the demand could be compared to the values of those points. This would give the stream of optimal numbers of devices over the whole horizon when just looking at one period at the time. The assumption is made that demand is either decreasing or increasing at a department at a certain location over the infinite horizon. This makes is possible to add a device in a period when needed according to the optimization, without having a negative influence on the TCO of the next period. For example, when the demand increases, and the optimal solution at period p is that there should be 4 devices, there are in period $(p+1)$ never less than 4 devices required when optimizing the TCO. So the hospital will not add a device at period p and has to remove it again in period $(p+1)$ which would impossible since the replacement interval did not pass yet.

The assumption of an either decreasing or increasing demand does not solve the problem when removing a device in the middle of a replacement period yet. Therefore, the model needs to be continued with an algorithm determining whether it is better to remove the device at the latest moment of replacement before or at the first replacement after the calculated removal period.

4.4.2. Model for determining the threshold values

Based on all the assumptions made at the Section 4.4.1, the model to calculate the threshold values which determines at what point the number of devices should be changed in order to meet the demand, is constructed. The first step in the model description is to recapture how the TCO costs are calculated. This way it is possible to describe how the TCO looks like with having a number of patients and a number of devices as input.

In order to calculate the costs associated with an expected demand of $f_{p,s,v}$, the required number of opening hours $H_{p,s,v}$ should be calculated first by combining Equation 18 and 31. Since the costs always increase when the opening hours increase, the least possible opening hours in order to meet the demand are used in the optimization.

$$H_{p,s,v} = \frac{f_{p,s,v} \cdot t_{s,v}}{y_s \cdot ut_s} + pu_s \cdot D_{p,s,v} \tag{36}$$

$H_{p,s,v}$ divided by the number of devices $D_{p,s,v}$ gives $O_{p,s,v}$, which is the number of time units that one device is open during the whole period. When $O_{p,s,v}$ is bigger than h_s^{MAX} the chosen number of devices is not a valid solution. Therefore, the least number of devices when expecting $f_{p,s,v}$ patients is determined by Equation 37. This equation is derived from Equation 36, where $H_{p,s,v}$ is replaced by h_s^{MAX} times $D_{p,s,v}$. The number is rounded up since only entire devices can be added to the hospital.

$$Minimal\ \ D_{p,s,v} = \left\lceil \frac{f_{p,s,v} \cdot t_{s,v}}{y_s \cdot ut_s \cdot (h_s^{MAX} - pu_s)} \right\rceil \tag{37}$$

Based on the required opening hours and expected demand, the TCO of the possible solution should be calculated in order to judge the solution. The costs for of all cost elements are straightforward when looking at just one period, compared to looking at a longer horizon. However, there is one difference in parameters used in the costs elements. Because the prices and the replacement interval of equipment in a category might differ, the model takes the average price and interval of equipment in that category into account. This is required since the composition of the devices at a department differs in every case. The TCO of a period could therefore be calculated by the following formula, where the demand and number of devices is used as input and the required number of hours is calculated by 36:

$TCO_{(f_{p,s,v}\,;\,D_{p,s,v})} =$

Confidential	MES
$g_s \cdot f_{p,s,v}\ +$	$Disposables$
$H_{p,s,v} \cdot o_s^{ON} + (h^{TOT} \cdot D_{p,s,v} - H_{p,s,v}) \cdot o_s^{OFF} +$	$Energy$
$\dfrac{b_s \cdot (1 - ut_s) \cdot (H_{p,s,v} - pu_s \cdot D_{p,s,v})}{t_{s,v}} +$	$Downtime$
$u_s \cdot z_s \cdot D_{p,s,v}\ +$	$Floor/space$
$\left(H_{p,s,v}^{REG} + H_{p,s,v}^{EXT} + (1+c) \cdot H_{p,s,v}^{IRR}\right) \cdot w_s \cdot e_s + (H_{p,s,v}^{EXT} + H_{p,s,v}^{IRR}) \cdot q$	$Labour$

(38)

The second step that is required before the threshold value could be determined, is to understand the behaviour of the TCO function with different inputs. An example of the TCO function for department s at location v with the input of $D_{p,s,v}$ and $(D_{p,s,v} + 1)$ is given in Figure 6. Based on this example the shape of the lines is explained.

The TCO functions displayed in Figure 6 show three different slopes. These slopes correspond with the cost increases in the three different types of time units, namely the regular, extra and irregular time units. Within the regular hours, when having $D_{p,s,v}$ devices, the hospital could process a demand of 100 patients. This number of patients is called $pa_{R,D}$. When the hospital adds another machine, the capacity of regular hours increases. The number of patients that could be processed in those regular hours with one extra device is called $pa_{R,D+1}$. Points $pa_{E,D}$ and $pa_{E,D+1}$ denote the number of patients where the limit of regular plus extra hours is reached for respectively $D_{p,s,v}$ and $(D_{p,s,v}+1)$ devices. The last two points in the graph, $pa_{M,D}$ and $pa_{M,D+1}$, show the maximal capacity of the two options of amounts of devices. The slopes of these different intervals differ since there are other costs per hour in every interval.

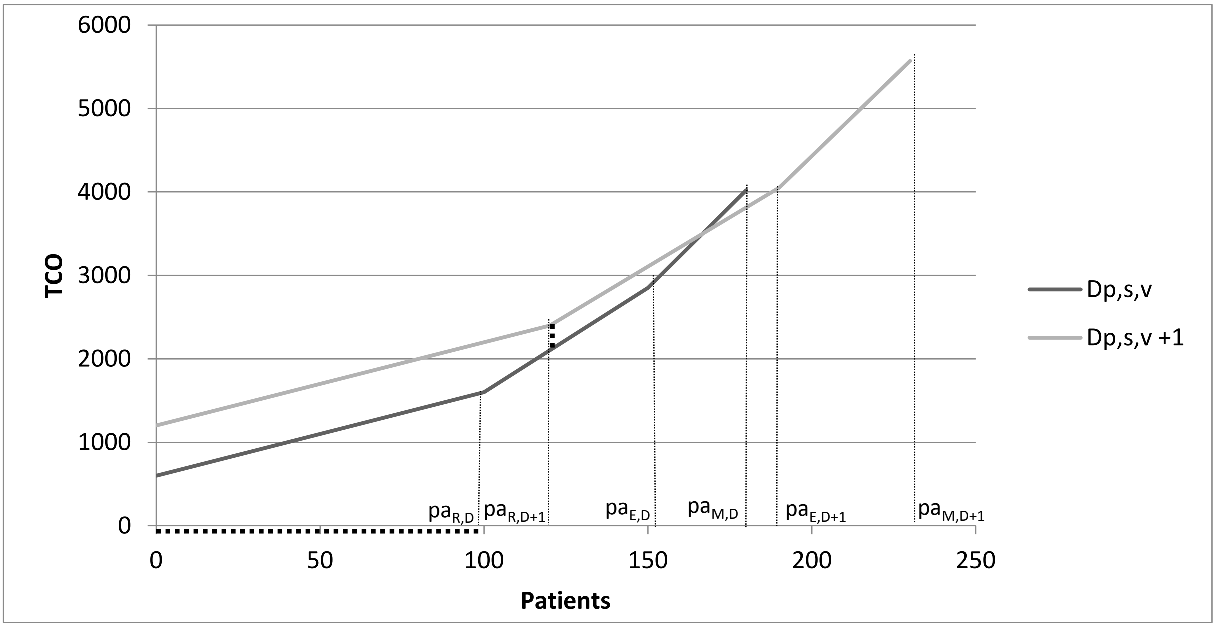

Figure 6: Example of the TCO function when having $D_{p,s,v}$ or $D_{p,s,v}+1$ devices

Equation 38 shows how one point on the TCO line is calculated. Now it is interesting to know how the TCO value changes when the demand increases with one patient. It is assumed that $f_{p,s,v}$ is continue since the intersections do not have to be at a integer number in all situations. Therefore the slope is determined by taking the derivative on the number of patients of the TCO function. To do so, the required number of hours is expressed in number of patients. This is done by combining Equation 36 and 43.

$$TCO' = \frac{dTCO}{df_{p,s,v}} = g_s + \frac{t_{s,v}}{y_s \cdot ut_s} \cdot (o_s^{ON} - o_s^{OFF}) + \frac{(1-ut_s)}{y_s \cdot ut_s} \cdot b_s$$
$$+ \begin{cases} w_s \cdot t_{s,v} \cdot e_s / y_s \cdot ut_s & f_{p,s,v} < pa_{R,D} \\ (w_s \cdot e_s + q) \cdot t_{s,v} / y_s \cdot ut_s & pa_{R,D} < f_{p,s,v} < pa_{E,D} \\ (w_s \cdot (1+c) \cdot e_s + q) \cdot t_{s,v} / y_s \cdot ut_s & pa_{E,D} \leq f_{p,s,v} \end{cases} \quad (39)$$

As can be seen in Equation 39, the slope of the TCO function is independent of the number of devices $D_{p,s,v}$, since only parameters determine the slope. Therefore, it could be concluded that in the interval of regular hours of having $D_{p,s,v}$ devices (from 0 to $pa_{R,D}$ patients), it will always be a better option to have the least number of device $D_{p,s,v}$, instead of having $(D_{p,s,v}+1)$ devices. The associated interval is also visualized in Figure 6 by the horizontal dashed line. For the same reason, it is sure that there will not be an intersection when the TCO of having $pa_{E,D+1}$ patients at $(D_{p,s,v}+1)$ devices is higher than the TCO of the same number of patients processed at $D_{p,s,v}$ devices. The difference in the TCO value at that point $pa_{E,D+1}$ is shown in Figure 6 by the vertical dashed line.

Thus, based on Equation 39, it could be concluded that the TCO of two different amounts of devices could only become the same value when the number of patients implies a required number of hours which could be processed in different categories of hours for the two optional numbers of devices.

From Equation 39 could also be concluded that just the threshold value between $D_{p,s,v}$ and $(D_{p,s,v}+1)$ need to be compared for all $D_{p,s,v}$'s. Because the slopes are equal, the intersection of those two possibilities will always be at less demand than the demand corresponding to the intersection of $D_{p,s,v}$ and $(D_{p,s,v}+2)$. Once $D_{p,s,v}$ and $(D_{p,s,v}+1)$ intersect, $(D_{p,s,v}+1)$ is always preferred over $D_{p,s,v}$. The choice of $\left(D_{p,s,v}+1\right)$ devices stays the best option until the TCO functions of $(D_{p,s,v}+1)$ and $(D_{p,s,v}+2)$ intersect. And thus is the TCO function convex in $D_{p,s,v}$. With all these conclusions, it leaves the possible equilibriums to three different circumstances. These situations are visualized in Figure 7 till Figure 9.

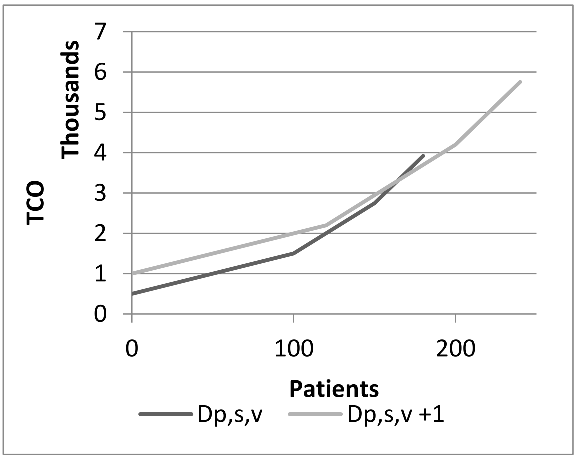

Figure 7: Intersection situation 1

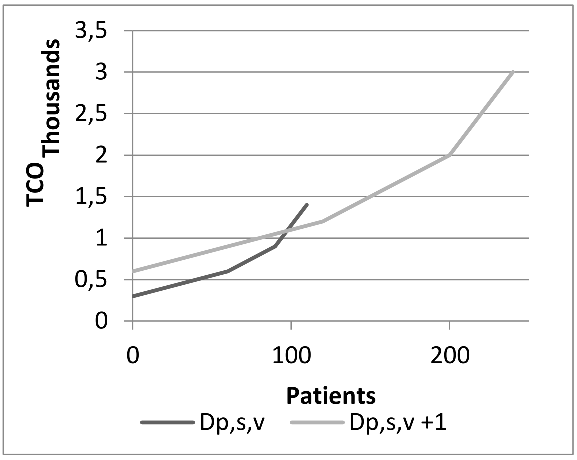

Figure 8: Intersection situation 2

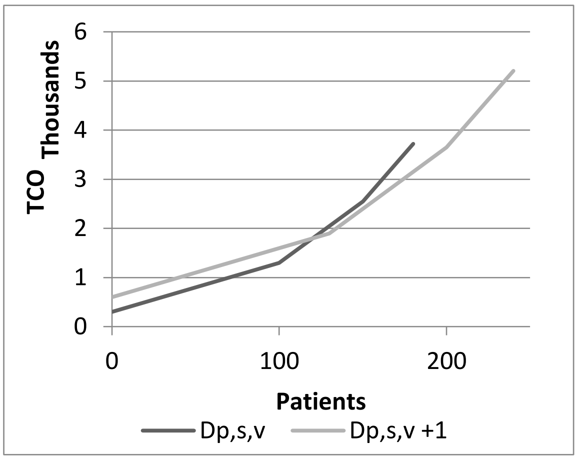

Figure 9: Intersection situation 3

In the first situation, the investment in a new device is already profitable when there are just a few patients that have to be processed in the extra time when having less equipment at the hospital. The equilibrium of the TCO's of the two possible numbers of devices lies therefore between the points $pa_{R,D}$ and $pa_{E,D}$. You are sure that you deal with a situation 1 if the TCO of having $(D_{p,s,v}+1)$ devices at point $pa_{E,D}$ is lower than the TCO of having $D_{p,s,v}$ devices at that number of patients.

The point of intersection, and thus the threshold value in this case, called $E_{D,D+1}$, is calculated by the difference of the costs at point $pa_{R,D}$ divided by the difference in slopes of the option of $D_{p,s,v}$ and

$(D_{p,s,v}+1)$ devices. As mentioned before, the slopes do only differ in the costs for labour. This results in Equation 40.

$$E_{D,D+1} = \frac{TCO_{(pa_{R,D}\,;\,D+1)} - TCO_{(pa_{R,D}\,;\,D)}}{\frac{(w_s \cdot e_s + q)\cdot t_{s,v}}{y_s \cdot ut_s} - \frac{w_s \cdot e_s \cdot t_{s,v}}{y_s \cdot ut_s}} + pa_{R,D}$$

$$= \frac{\left(TCO_{(pa_{R,D}\,;\,D+1)} - TCO_{(pa_{R,D}\,;\,D)}\right)\cdot y_s \cdot ut_s}{q \cdot t_{s,v}} + pa_{R,D} \tag{40}$$

$$if \quad TCO_{(pa_{E,D}\,;\,D+1)} \leq TCO_{(pa_{E,D}\,;\,D)}$$

The second and third situations, visualized in Figure 8 and Figure 9, happen when the opening hours of the department could be extended until the irregular hours. However the point of intersection is on a different line segment. Situation 2 might happen when there is a small amount of devices. For example, when going from one till two devices, the number of possible regular hours is doubled. The relative increase in regular hours is less when going from ten till eleven devices. Where in situation 2 an increase in patients results in more regular time on $(D_{p,s,v}+1)$ devices, in situation 3 this same change in demand results in more extra time at $(D_{p,s,v}+1)$ devices. So, in situation 3 the breakeven point happens for $(D_{p,s,v}+1)$ devices at the interval of number of patients where the second slope is applicable.

It is sure that situation two is the case, when the maximum number of patients that are possible to process in regular plus extra time on $D_{p,s,v}$ devices ($pa_{E,D}$), is smaller than the maximum number of patients in regular hours on $(D_{p,s,v}+1)$ devices ($pa_{R,D+1}$). Besides that, the TCO of $D_{p,s,v}$ devices and $pa_{M,D}$ should be higher than the TCO of $(D_{p,s,v}+1)$ devices at that same number of patients. The exact point of intersection is then calculated by dividing the difference in TCO at point $pa_{E,D}$ of having $D_{p,s,v}$ and $(D_{p,s,v}+1)$ devices by the difference in slope. This number is added to the point $pa_{E,D}$.

$$E_{D,D+1} = \frac{TCO_{(pa_{E,D}\,;\,D+1)} - TCO_{(pa_{E,D}\,;\,D)}}{\frac{(w_s \cdot (1+c)\cdot e_s + q)\cdot t_{s,v}}{y_s \cdot ut_s} - \frac{w_s \cdot t_{s,v}}{y_s \cdot ut_s}\cdot e_s} + pa_{E,D}$$

$$= \frac{\left(TCO_{(pa_{E,D}\,;\,D+1)} - TCO_{(pa_{E,D}\,;\,D)}\right)\cdot y_s \cdot ut_s}{(w_s \cdot c \cdot e_s + q)\cdot t_{s,v}} + pa_{E,D} \tag{41}$$

$$if \;\; pa_{E,D} < pa_{R,D+1} \quad and \quad TCO_{(pa_{M,D}\,;\,D+1)} \leq TCO_{(pa_{M,D}\,;\,D)}$$

The third situation happens as well when the TCO of having $pa_{M,D}$ patients on $D_{p,s,v}$ devices is higher than that number of patients on $(D_{p,s,v}+1)$ devices. However, the maximum number of patients that is possible to examine in the extra time of $D_{p,s,v}$ devices should be higher than the capacity in regular time of $(D_{p,s,v}+1)$ devices.

The point of intersection of the two different cases is calculated in quite the same way, it only differs on the difference in the slopes of the two lines. The calculation of the equilibrium $E_{D,D+1}$ is given in Equation 42.

$$E_{D,D+1} = \frac{TCO_{(pa_{E,D}\,;\,D+1)} - TCO_{(pa_{E,D}\,;\,D)}}{\frac{(w_s \cdot (1+c) \cdot e_s + q) \cdot t_{s,v}}{y_s \cdot ut_s} - \frac{(w_s \cdot e_s + q) \cdot t_{s,v}}{y_s \cdot ut_s}} + pa_{E,D}$$

$$= \frac{\left(TCO_{(pa_{E,D}\,;\,D+1)} - TCO_{(pa_{E,D}\,;\,D)}\right) \cdot y_s \cdot ut_s}{w_s \cdot c \cdot t_{s,v} \cdot e_s} + pa_{E,D} \quad (42)$$

$$if\ \ pa_{E,D} \geq pa_{R,D+1} \quad and \quad TCO_{(pa_{M,D}\,;\,D+1)} \leq TCO_{(pa_{M,D}\,;\,D)}$$

It is also possible that the TCO functions do not intersect. This is the case when the TCO of having $D_{p,s,v}$ devices at the point $pa_{M,D}$ is less than the TCO in the case of $(D_{p,s,v} + 1)$ devices at that point. When this is the case, it is always more profitable to have the least possible devices. The calculation of the least possible devices is described in Equation 37.

By combining the equations of $E_{D,D+1}$ for the different possible intersections and the option that they do not intersect, the threshold value for having $D_{p,s,v}$ or $(D_{p,s,v} + 1)$ devices is determined by:

$$E_{D,D+1} = \begin{cases} Eq\ 41 & if\ \ TCO_{(pa_{E,D}\,;\,D+1)} \leq TCO_{(pa_{E,D}\,;\,D)} \\ Eq\ 42 & if\ \ pa_{E,D} < pa_{R,D+1}\ \ and\ \ TCO_{(pa_{M,D}\,;\,D+1)} \leq TCO_{(pa_{M,D}\,;\,D)} \\ Eq\ 43 & if\ \ pa_{E,D} \geq pa_{R,D+1}\ \ and\ \ TCO_{(pa_{M,D}\,;\,D+1)} \leq TCO_{(pa_{M,D}\,;\,D)} \\ No\ intersection & if\ \ TCO_{(pa_{M,D}\,;\,D+1)} > TCO_{(pa_{M,D}\,;\,D)} \end{cases} \quad (43)$$

Once the threshold value is found, it should be interpreted correctly. The threshold value $E_{D,D+1}$ tells that when the number of patients $f_{p,s,v}$ exceeds the determined value, the TCO of owning and using the devices to process the required patients is cheaper when having $(D_{p,s,v} + 1)$ devices instead of $D_{p,s,v}$ devices. The preference of $(D_{p,s,v} + 1)$ devices counts till point $E_{D+1,D+2}$, the point where the TCO function of $(D_{p,s,v} + 1)$ and $(D_{p,s,v} + 2)$ intersect. Exceeding that value means that $\left(D_{p,s,v} + 2\right)$ is preferred, etcetera. The other way around, if $f_{p,s,v}$ is smaller than the threshold value, it is preferable to have $D_{p,s,v}$ devices at period p. This is the best option until the demand is less than $E_{D-1,D}$. Since it should always be possible to fulfil the demand, there will always be at least one device when there is demand for that device. When there is no intersection, the optimal number of devices would be equal to the least devices that is possible. The corresponding number of devices could then be calculated by Equation 37.

4.4.3. Application of determined optimal number of devices

In every period the optimal number of devices for a department and location is now known, given the assumptions in Section 4.4.1. In order to calculate the TCO over all periods instead of just for one period, the outcomes have to be implemented in the model. The process to do so is described in this section, the flowcharts associated with it and the pseudo code can be found in Appendix B.

The process continues with the optimization of every single department and location and starts with the installed base at the beginning of the contract. For the installed base, the first possible replacement in the contract is denoted by M_i. Before that moment, nothing can change to the number of devices, since equipment can only be removed at the end of a replacement interval. Therefore, all periods are examined sequentially for the selected department and location, starting at the first period that a device in that department and location could be removed, so the smallest period M_i. When the recommended number of devices at period p is higher than the number of devices in period $(p-1)$, the optimization of every period tells to add a device at that moment for the associated location and category. Adding a device is done straight forward by adding an item to the total set of items, assigning the added item to a location and category and making the moment of first install (M_i) equal to p and its removal L_i equal to the end of the contract T. With these operations the model will assign the item and replace it until the removal L_i is defined. Thus, the variable $J_{i,p}$ gets the value 1 for all moments from M_i to L_i.

When an item needs to be removed, since $D_{p,s,v} > D_{p-1,s,v}$, the process is less easy. This is because it is assumed with the use of thesholds that devices can be removed at any point of time. However, in reality this is not the case since devices always have to be installed for the whole replacement interval. This forms a barrier when it is recommended to remove devices during this interval. Because of this limitation, three options arise. At first the removal is exactly at a replacement of an item in that category or location. In that case the item could just be removed. Secondly, it is possible to remove the device at an earlier period, namely at the latest replacement of one of the items i of the department s and location v, at R_1. The third option, is to keep an extra device until the next replacement in that same category of devices and location at moment R_2. In order to decide on which of these options gives the lowest TCO, the moments of R_1 and R_2 need to be determined first.

In the example of Table 6, the number of devices of category s and location v decreases in period 4. This moment is denoted by the variable R_0. Items one and two are assumed to be completely the same, therefore it does not matter which one is removed when the demand is decreasing. So the possible moments of removal in this case are period two (R_1) and period six (R_2). The pseudo code describing how to determine the values of R_1 and R_2 in the model is visible in Appendix B.

	1	**2**	**3**	**4**	**5**	**6**	**7**
$D_{p,s,v}$	2	2	2	1	1	1	1
Replacements item 1	X					X	
Replacements item 2		X					X
		R_1		R_0		R_2	

Table 6: Example; Moments of replacement and optimal number of devices

Once both moments are determined, the costs of removing an item at R_1 should be compared with the costs of keeping it till period R_2. But first, it needs to be checked whether there is still enough capacity in period R_1 to process the expected demand when there is one device less. If this is not the case, the item will be maintained. If there is still enough capacity in period R_1 the question arises whether it is cheaper to decrease the number of installed devices from R_1 to (R_2-1) (option one) or if it is better keep an extra item at that same interval (option two). The costs of the first option are determined by calculating the TCO of every period over the interval from R_1 to (R_2-1) with the expected demand $f_{p,s,v}$ in the associated period and with one device less than the optimal number of devices at period R_1. For option two, the same calculation is performed, however this time with the optimal number of devices in R_1. When the calculated costs of option one are less than the TCO for option two, the item will be removed at period R_1. If the second option is cheaper, the item at category s and location v will be at least remained until period R_2.

It might be possible that more than one device needs to be removed at period R_0. In that case the process is started again, where the previously removed item is skipped in the removal algorithm.

When the whole algorithm is performed, the optimal number of devices is known in every period of the complete horizon. The total costs of ownership associated with the found solution can be calculated now to determine the value of the solution.

4.5. Adjustments for practice

In practice, the MES contract contains also other systems besides equipment, for example computer software. These systems are, unlike the equipment, unable to process patients and do not have a capacity that needs to be taken into account. Because there is also no labour directly assigned to the other systems and the energy and downtime costs are not known or not applicable, only the MES costs and not the hospital costs of these systems could be taken into account in the TCO calculations. Therefore, the optimization and capacity analysis is only possible for the patients processing equipment.

This adjustment is realized by putting all extra systems in one equipment category called 'Other', and then taking the hospital costs over all categories minus one ($\forall s \in S \backslash 'Other'$).

For the implementation, the model for the maintenance costs is adjusted slightly. This is because the maintenance costs of the first period that new/replaced equipment is installed, fall under the warranty from Siemens AG. towards Siemens Healthcare Nederland B.V.. Therefore, Siemens Healthcare Nederland B.V. and its customers do not have to pay for maintenance in those periods. In order to insert the warranty period in the model, variable $G_{i,p}$ is defined. This variable denotes at which periods p item i is installed and thus in which period no maintenance has to be paid by the customer. The installs or replacements happen at the first install M_i and after the replacement period r_i, until the item is removed at L_i or when the contract ends. This variable will be used in the calculation of the value of the cost element maintenance.

$$G_{i,p} = \begin{cases} 1 & If \quad p = \{M_i + k \cdot r_i \mid \ p < \min(L_i\ ;\ T+1), \quad k \in \mathbb{Z}^* \} \\ 0 & Otherwise \end{cases} \qquad \forall\, i \in I \qquad (44)$$

The costs associated with the cost element *maintenance* for item i at period p ($C_{i,p}^{Ma}$) are now calculated based on Equation 45.

$$C_{i,p}^{Ma} = \begin{cases} (1+j)^{p-1} \cdot m_i \cdot pr_i \cdot (1 - G_{i,p}) & If \ \ B_{i,p} = 1 \\ 0 & Otherwise \end{cases} \qquad \forall\, p \in P, i \in I \qquad (45)$$

4.6. Implementation

In Section 4.1 till Section 4.4 the model that determines the optimal number of devices based on the total cost of ownership is described. In order to make it possible that Siemens could use this model in practice, it is implemented in a Microsoft Excel tool with the adjustments proposed in Section 4.5. Section 4.6 explains the developed tool. For the explanation, the data of the theoretical case is inserted in the model.

The developed tool consists of thirty-four sheets that all represent the input, a TCO cost element, the capacity analysis, the output of TCO, or the optimization. Figure 10 shows the map that helps to navigate through the tool. This map forms the basis when calculations need to be made. The structure of the TCO model is visible in the different columns of the map. For example, the buttons of the forth column guide to the sheets where the costs of the hospital's cost elements are calculated.
Furthermore, the fifth column represents the constraint on the demand and thus the capacity analysis and the output could be found behind the buttons of column six and seven. The main goal of

the model is to determine the optimal number of devices to process the expected demand. This part is programmed behind the last two buttons.

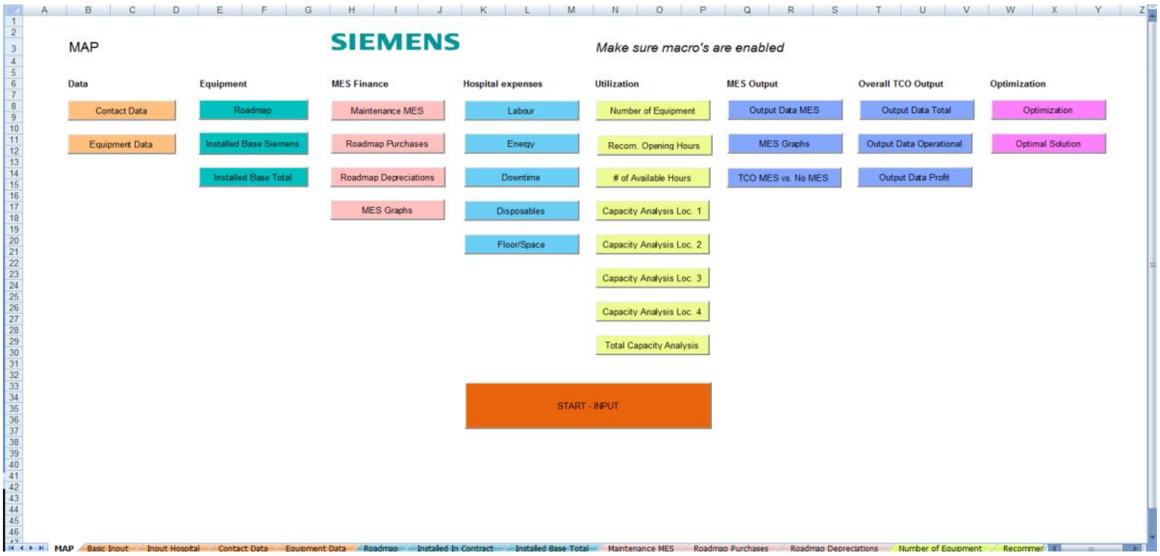

Figure 10: Map of the TCO optimization model

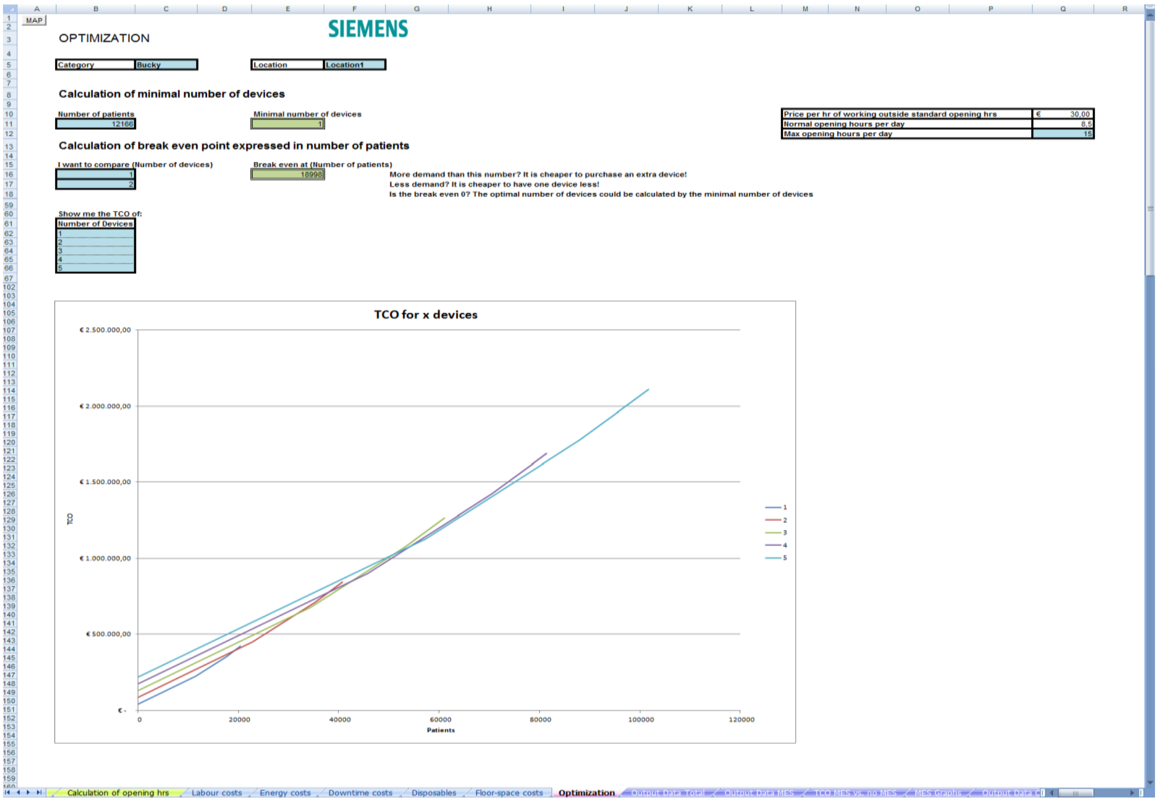

Figure 11: Screenshot of the optimization sheet

The sheet of the optimization is shown in Figure 11. Based on the input of the different cost parameters, the model gives two outputs for a requested department and location. At first the minimal number of devices, given an expected demand, is calculated. This calculation uses Equation 37, which is proposed in Section 4.4. The minimal number of devices is needed when the TCO functions do not intersect. Once maximal daily number of opening hours is known, different possible numbers of devices could be displayed in the graph. Doing this, provides extra insight for Siemens and the hospital about the threshold values. At last the breakeven point, where the costs of having a certain demand is equal for $D_{p,s,v}$ and $(D_{p,s,v} + 1)$ devices, is calculated. This breakeven point is the second output of the optimization model.

As mentioned in Section 4.4.3, the roadmap, showing all installs during the contract, could be created based on the outcomes of the optimization. An example of a roadmap worked out in the spreadsheet of the developed tool is given in Appendix C. The values '1' represent a new install or replacement. The given example is not the optimized solution of the theoretical case.

The tool provides besides the calculations also a few graphs representing the results of the calculations. The graphs visualize the effect of the chosen solution and therefore help to interpret the result of the optimization. Figure 12 shows an example of the graphs for the MES contracts. The right graphs show the difference in cash flow of equipment plus maintenance when a MES contract is used compared to the situation when there is not. The left graph represents the different expenses, the acquisition price, the maintenance costs and the extra MES service costs, in a MES contract of all periods. The flat fee of the MES contract is clearly visible in these graphs.

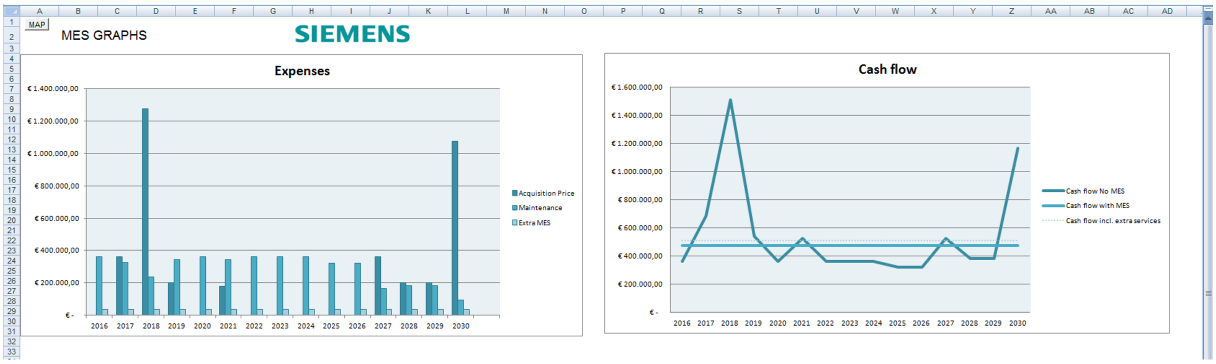

Figure 12: Example of the sheet: MES Graphs

In order to use the developed tool in practice, data has to be gathered by the user. The list of data required to use the developed model is shown in Appendix C and can be consulted when the model is used in a new case.

4.7. Summary

Chapter four described our model which is used to determine the optimal number of devices in a hospital and its implementation into a tool. In Section 4.1 we combined the input of the literature with the expertise of Siemens and Hospital A. We have chosen the following cost elements to include in our model: Acquisition, Maintenance, Extra MES service, Labour, Disposables, Operating supplies, Downtime, and Floor/Space. The equations which determine the cost elements are presented in Section 4.2, where after we described the constraints on the minimal capacity, maximum opening hours, and the moment of removal. We determined the optimization with the use of break even points, where the costs of using D and $(D + 1)$ devices are equal. At last, we developed a tool which makes it possible to use the model easily in practice. This tool is described in Section

5. Experiments

Two experiments are performed with the developed model and tool from Chapter 4 in order to understand the behaviour of the model. The first case is a smaller theoretical one with no reference to an existing hospital and the second case shows a practical, more complex situation. Section 5.1 explains the theoretical case. Thereafter, in Section 5.2, the practical is described.

5.1. Theoretical case

In the theoretical case we are looking at a hospital with two locations, namely The Hague (TH) and Scheveningen (SC). Not all kinds of equipment is available at these locations. In The Hague there are Bucky systems and MRI-scanners and at location Scheveningen there are just Bucky's. The MES contract should start in 2016 and the first contract will last for fifteen years. However, it is assumed that the contract will be continued afterwards. One unit of a period is equal to a year.

Set	Description	Cardinality
$\boldsymbol{P}$	Periods	15
$\boldsymbol{S}$	Equipment categories/departments	2
$\boldsymbol{V}$	Locations	2

Table 7: Summary of case description

The average price in the Bucky category is €200.000,- and a hospital pays on average €1.075.000,- for a MRI-scanner. These prices are indicative of the real prices. All Bucky's are replaced after 10 years and the MRI-scanners have a replacement interval of 12 years.

In 2015, location The Hague examined 49.000 patients on their Bucky systems. They expect a yearly growth of 1,5%. The Bucky department in Scheveningen is a lot smaller than the Bucky department in The Hague, namely 18.400, and the hospital expects that the demand will only shrink with -3%. The last department at The Hague, the department of the MRI's, processed 8.400 patients in 2015 and a growth of 2,5% is expected for the upcoming years. The future demand of every period based on the expected growth is given in Appendix B.

The supplier assumes that the maintenance percentage (m_i) in every period is equal for all items and has the value of 10% per period. No indexation on maintenance, as well as on the payment, is taken into account in the case. The hospital does not want a lot of extra training and consulting. Therefore the supplier uses an Extra MES percentage x of 1,5% of the price of equipment. The margin for the supplier's profit over the total value of the MES contract, is set to 5%. This data is summarized in Appendix D.

The hospital is normally open for 8,5 hours a day. The opening hours of the different departments are all allowed to be extended until 15 hours a day. The Dutch working conditions for the healthcare sector tell that for work between 6 and 7 a.m. and between 8 and 10p.m. employees get a compensation of 22% of their wages above their normal salary. When the opening hours are between 8,5 and 13 hours per day, the extra costs for labour are set to €30,- an hour. The irregular hour allowance is taken into account when the department is opened between 13 and 16 hours. For those hours, the extra amount of €30,- and the 22% compensation on the normal wages is taken into account. Since the hospital is open on 254 weekdays a year, the h^{REG} equals $8{,}5 \cdot 254 = 2159$ hours, $h^{EXT} = 1143$, and $h^{IRR} = 762$. Since the maximal number of hours on one day of every department is restricted by 15 hours a day, h_s^{MAX} equals 254*15 = 3810, which is smaller than the sum of regular, extra and irregular hours. The total number of hours in a year is equal to 8760 hours.

In order to calculate the TCO, values are assigned to all cost parameters. These parameters are representative for a real case. The data used, is shown in Table 35 which could be found in Appendix D.

5.2. Practical case

The practical case examined in this research is based on a middle size Dutch hospital. This hospital is called Hospital A due to confidentiality. There is currently a MES contract at this hospital and therefore multiple devices are already installed. Based on the data of the equipment that is within the MES contract, the model could be validated. If the model is a good representation of reality, it will give the same contract value as the real contract. Since the case is also used to validate the model, there is more data needed in the practical case compared to the theoretical case. Besides the expected and realized demand of patients and the values of the different parameters, the installed base is used as input for the model and is thus explained in this section. Information about the installed base makes it possible to compare the current situation with an optimal situation.

In order to implement the model at Hospital A, there is data needed from Siemens and their customer. The distinction between these two data sources is also used for the construction of the model for the total cost of ownership and is used as well in the data gathering part. Besides this distinction, a last data group is added which describes the utilization parameters used to determine the required capacity in hours.

Data from Siemens is gathered by interviews with financial controllers and other experts who work with the MES contracts. The data from Hospital A is retrieved from the financial director and the business analyst of the hospital, and operational team leads. A detailed list of data used in the implementation of the model at Hospital A can be found in Appendix F.

MES contract costs

The partnership between Hospital A and Siemens is fixed for p years. Therefore, the set P consists of p periods. Hospital A has just one location, however for this research two locations for devices are distinguished, namely radiology plus the SPECT scanner on nuclear (together called radiology in this research) and elsewhere. The optimization focuses on the radiology part, since most data is available on that department. Besides that, most of the departments in radiology use appointments. During an appointment the main goal is to make an image of the patient, whereas in other parts of the hospital not all appointments consist of an examination with a medical device. Therefore, it is better possible to determine how often the devices are used in radiology, and an optimization would make most sense at that location. Moreover, most of the equipment from the MES contract is installed at radiology.

In total, there are i different items in the MES contract. These items form together the set I. At radiology, there are i_{rad} devices installed. i_{other} of the residual items are items in the category 'Other'. This category consists of systems that do not process patients, like computer software. The remainder $i_{elsewhere}$ systems are installed elsewhere in the hospital. These last devices are used to validate the total price of the MES contract, however too less information is available on the expected demand to optimize the use of those devices.

In the practical case, 12 different categories of equipment or departments are distinguished, which are shown in Table 8. Eleven of these categories refer to equipment and one is for the remainder items which for example consist of computer systems like the syngo.via.

Categories in set S	
Bucky	Angio
Mobile	C-Arm
Ultrasound (US)	PET
MRI	SPECT
CT	Mammo
Dexa	Other

Table 8: Distinguished categories/departments

The prices of the i items are denoted by pr_i, the real values are confidential. The different replacement periods used in the model are the same values as the intervals used in the realized MES contract. These values differ between 7 and 14 years, but are constant within an equipment category.

Confidential

The maintenance costs are estimated to be m_i% per year. The maintenance costs are not just the purchase price times this percentage, but Hospital A and Siemens agreed on an indexation, denoted by j, of 2,5% per year for maintenance. When optimizing the portfolio of devices, the indexation is put to 0%, as mentioned before in the model description.

The extra MES contract costs per period x are approximately 1,364% of the total price of installed equipment. This value is rounded down from the actual value of this cost element of the realized contract. In the model, the exact value is inserted. Siemens mentions that this value is quite low compared to other contracts.

Once all costs are known of the cost elements *acquisition, maintenance* and *extra MES service costs*, the overall MES contract price could be calculated. In order to do so, the margin for profit of the cash flow should be set. Due to confidentially this value will be described as a.

Siemens and its customer could choose to use an indexation of the total cash flow l of the flat fee of the contract. In the case of Hospital A both parties decided to use a 1,25% indexation of the cash flow. The indexation does not have any influence on the TCO when the cash flow is not discounted in the NPV calculations. This value of l is just like all previously mentioned values of the different parameters given in the data summary, which is given in Appendix F.

Hospital costs

To calculate the costs that are associated with the use of the medical equipment in the hospital, five different cost elements are distinguished. The data from the practical case is explained based on this same structure. All values of parameters associated with the hospital costs, are displayed in Appendix G. There are no values assigned to the parameters for the equipment categories 'Mobile' and 'PET' since these types are respectively not in radiology or in the MES contract. Besides that, the products in category 'Other' do not process patients, so the parameters are not applicable (N/A).

Labour
The normal costs of one hour of labour are determined by Hospital A. The cost of labour for a hospital does not only include the wages of the employee, but also for example social charges. Only the executive staff, and thus the direct labour, like laboratory staff and operators is taken into account. The cost for a radiologist that needs to judge the images is not included since no data was available. The costs for one employee operating the equipment for one hour w_s is w_s. For the hours outside the regular opening hours, the hospital estimated that they will have extra costs of €100,- per hour. The value of this parameter is a rough estimation, since no in depth research was possible for the cooperating hospital. During irregular hours, the hospital has to pay an extra 22% over the normal wages of the employees (c) of w_s and the extra hospital expenses of €100,-. This number is determined in the Dutch collective agreement for hospital staff.

For some of the examinations, there is just one person required to help the patient and to adjust settings for the research. This is for example the case when a X-ray picture needs to be taken on a Bucky system. On other systems, there are more employees needed, but the number of operators might even differ between the examinations on one device. The average over all examinations of three year is taken to determine how many operators are required.

Disposables
Hospital A provided data on the costs of all different kinds of disposables over three years. These disposables are categorized under the different types of systems. The price of one piece of disposable, for example a needle or a stent, and the number of times it was used that year is given. Based on this data the total costs for the disposables in every year are calculated. Since the number of examinations during these same years is known, the average price per examination (g_s) is determined for every equipment category and is shown in Appendix G.

Operating supplies
To run medical equipment, there is only energy required. No gas or oil is consumed by the devices. Therefore, the cost for operating supplies consists just of the costs for energy. The costs for energy are divided in two parts, the part when the department is open and the part where it is closed, see Section 4.2.2. From all different product descriptions, information is gathered on the power consumption of the different systems. Within a product category, there are multiple different models which all have a slightly different power consumption. The average is taken over all models that Siemens provides to determine the amount of Watts a device uses. The current price per kWh of €0,23 is used to translate the power consumption into monetary terms. The outcomes of the data analysis and thus the prices per hour (o_s) are visible in Appendix G.

Downtime
Since the operating costs like labour and operating supplies during downtime are already included in the total costs for those cost elements, the downtime costs only consist of costs that are made to prepare the examination, and have to be made again when the examination is on another moment. The costs for downtime per lost examination are denoted by b_s. Since no data for this cost element is available from previous years, the value of the parameter is an estimate and based on the price of disposables.

Floor/Space
The space needed for one piece of equipment (z_s) is determined by the cooperating hospital. They provided information about the current situation at the hospital. In the total area where the equipment is installed is included, as well as the area for the control room and dressing room. The

price of one square meter over a year includes the exploitation costs. These costs are build up by the rent of the floor, the cleaning costs, the energy costs for lights etc. and service costs for the room. price of one square meter for the MRI scanner is more expensive than for other devices, since the area needs a cage of Faraday to block the magnetic radiation. The costs for one square meter per period are denoted by u_s.

Utilization parameters

In order to determine how many hours a hospital needs to be opened in a period to process the demand, several parameters are used. The values of all parameters are shown in Appendix G.

At first, the expected demand needs to be determined. The contract between Siemens and Hospital A is already going on for a few years. Therefore the realized demand is used as input for the previous years. After the already realized period, the hospital expects in the first two years a growth at the MRI and CT-scanners of 1,5%, thereafter a growth percentage of 2% at those systems is expected. The other systems are expected to have a stable demand in the future.

Data on the total demand on all devices of the past is given. This data contains the total production of the system, so also the trauma's and weekend production are included. Departments are not standard opened (except the MRI department) on weekends and examinations during the weekend are performed just in case it is required. Therefore, these examinations are filtered from the data. Since the MRI department has planned demand on Saturdays in Hospital A, the demand at that day is included in the normal demand. The data is filtered for traumas outside the current opening hours as well. Since the opening hours are adjusted to an expected number of traumas on that day, those trauma's are included in the normal demand, however the trauma's outside the opening hours are removed. Once the demand from the weekend and the trauma's are removed from the total production of the past years, the scheduled demand is left over. Based on this data, together with the growth percentage, the expected demand over all periods of every system could be given. The values of expected demand are shown in Appendix F as well as the trauma and weekend correction on the realized production per department.

Once the demand is known, the next parameter of interest determining the capacity of the hospital is the treatment time. The treatment time is the time that a patient Assigning value to this parameter is done based on the data of three years of examinations. In the treatment time, the time from the moment employees start preparing the examination until the patient walks out of the room, is taken into account. The average is taken over all performed examinations of all three years for every department. This gives the values of an average treatment time in minutes. This number is translated to hour for the parameter $t_{s,v}$.

The parameter that describes the yearly number of hours of preventive maintenance and updates (pu_s) is determined by the service manager of Siemens. This number is assumed to be independent of the opening hours. The used uptime guarantee ut_s of category s of Siemens towards the hospital is the average percentage that is used in contracts with Siemens' customers. The average value is taken since the agreement might differ between contracts and is dependent on the preferences of the hospital which are unknown in the acquisition phase. For example, if there is just one scanner, the hospital might prefer to have a higher uptime guarantee of that system than when it had two scanners. This is because the risks of downtime are shared when there are more scanners.

Siemens decided together with Hospital A that a utilization of 85% is preferred. This percentage makes sure that peaks in demand are covered. The value of y_s is the same in this case for all departments in radiology.

Hospital A is open every day from 8 a.m. till 5 p.m. Thus the yearly regular hours (h^{REG}) equal 2286 when the hospital is open 254 days a year. The number of days is the weekdays minus the six days of yearly Dutch holidays. The extra hours are taken into account when the total number of hours exceed 9 hours but are less than 13 hours. This makes the yearly extra hours (h^{EXT}) equal to 1016. The yearly number of irregular hours is in the practical case 762 ($= h^{IRR}$), this is the same as 3 hours per day for 254 days. Every department is allowed to be open for 16 hours a day. On a yearly base, a maximum of 16 hours (h_s^{MAX}) daily, equals 4064 hours for the other departments. The last parameter, h^{TOT}, gives the total hours in a year, which is 8760 if there are 365 days in a year.

5.3. Summary

We are going to perform two experiments with our model in this research. The first experiment is a smaller theoretical case of a hospital with two different locations; The Hague and Scheveningen. The hospital owns only Bucky and MRI scanners. We use for this case a horizon of fifteen years. The second experiment we are going to perform is a real case. The model is developed and tested for Hospital A, a middle size Dutch hospital. Since Hospital A and Siemens have already a MES agreement, real data is available. Hospital A works on one location and has equipment in eleven different categories.

6. Model verification and validation

Before the model could be used in practice, it should be checked whether the tool is developed as it should be and checked whether the tool represents the reality well. The first check is called the verification and could be read in Section 6.1. By comparing the real MES contract value of Siemens and Hospital A and the value determined by the tool, the tool is validated. The results of the validation can be found in Section 6.2.

6.1. Verification

The goal of the verification is to check whether the model is doing what it should do. In other words, in the verification the tool is checked on bugs and it is determined whether the TCO of having $D_{p,s,v}$ or $(D_{p,s,v} + 1)$ devices is equal at the threshold value of number of patients. This verification is done based on the data of the theoretical case.

At first, the model is debugged to make sure the tool is working. All errors are solved and calculations are checked with the designed model. This is an iterating process. After every step in the development of the tool, a check was performed. Because new parts of the tool had influence on the existing parts, previously developed parts were checked again when something changed. The tool is free of bugs at this moment.

The second step is to determine whether the threshold value is indeed the value where the TCO functions are equal. When looking at the possibility of having $D_{p,s,v}$ or $(D_{p,s,v} + 1)$ Bucky's (s) at location The Hague (v), the model gives the following values for $E_{D,D+1}$, which represent the threshold value expressed in number of patients.

$D_{p,s,v}$	$E_{D,D+1}$
1	18.998
2	31.233
3	42.683
4	54.134

Table 9: Threshold values for Bucky's at The Hague

At first the values are compared to the graphical representation of the TCO function for 1 till 5 devices. This graph is given in Appendix C. The found values look correct, however it is not proven that the TCO value at the $E_{D,D+1}$ is exactly the same. Therefore, the TCO associated with the number of devices and patients is put into the TCO formula of Equation 35. The following values are calculated by the model:

$D_{p,s,v}$	$f_{p,s,v}$	$TCO(f_{p,s,v}\,;D_{p,s,v})$
1	18.998	€ 391.314,35
2	18.998	€ 391.314,35
2	31.233	€ 628.392,49
3	31.233	€ 628.392,49
3	42.683	€ 853.245,60
4	42.683	€ 853.245,60
4	54.134	€ 1.078.098,70
5	54.134	€ 1.078.098,70

Figure 13: TCO values at the found thresholds

The TCO values are the same at the threshold values when $D_{p,s,v}$ and $(D_{p,s,v} + 1)$ are compared. The calculated value is therefore indeed the point of intersection of two TCO functions. Thus is concluded that the model gives the result that it should give.

The same calculations are done for the MRI's at The Hague. For having $D_{p,s,v}$ equal to 1 until 5, there are no intersections of the TCO. The corresponding graph is given in Appendix E. To check whether there are indeed no intersections, the costs at the maximal number of patients $(pa_{M,D})$ of $D_{p,s,v}$ devices should be less than having $D_{p,s,v} + 1$ devices for the same number of patients $pa_{M,D}$. To check whether this is true, the TCO of those points for several possible amounts of devices is calculated. The results of this calculation are also visible in Appendix E and show that the TCO of having the maximal capacity on $D_{p,s,v}$ devices is lower than having $(D_{p,s,v} + 1)$ devices at the same capacity for $D_{p,s,v} = 1\ to\ 5$. This indicates that there is indeed no intersection when those numbers of devices are compared.

The last step to verify the model is to determine whether the TCO of having less patients than $E_{D,D+1}$ but more than $E_{D-1,D}$ $(E_{D-1,D} < f_{p,s,v} < E_{D,D+1})$ would give the least costs when $D_{p,s,v}$ devices are used. This is checked for the Bucky's at location The Hague. The graph implies already that this is the case; however calculations could confirm this statement. The results for the comparison of the TCO of a certain demand on the optimal number of devices and two alternatives are given in Table 10. The data in that table show that the optimal number of devices gives indeed a better solution than the alternatives.

$f_{p,s,v}$	Optimal $D_{p,s,v}$	$TCO(f_{p,s,v}\,;D_{p,s,v}-1)$	$TCO(f_{p,s,v}\,;D_{p,s,v})$	$TCO(f_{p,s,v}\,;D_{p,s,v}+1)$
30.000	**2**	€ 658.546,46	€ 602.307,67	€ 609.179,16
40.000	**3**	€ 828.880,90	€ 796.479,02	€ 811.432,95
50.000	**4**	€ 1.008.026,23	€ 990.650,38	€ 1.013.686,75

Table 10: Comparison of the TCO of different possible numbers of devices for a given demand on the Bucky's in The Hague

Based on the debugging and the three verification steps it is concluded that the developed tool represents the designed model well.

6.2. Validation

The model is validated by the implementation of the contract of Hospital A. The model consists of two different parts, the MES contract costs and the costs of the hospital. There is already an existing contract and therefore it is possible to compare whether the model gives the same values for the MES contract as Siemens calculated in reality. Even though this research is focussed on the location radiology, the existing MES contract is a contract over all locations. Therefore not only the data from the i_{rad} devices installed at radiology is needed, but also data about which equipment is installed at other locations is required for the validation.

At first the roadmap with all the replacement is checked for all i items installed in the MES contract. The moments of the first install M_i and definite removal L_i of the items are taken from the contract and are inserted in the model. These values, shown in Appendix F, are used to determine at what moments equipment is installed. The roadmap for Hospital A is constructed by the values of $G_{i,p}$ and is shown in Appendix G. The created roadmap is exactly the same as the roadmap constructed by Siemens once the contract started.

The next step is to compare the costs associated with the three cost elements that make up the price of the MES contract. In Appendix G, the values of the variable $B_{i,p}$ and $J_{i,p}$ are visible. Based on the values of $J_{i,p}$ the value of the cost element *acquisition* is calculated. This value is checked with the value calculated by Siemens in the contract. The variable $B_{i,p}$ is used to calculate the costs of the maintenance.

Table 11 shows the values calculated by the model and those of the real MES contract. A little difference is visible between the results. There is some over estimation of the total value of the MES contract in the model, of 1,02%.

Confidential

Since the real costs of maintenance are dependent on the agreements on service and uptime levels of the different equipment, the model will always give an approximation of the real maintenance costs. Siemens prefers an upper bound in the acquisition phase and therefore the model is assumed to give a correct representation of the real MES contract costs.

Confidential

The second part of the model are the operating costs. The hospital of the practical case assigned costs to different examinations. However these costs are not comparable to the costs in the designed TCO model. This is because one kind of examination, for example brain research, could be performed on different types of medical systems. Thus, the calculated costs at the hospital are not directly associated to one type of equipment. Because no more data was available than the costs per type of examinations, it is not possible to compare the costs calculated by the model, with the costs in reality. So no validation is done on the operating costs.

6.3. Summary

We performed a verification of our model at first by debugging the programme. Our second step was to find the threshold values and the associated costs. Based on this second step, we could conclude that at the threshold values the TCO of the options is indeed the same value. The last step for verification we did is the check whether our optimal number of devices gives the minimal TCO for a specific number of patients. These three steps make us conclude that the model is working correct.

For our validation, it was only possible to compare the cost of the MES contract with the real data. Only a little difference was visible between our findings and the real contract, but this difference is completely assignable to the made estimations of parameters. Siemens prefers an over estimation of the MES contract costs, so we can conclude that the model represents the real contract costs good.
We were unable to validate the costs of operations at the hospital.

7. Results

The designed model from Chapter 4 is implemented in an Excel file. The developed tool is verified and validated in Chapter 6. With the input described in Chapter 5, the outcomes of the model could be determined. This is at first done for the theoretical case in Section 7.1. The outcomes for the real case are given in Section 7.2. The last section, Section 7.3, determines the sensitivity of the outcomes to changes in different parameters.

7.1. Theoretical case

In the theoretical case a hospital with two locations is taken into account, namely location The Hague (TH) and Scheveningen (SC). The first location has a department for Bucky systems where X-ray images are taken. Besides that, there is demand for MRI examinations. The location Scheveningen is just able process patients on Bucky's. The expected demand for the different departments from 2016 till 2030 is shown in Appendix D. In the same part of the appendix, the different parameters for the TCO calculations are given.

When the parameters of the theoretical case are filled in the developed tool, the threshold values expressed in number of patients could be calculated in order to determine the optimal number of devices at every single point of time. In Table 12 the threshold values are visible for having 1 till 7 devices. When N.I. is written, there is no intersection of the TCO functions and is thus the least possible number of devices the best solution for a given demand.

$D_{p,s,v}$	Bucky, DH $E_{D,D+1}$	MRI, TH $E_{D,D+1}$	Bucky, SC $E_{D,D+1}$
1	18998	N.I.	17098
2	31233	N.I.	28110
3	42683	N.I.	38415
4	54134	N.I.	48720
5	65584	N.I.	59026
6	77034	N.I.	69331
7	88485	N.I.	79636

Table 12: Threshold values for 1 till 7 devices at all departments and locations

With the found threshold values, the optimal number of devices at every department of all locations is determined per period. This is done by comparing the expected demand to the threshold values. The outcomes are presented in the graphs in Appendix I.

Once the optimal number of devices per single period are known, the optimal number of devices over the whole horizon should be calculated where the restriction on the removal of the items is taken into account. In this case, the optimal removal of the Bucky in Scheveningen would occur in 2018. The hospital was assumed to be empty prior to the start of the contract, and therefore all devices are installed at period 2016 for the first time. As a result of this, the Bucky could only be removed in 2016 or in 2026. The model determines these two moments and calculates which of these options gives the lowest TCO when looking at the full horizon. As a result of this calculation the model decides that there should always be only one device from 2016 till 2030, which can be seen in Table 13.

$s, v \setminus p$	‘16	‘17	‘18	‘19	‘20	‘21	‘22	‘23	‘24	‘25	‘26	‘27	‘28	‘29	‘30
Bucky TH	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5
MRI TH	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Bucky SC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 13: Optimal number of devices over full horizon

Once the number of devices of all locations and departments for the full horizon and the expected demand for all those locations and categories are known, the opening hours could be calculated. This gives insight for the hospital in the effect of the found solution in practice. The recommended daily opening hours associated with the optimal number of devices are given in Appendix H.

The optimal number of devices is now known for all periods when looking at the full horizon. The solution is based on multiple minimizations, so there is no clear picture of the TCO of the whole portfolio. Therefore, the next step is to determine the TCO of the whole portfolio which includes all devices at every location and department. When the optimal number of devices and the expected demand are inserted in the TCO model, the total TCO of the solution over the whole contract could be calculated. Every device installed in the contract has the average price and replacement period of the category, just like it is assumed in the optimization.

Since no discount rate is taken into account in the calculation of the NPV of the TCO of the portfolio of equipment at the hospital equals just the sum over all cost elements in every period. The result of the TCO calculation is visible in Table 14 and Figure 14.

	Cost per cost element over 15 years
MES contract	€ 10.222.960,53
Direct downtime	€ 37.841,64
Labour	€ 24.509.164,20
Energy	€ 1.867.678,90
Disposables	€ 3.118.256,24
Floor/Space	€ 1.129.672,78
TCO of portfolio	**€ 40.885.574,29**

Table 14: TCO of optimal portfolio full horizon

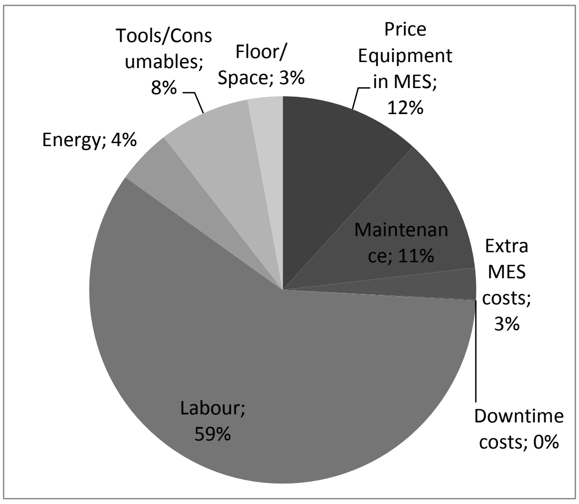

Figure 14: Share of each cost element in the TCO optimal portfolio full horizon

If the removal of a device was not restricted by the replacement intervals, the second Bucky would have been installed in 2016 and removed in 2018. The effect of including the removal restriction is calculated by forcing the model to remove the device in 2018. The hospital only has to pay the acquisition over the two periods in the TCO calculation since it is assumed that after two years it is possible for the supplier to use the device in another hospital. The value of the TCO is visible in Table 15 and is lower than the TCO of the optimal portfolio with the removal restriction. The same table gives the TCO as well for the situation where the hospital chooses to add the second Bucky in 2016 and remove it after the replacement period.

	Cost per cost element 15 years Removal of Bucky in 2018	Cost per cost element 15 years Removal of Bucky in 2026
MES contract	€ 10.304.013,16	€ 10.670.328,95
Direct downtime	€ 37.841,64	€ 37.841,64
Labour	€ 24.411.879,36	€ 24.187.570,09
Energy	€ 1.869.260,57	€ 1.875.587,22
Disposables	€ 3.118.256,24	€ 3.118.256,24
Floor/Space	€ 1.141.790,38	€ 1.190.342,38
TCO of portfolio	**€ 40.883.041,35**	**€ 41.079.926,52**
Difference to optimal solution with removal in 2016	*- 0,01%*	*+ 0,48%*

Table 15: TCO of portfolio full horizon. Left: Bucky removal in 2018, Right: Bucky removal in 2026

Besides value of the TCO in the different options of removing the Bucky system, another analysis of the solution is performed. Namely the TCO of the option of combining both locations is calculation. If the two locations of the hospital are combined, and thus the capacity of the Bucky systems is shared, the patients that need an examination on those devices could be processed in Scheveningen and The Hague. To be able to take all patients together, the treatment time needs to be adjusted because both locations have another average time to examine patients. This is done by taking the weighted average of the treatment times of both locations based on the demand over all 15 years. As a result, the new value of $t_{bucky,DH+SC}$ becomes 0,1543 hour. To see the influence of this change, the expected demand is summed and compared with the new threshold values, both of these values can be found in Appendix H. In the case of a combined Bucky department, the hospital needs in all fifteen periods six devices. No devices are removed during the period of fifteen years. Based on this number of devices, the required opening hours are determined. The recommended daily opening hours can be found in Appendix H as well. The new Total Cost of Ownership becomes in this case € 40.769.414,96. This is approximately € 116.000,- (0,28%) less over fifteen years than the option where the two locations are separated. Since there are also costs included in realizing a merge of the two departments, the benefits of 0,28% might not be enough to make the merge profitable. Therefore, the hospital should make a business case where they compare the benefits and the extra costs before they make a decision.

The last experiment performed on the theoretical case is the option where the hospital did not give a good forecast of the demand.. For the new situation the growing percentages are expected to be exactly the opposite, namely where a yearly increase is expected of 1,5%, in the new situation there will be a decrease of 1,5%. The old and new values are given in Table 16 and the new expected demand is given in Appendix H.

s, v	$f_{2015,s,v}$	Growth % normal	Growth % new
Bucky TH	49.000	1,5%	-1,5%
MRI TH	8.400	2,5%	-2,5%
Bucky SC	18.000	-3%	3%

Table 16: Expected demand of 2015 and growth percentages of normal and new situation

With the adjusted expected demand, together with the same parameters as used before, the optimal number of devices is calculated. The results are given in Table 17 and show the number of devices with the usual constraint that devices can only be removed after a full replacement period. The associated daily opening hours are given in Appendix H.

$s, v \setminus p$	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Bucky TH	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3
MRI TH	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1
Bucky SC	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Table 17: Optimal number of devices with adjusted demand

The situation with an adjusted demand has a TCO of € 35.259.751,44 over the horizon of 15 years. This number is 15,96% less than the TCO of the optimal situation with the normal demand. This highlights the importance of a accurate forecast. For the calculations are the opening hours displayed in Appendix H used. These are the least hours possible to fulfil the demand with the given number of devices.

7.2. Real case

In the real case, there is already equipment installed at the hospital. Choices on the number of devices over a period of p years is made at the beginning of the contract, which influences the flat fee of the MES contract, as well as the expected operating costs. The total cost of ownership with the made choices in the ongoing MES contract, is determined in Section 7.2.1. The results of the optimal number of devices that should be used in order to process the expected demand is determined by the model and shown in Section 7.2.2. The value of the total cost of ownership of the found solution is presented as well.

7.2.1. Current situation

The number of devices in the hospital in all cases is displayed for a contract length of 12 years, due to confidentiality. This might not be the real contract length. Besides that, the results are only displayed for six categories of equipment. However, the calculated TCO values are the values of the real contract length.

Even though the MES contract covers i items installed at the hospital, the optimization is just focussed on radiology, partly because of a lack of data of the other parts of the hospital. In the current situation are in total i_{rad} devices installed at location radiology. These devices have to process the given demand which is given in Table 41. During the MES contract, the number of devices changes twice, which is visible in Table 18 and Table 44. In period four a MRI-scanner is added, and in the ninth period an Angio system is removed.

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	5	5	5	5	5	5	5	5	5	5	5	5
MRI	1	1	1	2	2	2	2	2	2	2	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	3	3	3	3	3	3	3	3	3	2	2	2
C-Arm	3	3	3	3	3	3	3	3	3	3	3	3
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Table 18: Number of devices in current MES contract of Hospital A at location Radiology

Given the expected demand and the number of available devices in every period of the current situation, the recommended opening hours on one device in category s in every year can be calculated. Spreading the opening hours over all 254 days in a year, the average daily opening hours are known. The values calculated by the model are given in Table 19.

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	3,7	3,5	3,5	3,5	3,5	3,5	3,5	3,5	3,5	3,5	3,5	3,5
MRI	13,3	13,9	14,1	7,3	7,4	7,5	7,6	7,8	7,9	8,1	8,2	8,4
CT	5,8	6,0	6,0	6,1	6,2	6,3	6,4	6,6	6,7	6,8	7,0	7,1
Angio	0,8	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,4	1,4	1,4
C-Arm	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9
Mammo	4,6	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8

Table 19: Daily number of opening hours on every device in a category s at every period at Radiology in current situation

The number of devices together with the expected demand the associated opening hours form a solution that can be evaluated by the TCO. The result is visible in Table 20. Since the optimization does not keep in mind the indexations, the solution is also evaluated without indexation.

	NPV of TCO
Current situation incl. indexation	€ 44.222.647,63
Current situation excl. indexation	€ 42.655.540,05

Table 20: TCO value of proposed solution (current)

In the calculated value of the total cost of ownership are all eight cost elements included. All these cost element have a different share to the total costs. This share is influenced by the chosen solution of number of devices. The division of the TCO over all cost elements is shown in Figure 15. The same figure compares the current solution with the optimal solution.

7.2.2. Optimal solution implemented

The current solution does not have to be the option where the total costs of ownership are the least possible. Since no evaluation of the TCO happened when the contract started, it is interesting to see whether the hospital's fleet would change when the total costs of ownership are considered in the choice of adding or removing a device. Therefore the optimization is applied to the current situation with the parameters of Hospital A. Based on this input the threshold values can be calculated, where after the optimal number of devices is determined based on the expected demand.

The optimal number of devices is again determined by the use of the threshold values. In the calculations for the optimization, the prices ($\overline{pr_s}$) and the replacement interval ($\overline{r_s}$) for equipment in a category that are used are the averages of the price and replacement interval of the currently installed equipment. The devices that will be installed in the MES contract according to the optimization also have this same value ($pr_i = \overline{pr_s} \quad \forall\, s \in S,\ i \in R_s$). This is done since removing a more expensive model instead of a cheaper device, would give a distorted picture.

Based on the values of all parameters, the threshold value for having $D_{p,s,v}$ versus $(D_{p,s,v} + 1)$ devices is determined for every equipment category. The outcomes of the model are shown in Appendix J.

By combining the expected demand in all periods with the threshold values found by the model. It is possible to determine the optimal number of devices for Hospital A at every period for all equipment categories. The number of devices in the optimal situation is shown in Table 21.

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Table 21: Recommended number of devices in every period p and category s for Hospital A

Based on the number of devices, the recommended opening hours are calculated. These hours are visible in Appendix I. The TCO that is associated with the solution described above is calculated by the model and listed below in Table 22. In order to calculate the TCO associated with the optimal solution, it is assumed that all required devices at period 1 are installed by Siemens for the first time in that period, so no equipment of a third party is taken into account. The proportion of every cost element in the TCO of the optimal solution is visible in Figure 15.

Optimal situation	NPV of TCO
Optimal situation incl. indexation	€ 41.109.812,59
Optimal situation excl. indexation	€ 40.069.898,16

Table 22: TCO value of proposed solution (optimal)

Since there is already equipment installed at the hospital at the beginning of the contract, which cannot be removed immediately since equipment can only be removed after the replacement interval, the optimal solution is not realistic in the first periods. Therefore, next performed experiment is with the installed base of the current situation at period 1, and with the assumption that removals are only allowed after the replacement period of the already installed equipment. Based on these restrictions, the number of devices over the period of 12 years is determined and given in Table 23. The daily opening hours associated with the new recommended number of devices are shown in Appendix I.

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	5	5	4	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	3	3	3	3	3	3	3	3	2	1	1	1
C-Arm	3	3	3	3	3	3	3	3	3	2	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Table 23: Recommended number of devices starting with the installed base at period 1

Now all required data is known, it is possible to calculate the TCO of the solution again. Just like the implementation of the data of the current installed base, the TCO is calculated with and without the use of indexation.

Starting with installed base at p=1	NPV of TCO
Optimal situation incl. indexation	€ 40.258.708,85
Optimal situation excl. indexation	€ 39.111.776,06

Table 24: TCO value of proposed solution (optimal, starting with installed base)

It is remarkable that the TCO of the optimal situation, combined with the installed base at period 1 gives a lower TCO than the optimal solution. This could be explained by the fact that in the excising situation equipment is installed in the first periods where only maintenance costs have to be paid since the equipment costs are only included from the moment of first install in the contract. This first install might occur in this situation in, for example, the sixth period and therefore there are no costs for the purchase of that device over the first five periods. This effect is also visible in the graph that represents the shares of every cost element to the value of the TCO in Figure 15, since the equipment has only a share of 12% compared to a 17% share in the optimal situation. The graph in Figure 15 is also based on the indexed TCO, in order to compare the current and optimal solution better.

When looking at the share of the cost elements in the TCO of the current situation and the optimal solution with the installed base as starting point, it is clear that the costs for labour account for a bigger part in the optimal solution. Since the optimal solution suggests in many cases to have less devices, the opening hours will increase in order to meet the expected demand. When the opening hours are extended till over the regular hours, the labour costs will increase. This causes the effect visible in the shares of the cost element labour.

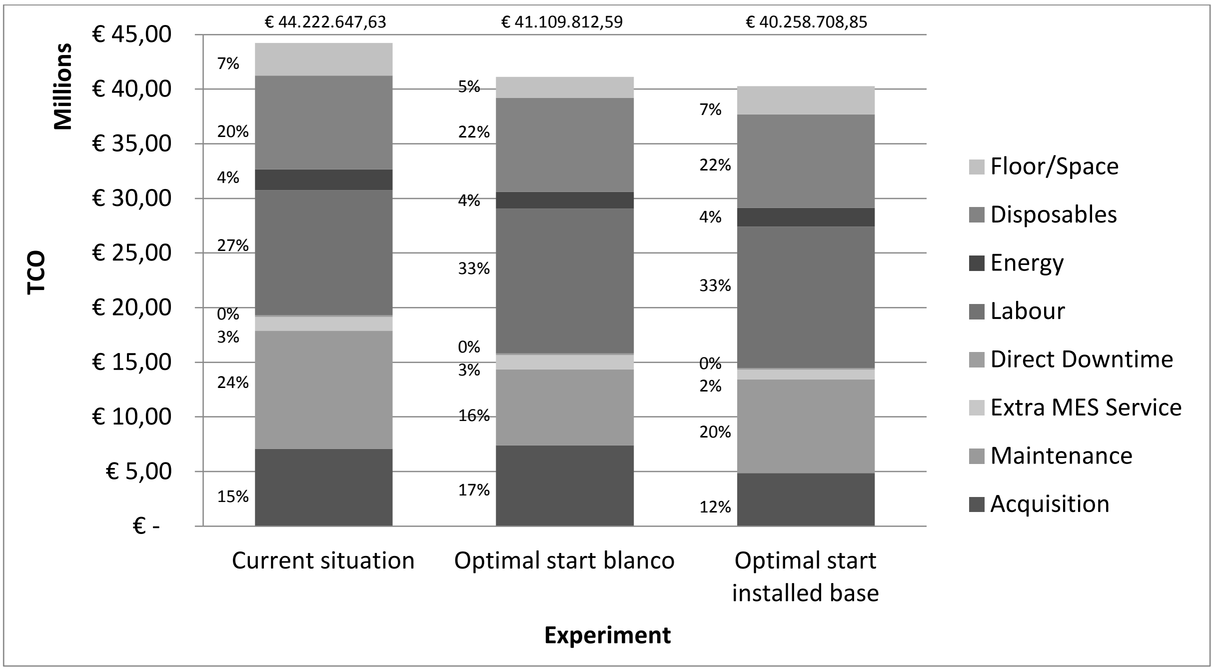

Figure 15: Shares of all cost elements in different experiments

The used treatment times in the above described experiments are averages of the realized treatment times over a few years. Some values of treatment times are numbers which are not possible to use when planning a department. For example, the treatment time on the MRI is determined to be 28 minutes. However, the MRI department makes in practice appointments of 30 minutes. Where other departments, like the Bucky, are able to plan approximately 8 patients in an hour. So in that situation the treatment time is representative. The case of Hospital A is also evaluated with appointment adjusted treatment times. The used treatment times are shown in Appendix J.

The result of the TCO calculation is based on the adjusted treatment times for the current and the optimal situation with both having the installed base at period 1 as starting point. The results, including and excluding indexation, are shown in Table 25. The associated threshold values and the number of devices are given in Appendix I.

Adjusted treatment times	Current situation	Optimal situation
Incl. indexation	€ 45.151.973,15	€ 42.120.137,50
Excl. indexation	€ 43.584.865,57	€ 40.858.420,75

Table 25: TCO value of proposed solution (adjusted treatment times, starting with installed base)

7.3. Sensitivity analysis

The results described in Section 7.1 and 7.2 are determined with the input of Chapter 5. The data from that section is based on information provided by Siemens and Hospital A. This section looks at the sensitivity of the model to changes on the used data.

There are two types of changes in the value of the parameters. At first, it is possible that parameters are estimated wrong. Besides that, operations can change in practice. For example, the hospital is able to scan its patients faster than before. The influence on the total value of the TCO of the practical optimal solution is firstly determined for the case that some parameters are different due to errors and afterwards the influence of changes in operations is examined. The sensitivity analysis is done for the case where there is no indexation. An empty hospital is used in the TCO calculations, so no equipment is installed at the beginning of the contract. This prevents the influence of the current choices of Hospital A on the results of the sensitivity analysis, since this influence is significant when the optimal solution was compared for the situation with and without installed base. All other data is used from Hospital A.

Some values of parameters in the practical case are estimates. At first, the energy costs are determined from product descriptions. However, every hospital uses their devices differently in practice. Besides that, a hospital might have the newest models installed which consume less energy than the taken average of devices or the price of one kWh might change. Therefore it is interesting to see what the influence is of a change in costs of a kWh per hour. These parameters influence the optimization, since the number of hours a device is off increases when an extra device is added. Moreover, when an extra device is added, the costs for energy when equipment is on is higher since more hours of preventive maintenance and updates is required and during these hours de equipment is running as well. The influence of an increase and decrease of 50% of the costs for one kWh of energy is examined. The threshold values for these options and all other changes in parameters that will be examined in this section, are given in Appendix J. The same appendix shows the required number of devices at every department in all periods for all options.

Even though the costs for energy have changed, the number of devices is equal when optimizing the case of Hospital A, see Appendix J. The value of the TCO is thus only based on different user costs, since there are no changes in portfolio. The results are given in Table 26.

Energy costs	NPV of TCO	Difference to normal
Optimal situation (-50%)	€ 39.291.810,27	-1,94%
Optimal situation	€ 40.069.898,16	
Optimal situation (+50%)	€ 40.847.986,06	+1,94%

Table 26: TCO value of proposed situation (changes in energy costs)

It is quite hard to give a good estimate of the costs for one hour of labour outside opening hours q, since a lot of factors influence this number. However, the value plays a major role in determining the optimal number of devices for the MES contract. Therefore, the influence of a wrong estimation of this number should be determined. In the current situation, the extra costs are estimated to be €100,-. The effect of a change of 50% positively and negatively to this amount is calculated. The determined values of the TCO of the new solution are shown in Table 27. The optimal threshold values and the optimal number of devices for the two alternative situations are given in Appendix J. Just like when changing the energy costs, the composition of the portfolio stays the same as in the optimal solution, when the costs outside regular hours change. However, the changes in threshold values are way bigger. Therefore, is another situation, with another demand, the choice of the number of devices would have been influenced.

Labour outside regular hours	NPV of TCO	Difference to normal
Optimal situation (-50%)	€ 38.892.744,00	-2,94%
Optimal situation (+50%)	€ 41.247.052,33	+2,94%

Table 27: TCO value of proposed situation (changes in cost of labour outside opening hours)

The costs for the cost element Extra MES service costs should be estimated every time the model is used. In the current situation, the real value of Extra MES costs is known and therefore the correct value. However, in the future the percentage of these costs will be estimated, since it is dependent on the preferences of the hospital which are unknown in the acquisition phase. The sensitivity of the TCO when this parameter is changed, is calculated for an under- and overestimated value of x.

Extra MES costs	NPV of TCO	Difference to normal
Optimal situation (-50%)	€ 39.426.115,36	-1,61%
Optimal situation (+50%)	€ 40.713.680,96	+1,61%

Table 28: TCO value of proposed situation (changes in extra MES costs)

Besides a wrong estimate of the parameters, it is possible that the parameters change because of operational changes. The first possible improvement is a reduction of the treatment time of a patient. This option is checked by reducing all treatment times with 10%, because it is unrealistic that treatment times half or double. Since it is also possible that the average treatment time is increasing, this option is worked out as well. The TCO of both outcomes are visible in Table 29. In the situation of a decrease of 10% of all treatment times, there are no changes in the portfolio. However, when the departments need 10% more time to perform the examinations, the optimal number of Bucky systems increases. There is also effect on the number of MRI-scanners; where previously an extra device is added in period 11, this happens in the new situation in period 6.

Treatment time	NPV of TCO	Difference to normal
Optimal situation (-10%)	€ 37.988.877,06	-5,19%
Optimal situation (+10%)	€ 43.383.740,91	+8,27%

Table 29: TCO value of proposed situation (changes treatment time)

The replacement period of all devices is determined by Siemens together with its customer. This choice is dependent on the vision of the hospital on innovation and on the wear out time of the devices. The determined replacement period influences the total cost of ownership of the devices since it changes the price of one device in one period. Therefore it affects the optimization as well. The influence of increasing and decreasing the replacement interval with one year is determined to determine the costs of being state-of-the-art. Table 30 shows the effect of the decision of changing the interval with one year on the TCO. In both situations, the choice of the replacement interval did not have influence on the portfolio of devices, see Appendix J.

Replacement interval	NPV of TCO	Difference to normal
Optimal situation (-1 year)	€ 41.067.524,21	+2,49%
Optimal situation (+1 year)	€ 39.282.945,05	-1,96%

Table 30: TCO value of proposed situation (replacement interval)

The last examined parameter is the yearly number of preventive maintenance and updates hours, in order to know what the influence is when Siemens performs its planned maintenance and updates outside opening hours when no employees and patients are scheduled, for example during the weekends. This effect is examined by changing the variables pu_s to zero for all equipment categories. The number of devices in the portfolio are not influenced by the proposed change. The result of the TCO of changing the preventive maintenance and updates to another moment, is given in Table 31.

Preventive maintenance and updates	NPV of TCO	Difference to normal
Optimal situation ($pu_s = 0$)	€ 39.648.015,89	-1,05%

Table 31: TCO value of proposed situation (preventive maintenance and updates)

Since hardly any of the above described changes of parameters resulted in a change of the portfolio, the effect of all these changes on the threshold values is determined. Appendix K gives all tables that show the differences in threshold values of the changed situation compared to the threshold values based on the normal input data.

When the energy costs are decreased by 50%, the threshold values decrease as well. The differences are between 0% and -0,04%. When comparing a lower number of devices, the influence of the energy costs is bigger than in the situation where for example 5 and 6 devices are compared. The exact opposite effect is visible when the energy costs increase with 50%.

A decrease in labour costs outside regular hours of 50% gives a change from +2,15% till +34,09% compared to the threshold values when the normal input data is used. The threshold value changes to a higher number when the costs decrease since the slopes of the TCO function gets less steep and will thus intersect at a higher number of patients. The other way around, when the costs of labour increase with 50%, the threshold value becomes -0,42% till -13,22% lower.

A change of Extra MES service costs of 50% results in a change of 0,04% till 1,1%. Just like the change of energy costs, the threshold value is higher when there are fewer devices considered. Besides that, a negative change of Extra MES costs influences the threshold value negatively as well, and the other way around for a positive change.

When the hospital is able to examine its patients in 10% less time, the change of the threshold value is almost constant over all equipment categories and numbers of devices; namely the threshold value is approximately 11,11% higher. The threshold values decrease with 9,09% when the treatment times increase with 10%. This result is visible in all categories and numbers of devices as well.

If the hospital decides to be state-of-the art and wants to decrease the replacement intervals by a year, the threshold values increase. This effect is between 0,03% and 1,25% compared to normal replacement intervals, and is bigger when less devices are considered. When the replacement interval is increased by a year, the threshold values decrease from 0,03% till 1,33%.

The effect of doing preventive maintenance and updates outside the opening hours is highest when more devices are considered. The largest difference in threshold value that is realized is for 5 and 6 SPECT devices and is 1,71%. The least change, which equals 0,22%, happens in the situation where 1 and 2 Ultrasound systems are compared.

8. Conclusions, limitations, and recommendations

Chapter 7 showed a lot of results for the theoretical and practical case. But which conclusions can be drawn from this research? Section 8.1 answers this question. The consecutive section, Section 8.2, describes the limitations to this research. That section looks at the considerations that should be kept in mind when using the developed model and the gained results. By combining the first two sections, practical recommendations to Siemens and other users of the model are made in Section 8.3. In that section also ideas for further research are proposed.

8.1. Conclusions

Our research is performed in order to answer the main question raised by Siemens. In Chapter 2 till Chapter 7 the eight steps that are described in Section 1.3 are taken in order to give a final answer to the following research question:

How to determine the optimal number of devices in a hospital's portfolio of equipment over a multiple period time horizon, when taking the total costs of owning the equipment into account, and how will the optimization influence the number of devices in the portfolio of equipment and the associated total costs of ownership of a Dutch hospital that has a MES contract with Siemens?

Our research is performed in order to make it possible for Siemens to advice their customers on the optimal number of devices based on costs. We are mainly focussed on the MES contracts which cover the costs of the purchase of equipment, the maintenance and some extra services like training and consulting over a horizon of approximately 15 years. These contracts and our developed model are a reaction on the changing healthcare sector. We see that there is a lot of demographical, economical and political pressure on the healthcare sector in the Netherlands, wherefore it is important that the investment decisions in a hospital are reviewed critically.

In the literature we found the concept of Total Cost of Ownership which takes into account the costs of a product over its entire lifetime, so not just the purchasing costs. Many research is performed on the concept of TCO by L. Ellram in 1993 and 1995. We see that in the previous years researches have tried to define a standard model and a core set of cost elements for the calculation of the TCO. No one clearly defined a standard model, but Geissdoerfer et al. (2009) found that companies use for TCO calculations of capital goods, like hospital equipment, mainly the cost elements which are part of the initial costs, operating costs, quality costs, logistic costs, and maintenance costs. We used this finding as a basis of the developed model.

We developed our TCO model for medical equipment with the input of the literature and the expertise of cooperating Hospital A and Siemens. The cost elements we have taken into account are displayed in Table 5 and are the costs for: Acquisition, Maintenance, Extra MES services, Labour, Disposables, Operating Supplies, Direct Downtime and Floor/Space. The developed TCO model helps us to evaluate a proposed solution of the model.

In our model we are able to influence the number of devices and the opening hours of every department and location in every period. We defined three constraints to a solution of our model. At first there is a maximum hours that a department could be opened on a day. Secondly the solution should give enough capacity to meet the expected demand in every period. The last constraint determines that a device is only allowed to be removed when it is fully depreciated.

Based on the TCO calculation and the constraints we developed an optimization which determines the optimal number of devices in every period and the associated opening hours. We implemented the developed model in a Microsoft Excel tool which we used to perform two experiments, a theoretical and practical case, with. With the data of these two experiments we have verified the model and thus we can conclude that we build the model right. We were only able to validate the costs of the MES contract, since a lack of data made it impossible to validate the costs from the hospital side.

Our first experiment is a theoretical hospital of two locations with only a Bucky and MRI department. We determined that the hospital has a TCO for its equipment of approximately € 40.886.000,- over fifteen years. We found that a reduction of 0,28% could be realized when the two locations merge. This is realized since less devices are needed to fulfil the demand and the risks in changes in demand is pooled. The effect of the constraint on the removal is also tested on the theoretical case. If the device could be removed in any period, there is just a reduction of approximately € 2.500,-. Our final experiment on the theoretical case looks at the effect of a wrongly estimated demand. If all growing percentages would have been the complete opposite, so for example instead of 1,5% there is -1,5% growth on the Bucky's in The Hague, a significant change in TCO occurs of -15,96% compared to the normal situation.

The second case we examined is the one of Hospital A. We found that the TCO of the radiology department in the situation as described in the existing MES contract is equal to approximately € 42.700.000,- over a period of p years, when no indexation is taken into account. We are able the realize a reduction of 8,3%, till approximately € 39.100.000,- , of these costs when we optimize the situation of Hospital A with our developed model. This reduction is realized since the number of devices in the optimal situation are always equal or less than the number of devices in the current situation. The recommended number of devices are visible in Table 23. Major changes are visible in the number of Ultrasound systems, Angio's, C-Arms and SPECT-scanners. If we look at the effect on the TCO of the MES contract when there is no installed base before the first period, so all equipment is installed during the contract, we realize a TCO of approximately € 40.100.000,-. This number is higher than the optimal solution, since the hospital only has to pay maintenance costs at the beginning of the contract and nothing for the acquisition for the years where no replacement in the MES contract have been taken place yet. This number is a better representation for the future contracts where a MES contract is continued after the expiration of it. We are able to realize a reduction of the TCO of 6,06%.

Our model calculated that the share of the cost element of the acquisition of the equipment accounts in all cases for 12% till 17% of the TCO. This is in line with the statement of Snelgrove (2012), which states that the equipment is approximately 15% or less of the TCO for capital goods.

Since it is possible that some of the data is estimated wrong, or that operations are changing over time, we performed a sensitivity analysis to determine the effects of changing parameters. The major effect on the value of the TCO that we found is when the treatment times are changing with ±10%. If all departments are able to examine their patients in 10% less time, the TCO of the solution decreases with 5,19%. We see that changes in parameters have hardly any effect on the optimal number of devices. Therefore, we determined the effect of the changes in parameter on the threshold values as well. From this analysis we conclude that the effect of a change of costs for labour outside regular hours of 50% resulted in the most significant change. A decrease of 50%, results in a change of the threshold value of at most +34,09%. We see that the effect of an increase of 50% is less, namely 0,42% till 13,22%.

8.2. Limitations

There are some limitations to this research which should be considered in order to make good use of the developed model and to use the conclusions in practice. At first, some assumptions are made in the design of the model, which influence the final solution. Thereafter the implementation is discussed. Section 8.2 is concluded with the limitations on the conclusions for practical use.

Assumptions

In the development of the model, several assumptions are made which influence the outcome of the optimization. At first, it is decided not to take the reconstruction costs of the building into account. This decision is made since it is too hard to know the expected expenses for this costs element in the acquisition phase and because these costs differ a lot between hospitals. Besides that, the reconstruction costs are different for a replacement and a removal of a device. When the model is used after the acquisition phase to be research a case in depth, it is recommendable to try to quantify the costs for this cost element and add it to the TCO calculation. Not taking the reconstruction costs into account might give a distorted picture of the real costs of adding an extra device. Therefore, when the model is used, these limitations should be kept in mind, especially when the hospital expects these costs to be significant. If the reconstruction costs are taken into account, the model would prefer to extend the opening hours even more over adding another device.

Secondly, it is assumed that the maintenance costs could be expressed as a percentage of the equipment price. However, the chance of failure increases when the equipment is used more often and more intensively, and thus will the amount of corrective maintenance increase as well. Therefore, the costs of maintenance will increase when the opening hours are extended. The maintenance costs are better represented when the costs are dependent on the opening hours, as well as on the acquisition price. Probably the failure curve is not linear, so if the hours on one device double, the number of failures will not double as well. Therefore there will be a difference in costs for maintenance when one device is running for 18 hours per day compared to two devices that run 9 hours a day. There is unfortunately too little time and data available to include this effect in the model. The result of this assumption is that the costs for maintenance are not increasing when opening hours are extended. Therefore, the break even point of the TCO functions of D and $(D + 1)$ devices will be at a too large number of patients in the current case. So, when a more detailed representation of the maintenance costs is added, the model would faster prefer to add another device over extending opening hours

Another limitation on the maintenance costs is that the hours of corrective maintenance are dependent on the hours of preventive maintenance. There exists a trade off between these hours where the expected costs are minimal. When really minimizing the TCO, the costs for preventive maintenance together with the cost of corrective maintenance could be minimized as well.

Besides the maintenance costs, another assumption is made in determining the costs of the MES contract. Costs associated with training and consulting, the Extra MES service costs are now taken into account as a percentage of the value of the equipment in the contract. However, when the opening hours are changing, nothing changes at this cost element. This might be incorrect when looking at trainings since extending opening hours indicates that more employees are required and thus more training is needed. However, the costs included in the Extra MES costs are also dependent on the number of devices. For example when utilization management is offered for consulting, the time and thus the fee increases only when extra devices are added. In our model, we have chosen that the costs of Extra MES is dependent on the value of the installed portfolio in order to keep it simpler for the users. However, this choice could be questioned.

The forth limitation to the research is that the lifetime of devices with an X-ray tube, like a CT-scan, decreases when it is used more intensive, which is not taken into account in the model. However the number of scan-seconds compared to the opening hours is non-linear according to Siemens' experts. When the device is used twice as intensive, the lifetime of the device decreases with less than 50%. This fact is neglected in the model design. This results in a too optimistic view on extending opening hours. Since, when the opening hours increase, the costs for the device in the MES contract should increase as well. Therefore the equilibrium will happen sooner, at a smaller amount of patients.

When there is downtime, we assumed that there are also employees of the hospital working, since these employees are already scheduled at those times. Besides that, the model calculates also energy costs during those hours, see Section 4.2.2. The costs for labour and energy during downtime are in the model included in the costs elements labour and energy. However, this gives a distorted picture of the real downtime costs. Right now, the downtime consists only of disposables that have to be bought again when a devices fails, so the costs will be very low compared to reality. It is advised to move the costs for labour and energy during downtime to the cost element downtime. Besides that the effect of downtime on patients health should be quantified and included in the model to give a better picture. The fact that the costs are not completely right, does influence the TCO, but it does not influence the optimization decision.

The last discussion on the assumptions in the development of the model is focussed on the optimization. The optimization uses average prices and replacement intervals of devices in an equipment category, see Section 4.4.1. However, a hospital might decide to have only the most expensive models. In that case the calculated equilibrium is at a too low number of patients and thus the decision on adding another device is made at a too low expected demand. The other way around, when a hospital prefers the cheapest models, the choice of adding another device should be made at a lower number of patients.

Implementation

Besides the limitations on the developed model, there are also points of discussion in the implementation of the model. Most of these limitations are due to estimations of parameters.

At first, the costs for energy are theoretical numbers. However, every hospital uses their devices differently and might therefore consume more or less power during opening hours. Besides that, the newest models use less energy than the older ones. This effect is not taken into account in the optimization, since the average power consumption over all currently available devices is taken. A wrong estimation on the costs of energy could influence the optimization since by adding an extra device, the total hours of off time increases and there are costs associated with that. However, the effect is not very big which can be seen in the sensitivity analysis.

The second limitation on the implementation is the fact that the labour costs only consist of the costs for the operators and laboratory staff. The price of a doctor examining the taken images is not taken into account. The expenses on doctors are very high and have a significant influence on the cost of labour of one examination. However, most of the time, the doctors do not have to check the images immediately, so extension of opening hours does not have the same effect on the costs for doctors as it has on the labour costs of the operators. If the doctors are still working in regular hours when the opening hours are extended, it would have no influence on the optimization. Therefore it is interesting to investigate the interaction of the working hours of a doctor with the hours of operators and laboratory staff. If that is done, the costs could be included in the TCO calculations to give a more precise view.

The parameter with the biggest influence on the threshold values, the costs for one hour of labour outside the regular opening hours, is a rough estimation in the examined practical case. Therefore, this number could influence the validity of the found solution. However, a decrease and increase of the costs for one hour of extra labour of 50% did not influence the portfolio of equipment in Hospital A compared to the optimal solution when using €100,- for this parameter. The estimation of the costs for labour outside regular hours affects therefore in that case only the value of the TCO.

Hospital A provided data about their realized production of the past years. Within the production of the past years there are big fluctuations visible. For example, at the Dexa department, there was a decrease in period $(p-1)$ to period p of 30%. In the subsequent year, the production decreased again, but this time with 9%. In the forecast for Hospital A all departments, except for the MRI and the CT department, will have a stable demand according to the hospital. So also the Dexa department which showed major decreases in the previous years. Since the final decision on the number of devices is based on the expected demand, a wrong estimation would have a significant influence. Therefore, it is very important that well founded research is done on the forecast of the demand of all departments. In the meanwhile, the optimal number of devices should be monitored yearly during the contract to check the available capacity during that year and the upcoming years.

Besides possible wrong estimations of parameters, there is also a point of discussion on the validation. In the validation of the model, only a comparison of the contract costs was possible. Because of a lack of available data on the total costs of the hospital, the part of the hospital expenses is not validated. When there is information from the hospital on the average costs per examination on every type of device, the calculated value could be compared. Not validating the operating costs has as a result that the calculated total cost of ownership might not be a good representation of reality. Since the optimization is also based on these costs, it is very important that the outcomes of the TCO calculations are critically checked by experts before conclusions are drawn.

Conclusions in practice

There are at last limitations to the conclusions drawn from the model. The first limitations arise due to the fact that the model gives a solution for an ideal world. However, the reality might differ. This is for example the case when looking at the advised opening hours. The model gives as a result that the hospital should be opened at least a certain number of hours daily. This number of hours might indicate that a department should be opened every day for 10,5 hours to process all demand, which is unrealistic since schedules for employees are made on hours or on shifts of multiple hours. An option to solve this, is to move the hours between days, which also happens in reality. In that case there is still enough room to process the demand. However a division of hours might also have influence on the costs for labour, since the hours might now fall in a different category of hours. The model uses the number of 10,5 hours per day to calculate the TCO, which is the cheapest way of dividing all hours over all days, since all regular hours are filled and the least possible extra hours are used. Therefore, in reality the costs for labour will be higher than the calculated costs in the model. The model could for example be extended with an extra requirement that the opening hours are multiples of the duration of one shift.

In order to use the model in more cases, most of the parameters need to be reviewed again. Since there is just one case examined in this research, there is too less data to know whether the values of the parameters are representative for other cases as well. However, the way of calculating, and thus the model is still applicable. It is therefore possible to generalize the model internally under the condition that the parameters are reviewed every time it is used. Besides that there are also possibilities to apply the developed model in other circumstances than a MES contract. In many more situations a consideration needs to be made between extending opening hours and adding an extra device. For example in the case in production facilities. Those companies need to process a certain demand as well and should have enough capacity to do so. However, there are some adjustments that need to be made to match another situation. For example, the calculation of the price and maintenance is quite specific for a MES contract. However, in literature it is visible that more and more contracts include equipment as well as the maintenance. The calculation of available hours should be reviewed in the new situation as well. When doing that, it is still important that the moments of corrective and preventive maintenance are taken into account somehow. At last, it is recommended to review the decision on not including the reconstruction costs. Especially when the model is used for just one company it might be easier to determine the costs for that cost element when adding or removing a device.

8.3. Recommendations

With the conclusions and limitations of this research in mind, recommendations to Siemens and the cooperating hospital can be made. At first, this part is focussed on the use of the model and developed tool in practice for Siemens. The second part is looking at the interpretation of the results of this research, and will give advice to Hospital A as well as Siemens. This section is concluded with suggestions for further research which are the result of the conclusions, limitations and recommendations.

Use of the model

We created a tool for Siemens which they can use in the acquisition phase of the MES negotiations. Since several assumptions are made on, for example the costs of maintenance and Extra MES service costs, we would like to point out that more detailed calculations are required when the results of this model are used in another phase of the contact between Siemens and its customer.

Our developed model gives a good representation of the costs associated with the MES contract of Hospital A in reality. When this model is used for other cases, we recommend to implement more existing contracts in the model to make sure that the results of Hospital A were not correct by chance. Besides that, we recommend that feeling is created for the estimation of the Extra MES service percentage by the users of the model by comparing the different values of that parameter of multiple contracts and by finding a reasoning why the percentage is different in every case. This needs to be done since the parameter for the Extra MES service costs, which is part of the value of the MES contract, is unknown in the acquisition phase, it will be estimated in the future. However, our sensitivity analysis on the case of Hospital A, shows us that a wrong estimation of the Extra MES costs parameters could have an influence of 0,04% till 1,1% positively and negatively on the threshold value, respectively for a decrease and increase of the parameter's value, and an influence of ±1,61% on the value of the TCO, which is almost the least influence of all investigated changes in parameters.

Since we were unable to validate the cost of the hospital, it is not sure whether the calculated values of the TCO are a good representation of reality. The validity is dependent on the input used in the model as well as the developed model itself. Several limitations are mentioned in Section 8.2 on the used data of Hospital A. Besides that, from the sensitivity analysis we conclude that the parameters that influence the outcome of the optimization the most; the treatment time and the extra costs for labour outside regular opening hours, are hardest to estimate. Therefore, we recommend that most effort is put in making sure these two values are estimated well. In order to check whether the model is designed well, we recommend to compare the outcomes of the model with information from the hospital, if that data is available. If it is sure that the used data is correct, but you see a major difference between the calculated costs in the model and the reality, there might be a mistake in the developed model. If the checkup procedure is performed for multiple cases, it is sure that the TCO gives a good representation of the operating costs.

The changes in expected demand, used for the case of Hospital A, are very rough estimates. Not all hospitals have a good forecasting method. A wrong estimation gives a significant change in the optimal solution. In the example of the theoretical case there was a decrease in costs of 15,96% when all growth percentages were different. Not only the total costs are influenced by a changed demand forecast, but also the number of devices installed at the hospital. Therefore it is very important that the MES contract is reviewed yearly. When the forecast is changed, it might have a crucial influence on the outcome of the model. A difference in growth percentage of even a half percent could indicate that a system is added a few years earlier or later. Therefore I recommend to perform the calculations on a regular base by critically looking at the new forecast of patients.

The user of the model should keep in mind that no reconstruction costs are included in the model. Therefore a replacement or an extension of the hospital's fleet could be more expensive than predicted by the model. As a result of this, the opening hours could be extended even more before the number of patients is reason for adding an extra device.

As a result of the above mentioned recommendations, we conclude that the model should now only be used as a guidance instead of a rule. This also matches with the goal of the acquisition phase, where it is important to have a quick and dirty solution which gives the best representation of reality possible. However, when the calculations are shown to customers, they might pin Siemens on the results. Therefore we would like to point out that it is always important that the user of the model checks the outcomes, to see whether the outcomes are reasonable.

Interpretation of the results

The optimization of the TCO of the whole portfolio implies a decrease of the total number of devices in the fleet of Hospital A. With the following adjustments to the current portfolio, we could realize a reduction of the TCO of 8,3%. Where the TCO of the current situation, determined by the model, is € 42.700.000,- if no indexation is taken into account, the optimized situation based on the current installed base, will result in a TCO of € 39.100.000,-.

At first, we advice that the number of Ultrasound systems should be reduced from 5 till 2 over the whole horizon of p years, see Table 21. If that department is open on average for 8,6 hours per day, the hospital should be able to process the required demand where a utilization of 85% is assumed. In the current situation, an extra MRI scanner is added in the fourth period of the contract. However, based on the capacity analysis and the calculation of the TCO of that department, we recommend that the extension of the fleet should happen at period 11. The number of Angio systems, C-Arms and SPECT-scanners is too high in the current situation according to the developed model. These categories could all be reduced to one device. The number of Bucky systems, as well as the number of CT-scanners, Mammo devices and Dexa's is the same in the real situation and in the optimized one. Since there is still room for changes in the MES contract, we suggest to investigate the possibilities of decreasing the number of Ultrasound systems, Angio's, C-Arms and SPECT-scanners in the future.

Since there are some limitations to this research, the recommended number of devices in every category should be critically reviewed before implemented in practice. However, based on the realized treatment times of previous years on all devices, we know that the number of devices determined by the optimization should be enough to cover all expected demand including a utilization of 85%. So for example, it would be enough to use just one Angio device on average 2,4 hours a day to cover all demand. This option will always be cheaper than having three devices which are used for only 0,8 hours on average per day, since these hours are still in the regular working hours. When the required number of daily opening hours exceeds 9 hours, it is not guaranteed that the proposed solution will have the lowest costs in reality, since we know that the costs for irregular hours is a rough estimation and thus might the final value of the TCO be slightly wrong. This is only the case for the Bucky's, MRI's, and SPECT's.

As mentioned before, the determined number of devices should be enough to cover the expected demand. However, the forecast of the number of patients is a very rough estimation. Moreover, historical data shows that the demand has major fluctuations. Therefore there are signs that the forecast might not be a good representation of the reality. In the theoretical case, it is shown that a wrong estimation could have a major influence on the choices in the future. To prevent the hospital from doing unnecessary investments, we highlight that is very important that Hospital A looks critically to its forecasted demand before taking actions based on the outcomes of the model. Especially in times where there is pressure from health insurers and government on the financial status of the hospital, this is a very important point of interest.

Our developed model gives insight in possible improvements of the current situation and the associated costs. At first, the effect of a more efficient way of working could be expressed in monetary terms. For example, when a hospital is able to improve their planning on all systems, it might be possible that the average treatment times decrease. In the sensitivity analysis a change of treatment time of 10% on all devices is evaluated. When Hospital A is able to decrease its treatment time, more patients can be scanned in regular hours. Compared to the TCO of the optimal situation, which is calculated based on an 'empty' hospital at the start of the contract, the hospital might decrease its TCO by approximately 5,19%. We recommend to calculate the effect of operational changes prior to the implementation of the proposed change.

Siemens was surprised by the low treatment time calculated for the Angio devices. From the provided data, the treatment time was calculated to be approximately half an hour. Based on experiences from other hospitals, Siemens would estimate the treatment time at the Angio devices to be approximately twice as long. Since the calculated daily opening hours are 2,4, an increase of 100% would not result in another number of optimal devices and doubling the hours would still be in regular time, no changes in the portfolio occur. However, we recommend to review the data of the Angio again, to make sure the treatment time is correct. Even though it would not influence the optimal number of devices, it will influence the value of the TCO.

A second insight we provided by the developed tool is the share of all cost elements to the TCO. Based on the graphs representing the shares of the different cost elements to the value of the TCO in Figure 15 it could be concluded that the costs for the disposables account for a significant part. The shares are namely 20% till 22% of the total value over p years. When a hospital needs to decrease its total expenses, it would be interesting to look at possibilities in purchasing the disposables for a lower price. Another operational expense where the hospital could save money, are the costs for labour, that accounts from 27% till 33% of the TCO. An option to reduce the costs is for example reducing the number of employees needed to run the equipment.

The costs of maintenance account for a significant part of the TCO. Therefore, it is interesting for Siemens to look for possibilities in providing the same quality of maintenance for a lower price. This way, Siemens is able to stay ahead of the competition, since they are able to offer contracts with lower fees. When Siemens focuses on the reduction of the maintenance costs, it should be kept in mind that the calculated maintenance costs are an overvaluation of the real maintenance costs in the MES contract of Hospital A.

Many of the devices in the optimal solution of Hospital A are still not used optimally. This is the case for the departments where just one device is required and the opening hours are still less than 9 hours per day. When a device is not used efficient, the costs for the equipment are very high compared to the value of the total costs of ownership. If the demand at those devices increases, the patients could still be processed on the available devices and therefore only the user costs will increase. When comparing the theoretical and practical experiments, it is clear that the devices in the theoretical case are used more efficiently. This difference is also visible in the TCO of both cases. Namely, the equipment in the theoretical case accounts for just 12% of the TCO, even when the very expensive MRI-scanners are considered. It is recommended for hospitals to try to maximize the usage of all their equipment until the moment where it is recommendable to increase the number of devices. For example it might be possible to cooperate with another hospital on one department. That way, both hospitals could examine patients on the equipment but the costs for the devices are shared.

8.3.1. Further research

The above described limitations and recommendations give food for thought on further research. At first, it is very important that the hospital costs in the model get validated. By comparing these costs with real costs, more valid conclusions can be drawn from the model. Further research should be done on proving that the model is a good representation of reality. Besides that, the model could be implemented for many more MES contracts. When multiple cases are compared, it is possible to determine general parameters which makes the use of the model much simpeler in practice. At this moment a lot of data is required to perform an analysis for a hospital. When generic data is available, less effort is needed in collecting all data, which speeds up the process. We suggest that research should be performed on finding good general parameters.

In the sensitivity analysis is shown that the costs of extra hours outside the regular opening hours have a big influence on the decicions made by the optimizaiton. In practice, it is very hard to determine the exact costs associated with the extra hours. Citing an employee of the cooperating hospital: “determining that value is a study itself!”. There might even be interaction on the costs for an extra hour when multiple departments decide to open outside the regular hours, since the costs could be shared between the departments. In this research an estimate of these costs is used, because of limited time. The costs are also independent of the opening hours of other departments. Since the influence of a wrong estimation is significant, it is suggested that further research is performed on determining the real value of an hour outside opening hours.

As mentioned before, the expected demand is not a valide number. Siemens mentiones that not only Hospital A uses very rough estimations, but many more hospitals have the same problem. Since decisions are made based on this number, it is very important that further research is performed on a forecasting model for hospitals.

The previously mentioned ideas for further research are focussed on improving the current model. However there are also possiblities to enlarge the use of the developed model. For example, it will be very interesting to compare the costs with the gainings. This way the model could be included in a business case which could maximize the profit. Cavinato (1992) mentioned already that the best way of decision making in purchasing is based on the total value and not just on the total costs. This statement is supported by Snelgrove (2012). When also the income effect is added, it might influence the choice of adding or removing a device in reality. This could happen when for example the TCO is just very small compared to the income. In that case, the hospital might chose to add another device because of qualitative reasons. Besides that, adding also the income side of the MES contract could help Siemens with selling their devices, since they can show that by using the devices when there is enough demand for a device, the hospital could gain money. Therfore, further research on the income side of the medical equipment is adviced.

Confidential

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Appendices

In the Appendix extra material for the research is given. It contains background information and data of the theoretical and practical case.

Appendix A

Appendix A shows the tables supporting Section 3.3.

Core cost categories	TCO analysis object						
	Capital goods	Raw materials	Sub-assemblies	Manufac-tured parts	Packaging	Service	MRO
Operating costs	58%	35%	33%	29%	36%	50%	38%
Quality costs	23%	65%	67%	76%	36%	44%	46%
Logistic costs	15%	50%	33%	35%	18%	19%	8%
Technological advantages	38%	15%	33%	29%	0%	6%	8%
Capabilities/ reliability of suppliers	19%	15%	28%	29%	27%	44%	23%
Maintenance and repair costs	62%	5%	11%	12%	0%	50%	38%
Inventory costs	4%	40%	17%	29%	18%	0%	8%
Transaction costs	0%	10%	17%	18%	9%	13%	23%
Life cycle costs	46%	5%	22%	18%	9%	25%	23%
Initial costs (incl. price)	81%	55%	72%	65%	64%	38%	54%
Customer related costs	8%	0%	17%	6%	0%	13%	15%
Opportunity costs	0%	5%	0%	0%	0%	0%	8%
Others (e.g. disposal costs)	0%	0%	6%	0%	18%	0%	0%
Number of surveys per object category	26%	20%	18%	17%	11%	16%	13%

Table 32: Core cost categories depending on the object of the TCO Analysis (Geissdoerfer et al., 2009)

In Section 3.3, just the first column of the table below is shown. For more information about the cost drivers, the following table can be consulted.

TABLE 7: Cost Categories and Cost Drivers Depending on the Object of the TCO/LCC Analysis

	Capital goods	Raw material	Sub-assemblies	Manufactured parts	Packaging	Service	MRO
Initial costs							
Price (inc. spare parts & warranty)	82%	48%	73%	81%	73%	60%	50%
Reconstruction costs	32%	7%	13%	25%	0%	7%	13%
Setup/installation customer/ supplier	18%	7%	13%	19%	9%	27%	13%
Operating costs							
Labor	46%	19%	33%	44%	45%	47%	38%
Tooling/consumables	39%	11%	20%	19%	18%	27%	13%
Operating supplies (energy, gas, etc.)	32%	37%	0%	13%	9%	7%	0%
Floor/space costs	18%	7%	20%	13%	18%	0%	6%
Quality costs							
Failure costs	18%	33%	87%	63%	36%	13%	19%
Inspection costs	14%	33%	67%	38%	27%	13%	25%
Logistic costs							
Freight/transport costs	18%	56%	87%	50%	64%	7%	25%
Duties and taxes	7%	15%	33%	19%	18%	0%	0%
Packaging	4%	11%	20%	13%	9%	0%	6%
Maintenance costs							
Labor	32%	0%	13%	13%	9%	53%	38%
Spare parts	46%	48%	7%	13%	36%	40%	50%
Special tools/ measurement devices	18%	4%	7%	6%	18%	7%	56%
Service costs	25%	0%	0%	6%	0%	40%	19%
Downtime costs	39%	15%	7%	19%	18%	33%	25%
n	28	27	15	16	11	15	16

Table 33: Cost Categories and Cost Drivers, Full table

Appendix B

Flowcharts associated with Section 4.4.3.

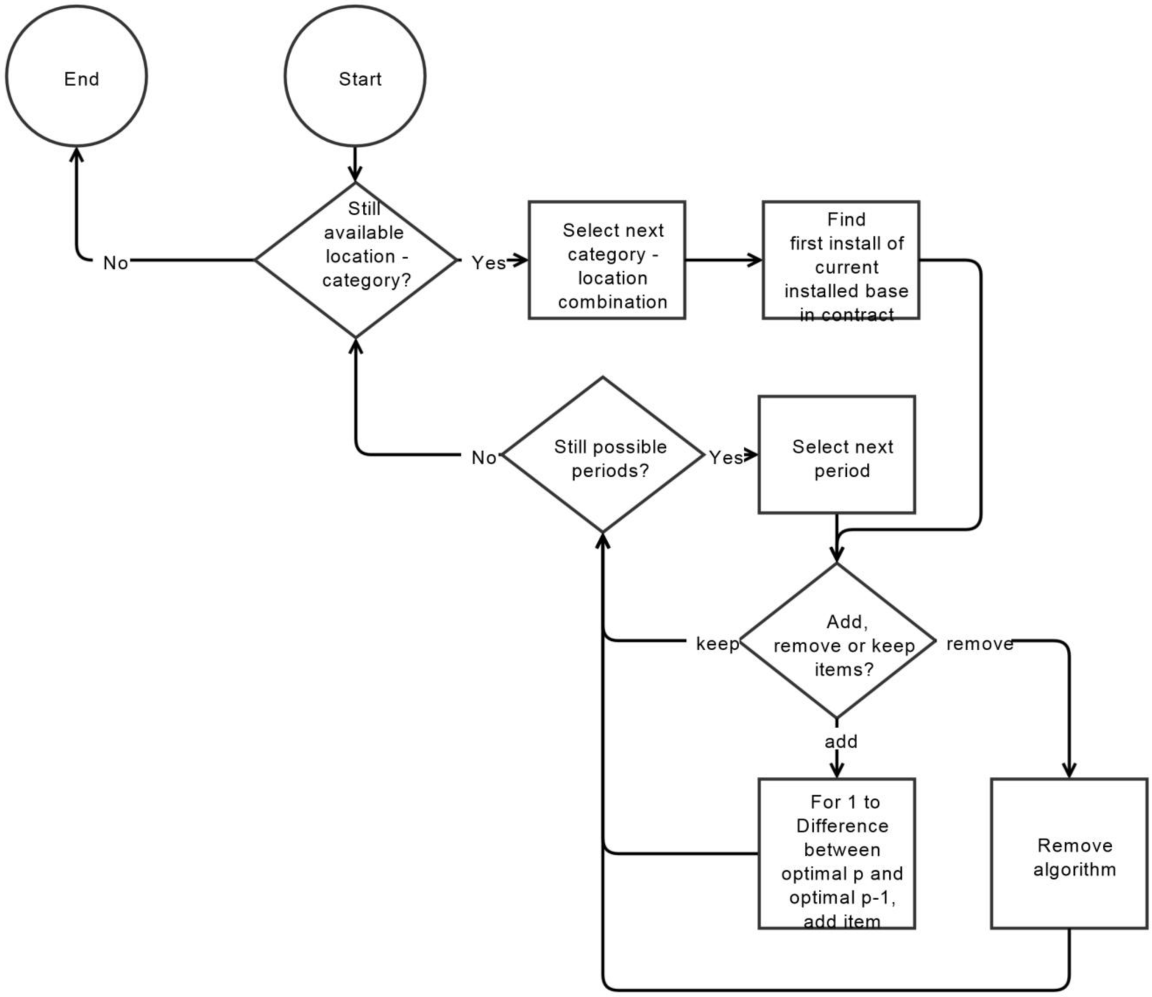


Figure 16: Flowchart for applying the optimal number of devices in every period to the total horizon

Figure 17: Flowchart for adding a device in a period

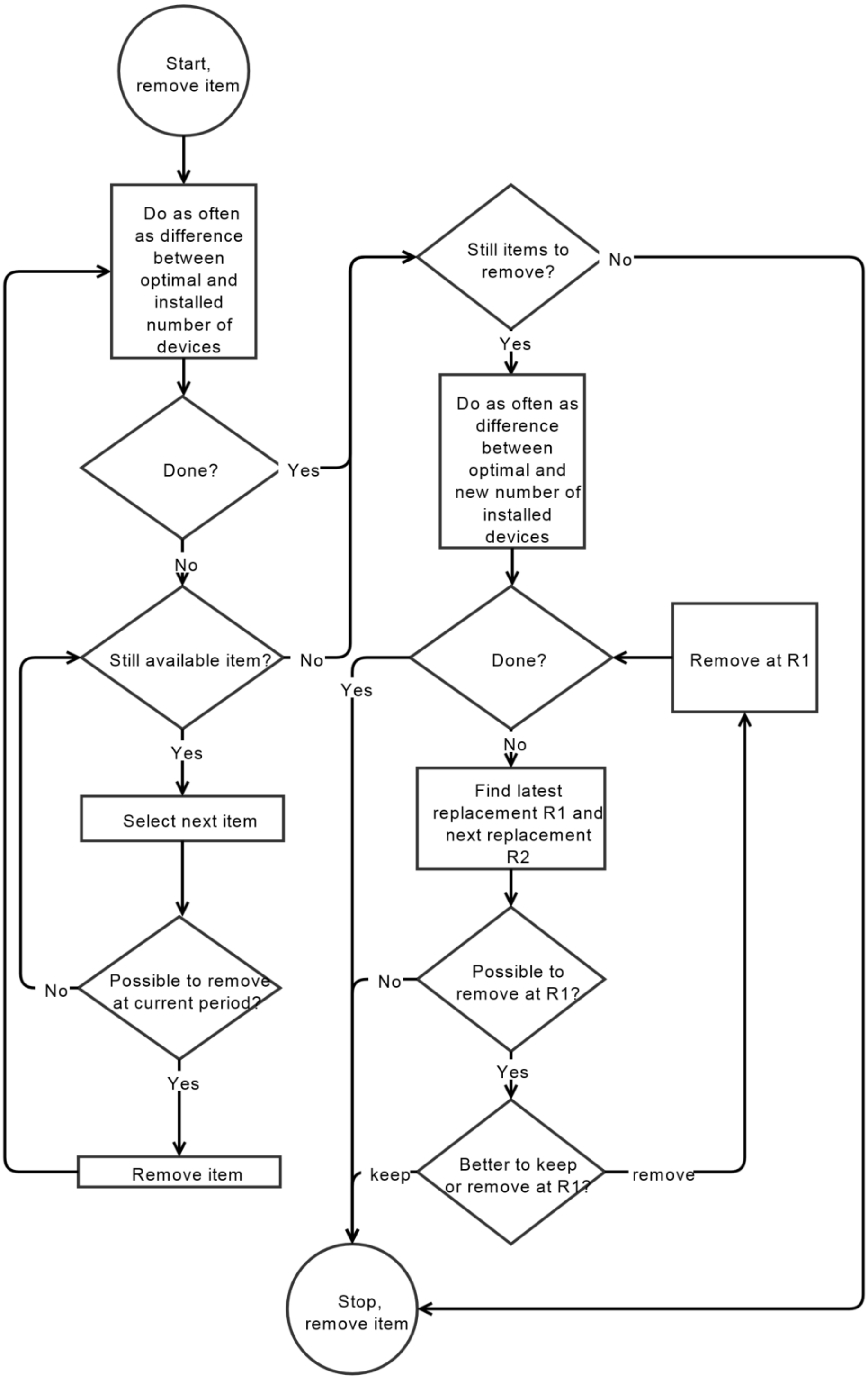


Figure 18: Flowchart for removing an item in a period

Pseudocode for the algorithm proposed in Section 4.4.2.

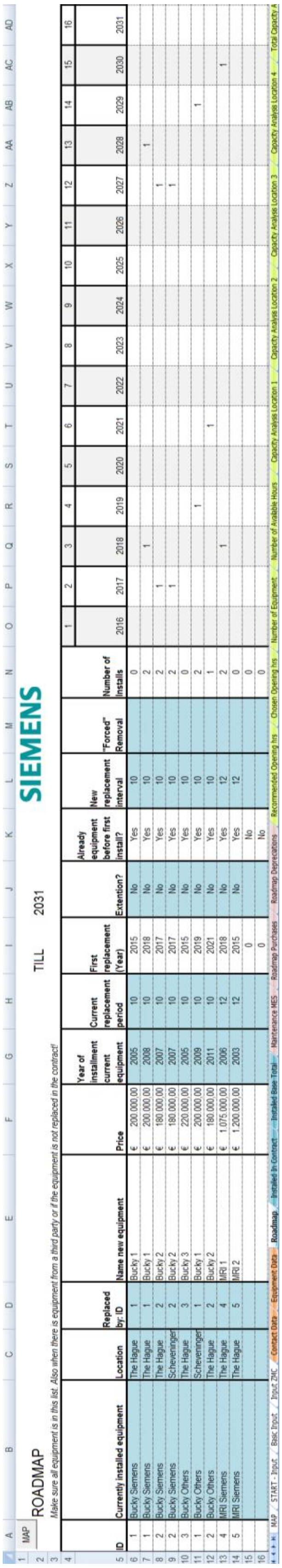
```
Algorithm for implementing the optimal number of devices in the model over full horizon

Over all categories
For all categories s in S
Over all locations
For all locations v in V
Over all periods
For all period p in P
  Add items as many items as required
  Do While Optimal installed at period p > Number installed at period p
    Add item to Set
    Assign characteristics of category to item
    Set moment of first install of added item to p
    Set moment of removal to end of horizon
  Loop
  Remove as many items as required; First try to remove an item at period p
  If Optimal installed at period p < Number installed at period p Then
    For b = 1 To Number installed at period p - Optimal installed at period p
      For all installed items of category
        Possible to remove immediately at p?
        If (item still installed at period p AND item is replaced at period p
          Set moment of removal to p
          Exit for loop
        End If
      Next item
    Next b
  End If
  Still items that need to be removed but impossible to remove at p?
  If Optimal installed at period p < Number installed at period p Then
    For b = 1 To Number installed at period p - Optimal installed at period p
      Find R1, latest replacement period before p
      For periods c from 1 to p
        For all installed items of category
          If (Item is installed at (p-c)) AND ((Item is installed at the first time at p-c) OR (Item is
replaced
          at p-c)) Then
            R1 = p - c
            RowR1 = row of item
            GoTo FindR2
          End If
        Next a
      Next c
      FindR2:

(Continues on next page)
```

```
            Find R2, first replacement period after p
            R2 = T
            For periods c from 1 to p
               For all installed items of category
                  If (Item is installed at (p+c)) AND (Item is replaced at p+c) Then
                     R2 = p + c
                     RowR2 = row of item
                     GoTo DetermineRemoval
                  End If
               Next a
            Next c
            DetermineRemoval:
            Is it possible to have one item less from R1 to p? (minimal number of devices)
            For period l from R1 to p-1
               If Minimal number of devices < Number of items installed at period l -1 Then
                  Keep item installed at R1 go to next period
                  GoTo NextPeriod
               End If
            Next l
            If possible to remove an item at R1, determine the costs of removing at R1 or keeping it
            SumR1 = 0
            SumR2 = 0
            For d = R1 To R2 – 1
              Determine costs of having one item less; Sum over whole interval
            Next d
            For d = R1 To R2 - 1
               Determine costs of having keeping the item at R1; Sum over whole interval
            Next d
            Cheaper to remove at R1 or to keep at R1?
            If SumR1 < SumR2 Then
               Set removal of Item to R1
               Adjust optimal number of devices since it is better to remove at R1
            End If
            Cheaper or indifferent to keep at R1compared to remove at R1?
            If SumR1 >= SumR2 Then
               Adjust optimal number of devices since it is better to keep item at R1 till R2
            End If
         Next removal if possible
      End If
   NextPeriod:
   Next period p
   Next location v
   Next category s
```

Appendix C



ROADMAP

Make sure all equipment is in this list. Also when there is equipment from a third party or if the equipment is not replaced in the contract!

TILL 2031

SIEMENS

ID	Currently installed equipment	Location	Replaced by: ID	Name new equipment	Price	Year of installment current equipment	Current replacement period	First replacement (Year)	Extention?	Already equipment before first install?	New replacement interval	"Forced" Removal	Number of Installs
1	Bucky Siemens	The Hague	1	Bucky 1	€ 200.000,00	2005	10	2015	No	Yes	10		0
1	Bucky Siemens	The Hague	1	Bucky 1	€ 200.000,00	2008	10	2018	No	Yes	10		2
2	Bucky Siemens	The Hague	2	Bucky 2	€ 180.000,00	2007	10	2017	No	Yes	10		2
2	Bucky Siemens	Scheveninger	2	Bucky 2	€ 180.000,00	2007	10	2017	No	Yes	10		2
3	Bucky Others	The Hague	3	Bucky 3	€ 220.000,00	2005	10	2015	No	Yes	10		0
1	Bucky Others	Scheveninger	1	Bucky 1	€ 200.000,00	2009	10	2019	No	Yes	10		2
2	Bucky Others	The Hague	2	Bucky 2	€ 180.000,00	2011	10	2021	No	Yes	10		1
4	MRI Siemens	The Hague	4	MRI 1	€ 1.075.000,00	2006	12	2018	No	Yes	12		2
5	MRI Siemens	The Hague	5	MRI 2	€ 1.200.000,00	2003	12	2015	No	Yes	12		0
								0		No			0
								0		No			0

ID	1 2016	2 2017	3 2018	4 2019	5 2020	6 2021	7 2022	8 2023	9 2024	10 2025	11 2026	12 2027	13 2028	14 2029	15 2030	16 2031
1																
1			1										1			
2		1										1				
2		1										1				
3																
1				1										1		
2						1										
4			1												1	
5																

Figure 19: Example of a roadmap sheet

The following information from the hospital of interest is required to let the tool perform the optimization:

- The expected demand of all departments, locations and periods ($f_{p,s,v}$)
- The average number of employees operating the devices of every department (e_s)
- The average costs of labour per time unit of employees (w_s)
- The extra costs for an hour outside regular opening hours (q)
- The average costs for disposables of one examination of every department (g_s)
- The costs for disposables when missing an examination during downtime per department (b_s)
- The exploitation costs per square meter per period for every department (u_s)
- The number of square meters required for one device (z_s) (it is also possible to use the surface recommended by Siemens in its product descriptions)
- The average treatment time of every department and location ($t_{s,v}$)
- The standard daily opening hours of the hospital and the number of working days which together form the total number of regular hours per period (h^{REG})
- The maximum number of opening hours on a day per department and the number of working days which together form the maximum number of opening hours per department per period (h_s^{MAX})

Besides the input of the hospital, there are parameters associated with choices of Siemens. The following data should be gathered from Siemens internally or should be determined together with the customer. Some of the data, like costs for energy, is independent of the case, and needs to be determined just once.

- The price of all equipment (pr_i)
- The replacement period of all equipment (r_i)
- The current installed base of the hospital. Based on this information the value of Q_i could be determined. Q_i denotes whether or not item i is already installed at the beginning of the contract.
- Maintenance percentage for equipment per period of all items (m_i)
- Indexation of maintenance per period (j)
- Extra MES service percentage (x)
- Margin of profit of MES contract (a)
- Indexation of cash flow of yearly fee (l)
- Average costs of energy per time unit when equipment in on and off per equipment category (o_s^{ON}, o_s^{OFF})
- Number of time units for preventive maintenance and updates of every equipment category (pu_s)
- Uptime guarantee per equipment category (ut_s)
- Utilization percentage of all equipment categories (y_s)
- The discount rate for the NPV calculation (d)

The input for these last parameters, together with the input for the parameters from the hospital, can be filled in the input sheet.

Appendix D

In this appendix extra data of the theoretical case is given.

$s,v \setminus p$	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Bucky TH	49735	50481	51238	52007	52787	53579	54382	55198	56026	56867	57719	58585	59464	60356	61261
MRI TH	8.610	8.825	9.046	9.272	9.504	9.741	9.985	10.235	10.490	10.753	11.022	11.297	11.579	11.869	12.166
Bucky SC	17.848	17.313	16.793	16.289	15.801	15.327	14.867	14.421	13.988	13.569	13.162	12.767	12.384	12.012	11.652

Table 34: Expected demand of a category, location period combination ($f_{p,s,v}$)

s,v	$t_{s,v}$	y_s	ut_s	pu_s	e_s	w_s	q	c	h^{REG}	h^{EXT}	h^{IRR}	h^{MAX}	h^{TOT}	o_s^{OFF}	o_s^{ON}	b_s	g_s	u	z_s
Bucky TH	0,15	85%	95%	32	2	€38,36	€30,00	22%	2159	1143	762	3810	8760	€0,07	€5,89	€ -	€0,25	€296,50	20,4
MRI TH	0,5	85%	96%	48	2	€38,36	€30,00	22%	2159	1143	762	3810	8760	€1,63	€3,84	€5,00	€18,50	€528,36	35,86
Bucky SC	0,17	85%	95%	32	2	€38,36	€30,00	22%	2159	1143	762	3810	8760	€0,07	€5,89	€ -	€0,25	€296,50	20,4

Table 35: Values of all cost parameters

Parameter	Value
m_i	10%
j	0%
x	1,5%
a	5%
l	0%

Table 36: Values of parameters in theoretical case

Appendix E

This appendix shows the graphs and results that support the verification of the developed tool which uses the designed model.

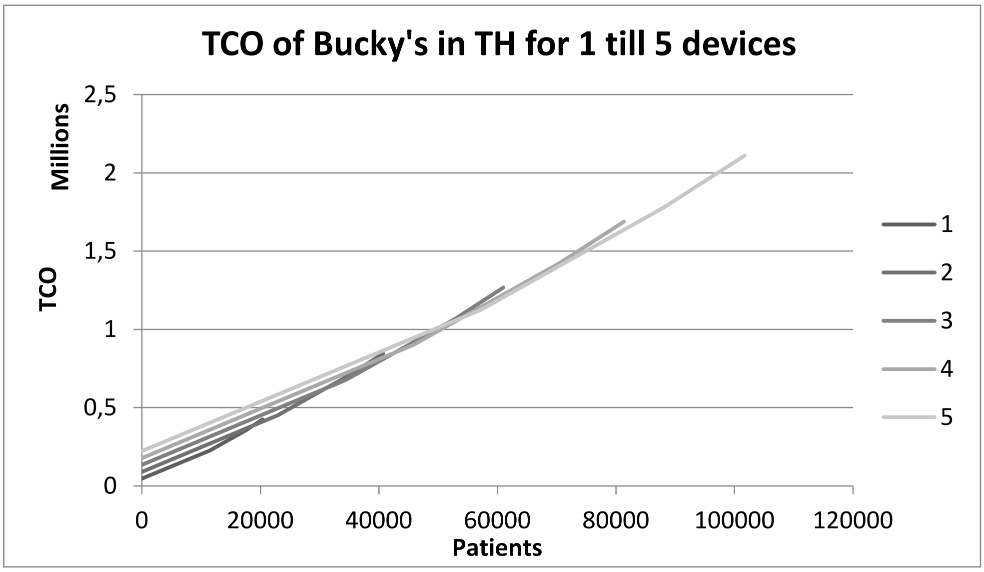


Figure 20: Plotted TCO functions of Bucky's in TH

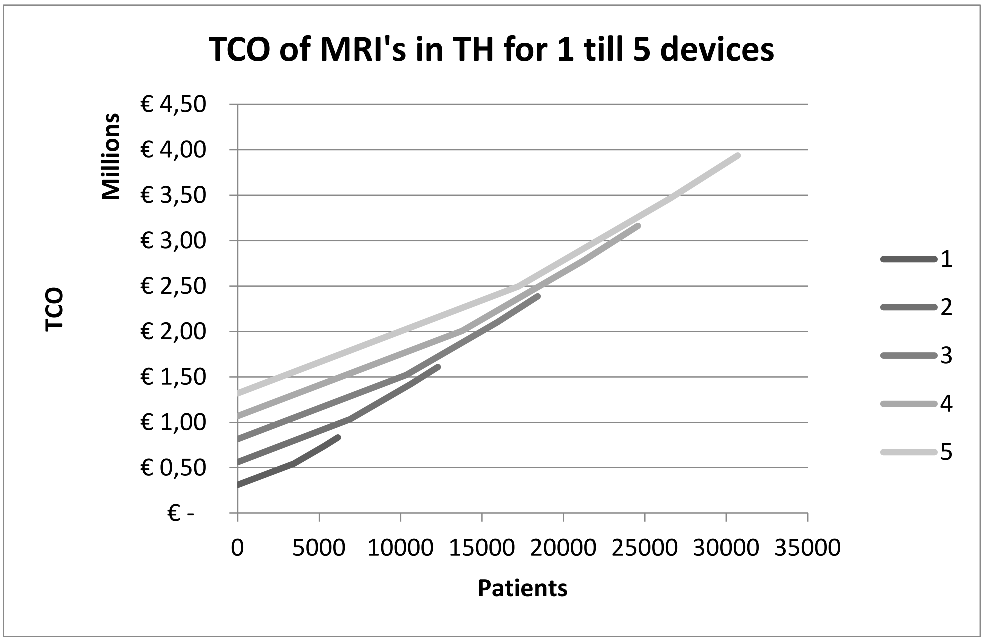


Figure 21: Plotted TCO functions of MRI's in The Hague

$D_{p,s,v}$	$pa_{M,D}$
1	6.140
2	12.279
3	18.419
4	24.558

Table 37: Maximal possible demand on $D_{p,s,v}$ MRI-scanners in The Hague

$D_{p,s,v}$	$f_{p,s,v}$	$TCO(f_{p,s,v}\,;D_{p,s,v})$
1	6.140	€ 833.233,42
2	6.140	€ 981.994,40
2	12.279	€ 1.609.246,52
3	12.279	€ 1.721.834,13
3	18.419	€ 2.385.259,62
4	18.419	€ 2.489.273,86
4	24.558	€ 3.161.272,72
5	24.558	€ 3.256.713,59

Table 38: TCO values of MRI's in The Hague for maximal capacity of $D_{p,s,v}$ devices

Appendix F

Data used in the implementation of the model for the partnership between Hospital A and Siemens.

Set	Description	Cardinality
I	Items	i
P	Periods	p
S	Equipment categories/departments	12
V	Locations	1

Categories in set S
Bucky
Mobile
Ultrasound (US)
MRI
CT
Dexa
Angio
C-Arm
PET
SPECT
Mammo
Other

Parameter	Value
m_i	m_i
j	2,5%
x	1,364%
a	a
l	1,25%

	Correction on past demand
Bucky	17%
Mobile	N/A
Ultrasound	2%
MRI	0%
CT	14%
Dexa	0%
Angio	0%
C-Arm	12%
PET	N/A
SPECT	0%
Mammo	0%
Other	N/A

Table 39: Correction for production outside opening hours (trauma's etc.)

s, v	$t_{s,v}$	y_s	ut_s	pu_s	e_s	w_s	q	c	h^{REG}	h^{EXT}	h^{IRR}	h^{MAX}	h^{TOT}	o_s^{OFF}	o_s^{ON}	b_s	g_s	u_s	z_s
Bucky	Confidential																		
Mobile																			
US																			
MRI																			
CT																			
Dexa																			
Angio																			
C-Arm																			
PET																			
SPECT																			
Mammo																			
Other																			

Table 40: Values of all cost parameters - Radiology

$s, v \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
Bucky												
Mobile												
Ultrasound												
MRI												
CT												
Dexa						Confidential						
Angio												
C-Arm												
PET												
SPECT												
Mammo												
Other												

Table 41: Realized and expected demand ($f_{p,s,v}$) of department s at radiology

i	Name	s	v	p_i	M_i	Q_i	r_i	L_i	N_i
1	Confidential								
2									
3									
4									

Table 42: Data and values of variables of MES contract with Hospital A

Appendix G

Values of variables of the verification of the model for Hospital A.

$i \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
1	Confidential											
2												
3												
4												

Table 43: Values of $G_{i,p}$; Roadmap of the equipment installed at Hospital A

$i \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
1	Confidential											
2												
3												
4												

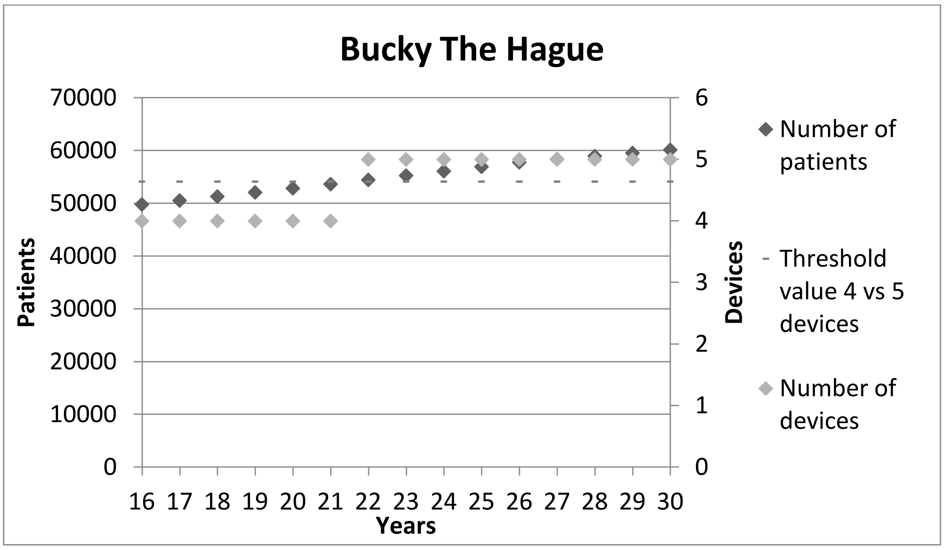
Table 44: Values of $B_{i,p}$ for Hospital A

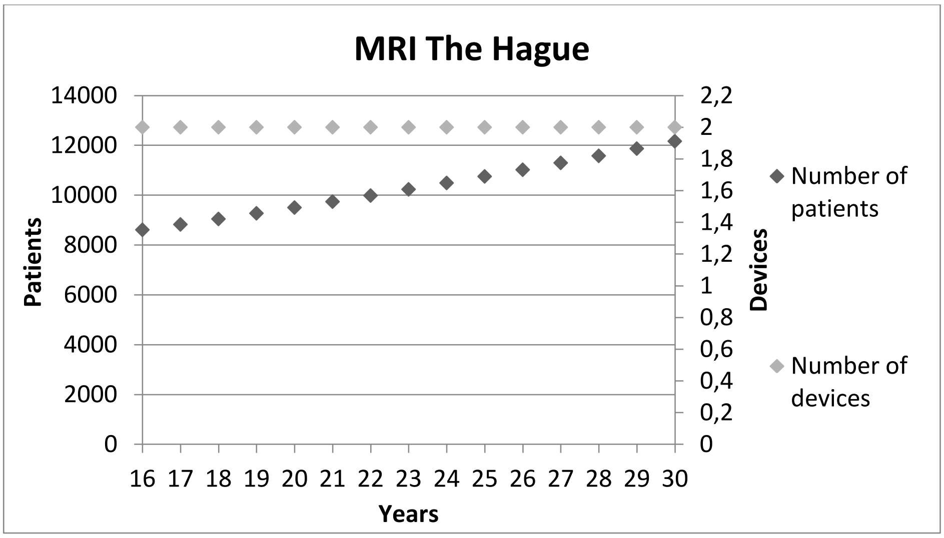
$i \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
1	Confidential											
2												
3												
4												

Table 45: Values of $J_{i,p}$ for Hospital A

Appendix H

In this fifth appendix, the attachments supporting the results for the theoretical case are given.





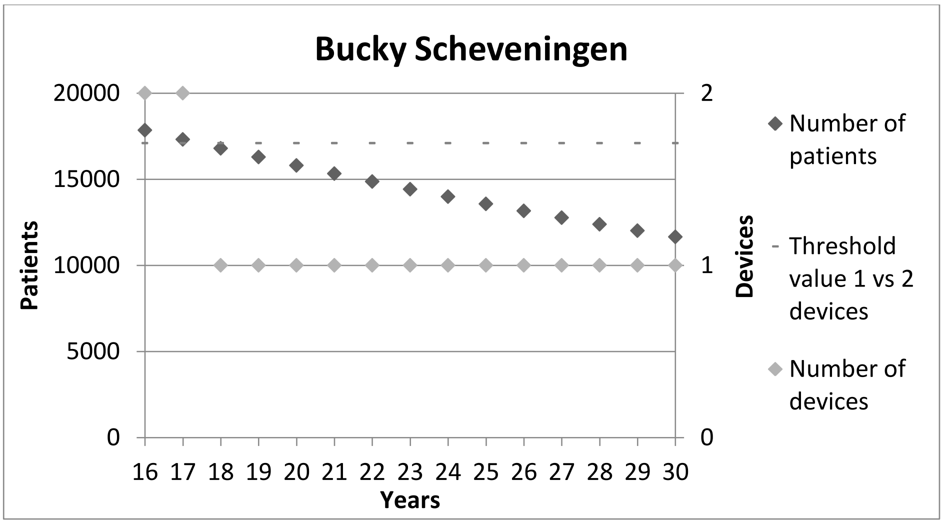


Figure 22: Demand and optimal number of devices per year

$s \setminus p$	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Bucky TH	9,2	9,4	9,5	9,6	9,8	9,9	8,1	8,2	8,3	8,4	8,6	8,7	8,8	9,0	9,1
MRI TH	10,6	10,8	11,1	11,4	11,7	11,9	12,2	12,5	12,8	13,2	13,5	13,8	14,2	14,5	14,9
Bucky SC	14,6	14,2	13,8	13,4	13,0	12,6	12,2	11,8	11,5	11,2	10,8	10,5	10,2	9,9	9,6

Table 46: Recommended daily opening hours in theoretical case

$s, v \setminus p$	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Bucky TH + SC	67583	67794	68031	68296	68588	68905	69249	69619	70014	70435	70881	71352	71848	72368	72913

Table 47: Combined demand of Bucky department TH and SC

$D_{p,s,v}$	Bucky, TH +SC $E_{D,D+1}$
1	18.474
2	30.372
3	41.506
4	52.641
5	63.775
6	74.910
7	86.044

Table 48: Threshold values when combining the Bucky department of TH and SC

$s \setminus p$	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Bucky TH + SC	8,6	8,6	8,6	8,6	8,7	8,7	8,8	8,8	8,9	8,9	9,0	9,0	9,1	9,2	9,2
MRI TH	10,6	10,8	11,1	11,4	11,7	11,9	12,2	12,5	12,8	13,2	13,5	13,8	14,2	14,5	14,9

Table 49: Recommended daily opening hours in theoretical case combined Bucky department

$s, v \setminus p$	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Bucky TH	48265	47541	46828	46125	45434	44752	44081	43420	42768	42127	41495	40872	40259	39655	39061
MRI TH	8190	7985	7786	7591	7401	7216	7036	6860	6688	6521	6358	6199	6044	5893	5746
Bucky SC	18540	19096	19669	20259	20867	21493	22138	22802	23486	24190	24916	25664	26434	27227	28043

Table 50: Expected demand when growth percentages are the opposite ($f_{p,s,v}$)

$s \setminus p$	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Bucky TH	9,0	8,8	8,7	8,6	8,4	8,3	8,2	8,1	7,9	7,8	10,2	10,1	9,9	9,8	9,6
MRI TH	10,1	9,8	9,6	9,3	9,1	8,9	8,7	8,5	8,3	8,1	7,9	7,7	14,8	14,4	14,0
Bucky SC	7,7	7,9	8,1	8,4	8,6	8,9	9,1	9,4	9,7	10,0	10,2	10,6	10,9	11,2	11,5

Table 51: Recommended daily opening hours in theoretical case with adjusted demand

Appendix I

Threshold values: Optimal solution

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19292	10273	N.I.	N.I.	4069	6891	3662	2975	8456
2	34893	19471	N.I.	N.I.	7735	10971	7105	4960	15710
3	50494	28668	N.I.	N.I.	11401	14899	10548	6932	22965
4	66095	37865	N.I.	N.I.	15067	18827	13991	8903	30220
5	81696	47063	N.I.	N.I.	18733	22755	17434	10875	37474

Daily Opening hours: Optimal solution

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	9,2	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6
MRI	13,3	13,9	14,1	14,3	14,5	14,7	15,0	15,3	15,6	15,9	8,2	8,4
CT	5,8	6,0	6,0	6,1	6,2	6,3	6,4	6,6	6,7	6,8	7,0	7,1
Angio	2,4	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7	2,7
C-Arm	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6
Mammo	4,6	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8

Daily opening hours: Optimal solution, starting with installed base at period 1

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	3,7	3,5	4,3	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6
MRI	13,3	13,9	14,1	14,3	14,5	14,7	15,0	15,3	15,6	15,9	8,2	8,4
CT	5,8	6,0	6,0	6,1	6,2	6,3	6,4	6,6	6,7	6,8	7,0	7,1
Angio	0,8	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,4	2,7	2,7	2,7
C-Arm	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	1,3	2,6	2,6
Mammo	4,6	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8

Adjusted treatment times

Confidential

Threshold values: Adjusted treatment times, optimal situation

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19292	8218	N.I.	N.I.	4069	6431	3349	2727	8456
2	34893	15576	N.I.	N.I.	7735	10240	6496	4547	15710
3	50494	22934	N.I.	N.I.	11401	13906	9644	6354	22965
4	66095	30292	N.I.	N.I.	15067	17572	12792	8161	30220
5	81696	37650	N.I.	N.I.	18733	21238	15940	9968	37474

Optimal number of devices: Adjusted treatment times, optimal situation

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	5	5	4	3	3	3	3	3	3	3	3	3
MRI	1	1	1	1	1	1	2	2	2	2	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	3	3	3	3	3	3	3	3	2	1	1	1
C-Arm	3	3	3	3	3	3	3	3	3	2	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Appendix J

Threshold values: Energy costs -50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19286	10273	N.I.	N.I.	4068	6890	3662	2974	8456
2	34887	19471	N.I.	N.I.	7734	10971	7105	4959	15710
3	50488	28668	N.I.	N.I.	11400	14899	10548	6930	22965
4	66088	37865	N.I.	N.I.	15066	18827	13991	8902	30220
5	81689	47063	N.I.	N.I.	18732	22755	17434	10873	37474

Optimal number of devices: Energy costs -50%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Energy costs +50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19299	10273	N.I.	N.I.	4071	6891	3662	2976	8456
2	34900	19471	N.I.	N.I.	7737	10971	7105	4962	15710
3	50500	28668	N.I.	N.I.	11403	14899	10548	6933	22965
4	66101	37865	N.I.	N.I.	15069	18827	13991	8905	30220
5	81702	47063	N.I.	N.I.	18735	22755	17434	10876	37474

Optimal number of devices: Energy costs +50%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Labour costs outside regular hours -50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	22944	11349	N.I.	N.I.	4472	N.I.	3882	N.I.	9657
2	38584	20546	N.I.	N.I.	8138	N.I.	7325	5928	16912
3	54185	29744	N.I.	N.I.	11805	N.I.	10768	8849	24166
4	69786	38941	N.I.	N.I.	15471	N.I.	14211	11715	31421
5	85387	48139	N.I.	N.I.	19137	N.I.	17654	14582	38675

Optimal number of devices: Labour costs outside regular hours -50%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Labour costs outside regular hours +50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	18062	9915	N.I.	N.I.	3935	5980	3589	2650	8055
2	33663	19112	11113	33170	7601	9933	7032	4621	15310
3	49264	28309	15026	44433	11267	13861	10475	6593	22565
4	64864	37507	18939	55641	14933	17789	13918	8564	29819
5	80465	46704	22853	66849	18599	21716	17361	10536	37074

Optimal number of devices: Labour costs outside regular hours +50%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Extra MES costs -50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19173	10243	N.I.	N.I.	4061	6814	3655	2950	8429
2	34773	19441	N.I.	N.I.	7727	10885	7098	4932	15683
3	50374	28638	N.I.	N.I.	11393	14813	10541	6903	22938
4	65975	37836	N.I.	N.I.	15059	18741	13984	8875	30193
5	81576	47033	N.I.	N.I.	18725	22669	17427	10846	37447

Optimal number of devices: Extra MES costs -50%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Extra MES costs +50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19412	10303	N.I.	N.I.	4077	6967	3670	3000	8483
2	35013	19500	N.I.	N.I.	7743	11057	7113	4989	15737
3	50614	28698	N.I.	N.I.	11410	14985	10556	6960	22992
4	66215	37895	N.I.	N.I.	15076	18913	13999	8932	30246
5	81815	47092	N.I.	N.I.	18742	22841	17442	10903	37501

Optimal number of devices: Extra MES costs +50%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Treatment time -10%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	21436	11415	N.I.	N.I.	4521	7656	4069	3306	9395
2	38770	21634	N.I.	N.I.	8595	12190	7895	5511	17456
3	56104	31853	N.I.	N.I.	12668	16554	11720	7702	25517
4	73439	42073	N.I.	N.I.	16742	20918	15546	9892	33577
5	90773	52292	N.I.	N.I.	20815	25283	19372	12083	41638

Optimal number of devices: Treatment time -10%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Treatment time +10%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	17538	9339	N.I.	N.I.	3699	6264	3329	2705	7687
2	31721	17700	N.I.	N.I.	7032	9974	6459	4509	14282
3	45904	26062	N.I.	N.I.	10365	13545	9589	6302	20877
4	60086	34423	N.I.	N.I.	13698	17115	12719	8094	27472
5	74269	42784	N.I.	N.I.	17030	20686	15849	9886	34067

Optimal number of devices: Treatment time +10%

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	3	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	2	2	2	2	2	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Replacement interval -1 year

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19379	10366	N.I.	N.I.	4075	N.I.	3668	3012	8495
2	34980	19564	N.I.	N.I.	7741	11097	7111	5002	15750
3	50581	28761	N.I.	N.I.	11407	15025	10554	6974	23004
4	66182	37958	N.I.	N.I.	15073	18953	13997	8945	30259
5	81783	47156	N.I.	N.I.	18739	22881	17440	10916	37514

Optimal number of devices: Replacement interval -1 year

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Threshold values: Replacement interval +1 year

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	19217	10203	N.I.	N.I.	4064	6799	3658	2945	8423
2	34818	19401	N.I.	N.I.	7730	10868	7101	4926	15678
3	50419	28598	N.I.	N.I.	11396	14796	10544	6897	22933
4	66020	37796	N.I.	N.I.	15062	18724	13986	8869	30187
5	81621	46993	N.I.	N.I.	18728	22652	17429	10840	37442

Optimal number of devices: Replacement interval +1 year

$s \setminus p$	1	2	3	4	5	6	7	8	9	10	11	12
US	2	2	2	2	2	2	2	2	2	2	2	2
MRI	1	1	1	1	1	1	1	1	1	1	2	2
CT	1	1	1	1	1	1	1	1	1	1	1	1
Angio	1	1	1	1	1	1	1	1	1	1	1	1
C-Arm	1	1	1	1	1	1	1	1	1	1	1	1
Mammo	1	1	1	1	1	1	1	1	1	1	1	1

Appendix K

Differences from threshold values determined with the normal input data. Used for sensitivity analysis.

Energy costs -50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	-0,03%	0,00%	N/A	N/A	-0,04%	0,00%	0,00%	-0,04%	0,00%
2	-0,02%	0,00%	N/A	N/A	-0,02%	0,00%	0,00%	-0,03%	0,00%
3	-0,01%	0,00%	N/A	N/A	-0,01%	0,00%	0,00%	-0,02%	0,00%
4	-0,01%	0,00%	N/A	N/A	-0,01%	0,00%	0,00%	-0,02%	0,00%
5	-0,01%	0,00%	N/A	N/A	-0,01%	0,00%	0,00%	-0,01%	0,00%

Energy costs +50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	0,03%	0,00%	N/A	N/A	0,04%	0,00%	0,00%	0,04%	0,00%
2	0,02%	0,00%	N/A	N/A	0,02%	0,00%	0,00%	0,03%	0,00%
3	0,01%	0,00%	N/A	N/A	0,01%	0,00%	0,00%	0,02%	0,00%
4	0,01%	0,00%	N/A	N/A	0,01%	0,00%	0,00%	0,02%	0,00%
5	0,01%	0,00%	N/A	N/A	0,01%	0,00%	0,00%	0,01%	0,00%

Labour outside regular hours -50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	18,93%	10,47%	N/A	N/A	9,91%	N/A	5,99%	N/A	14,21%
2	10,58%	5,52%	N/A	N/A	5,21%	N/A	3,09%	19,51%	7,65%
3	7,31%	3,75%	N/A	N/A	3,54%	N/A	2,08%	27,65%	5,23%
4	5,58%	2,84%	N/A	N/A	2,68%	N/A	1,57%	31,58%	3,97%
5	4,52%	2,29%	N/A	N/A	2,15%	N/A	1,26%	34,09%	3,21%

Labour outside regular hours +50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	-6,38%	-3,49%	N/A	N/A	-3,30%	-13,22%	-2,01%	-10,92%	-4,74%
2	-3,53%	-1,84%	N/A	N/A	-1,74%	-9,47%	-1,03%	-6,84%	-2,55%
3	-2,44%	-1,25%	N/A	N/A	-1,18%	-6,97%	-0,70%	-4,89%	-1,74%
4	-1,86%	-0,95%	N/A	N/A	-0,89%	-5,52%	-0,52%	-3,81%	-1,33%
5	-1,51%	-0,76%	N/A	N/A	-0,72%	-4,56%	-0,42%	-3,11%	-1,07%

Extra MES service costs -50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	-0,62%	-0,29%	N/A	N/A	-0,20%	-1,11%	-0,20%	-0,84%	-0,32%
2	-0,34%	-0,15%	N/A	N/A	-0,11%	-0,78%	-0,10%	-0,57%	-0,17%
3	-0,24%	-0,10%	N/A	N/A	-0,07%	-0,58%	-0,07%	-0,41%	-0,12%
4	-0,18%	-0,08%	N/A	N/A	-0,06%	-0,46%	-0,05%	-0,32%	-0,09%
5	-0,15%	-0,06%	N/A	N/A	-0,05%	-0,38%	-0,04%	-0,26%	-0,07%

Extra MES service costs +50%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	0,62%	0,29%	N/A	N/A	0,19%	1,11%	0,21%	0,84%	0,32%
2	0,34%	0,15%	N/A	N/A	0,10%	0,78%	0,11%	0,58%	0,17%
3	0,24%	0,10%	N/A	N/A	0,08%	0,58%	0,07%	0,41%	0,12%
4	0,18%	0,08%	N/A	N/A	0,06%	0,46%	0,05%	0,32%	0,09%
5	0,15%	0,06%	N/A	N/A	0,05%	0,38%	0,04%	0,26%	0,07%

Treatment time -10%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	11,11%	11,12%	N/A	N/A	11,10%	11,11%	11,10%	11,13%	11,11%
2	11,11%	11,11%	N/A	N/A	11,11%	11,11%	11,11%	11,10%	11,11%
3	11,11%	11,11%	N/A	N/A	11,11%	11,11%	11,11%	11,11%	11,11%
4	11,11%	11,11%	N/A	N/A	11,11%	11,11%	11,11%	11,11%	11,11%
5	11,11%	11,11%	N/A	N/A	11,11%	11,11%	11,11%	11,11%	11,11%

Treatment time +10%

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	-9,09%	-9,09%	N/A	N/A	-9,09%	-9,09%	-9,09%	-9,09%	-9,09%
2	-9,09%	-9,09%	N/A	N/A	-9,09%	-9,09%	-9,09%	-9,09%	-9,09%
3	-9,09%	-9,09%	N/A	N/A	-9,09%	-9,09%	-9,09%	-9,09%	-9,09%
4	-9,09%	-9,09%	N/A	N/A	-9,09%	-9,09%	-9,09%	-9,09%	-9,09%
5	-9,09%	-9,09%	N/A	N/A	-9,09%	-9,09%	-9,09%	-9,09%	-9,09%

Replacement interval -1 year

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	0,45%	0,91%	N/A	N/A	0,15%	N/A	0,15%	1,25%	0,47%
2	0,25%	0,48%	N/A	N/A	0,08%	1,15%	0,08%	0,84%	0,25%
3	0,17%	0,32%	N/A	N/A	0,05%	0,85%	0,05%	0,60%	0,17%
4	0,13%	0,25%	N/A	N/A	0,04%	0,67%	0,04%	0,47%	0,13%
5	0,11%	0,20%	N/A	N/A	0,03%	0,55%	0,03%	0,38%	0,11%

Replacement interval +1 year

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	-0,39%	-0,68%	N/A	N/A	-0,13%	-1,33%	-0,12%	-1,01%	-0,39%
2	-0,22%	-0,36%	N/A	N/A	-0,07%	-0,94%	-0,06%	-0,69%	-0,21%
3	-0,15%	-0,24%	N/A	N/A	-0,05%	-0,69%	-0,04%	-0,50%	-0,14%
4	-0,11%	-0,18%	N/A	N/A	-0,04%	-0,55%	-0,04%	-0,38%	-0,11%
5	-0,09%	-0,15%	N/A	N/A	-0,03%	-0,45%	-0,03%	-0,32%	-0,09%

Preventive maintenance and updates outside opening hours

$D_{p,s,v}$	Bucky	US	MRI	CT	Dexa	Angio	C-Arm	SPECT	Mammo
1	0,75%	0,22%	N/A	N/A	0,38%	0,21%	0,35%	0,67%	1,09%
2	1,05%	0,28%	N/A	N/A	0,53%	0,37%	0,44%	1,20%	1,41%
3	1,16%	0,30%	N/A	N/A	0,59%	0,46%	0,47%	1,47%	1,53%
4	1,22%	0,32%	N/A	N/A	0,62%	0,51%	0,48%	1,62%	1,59%
5	1,26%	0,32%	N/A	N/A	0,63%	0,54%	0,49%	1,71%	1,62%