Master's Thesis

From 'just-in-case' to 'just-in-time':

Modelling the optimal stock level of reusable instrument sets of Medisch Spectrum Twente

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Management summary

Hospitals are working hard to provide the best quality of health service to their patients, but their profitability is not showing the results for this hard work. This situation exists because as surgical specialists are aware that operating rooms are of the highest revenue generators for hospitals, the management department runs the hospital with the idea that the quality of their services is related with having 'more is better'. The Medisch Spectrum Twente (MST) hospital wishes to improve its inventory system and procurement practices to augment its financial performance. However, such intentions have been tied up by their current just-in-case practices which have led them to keep high inventory levels just-in-case the instrument set is required by a surgeon. Further, MST does not have a policy to manage the inventory of reusable instrument sets. Consequently, the decision of purchasing and determining proper base-stock levels of instrument sets are taken on the basis of experience and intuition, rather than on the analysis of forecasted (changes in) demand. Moreover, important performance indicators have not been identified and measured, which hides the trade-off costs of having high inventory availability.

The main goal of this study is to develop a decision-making tool for reusable instrument sets with the aim of minimizing the purchasing and holding costs, while ensuring that the health of the patient is not compromised. To achieve this, we answer the following research question:

How can we establish a target inventory level that minimizes the expected total cost over the lifetime of the reusable instrument sets while maintaining a high service level?

We aim to provide insight into the current inventory situation related to long-life cycle instrument sets, as well as a model that supports managers to take procurement decisions without the precise knowledge of the future demand. In other words, we deliver a model that allows making a trade-off analysis between service level and the total costs generated for holding different quantities of instrument sets.

In order to understand and create a simulation model that represents the current situation related with reusable instrument sets as closely as possible, a series of interviews with the staff were performed. In addition, the flow of the instrument sets through the system was assessed to understand how instrument sets are managed, as well as to identify which inventory practices are currently being used. Moreover, we did a literature study through scientific engines such as Google Scholar, Scopus. This allowed us to identify the key performance indicators (KPIs) and optimization methods that helped answering the overall research question. Once the KPIs and optimization models were identified, several adaptations were made to create a reliable tool that would represent the real-life situation. This tool was programmed by making use of Advanced Visual Basic. This tool was used to determine the optimal number of instrument sets (base-stock level) under different changes in demand. It allowed us to create a simulation of future demand and a comparison with the current situation. To assure the reliability of the simulation model, we verified and validated it throughout every step of its design, by consulting the expertise of both the hospital staff and the specialists at the University of Twente. As such, the results of this simulation provide a realistic prediction of future demand of instrument sets, as well as the costs involved.

Currently, there are approximately one thousand instrument sets in the MST. As it is unrealistic to study all of these sets together, we chose to focus on one particular instrument set: the laparoscopy instrument set. We opted for this set for several reasons, such as its frequent use in the ORs, the purchasing costs (€13,000 per set), and the relatively large space it occupies in the OR storage. Another

issue that we needed to take into consideration, was the fact that after being used, instrument sets return back sterilized to the OR storage after either one day, or two days. As this complicated the design of our simulation model, we decided to study two different scenarios; one in which the instrument set returns back sterilized the first morning after use (FMAU), and one in which it returns one day later (SMAU). Another advantage of making use of two scenarios, is that in case the MST would like to consider outsourcing its sterilization process, it would also take two days for instruments to return sterilized to the OR storage. Therefore, the SMAU scenario is also a representation of possible outsourcing. The last, but vital issue that we needed to tackle, was the identification of KPIs. Currently, the MST does not measure KPIs related to its inventory. As such, we identified 5 KPIs, namely: service level, stockout costs, purchasing costs, holdings costs, and total costs. In turn, these KPIs allowed us identifying the optimal base-stock level.

The results of the simulation analysis show that, currently, there are (far) too many laparoscopy instrument sets available in the MST's OR storage. At the moment, there are 20 instrument sets, but the results show that without a change in demand, 11 in the FMAU scenario, and 18 in the SMAU scenario. In this case, there would still be a very high service level (99.98% and 99.24% respectively). Moreover, it would allow a large cost reduction for the hospital, as 11 instrument sets would cost 42% less than the current 20, and 3% in case of the SMAU scenario. We also simulated the necessary number of instrument sets in case of changes in demand compared with that of 2016-2017. If the demand would increase by 16%, the hospital could still do with fewer instrument sets. Namely, 12 in case of FMAU, and 19 in case of SMAU, still taking into consideration a high service level. An overview of these results can be seen in Table 1.

Average annual performance of FMAU & SMAU scenarios							
% increase in demand	# Sets	Service level	Stockout probability	Stockout cost	Purchasing +Holding costs	Total cost	% cost reduction between current situation & S*
Current FMAU	20	100.00%	0.00%		€ 119,600.00	€ 119,600.00	-
0% FMAU	**12**	**100.00%**	**0.00%**	**€ -**	**€ 71,760.00**	**€ 71,760.00**	**-40%**
	11	**99.98%**	**0.02%**	**€ 3,836.00**	**€ 65,780.00**	**€ 69,616.00**	**-42%**
16% FMAU	**14**	**100.00%**	**0.00%**	**€ -**	**€ 90,794.49**	**€ 90,794.49**	**-24%**
	12	**99.00%**	**0.20%**	**€ 6,369.23**	**€ 71,760.00**	**€ 78,129.23**	**-35%**
Current SMAU	20	99.80%	0.20%	€ 2,823.06	€ 119,600.00	€ 122,423.06	-
0% SMAU	**18**	**99.24%**	**0.76%**	**€ 10,957.00**	**€ 107,640.00**	**€ 118,597.00**	**-3%**
	26	**100.00%**	**0.00%**	**€ 1,299.98**	**€ 155,480.00**	**€ 156,779.98**	**(+27%)**
16% SMAU	**19**	**99.50%**	**0.50%**	**€ 6,287.00**	**€ 113,620.00**	**€ 119,907.00**	**-2%**
	26	**100.00%**	**0.00%**	**€ -**	**€ 155,480.00**	**€ 155,480.00**	**(+27%)**

Table 1 Comparison between current situation and different levels of optimal (S) base-stock level. Empirical distribution. Holding cost h=.26 set price €1\3,000 and an increase of 16% from the demand of 2017.*

We recommend MST to make use of the simulation tool to assess its current number of instrument sets. It would provide more information about the demand of each instrument set, thereby helping to improve the accuracy of the forecasted demand and allowing cost savings. We also recommend that, at the moment of taking purchasing decisions, the MST evaluates the trade-offs between service level and base-stock levels. As we have demonstrated in this study, having fewer instrument sets in stock, does not imply the service level decrease as well. In fact, even with far fewer sets, the MST can still provide a high service level. The current just-in-case approach, in which sets are purchased without assessing its necessity, are not productive for the hospital. As such, a more conservative, just-in-time approach can help the hospital in its inventory management.

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List of acronyms

Acronyms	Description
CEDF	Cumulative empirical distribution function
CP	Constrain programming
CPR	Central preparation room (COR Centrale ompak ruimte)
CSD	Central sterilization department
CSL	Cycle service level
EOQ	Economic order quantity
FMAU	First morning after use
ILP	Integer linear programming
IMD	Instrument management department
KPI	Key performance indicators
MST	Medisch spectrum Twente
OR	Operating room
ROP	Reorder point
SKU	Stock keeping unit
SMAU	Second morning after use
TOP	Tray optimization problem

1 Introduction

In the framework of completing the Master of Industrial Engineering and Management, we have performed a study in the Operation Rooms, Central Sterilization Department (CSD) and the Instrument Management Department of Medisch Spectrum Twente (MST). In this study, we focused on the inventory control and base-stock determination of reusable instrument sets. The project consisted of providing a model that could guide the instrument manager in the purchasing decision of reusable instrument sets, while considering the trade-offs involved.

For the external readers, a small introduction to the research context is given in Section 1.1. Subsequently, in Section 1.2, we provide a description of the problem background where the relevance and motivation of the research are discussed, while in Section 1.3 we define the research objective and goal. Finally, in Section 1.4, we pose the research questions we aim to answer in this project as well as how we plan to do so. These questions are the drivers used to attain this study's goal and to solve the problem statement.

1.1 Context of this research

The last decades, Dutch hospitals have become increasingly aware of their financial situation and heavily focused on efficiency and cost saving. The fact that this does not always work out as planned was demonstrated by the recent case of the bankruptcy and foreclosure of the Slotervaart Hospital and the hospitals falling under the chain of IJsselmeerziekenhuizen (Nu.nl, 2018). In line with this, healthcare organizations have come to realize that supply chain processes can become a strategic cost saving tool instead of merely a daily operational process (Becker's Hospital Review, 2013). Whereas such supply chain processes were traditionally seen as costly and unavoidable means to make sure necessary medications, tools and instruments are available at the right place at the right time, nowadays, some healthcare organizations also consider these processes to provide opportunities for genuine cost savings. Nevertheless, even though these effective supply chain techniques have been applied in other areas of hospitals, this is less the case in the operating rooms (OR). This does not mean that operating rooms have been ignored but rather overlooked as it continues to generate revenues. This situation has caused that the desire to improve what seemed to be performing well, is mitigated (Jayanthi, 2013). Consequently, the cost of supplies in the OR has continued to increase and along with it the need for controlling costs, while providing optimal patient outcomes is of high importance (Petrohoy, Bleznak, & Toomey, 2011). Since inventory management is the very heart of the supply chain, this thesis concerns a study into supporting the Medisch Spectrum Twente to determine a model which allows them to optimize the stock level of long-life reusable instrument sets (non-disposable) while increasing cost efficiency and keeping a high-quality service.

This section is organized as follows. In Section 1.1.1 we provide an introduction to the hospital where this study takes place, while a description of the departments involved in this study is provided in the next sections. In Section 1.1.2 we describe the operating room department, in Section 1.1.3 we introduce the central sterilization department CSD, and in Section 1.1.4 we describe the medical logistics department.

1.1.1 MST hospital

This study is done within the Medisch Spectrum Twente (MST), which is a hospital in Enschede, the Netherlands. The MST (Figure1) was created by the merging of two hospitals in Enschede and Oldenzaal and two clinics in Losser and Haaksbergen in 1990. These days, MST is one of the largest non-academic hospitals of the Netherlands, with an annual budget of approximately €500 million. Around 2,864 employees, including 224 medical specialists, are responsible for 30,000 admissions and 406,181 outpatient visits (MST, 2017). To be able to deliver the highest quality of healthcare, MST moved to a new building, in January of 2016. The new building contains only single-patient rooms to increase customer satisfaction as well as decrease the risk of transmitting infections. To realize this, the number of beds was reduced to 547 (Website MST, 2017) in order to decrease the quantity of inpatients and the staying time and, therefore, reducing the cost. The MST performs on average 21,000 surgeries per year.

Figure 1 Medisch Spectrum Twente opened in January 2016.

1.1.2 OR department

One of the most expensive resources in hospitals is the operating room (OR). Around 60% of hospital patients require a surgical procedure performed in the operating room (OECD, 2017). This number is also the case at MST, where according to its employees, 60% of the patients visit the operating room. As such, it is safe to state that the OR is one of the central departments in the MST, also taking up a large part of the hospital's expenses.

The MST has 15 operating rooms, which it divides between 3 thoracic ORs and 12 general ORs. The general ORs are focused on 11 specialities: orthopedy, traumatology, neurology, urology, general, plastic, gynaecology, otolaryngology, and vascular (see Table 2). These general ORs perform on average 21,000 procedures a year.

Number of surgeries performed during 2016-2017				
OR type	**Type of surgery**	**2016**	**2017**	**Average**
General unit	Stomach, guts & liver	180	157	18677
	Otolaringology	2,158	2,084	
	Neurology	1,198	1,223	
	General	6,576	6,449	
	Eye	1,875	1,785	
	Urology	1,061	1,170	
	Pulmonology	5	5	
	Orthopedy	2,219	2,299	
	Gynaecology	1,632	1,733	
	Plastic	1,256	1,447	
	Jaw	393	449	
	Total General unit	18,553	18,801	
Thorax unit	Cardiology	6	5	2,159
	Cardio-Toraxic	2,073	2,234	
	Total Thorax unit	2,079	2,239	
TOTAL		20,632	21,040	**20,836**

Table 2 Surgeries performed in the general unit per speciality during 2016-2017 (Data provided by the planning staff of the OR department, 2018)

This department uses a vital software for this study called OR suite, providing the planning of each operating room, where the name of the patient, treatment, and surgeon is registered. For further details on this software see Section 2.2.

1.1.3 Central Sterilization Department

Each surgery performed in an OR requires that clean and sterilized instruments are on time at the right location. As each surgery requires different instruments, MST has around 1,900 instrument sets consisting of approximately 600 different types of instruments. Examples of such instruments are scalpels, scissors and bandages. These instruments need to be sterilized before surgery. Sterilization is a process in which all microorganisms on or in a medical device are killed or inactivated, such that the chance of remaining living organisms is less than 1% (WHO, 2018). At MST, this process is performed by the Central Sterilization Department (CSD), which is also in charge of monitoring the performance and quality of the instruments, as well as managing the instruments around the hospital. From a logistics perspective, the general OR is the main client of the CSD, as approximately 80% of the CSD's throughput comes from this department.

The CSD works during the week from 08:00 to 22:00. Moreover, there is always an employee present for urgent matters outside these hours. During office hours there are around 15 employees present, even though this varies according to the demand and planning. During the weekends, there are always two employees available in case that the general OR requests urgent sterilization. On average, the CSD sterilizes 350 instrument sets per day.

Instrument management department (IMD), is a sub department of the CSD, which is in charge of the purchasing, administration and reparation and maintenance coordination of the instruments. Together with the surgeon and OR assistant, the IMD determines which instruments belong to each set.

1.1.4 Medical logistics

The medical logistics department is charged with the task to ensure that goods arrive at the desired time and in the right shape to the outpatient clinics and the ORs. These goods are divided into sterile and unsterile articles. The activities of the medical logistics department vary from ordering instruments to distributing them to the department which had raised an order.

One of the medical logistics' main goals is to ensure that the flow of the instruments works without any problem. Previously, the CSD was located just next to the ORs, but when the MST relocated to its new building, the distance between both departments was increased considerably. This situation created the need of a transport section called Transferium. This logistics hub, comparable to a small airport, is located in the basement of the new building. Its main function is to sort and arrange the goods to be transported from or to the operating room and outpatient clinics. This department also plays an important role in the transportation of reusable instrument sets.

1.2 Problem background

The central problem of this thesis is founded in two observations. On the one hand, operating rooms have been one of the highest revenue producers for hospitals. However, the revenues from surgeries have decreased. This has raised awareness from hospitals to analyse the supply management in the operating rooms from a bottom line perspective. Usually, this area has been underexposed because higher management of the hospitals are reluctant to challenge their surgeons and staff practices. On the other hand, the operating rooms generate about 40-60% of total hospital expenditures (Pfiedler, 2016), making them a potential area of improvement. Poor inventory management, scarce data, lack of standardization, and inefficient practices contribute to a system that is costly and ineffective. It has been estimated than around 25% of the time of the staff in a hospital is invested in supply management (Gagliardi, 2010).

This study is motivated by the MST's desire to reduce costs while maintaining a high standard of clinical effectiveness and patient satisfaction. The operating rooms represent a large cost because of the high flow of inventory as well as expensive fixed assets. The MST annually invests approximately €4.5 million in reusable medical instruments and around €900,000 in disposable instruments, reparations, and spare parts.

Several studies have shown that the procurement of reusable instruments is more cost efficient and more environmentally friendly than disposable instruments (Adler et al., 2005; DesCôteaux,1996; Apelgren et al., 1994; Diamant et al., 2017). However, reusable instrument sets come along with reparation and sterilization costs, as well as depreciation. Furthermore, hospitals tend to overstock instruments to avoid possible shortages. In Section 2.1 we have developed an estimation of cost-efficiency of reusable vs. Disposables instruments. A typical Dutch hospital has invested millions of euros in sterile instruments. On a national level, the investment in sterile equipment is estimated to exceed 500 million euros (Van de Klundert et al., 2008).Moreover, central sterilization departments are capital intensive and, at a national level, employ thousands of people. All of these costs, whether through taxes or insurance payments, are in the end paid by the customer and other taxpayers. Therefore, the objective to lower costs through smarter and more efficient planning of sterile instruments sets, is highly relevant for both hospitals and Dutch citizens.

This section is divided in Section 1.2.1, where we provide an overview of the current practices that are related with this study. In Section 1.2.2 we identify the research objective, which is based on the findings of the previous section. To finalize this section, in Section 1.2.3, we present the research question formulated to mitigate the negative effects produced for the current practices.

1.2.1 Current practices

The current medical staff inventory practices can be characterized as a *just-in-case* approach (JIC), with which we mean that the medical staff tends to keep a large number of instruments sets in stock in different storage units closely located to the ORs. Hence, they have the instruments sets *just-in-case* they might be required by a surgeon. This is one of the main reasons why the staff is reluctant to eliminate or reallocate these instrument sets. This JIC practice might reduce the fear of running out of supplies in the operating rooms, but at the same time it produces an increased pressure in terms of purchasing, inventory, and holding costs, as well as an increased demand for handling and redundant sterilization. As such, these JIC practices may cause unnecessary costs to the MST.

Until now, an approach to determine the number of instrument sets necessary to cover the demand has been overlooked. Currently, the MST does not have an inventory policy to determine the necessary inventory levels to satisfy the demand while keeping a high service level. Moreover, important performance measures such as instrument usage, implied stockout costs, holding costs and purchasing cost are not being tracked. The prices of the instruments are difficult to assess, while the costs of handling and sterilization are mainly estimated (Personal communication, Business controller MST, 2018). As a result, purchasing decisions and inventory levels are mostly based on experiences, gut feeling and perceived demand, rather than meticulously forecasted on changes in demand. This lack of information about the high costs and the investment that instrument sets involve, leads to less conscious procurement practices, handling and inventory practices within the direct and indirect users.

These practices positively influence the investment cost, due to the high value that the instrument sets represent. An instrument set price can vary between €10 to €25,000. Instrument set of categories between 3-4 have an average value of €10,000 with a handling and sterilization cost that is between €40-€80 (Personal communication, MST, 2018). Moreover, a large number of instrument sets leads to more storage and labour costs due to the handling and management of redundant inventory. Therefore, the JIC practice creates unnecessary costs for MST.

1.2.2 Research objective

The main objective of this study is to develop a method to determine the optimal base-stock level of reusable instrument sets that the MST needs to keep in inventory, while maintaining a high service level. We will compare the service level and involved costs of the current situation, with the changes of the base-stock level produced in the present model.

1.2.3 Main research question

The objective of this study is to decrease the inventory value by designing a method for determining the stock level while keeping a proper service level. This analysis is based on historical data and literature review. To achieve this objective, it is essential to decompose the overall research question into sub questions to get a better understanding of the problem and more importantly, to answer the main question through the process. The overall research question guiding this thesis is:

How can we establish a target inventory level that minimizes the expected total cost over the lifetime of the reusable instrument sets while maintaining a desired service level?

1.3 Structure of this thesis

This study consists of eight chapters (see Figure 2): Current situation, Literature research, Modelling, Experiments, Results, Implementation plan, Conclusions, Limitations, and Recommendations. Each chapter is connected to a set of sub questions and is grouped according to the development of this study. In the remainder of this chapter we assess these sections as well as the scope of this study.

This section is divided according to the main objective of each sub question. In Section 1.3.1 we provide the sub question related with the context and problem analysis of this study. In Section 1.3.2 the sub question that aims to find through the literature review possible key performance indicators (KPIs) and models is formulated. In Section 1.3.3 we create the question that aims to adapt the models found in through the literature review. In Section 1.3.4, we formulate the sub question that focuses on finding the proper experiment design to come out with a reliable model. In Section 1.3.5 it is presented the sub question where the results of the experiment are analysed. In Section 1.3.6 the sub question that aims to find the means to implement the tool created during this research is formulated. Finally in Section 1.3.7, the sub question that tackles the conclusions, limitations, and recommendations of this study is formulated.

1.3.1 Context and problem analysis

To optimize MST's inventory management from a logistics perspective, we first need to analyse how the logistic and inventory control of instrument sets is currently performed, in order to identify the potential improvements for their weaknesses. For this purpose, we formulate the next sub question:

Sub question 1: *How is the MST currently managing the inventory of reusable instrument sets?*

In this sub question, we plan to describe the current situation of the system structure and operating procedures related with the inventory and supply of reusable instrument sets. To achieve this, we first explain the flow of instrument sets trough their cycle and the resources involved in it, such as: instrument sets, data base systems and storage. Subsequently, we conduct an analysis of the planning and control of reusable instrument sets by defining the current inventory and purchasing practices, then we identify the key performance indicators (KPIs) related with this research to perform a zero-measure analyse of the current situation. Finally, we define the problem bundle which provides the bases which to identify the root causes of the identified problem.

To collect this information, we address interviews and meetings with experts and people involved in the process, as well as the observation of processes of the instrument sets through their flow. Thus, the critical perspective from an outsider's point of view can be used in a more analytical way during discussions with the people involved in the logistics and inventory system. Furthermore, reviewing documentation about the instrument sets is needed to determine whether or not there is coherency between the documented and the current practices. We answer sub question 1 in Chapter 3.

1.3.2 Literature review

After having a clear understanding of the current situation and the problem to be tackled, we continue with the next sub questions:

Sub question 2A: *Which methodologies are found in literature suitable to determine an optimal base-stock level?*

Sub question 2B: *Which KPIs are important to evaluate to determine an optimal base-stock level?*

In these second sub questions, we perform a literature study by using reliable literature sources such as: Google Scholar, Scopus and Web of Science. In Sub question 2A we aim to find what is already known in the literature about inventory management of reusable instrument sets and which mathematical methodologies could be used to answer our main research question. We continue with sub question 2B, to identify the performance indicators and parameters that are commonly used as performance measures for determining an optimal base-stock level of reusable instrument sets. We answer Sub questions 2A and 2B in Chapter 3.

1.3.3 Model formulation

Each method comes with its own requirements and formulations. Therefore, a comparison and an analysis are relevant to create a suitable model to come up with an optimal solution. Hence, the main challenge of this research is to formulate in a mathematical way all metrics and KPIs related with base-stock levels within different scenarios. To achieve this, we formulate the next question:

Sub question 3: *How can we create a model based on the found methodologies that helps to answer our main research question?*

In this third sub question, we present the conceptual adaptation of the models found during the literature review, which help us to adapt and evaluate the KPIs within different scenarios. Moreover, the limitations and assumptions of each model is formulated.

This sub question helps us achieving our goal in a theoretical and practical way. We answer sub question 3 in Chapter 4.

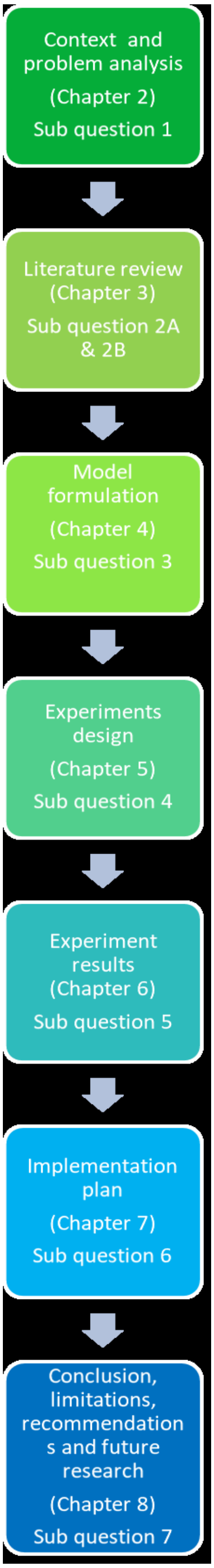


Figure 2 - Structure of this thesis.

1.3.4 Experiment design

Various experiments are performed to determine whether the literature research would support us to come up with important KPIs which provide a quantitative comparison between the current situation and the various experiments. In order to be able to evaluate the benefits of this research and provide recommendations for the users, we ask the following question:

Sub question 4: *How should the experiments be designed?*

For the fourth sub question, we design various experiments to test under different circumstances each scenario. We identify the required data and the software needed to evaluate the performance of each scenario according to different parameters. Sub question 4 is answered in Chapter 5.

1.3.5 Experiment results

Sub question 5: *What are the results of the performed experiments?*

This sub question provides a comparison of the current situation and the results from the experiments that are given by the formulated model according to different scenarios. Moreover, we perform a sensitivity analysis. In Chapter 6, we answer sub question 5.

1.3.6 Implementation plan

Sub question 6: *How can the MST implement the methodologies provided by this research?*

Sub question 6 provides the actions to be taken for implementing the methodologies provided by this research. This sub question is answered in Chapter 7.

1.3.7 Conclusion

Sub question 7: *What is the conclusion of this study, and what are the recommendations for the CSD at MST?*

In Chapter 8, we provide an overall conclusion of the study together with potential improvements and recommendations. We also discuss the limitations and possible future research.

1.4 Research Scope

In order to tackle the objective from an insightful view on the operation management, Hans et al. (2012) proposed a framework to provide a holistic view on the operation management. This framework consists of a matrix with on the horizontal axis managerial areas and on the vertical axis hierarchical levels. Vertically, four hierarchical levels are defined: the strategic level, the tactical level and the offline and online operational level. Furthermore, three functional planning areas can be distinguished: technological planning, capacity planning and material coordination. On the top of the hierarchy the strategic planning addresses structural decision making, which has a long planning horizon. The offline operational level consists of controlling the execution. So, scheduling is done given the assigned workload and the available resources (people, machines and tools) that the resource loading module at the tactical level determines. Therefore, this research project is nested in the tactical level, which is between the strategic and the offline operational level. The tactical level implies changes in a medium-range planning horizon, which is concerned with allocating sufficient resources to deal with the incoming demand. Hence, the scope of this research is tools, which involves the determination of the number of instrument sets needed to fulfil the demand. Therefore, the scheduling of instrument sets is beyond this research.

1.5 Conclusion

In this chapter we introduced the main research question of this case study, which is:

“How can we establish a target inventory level that minimizes the expected total cost over the lifetime of the reusable instrument sets while maintaining a desired service level?”

With this question we aim to find a model that guides the procurement and inventory decisions of reusable instrument sets.

The next chapter provides the context of this research, where the explanation of the flow of the reusable instrument sets is explained. Moreover, a description of all the resources involved is introduced as well.

2 Context and problem analysis

Chapter 1 provided us with the introduction of the problem. This problem is summarised as the absence of a model that guide to the users at the moment of determining cost-efficient optimal base-stock level of reusable instrument sets.

In order to solve this problem, we first need to get an insight of how the system currently works and performs and the resources that conform it. Therefore, in Chapter 2.1 we provide the motivation of why this study is based on reusable instrument sets rather than disposables. Then, in Section 2.2, we define the resources that are involved in this case and the flow of reusable instruments sets through the system in Section 2.3. Next, we define the Key Performance Indicators important for this study in Section 2.4, to then be able to measure the performance of the current situation in Section 2.5. In Section 2.6 we describe the planning and control of reusable instrument sets, while in Section 2.7 we provide an overview of the current practices related with the study problem. In Section 2.8 we discuss the boundaries of our problem and the root causes. To finalize, in Section 2.9 we provide a conclusion and demarcation of the scope of this research.

2.1 Reusable instruments vs disposable instruments

When discussing medical instruments, it is essential to realize that there are two types of instruments: they can either be disposable or they can be reusable. In the following section, we will discuss the advantages and disadvantages of either.

Several studies have demonstrated that the purchasing of reusable instruments can achieve considerable savings without compromising staff and patient safety (Demoulin et al., 1993). Moreover, reusable instrument sets have shown to be more environment friendly than disposable ones which generate a large amount of plastic packaging and hazardous material waste (Diamant et al., 2017). Adler et al. (2004) performed a study in Freiburg University Hospital in Germany, in which the economic and environmental performance of both disposable and reusable laparoscopy instruments were examined. The authors concluded that disposable instruments were 19 times more expensive than reusable instruments. They attributed these high costs to the purchasing price of the instruments, compared to the costs of disposing disposable instruments. Like Diamant et al. (2017), the authors stated that reusable instruments have advantages regarding environmental factors over disposable instruments. The authors concluded that purchasing disposables is only suitable if these have a clear cost advantage over reusable instruments. Another study - performed in three private hospitals and a university hospital in Canada (Apelgren et al., 1993) - showed that reusable laparoscopy instrument sets are 10 times more cost-efficient than disposable laparoscopy instrument sets. The costs examined in both studies (Apelgren et al., 1993; Adler et al., 2004) involved the costs of cleaning, sterilization, wrapping, maintenance, repair and waste disposal.

Recently, MST was facing the decision whether to focus on purchasing reusable or disposable instruments. To support the discussion from an economic perspective, let us propose a simple break-even model, which may be useful in comparing the costs of reusable versus disposable instruments. Equation 1 shows our model. We focus on a single instrument. We ask ourselves: what is the cost of that single instrument per operation where it is used? On the right, we indicate the cost for the disposable version. This is simply *dip*, the purchasing price of the disposable instrument. This price is incurred each time that this type of instrument is required during surgery.

Now for the left. What is the cost of the reusable version?

This cost consists of: depreciation, sterilization and reparation. The *depreciation cost* is given by the instrument price minus the selling value that the instrument could have after the end of its life cycle, divided by the maximum number of times that the instrument can be used before it become obsolete. To the depreciation cost we add the *sterilization cost* (*isc)*, as well as the *reparation cost (irc)*. The latter is given by the probability that the instrument has to be repaired after an operation multiplied by the cost of reparation.

Break-even model:

$$\left[\underbrace{\left(\frac{ip - isv}{MU}\right)}_{\text{Depreciation}} + \underbrace{isc}_{\text{Sterilization}} + \underbrace{\alpha * irc}_{\text{Reparation}}\right] \leftrightarrow \underbrace{dip}_{\text{Disposable cost}} \qquad (1)$$

SYMBOL	DESCRIPTION
$\boldsymbol{ip}$	Instrument price
$\boldsymbol{isv}$	Instrument salvage value
$\boldsymbol{MU}$	Maximum times of usage
$\boldsymbol{isc}$	Instrument sterilization cost
$\boldsymbol{irc}$	Instrument reparation cost
$\boldsymbol{\alpha}$	Reparation rate
$\boldsymbol{dip}$	Disposable instrument price

A straightforward way to evaluate the decision of purchasing disposable over reusable instruments, is by considering the sterilization cost of a reusable version vs. the purchasing cost of a disposable version. It is easy to discard the purchasing of a reusable instrument if the $disposable\ instrument\ price$ is smaller than the $instrument\ sterilization\ cost$. In other words, if $dip < isc$, then it would make most sense to opt for disposable instruments. Conversely, dip should not be too far above isc.

Figure 3 shows the additional costs that a hospital should take into consideration when considering to replace reusable instruments with disposable ones.

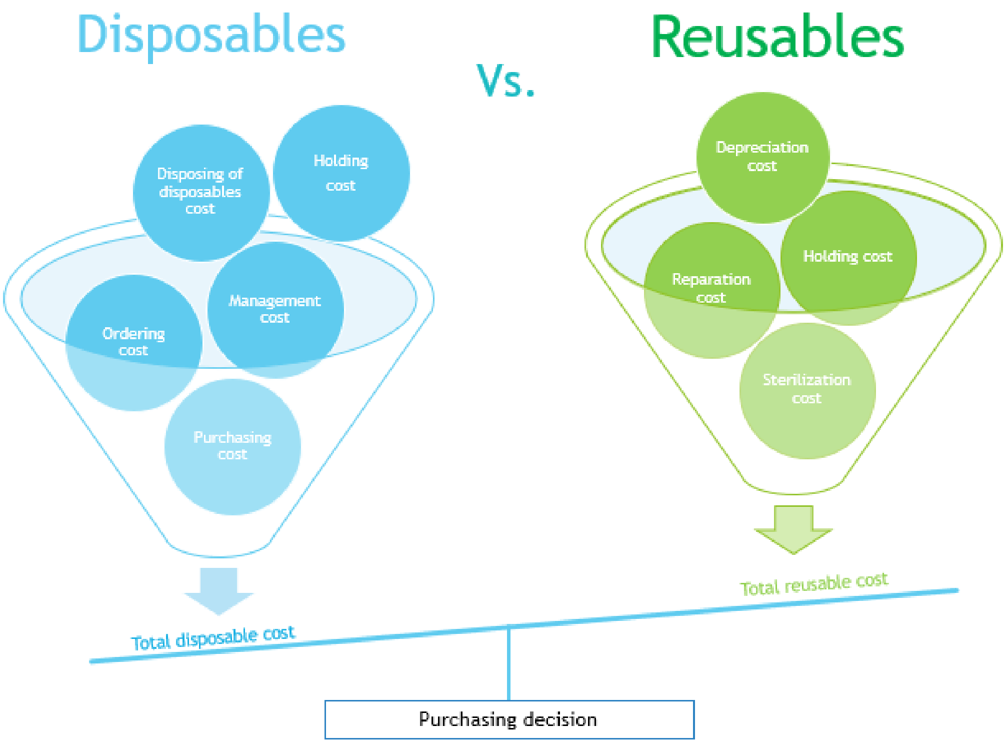


Figure 3 Disposables vs. Reusables costs to take into consideration before purchasing

The costs portrayed in Figure 3 should be analysed carefully, since the MST already has invested in reusable instrument sets which are still in good condition for several more years. As the purchasing cost is the highest cost for both types of instruments, the MST should evaluate a long-term scenario focusing on the cost-efficiency between purchasing disposable instruments that show a lower price than the corresponding sterilization costs.

2.2 Resources

In this section, we define the resources that are relevant for this study. In Section 2.2.1 we provide a description of the main objects of study for this investigation which are reusable instrument sets. In Section 2.2.2 we explain the database systems used related with this case study. In Section 2.2.3 we give an insight of the type of patients scheduling. Finally, in Section 2.2.4 we discuss the type of patients involved.

2.2.1 Instrument sets

An instrument set is defined as a group of instruments and used in conjunction with one another, which are placed together in a sterilized package to perform a particular surgical procedure (Diamant, Milner, Quereshy & Xu, 2017). Given that the MST does not have a system that allows to determine the real cost of sterilization per instrument, it has provided four different categories to each type of instrument set to estimate their sterilization cost. This categorization is determined by the number of instruments or their complexity. If the number or complexity of instruments increases, so does the size of the containers where the instruments stand, as well as the space required in the washing and sterilization machines, handling, and inventory costs. The MST manages two costs of sterilization: one that includes just the cost of sterilization processes called CSD price and one which includes the management costs called MST price. The first category is composed of one or two instruments, which are placed in a laminated package to go through the sterilization process and keeps the instrument sterile until its use. The second category consist of 7 to 15 instruments, while the third is composed from 16 to 50 instruments. The fourth category is composed of instruments that are complex in shape or contain more than 50 instruments. These last three categories required special metallic containers that keep the instruments organized and safe during the sterilization procedure and their handling. Table 3 the different instrument set types and their sterilization prices.

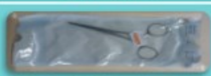
Category & # of instruments	Top container	Single /Bottom container	CSD price	MST price
1 (1-6)	-		€ 5.23	€ 9.98
2 (7-15)	-		€ 10.46	€ 19.96
3 (16-50)			€ 20.93	€ 39.95
4 (50> or complex instruments)			€ 41.86	€ 79.89

Table 3. The first category shows laminated package containing one scissor, the second the Otolaryngology basic set (Basic KAAK), the second category the general basic set and the third one the laparoscopy set. This Table is based on information provided by Central Sterilization Coordinator and Business controller, 2018.

Since each sterilization time represents the usage of instrument set into the ORs, the next chart shows that category 2 and 3 are the most demanded, while category 1 and 4 represent just the 9% and 15% of the demand respectively (See Figure 4).

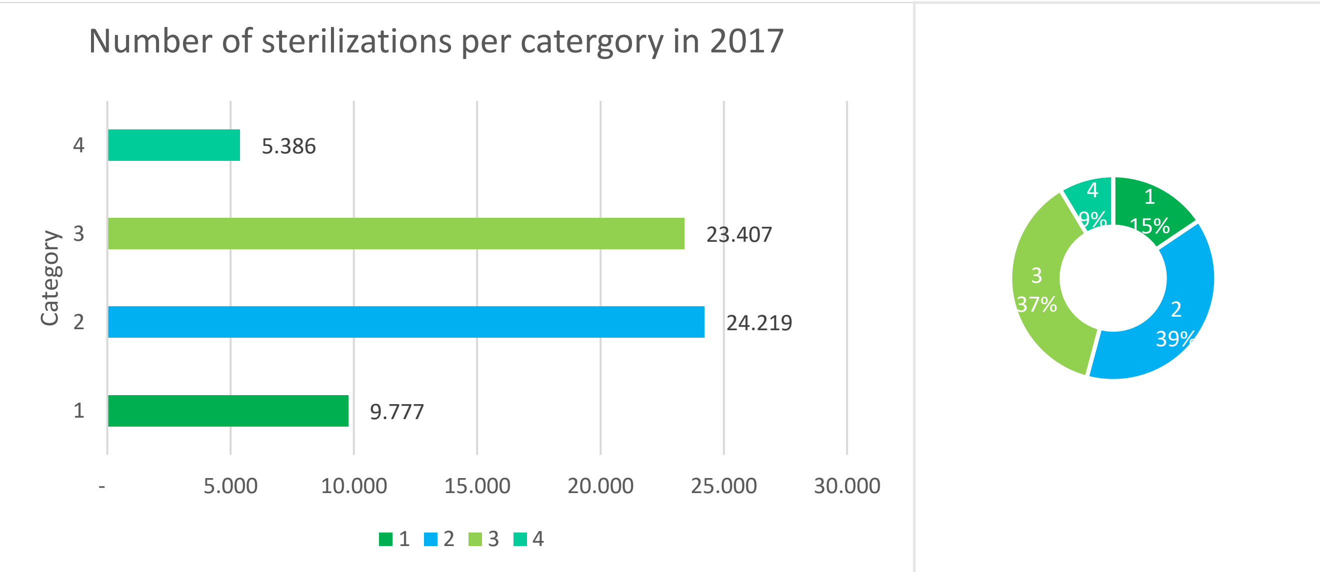


Figure 4 Sterilization times in 2017. This Figure is based on data extracted from Steriline (2018)

2.2.2 Database systems

The hospital manages two important systems for this research: ORsuite and Steriline. OR suite contains information related with the planning of the ORs, the patient, the description of the surgery, the surgeon, and the assistance involved, while Steriline contains information related with the instrument sets, the stage of the sterilization process, the monitoring and sterilization duration time, and the time at it was used in the ORs.

2.2.3 The sterile OR storage

The OR storage is located next to the General ORs and in it are stored most of the hospital's instrument sets. This storage has 83 closets with 13 shelves, which provides 1079 places for instrument sets. From these positions just 767 are occupied (see Table 4). Nevertheless, the hospital is planning to reduce the number of shelves used for instrument sets from 13 to 8, because the high locations of instrument sets within the closets violate ergonomic specifications (CSA planner, 2018). This situation reduces 38.4% of the number of available locations for reusable instrument sets.

Sterile OR storage			
Description	**Units**	**# closets**	**# shelfs**
Sets	767	83	13
Positions	675		
Laminated packages	47	1	
Optical sets	24	0.5	
Total	1513		

Table 1 Sterile OR storage locations. Data provided by the CSA planner in 2018.

This reduction is a problem for instrument sets that occupy a large number of locations in the sterile OR storage, such is the case of laparoscopy instrument sets. In the storage there are 2 closets with 13 places which are used for the 20 laparoscopy instrument sets. Each laparoscopy instrument set has a volume of 12.96cm^3 (53.5cmx25.5cmx9.5cm), so it requires a complete shelf for each one. Therefore, a solution should be found to reduce the space used for this type of instrument sets.

2.2.4 Type of patients scheduled

The MST performs on average 21,000 surgeries per year. Each of the patients is scheduled according to the level of urgency. The most urgent patients are admitted to an OR within 30 minutes, the rest between 5 and 24 hours. The majority of the patients admitted in an OR are elective patients, who are scheduled in advance at a time which suits the surgeon, hospital, and patient. Therefore, it does not involve medical emergency (Mosby, 1994). Between 2016 and 2017, 84% of MST's patients were elective patients, while the rest were urgent patients (see Figure 5).

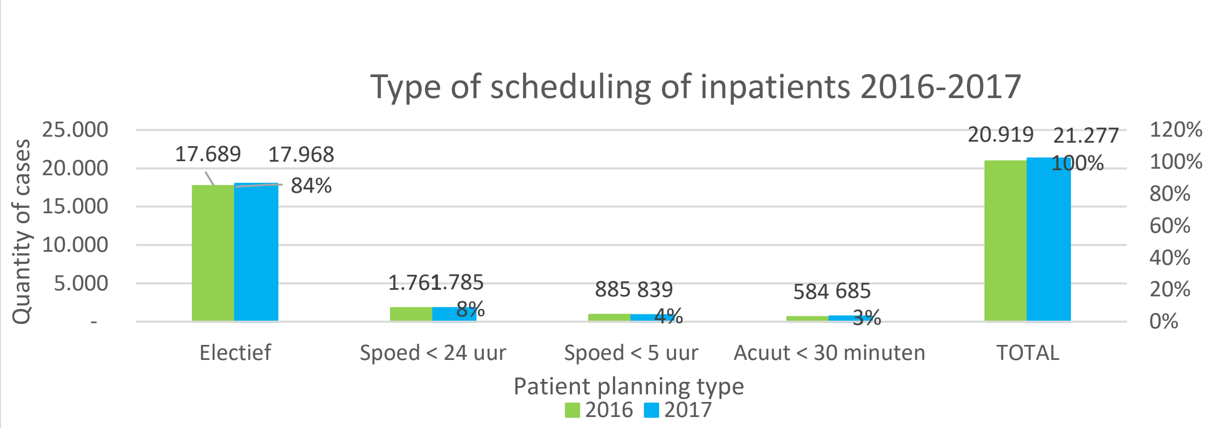


Figure 5 Quantity and percentage of type scheduling of inpatients from (2016-2017): Elective and urgent planning: 2.5 hours or 30 minutes. Data gathered from Steriline (2018).

2.3 Flow of reusable instrument sets

In this section we describe the flow of instrument trays through their complete cycle. The flow, which is portrayed in Figure 6, is described from the planning of the instrument set until it returns sterile to the OR storage after being used in an OR. Below, this process will be explained more into detail.

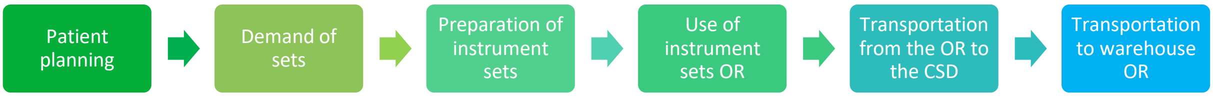


Figure 6 Flow of reusable instrument sets at MST

Patient planning

The process through which reusable instruments go at MST starts when the patient enters the hospital at the outpatient clinic. Here, the specialist decides the type of treatment that is required and whether or not a surgery is necessary. If a surgery is essential the patient is placed on a waiting list. All the necessary patient information is recorded in Xcare. Subsequently, the planners assess the urgency of the doctor's conclusions – whether the patient is highly urgent, medium urgent or low urgent. The doctors also take additional information about the period where the operating might take place. Urgent patients are scheduled with first priority in the ORsuite schedule.

The patient is called to schedule a possible OR date and Pre-Operational Screening (POS); a series of questionnaires, steps and preparations that the patient has to follow to decrease the risk of complications and make the surgery as safe and effective as possible. This appointment is scheduled no earlier than 6 weeks prior to the OR date. During the POS the patient goes through different tests and analyses, the results of which are recorded in Xcare and OR suite to fulfil the OR program. The surgery is scheduled automatically with average time of the surgery. This schedule can be adjusted by the surgeon. The program of the OR planning is checked during a meeting with the specialist. This meeting takes place on Wednesdays at 16:30. The OR team discusses the planning of staff, material, such as reusable and disposable instruments, as well as medical equipment. Then, if necessary, the planning is adjusted and updated in ORsuite. Once the adjustments and updates have been made, the patient gets a letter of confirmation with a final date and time of the surgery. After the patient has accepted the date, the surgery can take place.

Demand of sets

The planning for the surgeries generates a demand for instruments sets. The required sets are not booked for determined surgery during the week, so if there are multiple surgeries that require the same instrument sets during the same week, this goes unnoticed. The approved patient plan for the next day is provided to the OR assistants via OR suite.

Preparation of instrument sets

The OR assistants start preparing the required sets one day before the surgery by checking OR suite. They know which instruments sets are needed for each kind of surgery, as each surgery has a protocol that describes the type of sets that are required. There are sets types that are used for different surgical types. This standardization of sets reduces the variety of the sets in the OR storage, thereby facilitating the staff to recognise the necessary for each surgery type. However, frequently the surgeons add or change sets according to their preference. This means that the protocols are not always followed, mitigating the benefits of standardization over the reduction of intraprocedural variability, because the staff constantly need to check the specialist's preference.

The OR assistants, together with the logistics employee, collect the sets from the OR storage and place it in a trolley which indicates the scheduled surgery. Unavailable sets are put on a list to request to the CSD. At 16:00 of each day the OR assistant calls the CSD to inform which sets are missing (see Figure 7 & 8). The first two surgeries scheduled during the next day are placed as 'high priority' for being sterilized.

Figure 7 Missing list located on a trolley in the sterile OR storage.

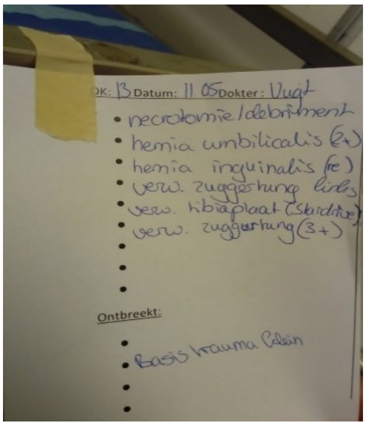


Figure 8 Missing instrument set list.

When the set has been sterilized or replaced, it is collected by a logistics employee between 20:00 and 22:30. Then, a CPR employee can complete the instrument set for the surgery for the next day. However, if a required set type is unavailable, and it cannot be replaced or sterilized on time, the surgery is rescheduled or cancelled by the OR planner. This leads to stockout costs, such as overtime hours for staff and administrative costs (Diamant, Milner, Quereshy & Xu, 2017).

Use of instrument sets

On the day of the surgery, the OR and CPR (Central preparation room) assistants bring the sets to the sterile area behind the corresponding OR. There, a last check of the package and its expiration date is performed. If everything is in line with the specifications, the sets are opened and arranged for their usage in the OR. In case the surgery has already started, and the surgeon diagnoses an unanticipated problem which requires different instruments, the instruments assistant enters the OR storage to get the required sets. After checking the sets, the surgery continues.

Once the surgery has been concluded, the instrument assistants locate all the instruments into their set, while counting and checking if the sets are complete. If there is at least one instrument that needs repairs, each instrument set is scanned reporting which instrument needs work. This information is sent to the CSD through Steriline for determining whether it can be repaired or needs to be replaced. However, there are cases in which the demand of sets is higher than the available inventory. For instance: there are five surgeries that require one type of instrument set while there are just 4 sets available. In this case, after finishing the first surgery, the set is sent immediately to be sterilized as a 'high priority' set. If an instrument or instrument set needs to be sterilized with urgency, a report is made in Steriline with a red exclamation mark. In addition, the emergency network is personally handed over to the CSD employee in the disinfection room. Moreover, CSD employees communicate among themselves about these urgent assignments. In the entire routing of a medical device within the CSD, these sets are treated first so that the circulation time is as short as possible.

Transportation from the OR to the CSD

When a set has been used it is placed in a trolley. The OR assistant brings the trolley to the 'dirty room' (located in front of the ORs) and the used sets are scanned to inform the logistics employees located at the Transferium that the sets are ready for pick-up. This information is displayed on a screen (Figure 9 & 10). On average, it takes between 20-30 minutes to transport used sets to the CSD.

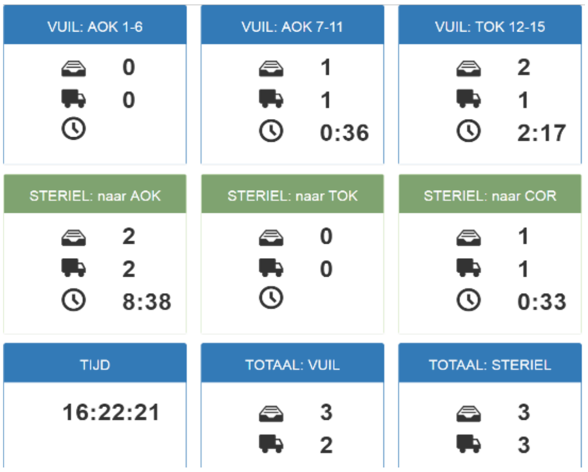


Figure 9 Instrument sets that need to be recollected from the dirty room.

Figure 10 OR assistant scanning instrument sets that need to be recollected

Central sterilization department

In addition to making the set sterile, they also need to be kept sterile. This is done by the Central Sterilization department (CSD). Therefore, they are charged with cleaning, packaging and storing the sets according to the legal requirements. The CSD will be discussed in the remainder of this chapter.

Spatially, the following areas can be distinguished:

- The dirty area (reception, pre-treatment, cleaning & disinfection);
- The clean area (check, assemble, pack and sterilize);
- The sterile area (storage and distribution).

Due to cleanliness requirements, direct traffic between the different rooms is not allowed and must be done through pass-through washing machines, relay sterilizers and hatches with lock function. Once the sets are picked from the dirty room, they are transported to the CSD for sterilization. The sterilization process involves several procedures, which are performed in different areas: dirty area, clean area and sterile area (see Figure 11).

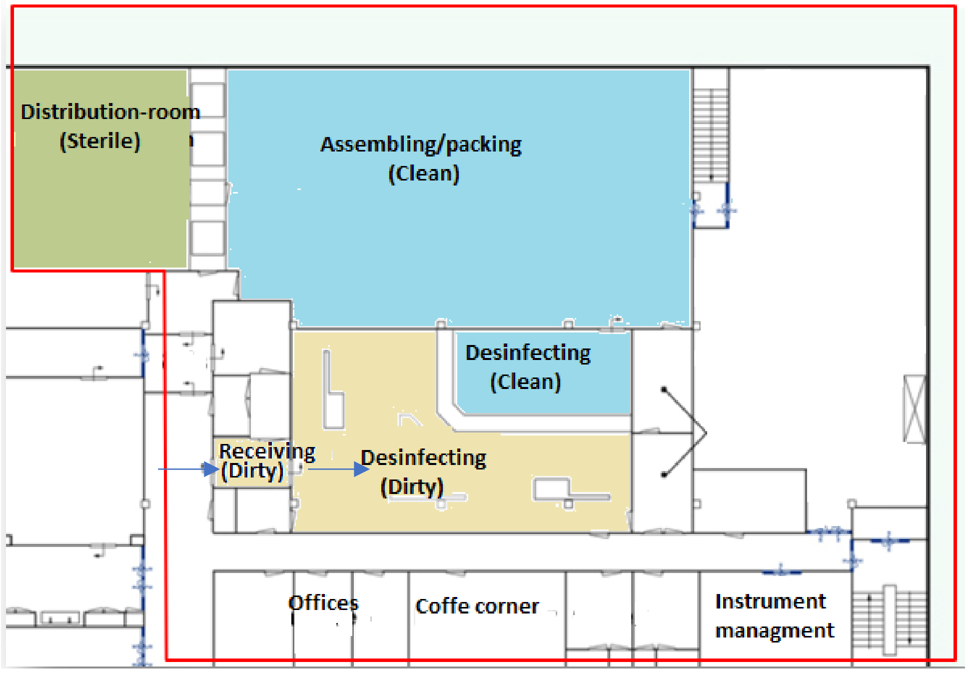


Figure 11 CSD layout. Based on the CSD layout (2018).

Receiving

First, the contaminated instruments are received after being used in the ORs or outpatient clinicss. The logistics employee unloads the trolley and scans the sets or loose instruments before entering the disinfecting area. Once inside, the medical devices are cleaned and disinfected. There are three separate streams:

- Ultrasonic cleaning: human tissue and blood is removed by means of vibration, as water alone is insufficient.
- Washing machine: after ultrasonic cleaning, the instrument sets are placed in a washing machine. The washing machine can only be opened from one side to avoid contamination.
- Manual cleaning and disinfection: some instruments such as drills, require to be cleaned manually with alcohol or other disinfectants.

All instrument sets are scanned before and after each process, to record the status of the set in Steriline through the process flow. Thus, the staff is able to know where the instruments are located and whether or not they are going to be ready for any request.

Control

After the instruments have gone through the disinfection process, they need to be cleaned, functionally checked and maintained. In this stage of the sterilization process, a timely replacement of defect instruments and assembly is performed, in order to prevent problems during future operations. And, as mentioned earlier, if during the preparation for a surgery or during the surgery itself an instrument does not work properly, this is registered in Steriline. Hence, when the instrument set is scanned within the control stage, a note appears informing which instrument is defect. Moreover, a functionality check is performed to ensure that instruments that are no longer suitable for their application are removed and replaced. Dismountable instruments are assembled before the functionality check.

If during their functionality check or by a user's note in Steriline malfunctions are discovered, instruments that are no longer function are removed and, if possible, offered for repair. Incomplete sets are completed by the instrument stock located in the instrument management department. In case a necessary instrument is not in stock, an order is created. If an instrument is not working properly, the instrument manager sends it to the medical technician's department or to the supplier to be repaired. In case that the instrument cannot be repaired, the instrument manager sends an order to the Transferium which, in turn, sends it via ORACLE to the purchasing department.

Assembly

After the cleaning and functionality control stage have been performed the instruments are placed together. To prevent instrument from being missing during an intervention or that instruments are presented in the wrong order on the instrument set. The staff is supported by images indicating and showing which and how many instruments should be present in the set (see Figure 12).

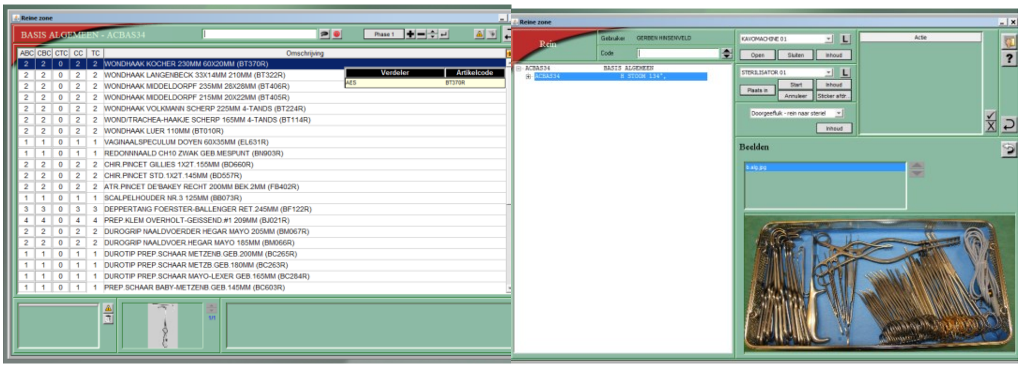


Figure 12 Steriline instrument content.

Packing

Subsequently, the sets are packed in an inner and outer layer of paper clearly distinguished from each other. The outer layer protects the set from damages during the transport, while the inner layer protects the medical devices of micro-organisms until their use within the OR.

Single instruments are packaged in laminate. These materials allow the steaming process to get in and out during the sterilization. The packed instrument sets get a sticker that changes of colour. If the sterilization goes well, the indicator changes from blue to brown.

Sterilization

After cleaning, disinfecting, controlling and assembling, the medical dives are sterilized in a process which takes on average 80 minutes. Each set is scanned into batches and placed inside of a steam or plasma sterilizer. Sterilization with steam is a process of phases, and each phase needs to be monitored; a graph showing the pressure, temperature and time is used by the CSD specialist. After sterilization, the sets are hot, and take around 20 minutes to cool down.

Parametric, visual and manual control

Every instrument set must go through a parametric report, which entails a visual and manual check performed by a certified CSD employee:

- Check process parameters: sterilization indicators (e.g. temperature, pressure, time) are measured to ensure that the parameters are between their control limits.
- Visual check: this procedure takes 5 minutes on average and consists of a visual check without touching the sticker, moisture and packaging control.
- Manual control: after full cooling of the load (approximately 20 minutes), the staff is able to check the moisture and inspect if there is any damage on the packaging material.

A sterilized batch is only released if all the following conditions are met:

- The process parameters are within the control limits.
- The process report indicates "PROCESS GOOD" (steam sterilization) or "SUCCESSFUL" (H_2O_2 gas plasma).
- The visual and manual checks show no deviations.

Once the instrument sets have been successfully passed through their control checks, the instrument sets are scanned and subsequently allocated in batches inside a trolley with labels that indicate that it is carrying sterilized medical devices.

Transportation to warehouse OR

The logistics staff brings the trolley to the Transferium or it is taken directly to the OR in case that they are immediately needed. Otherwise, they are picked up from the Transferium by a logistics employee and placed in their corresponding shelf in the sterile storage room.

Flow time of instrument sets

Instruments follow a closed logistic chain which takes approximately 5 hours to be completed. Table 5 shows the time that it takes for the instrument set to go through the entire process. Since the operation depends of the type of surgery, it is not accounted in the total time (See Table5).

Department	Stage	Time(min)
OR	Operation time	-
Transportation	OR-CSD	20-30 urgent (15)
CSD	Cleaning	10
	Disinfecting	100
	Control	5
	Assembly	10
	Packing	5
	Sterilization	80
	Visual & manual control	30
Transportation	CSD-OR storage or OR	10
TOTAL	Urgent sets (hr)	4.42
TOTAL	Normal set (hr)	4.59

Table 2 . Flow time of instrument sets at MST. Information extracted from the CSD manual and by the CSD staff (2018).

2.4 Key performance indicators

In order to manage a project, it is necessary to measure its performance. This performance should be determined by the hospital. Nevertheless, the MST is mainly focused on the care of the patient, without taking into account essential information which could help them use their resources more efficiently while providing high-quality care. Therefore, in this section the key performance indicators (KPIs), important for this case study are described. These KPIs are divided by section according to the stakeholders' interests. In Section 2.4.1 the KPIs more related to management and staff are presented, while in Section 2.4.2 the same is done for the patient perspective.

2.4.1 Management and staff

The board of the MST wants to provide care service to all its patients and as any organization it needs to survive within the healthcare market. To achieve this, it is essential to use their resources wisely. Therefore, the next performance indicators of the inventory of instrument sets need to be measured evaluate the needs of the personnel and management.

Service level

From the point of view of an inventory manager, it is crucial to track the percentage of any patients arriving to the OR that do not experience any delay for their surgery caused for not available instrument sets. A way to do this is by identifying a targeted service level. Heizer and Render (2001) define service level as the complement of the probability of stockout.

Stockout costs

From the financial perspective, to evaluate the financial consequences or benefits at the moment of setting a desired target service level, the stockout costs also need to be measured.

Capital tied up in stock

Sterile instrument sets represent a high capital investment in any hospital. If the capital invested in such a resource can be reduced by lowering the number of instrument sets and while maintaining a high service level MST will free up capital that could be invested in other business needs.

Holding cost

This KPI is relevant to measure since it is frequently ignored in the health care system, even though it is a relevant indicator that shows the costs involved in keeping different levels of inventory. Holding costs are the costs associated with keeping or carrying inventory over the time. Therefore, holding cost also include obsolescence and costs related to storage, such as insurance, extra staffing, and interest payments.

2.4.2 Patient perspective

Since the patient main interest is to be cured, any improvement in this key performance would be beneficial for ensure the effectiveness of their treatment. Nevertheless, the inventory service level is a good indicator of the patient's satisfaction, since any out-of-stock event, could increase the stress of the patient due to the delay of the surgery affecting the reputation of the hospital or in the worst case the patient could cancel the surgery, which will be considered like a lost sale.

2.5 Zero measurement

In this section the current performance of the system is measured. Table 6 shows the performance of the system according to the KPIs defined in the last section.

KPI	Description	Objective	2017
Service level	Probability of no stockout	Maximize > 95%	100%
Holding cost	Percentage of unit cost	Minimize	Unknown
Stockout cost	Cost of rescheduling a surgery	Minimize	Unknown
Capital tied up in stock	Capital invested in instrument sets	Minimize	Unknown

Table 6 Zero measure of the KPIs.

Several performance indicators cannot be measured, either due to a lack of data or because they are not documented., which is the case of holding and stockout costs. Currently, the service level is not being measured, although it is an important KPI to help the MST to determine if the demand has been accomplished with the current number of instrument sets available. Therefore, we track information related to the service level and we find that in 2017, only one surgery delayed for 10 minutes because of the absence of an instrument set in the OR storage. Nevertheless, this surgery was not rescheduled, leading to no stockout. As such, the service level for 2017 was 100%.

The stockout of instrument sets inventory is not being measured. However, a weekly report is delivered where the reason of waste of time are shared with the head of the departments. In 2017, there was only one event where the instrument set was not sterilized before the surgery.

2.6 Planning and control in the current situation

In this section we provide an overview from the top down inventory planning of reusable instrument sets, and we target the single echelon inventory system as the objective of this research. To achieve this in Section 2.6.2, we define and adapt the departments involved in a typical hierarchical supply chain into the supply chain system of reusable instrument sets. Having this adaptation, in Section 2.6.2, we convert this hierarchical system into cyclical supply chain, which is the case of reusable instrument sets. With this analogy, we give an overview of the current practices related with instrument sets inventory management.

2.6.1 Hierarchy of inventory planning and control

The health care supply chain for reusable instrument sets can be divided in an external and an internal chain. A general framework (see Figure 13) shows the supply of instruments from the highest to the lowest level. The external supply chain is related to the external suppliers of instrument sets manufactures and their distribution to customers such as the MST. Given that the focus of this study is to find the base-stock level of instrument sets in the OR storage, the external supply chain is outside of the scope. Therefore, we focus this section only the internal supply chain. Figure 13 shows the two-echelon supply chain. With echelon we refer to the physical location where the instrument sets are stored (Vila-Parrish & Ivy, 2013). The MST stores single instruments in the IMD storage, while the instrument sets are stored next to the ORs in the OR storage. Therefore, our scope narrows, and we study the inventory system from a single stockout point (OR storage), indicated by an oval in Figure 13.

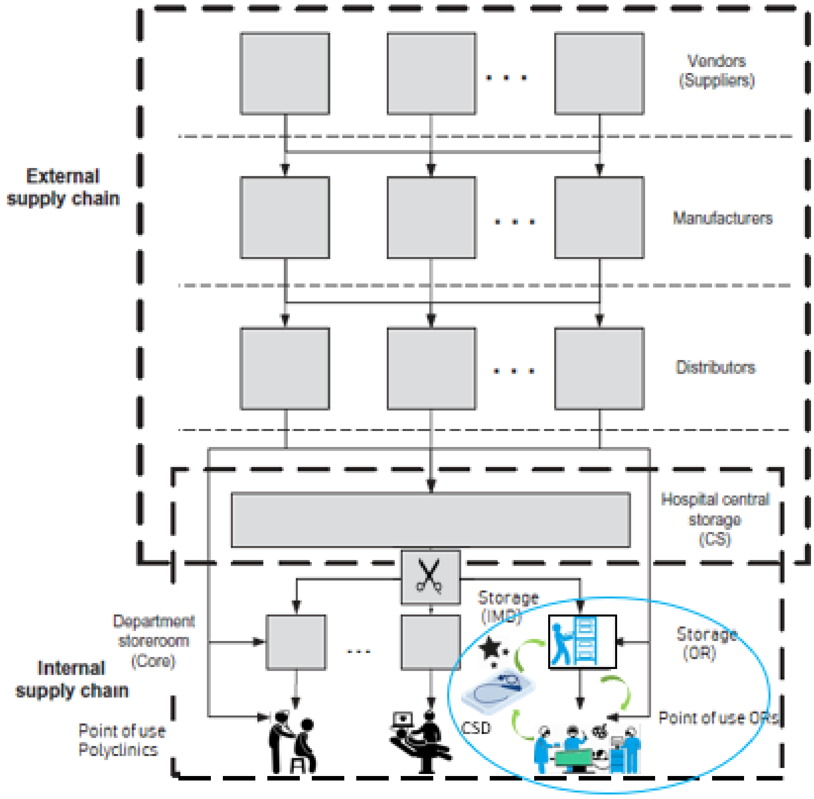


Figure 13 Hospital supply chain. Adapted from Ahmadi, Metcalf & Schuller (2018).

The representation of serial chain of stock points is mainly represented hierarchically for disposable goods, but for reusable instruments that have to get through the sterilization process between use, it is different. The next section provides an adaptation of the traditional supply chain to cyclical reusable assets such as instrument sets.

2.6.2 Cyclical supply chain

In this case study, we describe the inventory planning from the lowest level of the internal supply chain. Disposable instruments have a hierarchical supply chain, while reusable have a cyclical supply chain. Therefore, we represent analogically its internal supply chain from instrument sets from a downstream perception. The traditional actors in any supply chain are represented by suppliers, customers and warehouses. In this case, the supplier is the CSD, the OR storage represents the local warehouse and the OR department its customer. Therefore, the cyclical supply chain starts with the OR department which orders sterilized instrument sets. In its turn, CSD makes sure the sets are sterilized, after which it sends them to the OR storage. Last, the instrument sets are sent to the OR department by the storage. The cyclical aspect of this process is that instead of using the instrument sets just once, the OR department sends return them after usage back to the CSD department. This process is portrayed in Figure 14.

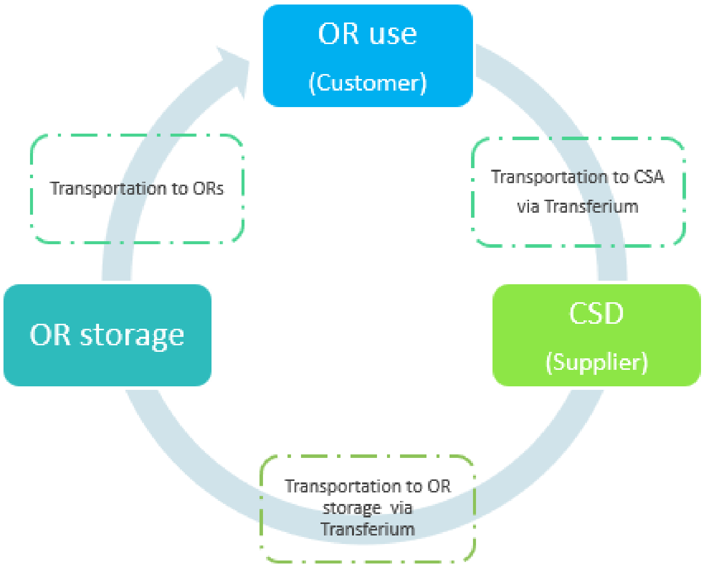


Figure 14 Cyclic flow of instrument sets and departments interaction.

2.7 Current practices

In this section we describe the current practices related with inventory management, such as inventory policies and methods to manage the instrument sets located in the OR storage. Section 2.7.1 details the inventory policies currently applied by the MST. In Section 2.7.2 we illustrate the replenishment methods. To continue, in Section 2.7.3 we describe the stock policies currently applied, while in Section 2.7.4 we identify the issues related to the absence of information related with the capital invested in reusable instrument sets. In Section 2.7.5, we describe the planning of the instrument sets. Finally, in Section 2.7.6, we show the data issues of the current situation.

2.7.1 Inventory policies

This section gives an overview of the current inventory practices. Currently, MST does not have an inventory policy. Nevertheless, the actual practices are related with the (R,S) inventory system, where every morning between 7:00 am to 10:00 am the employees check the scheduled surgeries for the next day. In case the number of instrument sets needed for the next day is not present on inventory, an order is raised to the CSD at 16:00 to inform which and how many instrument sets are needed for the next day. These instrument sets are prioritized in the sterilization line. On average, it takes 5 hours for an instrument set to be sterilized and returned to the OR storage. However, this time depends on the queue of instruments already being sterilized. Figure 15 shows a description of the current flow between departments involved.

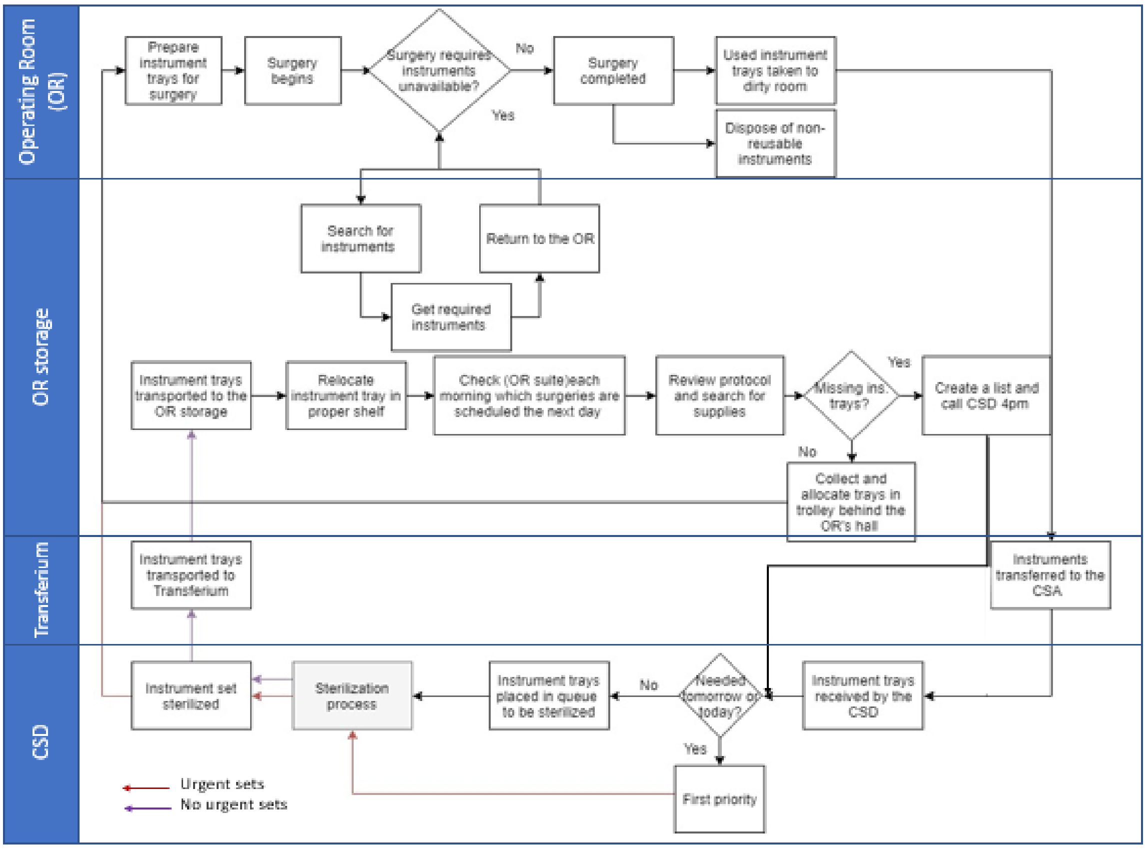


Figure 15 Instrument sets flow by departments involved. Adapted from Diamant et al. (2017) and information provided by the planner and coordinator of CSD (2018)

2.7.2 Replenishment methods

Some identical instrument sets are used hundreds of times more than others, which leads to some instrument sets being sterilized without being used while others are used excessively. This situation causes that sterilization expenditure and the depreciation of some instrument sets increases.

The instruments sets are stored and used merely by considering the expiration date of sterilization. However, the storage does not allow to the employees to apply any inventory method which could help to equilibrate the rate of usage between identical instrument sets. The employees tend to choose the sets which are easiest to get. Therefore, they mainly make use of the sets located in the middle shelfs (see Figure 16).

Figure 16 OR storage closet.

To exemplify this, the Figure 17 shows the case of laparoscopy instrument sets. As we can observe there are identical instruments sets that are used 110 times per year while others are used only 9 or even 0 times per year.

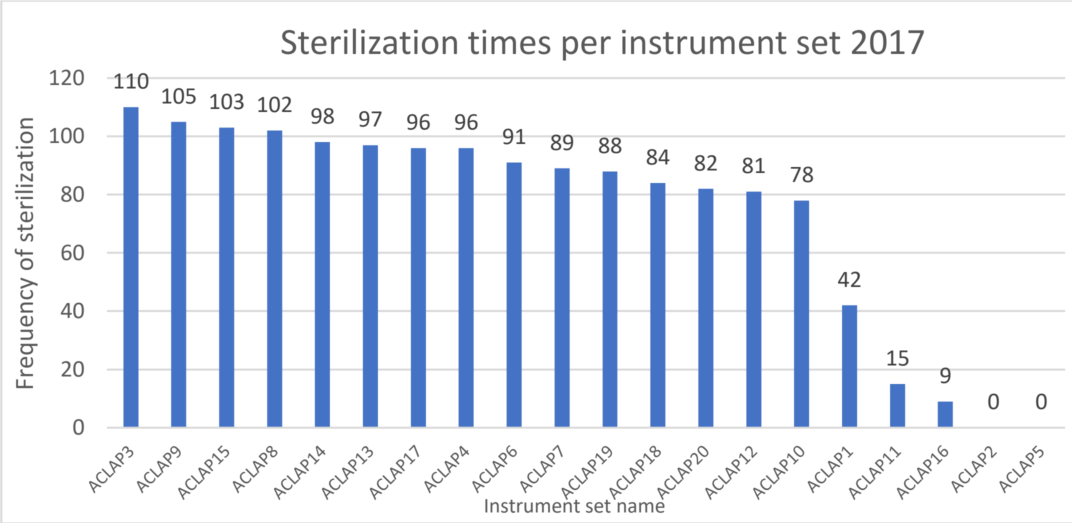


Figure 17 Sterilization times per each identical laparoscopy instrument set in 2017. Data gathered from Steriline (2018).

2.7.3 Stock policy

MST determines the number of instrument sets to keep on inventory according to the surgeon requests, which is mainly based on experience rather than analysing the demand. So, a large number of instrument sets are purchased and kept on inventory while the demand is lower than the inventory capacity. To exemplify this situation, in this study we make use of the laparoscopy instrument set, of which MST has 20 instrument sets in inventory. Figure 18 shows that from January 2017 to July 2018, the highest number of laparoscopy instrument sets which was used was 13 sets. This happened only twice during the entire period. As such, it seems that the 20 sets that MST has in stock is too high for the hospital's demand. This leads to extra expenses such as holding and purchasing costs caused by an inefficient use of resources. Laparoscopy instrument sets have a value of around €13,000, which represent a capital investment of around €260,000 considering the 20 instrument sets kept in inventory.

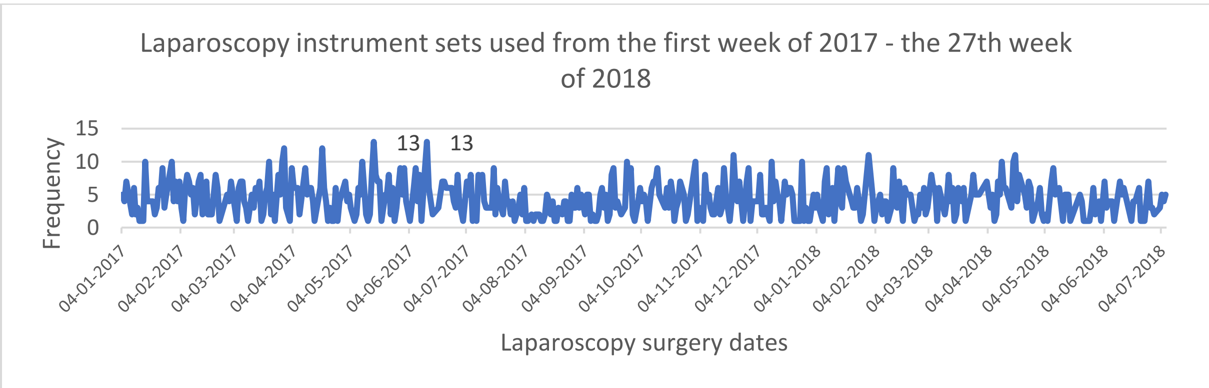


Figure 18 Frequency of laparoscopy instrument sets requests first week of 2017- 27th week of 2018. Data gattered from Steriline and ORsuite (2018).

2.7.4 Capital invested

The prices of each type of instrument sets is not documented. In order to obtain the total costs, it is necessary to track the prices of each single instrument contained in the instrument set. Nevertheless, not all the instruments have a code, so their price have to be approximated. This situation generates a lack of awareness regarding the investment costs between the direct users, who decide the number of sets to be purchased. This leads to surgeons ordering new instrument sets without being aware of the costs involved.

2.7.5 Instrument set planning

No accurate documentation of lead-time is recorded. According to the hospital's staff, it takes 5 hours for each instrument tray to be returned to the storage location. Nevertheless, it is not possible to accurately define this time per instrument set making it difficult to determine the inventory level at the beginning of each day. However, the capacity planning of the system is high. According to the data between 2016-2017, elective patients are the most frequent type with 77% and 76% from 2016 and 2017, respectively, while the rest is scheduled within less than 24 hours (See figure 19).

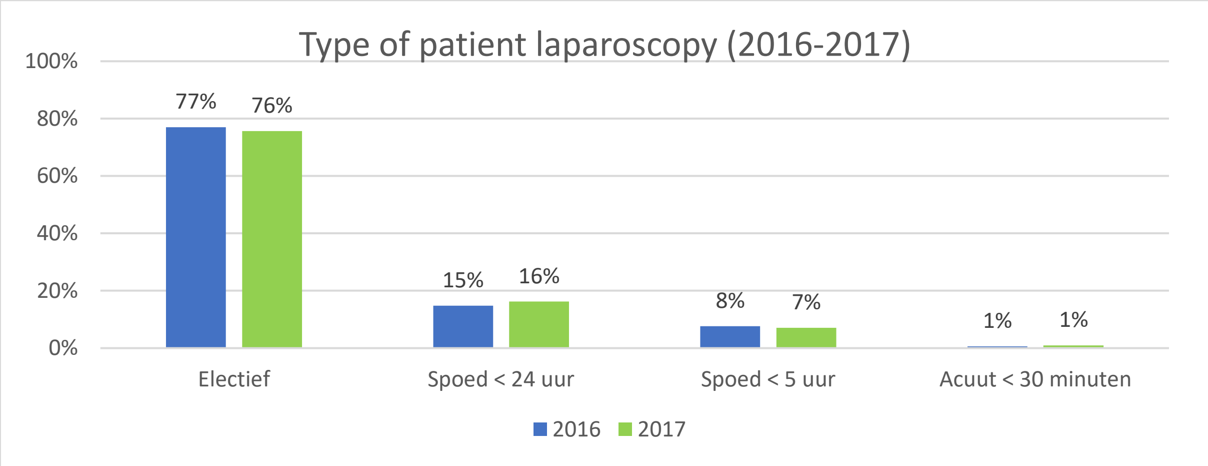


Figure 19 Type of patient laparoscopy from 2016-2017. Data gathered from Steriline in 2018.

Figure 5 (see Section 2.2.4) demonstrates that the percentage of each type of patients of all surgeries (hence, not limited to laparoscopy patients) has remained the same from 2016 to 2017. This information shows that there is a large range of planning capability for the management of the instrument inventory. Only 15% of the surgeries are scheduled with less than 24 hours. So, the rest of the patients are scheduled with more than one week in advance. This means that 85% of the instrument sets demand could be planned in advance. Moreover, if we take a look to the distribution of the types of patient arriving to the ORs during the day, is possible to see that the major number of elective patients are scheduled at 8:00 AM, while the rest is distributed mainly from 9:00 to 15:00. This situation shows that if we considered the flow time of the instruments sets after their use in the ORs and sterilization, it takes about 5 hours for instrument sets to be placed back in the OR storage (see Table 5).This provides a great planning capacity for the instrument sets designated for elective patients, since the number of patients that need to be attended with less than 24 hours are mainly arriving after the highest picks of the elective patients' arrivals (see Figure 20).

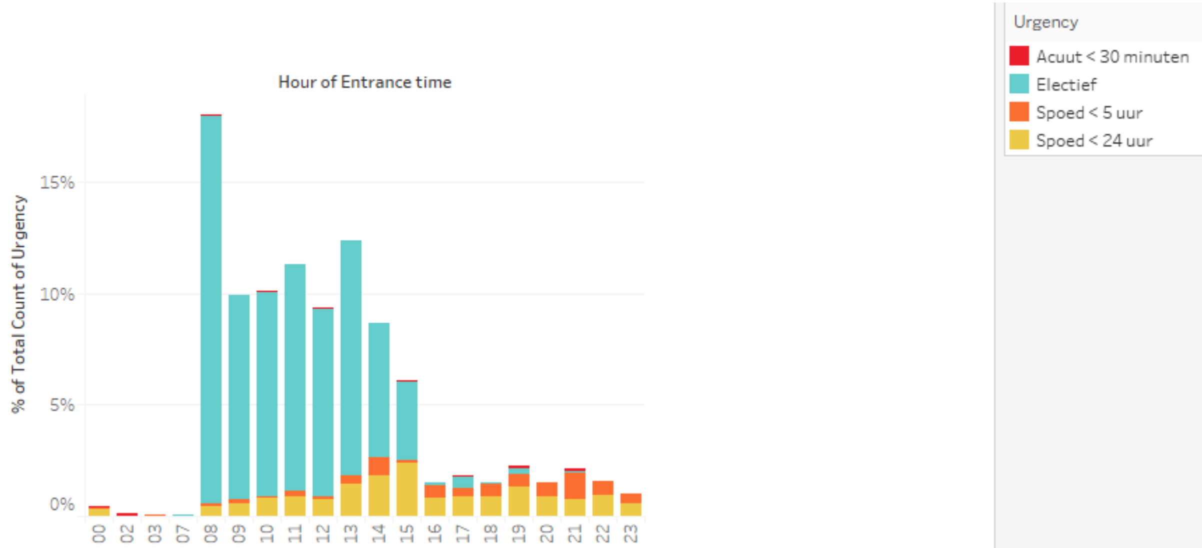


Figure 20 Average arrival time to the OR per patients type during 2017. Data gathered for ORsuite in 2018.

From an annual and daily perspective, elective patients could be planned together with the instrument sets. This could help to the CSD and logistics department to establish a suitable inventory policy, which increases the cost-efficiency of the inventory system.

2.7.6 Data issues

There is no connection between patient and instrument used per patient. The data provided for both OR suite and Steriline is not connected, which makes it difficult to identify which instruments where used per number case. This information is essential for this case study, to determine the demand per day and the time that each instrument set takes to come back sterile to the OR storage after its use in the OR.

2.8 Problem analysis

The MST is facing a typical problem for most hospitals, namely purchasing and stocking materials and equipment without analysing the trade-offs of each decisions. This problem is mainly caused by a lack of inventory policies that helps the staff to identify KPIs. These KPIs are essential to evaluate the benefits or disadvantages of any decision. An example of this is determining the number of instrument sets in stock necessary for providing a desired service level and finding an equilibrium between costs and benefits. Therefore, in this study we propose a model to find the methodology that helps MST to determine the base-stock levels suitable for maintaining a desired service level while minimizing the costs involve on having inventory.

This section aims to identify the original causes of this research problem, Therefore, in Section 2.8.1 we stablish the problem boundaries of this research and in Section 2.8.2 we discuss the causes and effects that produce the costs of reusable instrument sets.

2.8.1 Problem boundaries

Since the main interest of this study is finding a base-stock level of reusable instrument sets that minimizes the inventory cost involved while keeping a desired service level, we draw the boundaries of this research with the next statements:

- This model is focused on instrument sets and not on single instruments;

- This model only addresses reusable instrument sets. Therefore, no disposable items are taken into consideration;
- The external supply chain of instrument sets is outside the scope of this research. So, we consider the single-echelon inventory systems which involve just one warehouse. This was defined in Section 2.6.1 and adapted to instrument sets in Section 2.6.2. Therefore, the main stakeholders of the single inventory system are: the OR department, OR storage and the CSD;
- In order to exemplify the performance of the current and improved situation, the laparoscopy instrument sets are the case of study of this research. The reasons for choosing this instrument set are explained in Section 5.1.

2.8.2 Discussion of root causes

In this section we analyse the root causes that generate inventory costs of reusable instrument sets. In order to analyse the root causes we create a cause and effect fishbone analysis based on the Ishikawa diagram. The major categories were adapted to this problem: material management, users, management department, material and storage, and lack of data and demand documentation (see Figure 21).

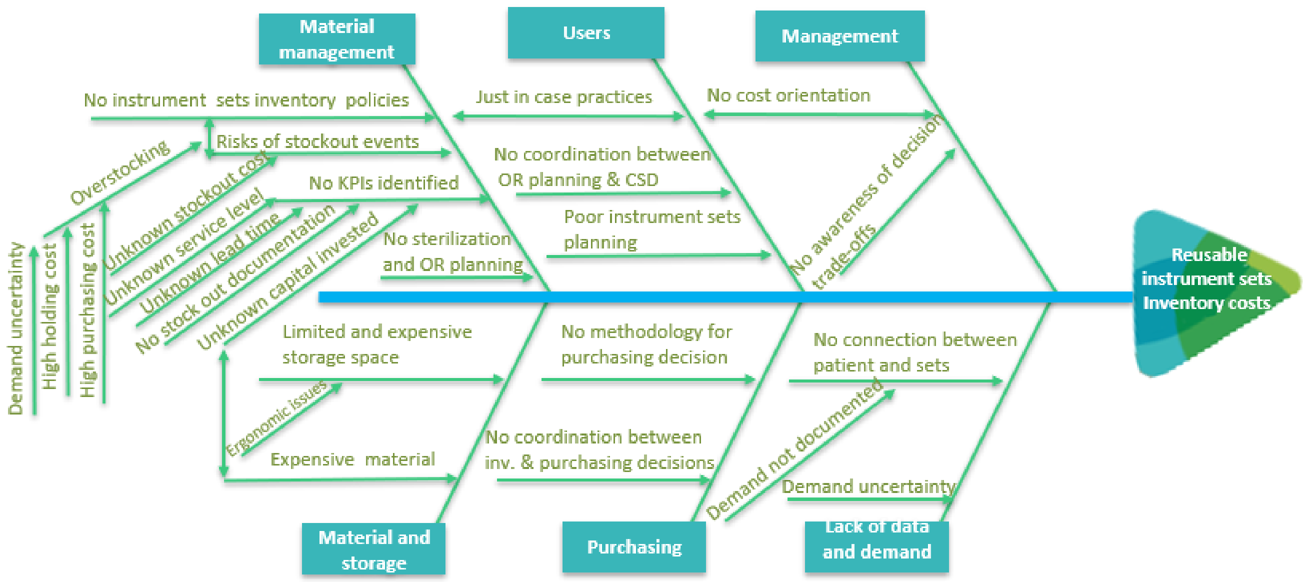


Figure 21 Root cause analysis of reusable instrument set inventory costs.

Management

Unawareness among employees regarding the trade-offs of having high levels of inventory leads to higher than necessary inventory. It is essential that the direct users – in this case surgeons – are aware of the real costs behind a high service level and a base-stock level.

Users and material management

The *just-in-case* practices have caused that the surgeons overstock instrument sets to avoid out of stock events. These decisions are made without any analysis of the current performance. This lack of performance analysis is also caused by the feeling that having more is better, hence mitigating the need of analysing other important aspects that lead overstocking. Therefore, it is fundamental that performance indicators are identified to know the real trade-offs that any decision could bring. Having high levels of inventory, produces a high service level, but it comes along with high purchasing and holding costs. These KPIs are essential measures for any inventory system. This is why not having an inventory policy, limits capacity of the users in terms of their awareness the actual needs of the system and the consequences of *just-in-case* practices.

Currently, the CSD sterilizes all the instrument sets that were used in the polyclinics and the OR department. However, the instrument sets that are scheduled for the next day are planned for sterilization just when the staff from the OR calls to the CSD. This lack of communication and coordination between OR planning and the CSD department makes it difficult for the CSD to determine the real needs beforehand. This leads to a more reactive than a proactive sterilization instrument supply. Having a reactive sterilization process limits the CSD's capacity to react to unexpected changes in demand, which could cause stockout events. Moreover, the planning of surgeries and instrument set sterilization is not being performed, even when 77% of the patients are elective (planned weeks in advance).

Material and storage

Instrument sets represent a high capital investment. However, the staff is not aware of the real cost of this expensive equipment, leading to unmeasured purchasing decisions. Moreover, the instrument sets occupy a large space in the OR department which could be used more efficiently. Having high quantity of instrument sets in inventory, affects the ergonomic of the users at the moment of picking instrument sets from the shelves. Currently, the MST is looking for opportunities to reduce the number of instrument sets in the OR storage. The CSD planner stated: "Now the employees have to stretch or lean to reach instrument sets that are allocated at the top or bottom of the shelves. This situation is caused because each shelve has 13 instrument sets, but we want to reduce this quantity to 8, for ergonomic issues. Nevertheless, we do not have enough place to spread the instrument sets across the sterile storage, we have more instrument sets than the available storage capacity"

Purchasing decisions

There is no methodology to help the staff with determining the trade-offs that purchasing extra instrument sets represents. Moreover, the coordination between inventory and purchasing should be linked, according to the current quantity of inventory available in the system and the prices that each instrument set represents. Currently, the instrument management department does not have the prices of each instrument nor the prices of each type of set. This, together with an inventory policy, would help to evaluate efficiently each instrument set purchasing decision.

Lack of data and demand documentation

Essential information is not registered properly, which makes the implementation of an inventory policy difficult. This situation is produced by the lack of links between patients and instrument sets. Currently, both systems Steriline (Database system that controls the information of instrument sets) and OR suite (Patient-ORs planning) are not connected. Therefore, the patient and the instrument sets that is used for each patient in surgery is not present. Having this connection, would help the staff to determine the demand of each instrument set and the time that each instrument set takes to return sterile to the OR. This information is essential to create a model which helps to implement a more accurate inventory policy which provides information to evaluate the trade-offs of having a determined quantity of instrument sets and a desired service level even with the uncertainty in the demand.

2.9 Conclusions and demarcation of scope

This section allows us to answer our first research question: "How is the MST currently managing the inventory of reusable instrument sets?"

We observed that the MST does not have a specified methodology to manage the inventory and purchasing of instruments sets. These decisions are mainly taken according to experiences and the feeling of having more is better. These *just-in-case* practices cause that MST purchases and overstocks instrument sets in its expensive and limited storage capacity. This also produces ergonomic problems due to the allocation of instrument sets in inconvenient positions caused by the limited space availability. We observed that instrument sets represent a significative investment cost and therefore its holding costs. Since the hospital is overstocking instrument sets in an expensive and limited storage, we contemplate that the reductions of costs can be achieved by finding an optimal inventory position and guiding purchasing decisions of reusable instrument sets, while analysing the trade-offs between costs and service levels.

Moreover, we identified that the MST is not measuring any performance indicator related to inventory management. This limits the decisionmakers in realising the real needs of the current system, keeping them far from achieving a desired performance with the minimal costs involved.

Providing the above observations, we conclude that in order to find a base-stock level that minimizes the costs, while keeping a desired service level, we should present an integrated approach for deciding how many instrument sets should be purchased and stored according to the stochastic demand. To achieve this, we should create a realistic model that helps the user to find an optimal base-stock level which could provide a balance between costs and a desired service level.

In order to find the previously described in the last paragraphs, it is essential to perform a literature study, which helps us to establish what is already known in the literature about the internal logistics of reusable instrument sets and its optimization techniques, focusing especially on the single echelon inventory systems, which involve just the logistic between OR storage, ORs and CSD. This study is presented in the following chapter.

3 Literature review

In this chapter, the current scholarly knowledge in the field of instrument sets is examined in order to find a methodology which help us to find the answer of our main research question. First, in Section 3.1 we describe our search strategy, then in Section 3.2 we show the studies that describe the logistics of reusable instruments in similar environments. To continue, in Section 3.3 we present the literature that discusses optimization techniques for the management of reusable instrument sets. Moreover, in this section we identify the KPIs that could help this hospital to measure the trade-offs between inventory costs and a desired service level. In Section 3.4 we provide the results of our findings through this literature search. In Section 3.5 we introduce the scenarios of this study together with the selection of the models suitable for each scenario. Finally, in Section 3.6 we provide the conclusion of this literature study.

3.1 Search strategy

In this literature research we focus on finding studies related with the internal supply chain and a single echelon inventory system described in Section 2.6.1 applied for reusable instrument sets that go through a cyclical sterilization process described in Section 2.6.2. The literature used to conduct this study was collected by using different search engines such as Google Scholar and Scopus and by reading related theses which were performed in hospitals in the Netherlands, some of which in MST. To get an insight of how this research is performed Appendix I shows the research strategy applied on this study.

3.2 Logistics of sterile instruments

The logistics and inventory of instrument sets are different than the disposable. Sterile surgical instruments are packed together in a sterile container called either tray, net or set. Since these containers are reused, they go through a sterilization process (see Figure 6 , Section 25). Klundert, Muls and Shadd (2007), Florijn (2008) and Kroes (2009), present an explanation of the internal logistic of sterile instrument sets in three different hospitals in the Netherlands: Maasland Ziekenhuis in Sittard, Academic Medical Center in Amsterdam and the MST in Enschede, respectively. The authors overlap in the description of the logistic process. This process is described from the OR storage, where the instrument sets are stocked and grouped by type in determined location inside the storage. There are sets that are destined for a particular type or surgery but there are others that the content is general and can be used for other type of surgeries. Before an operation the sets are taken from the storage and placed into a car, to then be taken into the required OR. After the surgery, regardless whether the set is opened or not, it is considered contaminated. Thus, when the surgery is finished, every set is brought to the contaminated storage, from where they are taken to the Central Sterilization Service Department (CSSD), which is often located next to the ORs, to be dismounted, disinfected, precleaned and placed into the washing machines. After this process the instruments are once again placed together into their metallic containers to then be placed into the autoclaves where the sterilization processes are carried out. Finally, the sterilized sets are taken back to the OR storage to complete the loop.

3.3 Literature containing optimization techniques and performance measures

In this section, the current scholarly knowledge in the field of instrument sets is examined. This study helps us to find the answer to our main research question. To conduct this study in Section 3.3.1 we show the optimization techniques found in literature related with the management of reusable instrument sets. MST is currently not identifying and measuring any performance, so they are unable to identify the trade-offs between inventory costs and a desired service level. Therefore, in Section 3.3.2, we explore which performance indicators are important to measure according to the literature.

3.3.1 Optimization techniques

Although managing sterile instrument have proved to be a potential cost saving, it has been less studied in the literature. Surprisingly, there is a limited number of studies related to inventory management of reusable instrument sets that go through the sterilization process. The majority of the papers are related to inventory management policies of consumable articles. Possibly, the lack of scientific interest could be explained by the absence of urgency given to controlling the cost of secondary process of sterile inventory and supply management by hospitals themselves. Instead, the attention has been placed in the reliability. If an instrument is not properly sterilized it could produce serious infections to the patients. However, poor logistics could lead to the absence of instrument sets at the moment that they are needed, even endangering the patients' lives (Klundert, Muls, & Shadd, 2008). The research papers that have addressed this problem, have called this the tray optimisation problem (TOP). For the propose of this research we use the term instrument sets instead of trays. This optimization problem of managing of sterile instruments requires to answer the questions: I) which and how many instruments should be allocated in each instrument set? II) which instrument sets should be used for a specified surgery or procedure? III) how many sets of each instrument set should be kept on inventory? (Ahmadi et al., 2018).

The first two questions are focused on single instruments and are currently addressed in MST by the protocols which are based on the surgeons' preferences. The third question depends on the scheduling and frequency of the surgeries, and which main propose is to determine the base-stock level of instrument sets. Therefore, answering this last question is more closely related to our research question.

There are some methodologies which could be useful to answer our research question, we divide these methodologies in different categories: constant and stochastic demand inventory control models, integer linear programming, constrains programming, Markov Chain technique, and Simulation models.

Constant demand inventory control model

The majority of the studies uses the fundaments from inventory control models. Nevertheless, there is a study that analyses the inventory of reusable instrument sets fully using one of these inventory models. This research is addressed by Fineman and Kapadia (1978), which is the first literature study that analyses a cyclical supply system of reusable instrument sets. The authors assume a constant demand, which provides a deterministic approach, that simplifies the problem using the Economic order quantity (EOQ) model to minimize the purchasing cost, order cost and holding cost of sterile supplies. An example of another study is provided by Burns, Cote, & Tucker (2001), in which the authors develop an ABC-analysis to determine which disposable materials from a health care system are the most relevant to prioritize, in order to generate a cost savings inventory system by applying EOQ inventory policies. Nevertheless, this study does not apply a methodology for cyclical inventory systems.

Stochastic demand inventory models

Burns et al. (2001) present a model with a constant demand which is easily handled using EOQ. However, the stochasticity of the demand is not taken in consideration, which is a common characteristic of the material managed in healthcare systems. For this reason, in this study we provide a brief description of models which deal with a stochastic demand. These inventory models provide closer representation of the real demand behaviour of a health care system, assuming a normal distribution in the demand. These inventory policies aim to answer when and how much of each stock keeping unit (SKU) should be replenished. These policies are grouped according to their review period (R), which represents the time interval between two moments at which a replenishment order can be released. This review period could be continuous or periodic (Van der Heijden et al., 1999):

- Continuous review
    - Inventory is continuously tracked
    - Order with constant size Q is placed when the inventory declines to the reorder point (s)
- Periodic review
    - Inventory status is checked at regular periodic intervals
    - Order is placed to raise the inventory level to a specified threshold

Table 7 shows the description of each control inventory policy grouped by periodic or continue review period.

Control inventory policies		
Review	**Symbol**	**Description**
Periodic	(R,s,S)	In each review period R, if the inventory level is ≤ to the reorder point (s), an order would be generated to rise the inventory up to level (S). The quantity of SKUs ordered depends on the inventory on hand.
	(R,r,Q)	In each review period R, if the inventory level is ≤ than the reorder point (r) the replenishment order will be full fill with a constant quantity (Q)
	(R,S)	In each review period R, an order is raised to increase inventory up to level (S)
Continues	(s,S)	When the inventory level for a determined SKU goes below the reorder point (s), a replenishment order is generated to increase the inventory up to level (S)
	(r,Q)	When the inventory level for a determined SKU goes below the reorder point (r), an order is created with a constant quantity (Q)

Table 7 Inventory policies. Based on Inventory management of surgical supplies and sterile instruments in hospitals: a literature review by Ahmadi et al., 2018).

Most of the hospitals use the (R,S), due to its simplicity to understand and to manage (Rossetti, Buyurgan, & Pohl, 2012). The inventory control policies presented in Table 7 are widely applied for disposable materials, but it is not the case for SKUs that go through a cyclical inventory process like instrument sets do (see Section 2.6.2).

Integer linear programming and constraints programming

Integer linear programming (ILP) and constraints programming (CP) are widely used to optimize inventory and logistics processes where all variables are discrete, both of them manage the same structure: objective functions, decision variables and constraints. These constraints are meant to create a more realistic scenario, where an optimal solution can be found. Moreover, these models prove to find optimality in their solutions, but do so in different ways. Constraint programming proves that no better solution than the current one can be found by using logical inferences, while linear programming uses for instance: branch and bound or relaxation techniques to create a lower and upper bound within which the optimal solution lays (IBM, 2018). Van de Klundert et al.(2008) show how these methodologies can be used to tackle reusable instrument sets management problems by addressing an optimization model of the flow of instruments sets within the ORs and the sterilization supplier. In this study the hospital plans to cut costs by outsourcing sterilization tasks. These authors create a deterministic model by making use of integer linear programming to determine the optimal delivery time, with the goal of minimizing the delivery and storage costs, having as constrains the vehicles and the OR storage capacity. Little and Coughlan (2008) performed a study in Cork University Hospital in Ireland, which is based on a stochastic constraint programming to determine the number of units of different types of sterile supplies that need to be stocked within an OR storage. The authors' objective function is the maximization the minimal service level while being limited by space storage constrains.

A study that provides an exemplification of the environment in the hospitals in the Netherlands related with instrument sets was performed by Essen et al. In the Hagaziekenhuis in the Netherlands, these authors propose two approaches which promise to reduce the 20% of the number of required beds while taking into account several restrictions such OR surgeons, and instrument availability. The first approach is based on local search through Simulated annealing, while the second approach linearized the objective function which results in a NP-hard problem to be solved like an ILP.

Simulated annealing

Simulated annealing is a heuristic method, which starts with a random initial solution, and then in each step it generates a neighbour solution space by small changes (swaps in the current solution). The method starts with a high probability, which makes that it accepts almost any better solution than the current, after certain iterations this probability decreases and ended in a local search from the optimal space solution. This method was applied in a similar case study and in the same environment. Florijn (2008) carried out a study in the Academic Medical Centre in Amsterdam, focused on the first question of TOP. This research focused on finding the optimal number of single instruments that should be placed inside of a set, while minimizing cost and having as constraints the weight and the space available. The author tackled this NP hard problem by creating a feasible solution using constructive heuristics and changing this solution by swapping. This change creates a neighbourhood solution which use simulation annealing to minimize the risk of be trapped in a local optimal solution instead of finding the global optimal.

Markov Chain technique

Markov Chain is a discrete-time stochastic model, which describes the sequence of future events, where their probability is based on previous states. This methodology is widely used because it has demonstrated to be an efficient model to provide feasible solutions when the data is limited. Winston

& Goldberg (2004) define Markov chain with Equations 2, whereX_t represents the state of the system at certain time t .

$$P(X_{t+1} = i_{t+1} | X_t = i_t , X_{t-1} = i_{t-1} , \ldots , X_1 = i_1 , X_0 = i_0) = P(X_{t+1} = i_{t+1} | X_t = i_t) \qquad (2)$$

Equation 2 defines that the probability distribution of the state at time $\mathrm{t} + 1$ depends of state t $(\mathrm{i_t})$ and it does not depend on the state the chain passed through on the $\mathrm{i_t}$ at time t. Markov Chain includes the assumption that the current state i in time t is independent of j at time $t + 1$, this independency between states is shown in Equation 3. Where p_{ij} represents the transition probability, which implies that the next state in determined period is related with its previous state remains stationary. For this reason, when the Markov chain follows equation 2, it is called stationary Markov chain.

$$P(X_{t+1} = j | X_t = i) = p_{ij} \qquad (3)$$

Some authors have used the Markov Chain method to solve the third question of the TOP: *How many of each instrument sets should be kept on inventory*?

Diamant et al. (2017) focus their research on finding a framework which provides them the means to determine the optimal number of instrument sets while maintaining a high service level. The authors manage the problem by deriving a long run average fraction of the time where the inventory is at determined level, using a discrete Markov chain. This steady-state likely is used by the authors to determine the service level of a Canadian Hospital, which has outsourced its sterilization process. This model analyses a scenario where it takes two days (the morning of the second day) for the instrument sets to return sterilized to the OR storage after being used.

Simulation model

Since we aim to provide a good representation of a real health care system, the fluctuation of the demand is a common characteristic of this environment. Therefore, the use of a simulation provides the means to create a model, which is more representative of the inventory flow of the instrument set.

Simulation is gaining more place for evaluating stochastic systems. Law and Kelton (2000) define simulation as the use of a computer to evaluate a model numerically, where the data is gathered in order to estimate the desired characteristics of a real model. Kumar and Shim apply a simulation model in The National Hospital of Singapore, which at the moment of their study was in the need of finding the optimal number of healthcare assistance needed for delivering the instruments in the ORs. The authors evaluated the waiting times and the queue length of the system (Law et al., 2000).

A widely used simulation model is the Monte Carlo simulation. This is defined as a scheme that creates random numbers, which is used for solving certain stochastic or deterministic problems (Law, 2007). The Monte Carlo simulation is used in several studies to determine the inventory levels of disposable materials. It allows generating random samples based on a determined theoretical or empirical distribution in order to obtain a numerical result (Kroese, Taimre, & Botev, 2014). Monte Carlo simulation is an effective technique in the inventory system to determine the optimal quantity of inventory when the demand is stochastic. This technique was applied by Sonnemann, Shuhmacher, & Castells (2003) for a cycle inventory of electricity in a waste incinerator in Spain. The authors select different parameters and determine the proper distribution of the Life Cycle Inventory (LCI). This distribution was simulated to determine the inventory levels of energy produced.

3.3.2 Finding suitable key performance indicators (KPIs)

It is relevant to determine which key performance indicators (KPIs) are important to measure to make possible a comparison between the current an improved situation. Moreover, the way the KPIs are defined and measured are relevant for this research. Therefore, an analysis of the KPIs used to measure the performance of the models proposed by different authors is described in the next paragraphs.

Base-stock level

Since this study aims to find the base-stock level, which in this case is represented by the order up-to-level. Cachon and Tewiesch (2008) define order up-to-level as the maximum inventory position or base-stock level which should be kept in inventory in order to satisfy a stochastic demand. Diamant et al. show a model where the base-stock level is found through the minimization of stockout cost subject to a desired service level.

Service level

Within the context of healthcare inventory management, the failure to have the supplies in stock when they are required, has serious impact on the quality of the care (Moons, Waeyenbergh, & Pintelon, 2018), potentially leading to patient death (Guerrero, Yeung, & Gueret, 2013). With the attempt of reducing the factors that affect the quality of care, several authors have introduced the service level as a constraint or objective functions, which helps to prevent the occurrence of a shortage. Service level is commonly defined as the part of the demand that is directly fulfilled by the inventory on hand, without incurring to substitution or emergency deliveries (Bijvank & Vis, 2012). The authors that have considered service level as an objective function are: Blijvank and Vis (2012), Diamant et al. (2017), and Little and Coughlan (2008). Another model was developed by Bijvank and Vis (2012) who proposed two Markov chain models. The first one, with the objective of minimising the capacity by having the service level has a limitation, while the second one with the objective of maximising the service level and capacity as a constraint. For this study it is also necessary to determine which service level could represent a good target. Usually a service level below 95% could produce a high rate of patient complaints, which could damage the hospital reputation. Therefore, it is suggested to place the target service level above 95% (Schalit & Vermorel, 2014).

Stockout cost

The service level defined previously is highly correlated to the stockout event. To exemplify this, having a high service level is produced by the low probability of stockout events, while having a low service level is produced by a high probability of stockout events. Therefore, it seems obvious to include stockout costs in this study. Stockout costs is defined by Diamant et al. (2017) as the costs reflected by extra overtime hours of nurses, staff and surgeons, administrative costs of arranging a OR for a scheduled surgery that did not happen at the scheduled time and which now has to be rescheduled, as well as the costs of leaving a OR room inactive. Moreover, the stress that this situation may cause to the patient can produce a negative effect on the hospital's reputation. A study of 4,876 elective surgeries performed in Tulane University Medical Center by the American Society of Anaesthesiologists (2012) found that 6.7% of those elective surgeries were cancelled. It was also found that cancelation of some surgeries costs more to cancel than others, depending on the speciality. For instance, the cancelation of neurosurgeries could reach around $6,000 USA while thoracic, ophthalmology, orthopaedic, plastic and general surgeries could cost around $2,000-$5,000 (Appavu et al., 2016).

Holding costs

Inventory costs are all the costs related to the management, storing and maintenance of SKUs over a certain period of time. Each instrument set is considered fixed SKU. Holding cost is a relevant performance indicator. However, it is frequently no measured. Melson and Shultz (1989), recommended that not more than 20% of the inventory should be stocked in the OR and sterile storage room.

Since this study is focused on the management of reusable instrument sets and MST stores all the instrument sets in the OR storage, it is a good area for improvement. Holding costs are always hidden costs. Finding a suitable way for measuring an estimate, it is relevant for analysing the trade-offs of any possible inventory or purchasing decision. Heizer & Render (2001) define the holding costs as the percentage of total capital invested. This involves:

- Housing costs: such as building rent, depreciation, operating cost, taxes, insurance. These costs usually represent an approximate of 6% of the inventory value, but they can range between 3-10%.
- Material handling costs: include equipment payments (which can include lease), depreciation of equipment, power, and others related to this aspect. These costs range between 1 -3.5% of the inventory value, but normally they represent a 3% of it.
- Labour cost: involves labour force used on receiving and warehousing inventories, as well as security employees hired for keeping inventories safe. These costs generally represent an approximate of 3% of inventory value.
- Investment costs: they can include borrowing costs, taxes associated to the inventory value, and insurance on inventory. They can represent an approximate of 11% of inventory value. This percentage ranges from 6% to 24%
- Spoilage and obsolescence: mainly in health care services, spoilage of products is a common situation. This cost probably would represent about 3% of inventory value, but it can range from 2-5% approximately.

The overall annual carrying cost approximates to 26% of the inventory value. This is an extra cost of the pure investment on the physic inventory kept on storage. On the one hand having a holding cost of less than 15% is suspicious, while on the other hand companies that store high technology estimate a holding cost of around 40% (Heizer & Render, 2001).

Having identified the KPIs that measure the base-stock level of reusable instrument sets, we continue with the identification of literature that provides us with optimization models that could describe and improve the behaviour of laparoscopy instrument sets trough the current system.

3.4 Results of literature search

Surprisingly, little literature is found related to the inventory management of reusable instrument sets (see Appendix I). As is displayed in Table 8 only three papers apply optimization technics for finding the base-stock level of reusable instrument sets (third TOP question). These authors use EOQ (constant demand), inventory control policies (stochastic demand), constraint programming or Markov Chain technics. Nevertheless, the rest of the authors provide use with a good insight of instrument sets flow in similar study context.

Authors	Type of material	Method	Objective	Decision variables	Constrains	TOP question(s)
Fineman & Kapadia	Reusable and disposables sets	EOQ (Deterministic demand)	Purchasing, ordering and holding cost	Replenish quantity	NE	I & III
Little & Coughlan	Instrument sets	Constraint programming (Stochastic d.)	Service level	Delivery cycle and service level	Storage space	III
Diamant et al.	Instrument sets	Markovian Chain (Stochastic d.)	Minimizing Total costs	Base-stock level	Service level	III
Van de Klundert et al.	Single instruments	Linear programming (Deterministic demand)	Delivery and storage costs	Delivery time	Transportation space	NA
Essen et al.	Instrument sets	Simulated Annealing and ILP (Stochastic demand)	Minimizing beds usage	Usage time and number of beds	OR surgeons and avl. Instruments sets	NA
Florijn (2008)	Single instruments	ILP and Simulated annealing (Stochastic d.)	Minimizing Total costs	# instruments per try type	Weight and volume	I
Kroes (2009)	Instrument sets	Improving instrument sets flow	Optimizing instrument sets flow	-	-	NA

Table 8 Results of the literature review. NE=Not explained, NA=Not applicable to the TOP.

Having identified these optimization methodologies through this literature research, we continue with the selection of a model that could be better adapted to our research problem.

3.5 Selection of possibly suitable models for this research

The objective of this research is to find the base-stock level of instrument sets that reduces the costs involved (holding, purchasing, and stock out costs), while maintaining a desired service level. Therefore, we need to determine which methodologies could best handle the uncertainties of our current situation presented in Chapter 2.

Given that in the current situation there is not a reliable estimation of the time that the instrument sets take to return sterilized to the OR storage, for the reasons mentioned in Section 2.7, we need to approach the problem by creating a best-case scenario where the instrument sets arrive to the OR storage sterilized to the first morning after their use (FMAU) and a worst-case scenario where the sets arrive sterilized the second morning after use (SMAU). These scenarios are presented in Section 3.5.1 and Section 3.5.2 respectively.

3.5.1 First Morning After Use (FMAU) scenario

This model represents the best-case scenario where we assume that all the instrument sets are available each morning in the OR storage after being sterilized. We aim to approach this scenario by applying (R,S) inventory control policy (see Section 3.3.2). Although this policy is mainly applied to disposable materials, we believe that it could be suitable to tackle this scenario for the next reasons:

- The stochasticity of the demand and the lead-time is considered.

- The (R,S) policy is more closely related to the current system, which make it easier to implement into our model.
- It can be easily adapted to disposable material inventory management. So, the MST could manage the inventory of both: disposables and reusable materials.
- The model can be adapted from a hierarchical supply chain to a cyclical supply chain (see Section 2.6.2).

An important aspect to considerate is that inventory control policies assume a normal demand distribution. However, not all systems are defined by this distribution, thus, we need to identify an alternative approach to tackle this situation. A suitable way to do so is by applying simulation techniques. An efficient simulation model for producing random number with any demand distribution defined by the user is Monte Carlo simulation.

3.5.2 Second Morning After Use (SMAU) scenario

The model that most closely answers our research question is the discrete long run average Markov Chain technique proposed by Diamant et al. This study is one of the few studies that addresses the third TOP question (finding an optimal base-stock level). The main reasons are listed below:

- The model addresses the inventory management of reusable instrument sets.
- This model takes into consideration the KPIs that our research question aims to measure.
- This model is adaptable to any distribution.
- The paper provides data which could help us to verify the functionality of our model.

A drawback that could be taken as a benefit is that this model shows a scenario where the sterilization process is outsourced. This produces that the instrument sets return sterilized to the OR storage two mornings after their use in the ORs. Therefore, we take Markov Chain model to represent:

- Our worst-case scenario to determine the maximum quantity of instrument sets needed in delay supply situations.
- A tool to indicate how many instrument sets the MST would require if it decide to outsource the sterilization process of all its instrument sets.

In order to analyse the effects produced by the changes between parameters, we apply Monte Carlo simulation technique, which could help us to analyse the risk that any inventory and purchasing decision could bring. Another

3.6 Conclusion of literature review

In this chapter we carried out a literature review which helps us to find the answer to these research questions: “Which methodologies are found in literature to determine the base-stock level?” and “Which KPIs are important to evaluate to determine an optimal base-stock level? Surprisingly, we found that there are not many studies related to reusable supplies that go through a sterilization process the majority of the studies are addressed to disposable materials. Moreover, most of the articles found addressed just the first and second TOP questions which just studied the optimization of single instruments. Nevertheless, we found an article which approaches our case study closely. This study is carried out by Diamant et al. (2018). The authors made use of the discrete-time Markov chain technique to determine the average fraction of the time that the inventory is a certain level. This model provides a good approach for the worst-case scenario when the instrument sets arrive at the OR storage the SMAU. For the best-case scenario where the instrument sets arrive to the OR storage the

FMAU, we make use of inventory control methods. However, we need to adapt these to incorporate them into a cyclical inventory system for reusable instrument sets.

Since the MST does not have any KPIs defined (see Section 2.4) the performance of the current situation is unknown. For this reason, we needed to find the KPIs that could help us comparing and determining the performance of both the current and improved situation. Therefore, in this chapter we determined the KPIs along with the models suitable for answering our main research question. The KPIs to be measured are holding, purchasing, and stockout costs.

To conclude this chapter we summarize the methodologies that are suitable to approach our main research question in Figure 22.

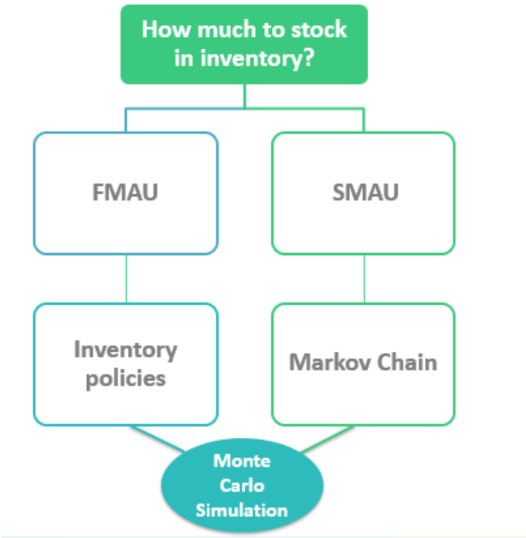


Figure 22 Methodology to find the number of instrument sets to keep in inventory (third TOP question).

The next chapter provides us with the necessary conceptual and mathematical adaptations of the methodologies found through this literature research.

4 Models for optimizing OR inventory management

This chapter presents the conceptual and mathematical adaptations of the models discussed in Chapter 3. This chapter is structured in the following way: In Section 4.1, we provide a recapitulation of the problem description together and the trade-offs between the main KPIs and metrics important for this study. In Section 4.2, we present the conceptual adaptations of the models found during the literature review into each case scenario, FMAU and SMAU. These adaptations are presented in Section 4.2.1 and 4.2.2 respectively. Section 4.3 introduces the mathematical adaptation for FMAU scenarios to determine the base stock and service level. Since two different models are required, because inventory control policies are addressed for normal distribution, we divided this section in Section 4.3.1 and 4.3.2. In Section 4.3.1 we model FMAU scenario when the demand follows a normal distribution. In this section we calculate the base-stock level under periodic review period using the formulations from the (R,S) inventory control policy. In Section 4.3.2, we present the FMAU model when the demand does not follow a normal distribution. In this case we use the empirical distribution to determine the base-stock and service level. Since the costs are calculated in the same shape for the normal and empirical distribution of the FMA scenario, we describe their formulation in Section 4.3.3. In Section 4.4, we describe the Markov chain transition matrix model created by Diamant et al. (2017) and which we use to formulate our SMAU scenario to find the service level (Section 4.4.1) and the costs involved to be able to find the optimal base stock level (Section 4.4.2). In Section 4.5, we describe the Monte Carlo simulation, which is used to analyse the trade-offs of having different number of instrument sets. To continue, in Section 4.6, we identify the assumptions needed to be able to apply the mathematical models found through the literature. Finally, in Section 4.7, we show the conclusion of this chapter. This chapter structure is demonstrated in Figure 23.

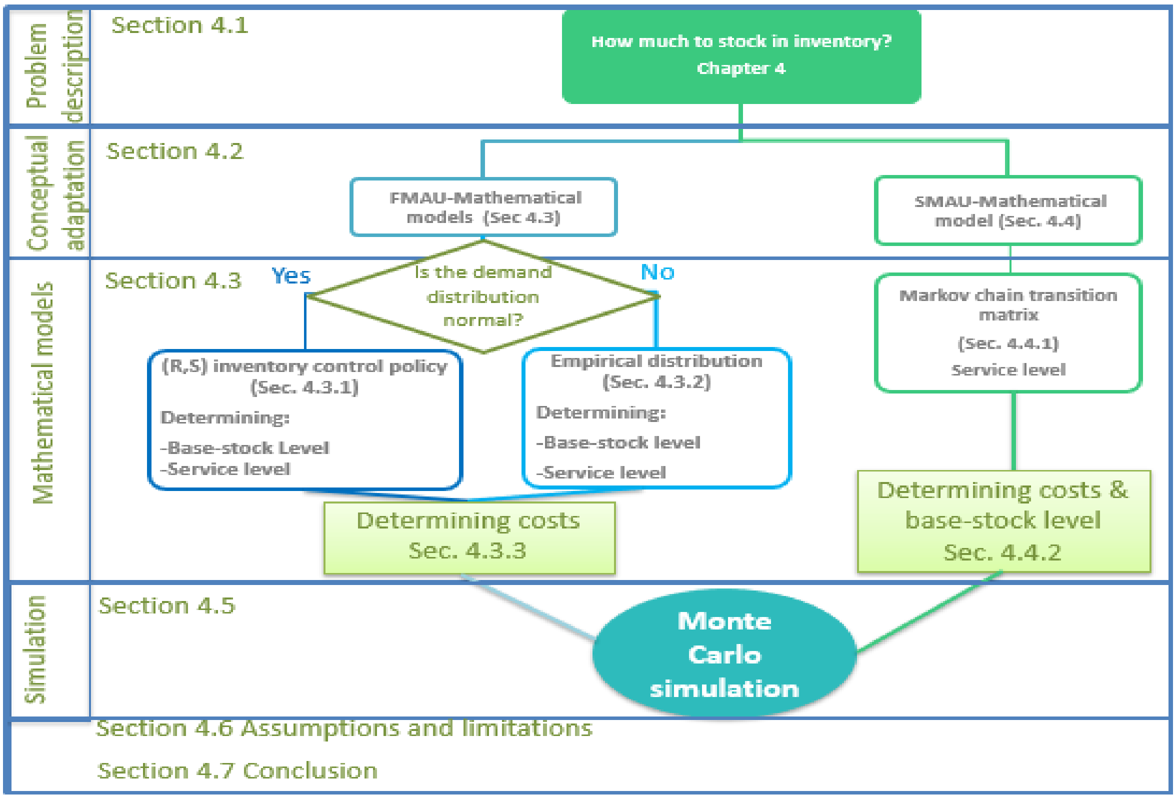


Figure 23 Models to find the optimal base-stock level along with structure of Chapter 4.

4.1 Problem description

We begin with this chapter providing a summary of the problem definition, which was discussed in Chapter 1. With this mathematical approach we want to achieve the goal of our research: to create a model that allows the MST to determine the optimal number of instruments sets to keep in inventory, while keeping a desired service level. The problem of this study is related around the issue how the MST can determine the base-stock level of reusable instrument sets while:

- Keeping a desired service level
- Minimizing the stockout cost
- Minimizing the inventory holding cost
- Minimizing purchasing cost

The purpose of this model is to ensure that each inventory and purchasing decision is taken with the proper analysis of the trade-offs that come along with them.

4.1.1 Trade-offs

Each inventory decision leads to a cost saving of one aspect while it results in extra costs in another. This model provides an optimal solution that looks for the equilibrium between these trade-offs in such a way that the overall costs are minimized. Figure 24 shows the main trade-offs caused by different inventory levels.

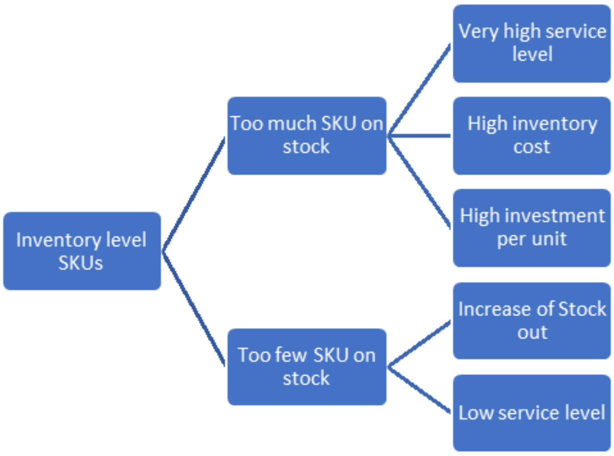


Figure 24 Trade-offs of high and low inventory levels.

Service level and inventory

Hospitals try to provide the best service as possible. Therefore, they tend to keep high inventory levels to minimize the risk of stockout. The more inventory is carried, the higher the cost and the risks: instrument sets are expensive to buy and sterilize, they need expensive space to be stored in, they get obsolete, and so on. There is a theoretical optimal stock level after which an increase in stock level does not increase overall profits. From a business perspective, the service level represents a trade-off between cost of inventory and the cost of stock-out. The challenge for the inventory is to find the balance between costs: to have enough to provide a desired service to the patients, but not so much that the inventory could not recover the benefits of extra sales.

Having high service levels generally comes with having high inventory carrying cost and investment cost, while having low inventory levels generally comes with having low inventory carrying cost and low investment cost, it generally increases the probability of running out of stock. Heizer (2008) describes that the cost of the inventory policy increases dramatically with an increase in service levels. Indeed, inventory costs increase exponentially as service level increases.

4.2 Introduction to the conceptual models

As we mentioned in Section 4.1.1, different levels of inventory come with earnings and collateral costs. In this section we present different models where an optimal base-stock level balances the trade-offs of having determined service levels. As mentioned before in Section 3.5, MST does not have a reliable measure of the time that the instrument takes to return sterilized to the OR storage after their use, therefore, we divide conceptual models into two sections: In Section 4.2.1 we explain the conceptual adaptations for our best-case scenario First Morning After Use (FMAU), while in Section 4.2.2 we explain the conceptual adaptation for our worst-case scenario Second Morning After Use (SMAU).

4.2.1 FMAU model conceptual adaptations

Inventory control policies are formulated for hierarchical inventory systems rather than cyclical inventory systems, which represent the life cycle of a reusable instrument sets. In order to adapt the (R,S) inventory policy, we summarise what is described in detail in Chapter 3.2.

A hierarchical supply chain that is focused on a single echelon inventory model is based on three main actors: customer, supplier, and warehouse. In this case the CSD acts as the supplier and the ORs as the customer, because the CSD provides sterilized instrument sets to ORs according to their demand. These instrument sets are stored in a sterilized warehouse called OR storage. With this representation we can assume that the lead-time represents the time that an instrument set takes to comeback sterilized to the OR storage after their use in the ORs and the demand the orders of sterilized instruments raised by the OR to the CSD (see the Figure 25 and detailed explanation in Appendix 2).

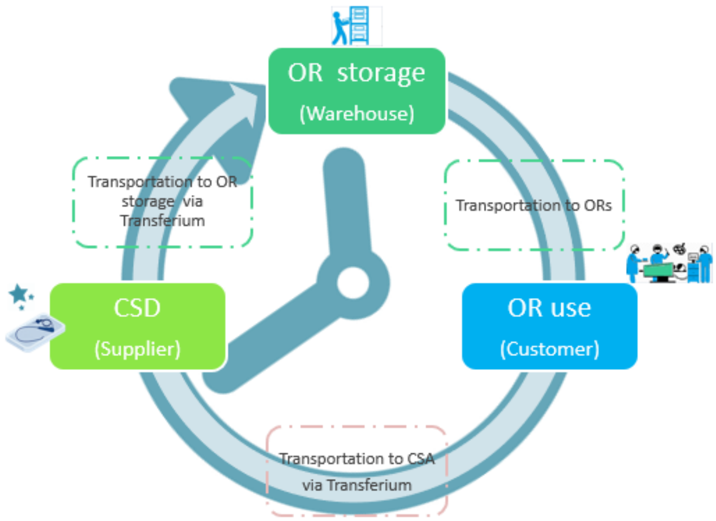


Figure 25 Cyclical supply chain for reusable instrument sets. Based on information provided by the CSD planner (2018)

In order to achieve the main goal of this research, the key factors that have an influence on the quantity of inventory needed are listed below:

- The length of the replenishment lead-time: the time that an instrument set takes to comeback sterilized to the OR storage.

- The desired service level (fill rate or in-stock probability): the probability of not running out of sterilized instruments during the lead-time.
- Demand of instrument sets: each surgery performed in an OR requires sterilized instrument sets, therefore, each instrument set used in a surgery represent the demand for the CSD, which has to sterilize all the instrument sets after use.

Having explained the main concepts and theoretical adaptation for approach the FMAU scenario, we continue with the mathematical model, which is provided in Section 4.3.1, but not before explaining the conceptual adaptations of the SMAU model.

4.2.2 SMAU model conceptual adaptations

The worst-case scenario where the instrument sets arrive to the OR storage the second morning after their use in the ORs is approached by a discrete-time Markov chain, to derive the long run average fraction of the time that there is certain quantity of inventory on hand at the beginning of the second morning. With this method we can identify the optimal quantity of instrument sets that should be kept in inventory along with analysing the trade-offs of having a determined service according to a defined base-stock level. These trade-offs are defined in Section 4.1.1, while the reasons for making use of the Markov Chain technique for our SMAU scenario, are discussed in Section 3.5.2.

Since this model handles the same research questions, no conceptual adaptations were made. Moreover, the Markov chain model can be adapted to any type of distribution that better represents the observed data, or by using the empirical distribution. This characteristic defines our Markov chain tool a handy tool for analysing the SMAU scenario. The mathematical model is provided in Section 4.3.2.

4.3 Introduction to the FMAU mathematical models

In this section is formulated the mathematical adaptations from the models selected in Section 3.5 to tackle the FMAU scenario. Since inventory control policies described in Section 3.3.1 apply only for a demand that follows a normal distribution, we found the need to create a model that takes into account that not all instrument sets have this distribution. For this reason, in this section is presented a mathematical approach to determine the base-stock lever for situations where the demand follows a normal distribution. If after proving that the demand follows a normal distribution, it is applied (R,S) inventory policy , to determine the base-stock and service levels, this is done in Section 4.3.1. Otherwise, it is applied empirical distribution, this is performed in Section 4.3.2. Since in both cases the costs are determined in the same shape, we address our mathematical costs adaptations in Section 4.3.3. Figure 26 illustrates the structure of this section.

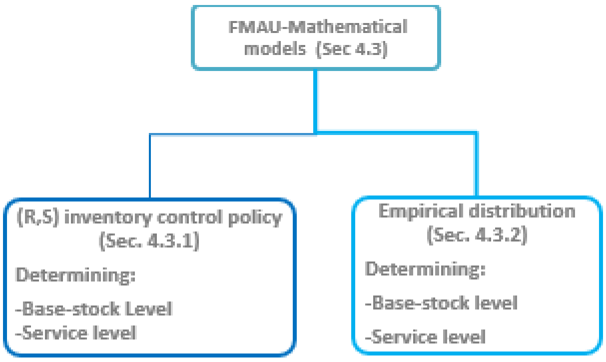


Figure 26 Structure of FMU scenario.

Since the demand of instrument sets is an essential factor to consider when determining an optimal base-stock level, we perform a normality test to determine whether the observed demand follows a normal distribution, which can be found in Section 5.2.

4.3.1 Mathematical model FMAU-Inventory control policies

This section analyses the FMAU scenario, when the demand of instrument sets follows a normal distribution. Therefore, we are able to adapt the inventory control policy (R, S) to our model. R stands for the review period and S denotes the order-up-to level or base-stock level:

- A (R, S) , meaning that with frequency R , inventory is raised to level S.

Since the objective of our study is to find the base-stock level while keeping a desired service level, we provide the approach for determining base-stock level and service level in the next paragraphs.

Determining base-stock level

The main objective of applying (R,S) control policy is to determine the base-stock level which represents the quantity of instrument sets that should be kept in inventory to satisfy the stochastic demand. In an inventory control system, the base-stock level is also known as the order-up-to level. The base-stock is composed of expected demand during the lead time plus the safety stock. The last is defined as the average demand just before a replenishment order arrives. Since the demand is stochastic, this safety stock works as a buffer, that covers the demand when it is higher than expected. The period between the order is raised and it arrives is called lead time (L). Therefore, the base stock also includes the expected demand during the lead time. (R, S) control policy reviews periodically its inventory level. The formulation for determining base-stock level (S) under periodic review period is illustrated in Equation 5, which consists of the mean demand during the lead-time and review period $D_{L+R} = D(L+R)$ plus an additional portion of the standard deviation of demand during the lead-time and review period $\sigma_{L+R} = \sigma_D \sqrt{L+R}$, this last portion dependents on the safety factor z, which in overall represents the safety stock (see Equation 4).

$$Safety\ stock = z * \sigma_D \sqrt{L+R} \qquad (4)$$

The following formula is used:

$$S = D(L+R) + z * \sigma_D \sqrt{L+R} \qquad (5)$$

SYMBOL	DESCRIPTION
$\boldsymbol{S}$	Base-Stock or order-up-to level
$\boldsymbol{R}$	Review period, time interval between two moments at which a replenishment order can be released
$\boldsymbol{L}$	Replenishment lead-time from the CSD (supplier) in days
$\boldsymbol{z}$	Safety factor
$\boldsymbol{\sigma_D}$	Standard deviation of instrument sets demand
$\boldsymbol{D(L+R)}$	Mean demand during lead-time *L* and review period *R*

Determining service level

When determining our base-stock level (S) from a customer service perspective we need to evaluate the so-called cycle service level CSL, which is provided by Equations 6 & 7:

$$CSL = P\{D(L) \leq D(L) + z * \sigma_D \sqrt{L}\} \qquad (6)$$

To calculate the safety factor z the Equation 7 is necessary:

$$z = \Phi^{-1}(\mathrm{CSL}) \qquad (7)$$

SYMBOL	DESCRIPTION
$\boldsymbol{z}$	Safety factor
$\boldsymbol{\Phi^{-1}}(.)$	Standard normal inverse distribution function
$\boldsymbol{CSL}$	Cycle service level: $CSL = \mathrm{P}$\{Lead-time demand ≤ Reorder point\}

The probability of running out of stock in a replenishment cycle is expressed in Equation 8.

$$Probability\ of\ running\ out\ of\ stock\ = 1 - CSL \qquad (8)$$

Having outlined the mathematical adaptations for the model that can be applicable to our FMAU scenario, where the demand fits a normal distribution, we continue in the next section with description of the model created for the FMAU scenario where the demand does not fit a normal distribution.

4.3.2 Mathematical model FMAU-Empirical distribution

In some situations, the observed data does not fit any theoretical distribution. In these cases, we might want to use observed data themselves to specify directly a distribution, which is called *empirical distribution*. This distribution helps us to reproduce random values that follow the behaviour of the observed data, when using a simulation model. In order to define the *empirical distribution* also called *cumulative empirical distribution function* (CEDF). Lets $(X_i, \ldots, X_n)$ be the set of independent and identical distributed (i.i.d) random variables where $F_n(x) = \mathrm{P}(X_i \leq \mathrm{x})$ represents the proportion of the observations that are less than or equal to x , being the sum of all these proportions 1 (Castro, 2015). The formulation for the CEDF is presented in Equation 9, where 1 is the indicator function, namely 1{X_i ≤ x} is one if X_i ≤ x and zero otherwise (Law,2015).

$$F_n(x) = \frac{number\ of\ X_i's \leq x}{n} = \frac{1}{n}\sum_{i=1}^{n} 1X_i \leq x \qquad (9)$$

The main reasons why an empirical distribution represents a suitable method for cases in which the normal distribution is not feasible for finding the base-stock level are:

- Fitting the observed data to a normal distribution is a complex task, which requires knowledge about probability and statistics. This complexity could diminish the intention of the users for using the tools provided for this research.
- Using the empirical distribution requires less input data than the FMAU model: the service level, observed demand, and costs related.
- Lead-time review periods are not essential, since the model assumes that the instrument sets are available in inventory each morning after their use.

Determining base-stock and service level

Not having a normal distribution, prevents us from using Equation 8 to target our desired service level. However, with the support of Monte Carlo simulation created using VBA programming tool in MS Excel, we model a distribution based on the CEDF. This simulation model provides us with random values which properly represent the behaviour of the observed demand. The empirical random demand distribution helps us to determine the optimal base-stock level, which is the objective of this formulation. To achieve this objective, we apply the PERCENTILE.EXC (array of daily demand, service level) function in MS Excel. This function interpolates from the empirical demand the amount of instrument required, to reach a desired target service level which represents the percentile. This percentile is defined in statistics as number where a certain percentage of observations fall below that number (Murthy, 2004).

4.3.3 Determining costs for FMAU scenario

The costs determination is a fundamental part for this study, which helps us to measure the trade-offs of having different service levels. Once the instrument sets are purchased, they represent an invested cost which generates expenses as a fixed asset that stays in inventory until it is replaced or removed. Therefore, their costs determination is not formulated like the control inventory policies usually do with the disposable material, which are consumed and thrown away after their use or expiration date. For this reason, the total cost for normal and empirical distributions of the FMAU scenarios are divided in the next shape: holding costs, purchasing costs, and stockout costs.

Holding costs

Reusable instrument sets are fixed assets, which are kept in inventory the complete year. Therefore, the calculation of their holding costs is not the same as disposable materials. In this research we formulate the holding cost as a percentage of the capital invested in Equation 10.

$$HC = h * S * SP \qquad (10)$$

SYMBOL	DESCRIPTION
$\boldsymbol{HC}$	Daily holding cost
$\boldsymbol{h}$	Fraction of the capital invested on instrument sets S dedicated to holding inventory
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR being sterilized
$\boldsymbol{SP}$	The price in € per instrument set

Purchasing costs

Reusable instrument sets have a long lifecycle, so their purchasing cost $PC(S)$ occurs within a time-horizon. Diamant et al. (2018) calculate the procurement cost in Equation 11.

$$PC(S) = \frac{NS * SP}{T} \qquad (11)$$

SYMBOL	DESCRIPTION
PC($\boldsymbol{S}$)	Daily purchasing cost given S
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR being sterilized
$\boldsymbol{SP}$	The price in € per instrument set
$\boldsymbol{T}$	Life time of each instrument set

Stockout costs

The stockout cost (SC) is easily determined, by adding the number of patients per day that were not served during the year, due to the available number of instrument sets in inventory were not enough to fulfil their demand, multiplied by the cost (€) that the hospital incurs for rescheduling patients.

Total costs

The total cost results from the addition of the holding, purchasing and stockout costs. This is represented in Equation 12.

$$TC = h * S * SP + \frac{S * SP}{T} + SC \qquad (12)$$

Having formulated the mathematical model for determining the optimal base-stock level for the FMAU, which considers the service level and the costs involved, we continue with the mathematical formulation for the SMAU scenario in the next section.

4.4 Introduction to the SMAU mathematical model

In this section we present the mathematical formulation of the model that help us to find the optimal base-stock level, for the scenario were instrument sets are ready to be used in the OR storage the second morning after their use in the ORs (SMAU scenario). This model is based on the Markov chain transition matrix which is used to calculate the service level that results from having a determined number of instrument set in the system. In Figure 27 we illustrate the structure of this section. In Section 4.4.1 we describe how the Markov chain transition Matrix is used to determine the service level. Moreover, in Section 4.4.2, we formulate the costs that each inventory level involves in order to be able to find the optimal base-stock level.

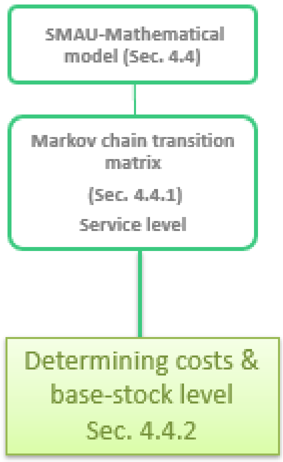


Figure 27 SMAU section structure.

4.4.1 Mathematical model SMAU-Markov Chain

The SMAU scenario is handled using the model proposed by Diamant et al.(2017). This model has the objective to find an optimal base-stock level that minimizes the total costs, while ensuring that stockout events do not exceed the desired service level.

The authors use the stationary Markov Chain transition probability matrix (described in Section 3.3.1), to determine the average fraction of the time that there are determined number of sets j at the beginning of day t+1, when in day t were i, which can be seen in Equation 13. This equation is composed by p_{ij} and $\pi_i(S)$. With the assumption that the demand is stationary and independent and identically distributed (i.i.d.), let $\pi_i(S)$ represents the steady state probability that approximates the fraction of the time that there are i instrument sets in the inventory on hand at the beginning of day t, and let p_{ij} denote the probability that the stock on hand the next day is j, given that in the present day the available number of instrument sets is i.

$$\pi_j(S) = \sum_{i=0}^{S} \pi_i(S) p_{ij} \qquad (13)$$

Where $0 \leq \pi_i(S) \leq 1 \;\; for\; i = 0, \ldots, S \;\&\; j = 0, \ldots, S$

SYMBOL	DESCRIPTION
$\boldsymbol{\pi_j(S)}$	Stationary Markov chain transition probability matrix. Average fraction of the time that there are j instrument sets at the beginning of day t+1.
$\boldsymbol{j}$	Instrument sets on inventory at the MST at the beginning of day t+1
$\boldsymbol{i}$	Instrument sets on inventory at the MST at the beginning of day t
T	Current day
$\boldsymbol{p_{ij}}$	Probability that the units of inventory on day t+1 is j, given that in day t was i
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR or being sterilized
$\boldsymbol{\pi_i(S)}$	Long run average fraction of the time that there are i sterilized instrument sets at the beginning of day t in inventory. $i = 0, \ldots, S$

To adapt Equation 13 to our case study, it is necessary to consider that there are changes in the demand that produce that the inventory goes from i units to j. These demand changes are formulated in matrix p_{ij} (Equation 14) and explained in Table 9.

$$p_{ij} = \begin{cases} P(D = S - j) & if\; i + j > S \\ P(D \geq i) & if\; i + j = S \\ 0 & if\; i + j < S \end{cases} \qquad (14)$$

Note: the addition of $i + j$ shows the inventory available in the OR storage at the beginning of two consecutive days and $i + j - S$ the number of sterile instruments sets left from day t.

SYMBOL	DESCRIPTION
$\boldsymbol{p_{ij}}$	Probability that the units of inventory on day t+1 is j, given that in day t was i
$\boldsymbol{i}$	Instrument sets on inventory at the MST at the beginning of day t
j	Instrument sets on inventory at the MST at the beginning of day t+1
D	Observed daily demand for instrument sets
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR or being sterilized
P(.)	Probability of observing determined demand instance D

Demand instances	Explanation
$\boldsymbol{p_{ij} = P(D = S - j)\; or\; P(D = i)}$	Represents the situation when the demand is equal to the available number of instruments. It is only possible if the inventory of two consecutive days is bigger than the total number of units on the system $i + j > S$. This means that there are some instrument sets from day i still available the next day j

$\boldsymbol{p_{ij} = P(D \geq i)}$	Represents the situation when all the instrument sets are used, since the number of surgeries that require determined instrument sets on day t is at least as big than the available inventory on hand i. This situation just could happen if the inventory $i + j = S$.
$\boldsymbol{0}$	The last equation cannot happen because it would mean that more than the instruments available in the hospital are in use $i + j < S$

Table 9 Probability demand instances. Information based on Diamant et al.,(2017).

Having formulated p_{ij}(see Table9) we are able to adapt Equation 14 into Markov chain transition matrix (Equation 13). This adaptation results in the stationary state distribution (Equation 15), which helps us to determine the number of sterile instruments sets ready for their use in the OR storage on day t+1. The first two parts of Equation 15 represent the Markovian transition equation of the demand instances $P(D \geq i)$ and $P(D = i)$, while the last part is the normalization condition that ensure that all the probabilities add to 1. The procedures to find Equation 15 are shown in Appendix III.

$$\pi_{S-i}(S) = \pi_i(S)P(D \geq i) + P(D = i) \sum_{k=i+1}^{S} \pi_k(S) \ for \ i = 0, \dots, S \quad (15)$$

$$and$$

$$\sum_{i=0}^{S} \pi_i(S) \ = 1$$

SYMBOL	**DESCRIPTION**
$\boldsymbol{\pi_{S-i}(S)}$	Stationary state distribution
$P(.)$	Probability of observing determined demand instance D
$\boldsymbol{k}$	Instrument sets in inventory at the MST at the beginning of day t+1
$\boldsymbol{i}$	Instrument sets in inventory at the MST at the beginning of day t
D	Observed daily demand for instrument sets
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR or being sterilized
$\boldsymbol{\pi_i(S)}$	Long run average fraction of the time that there are i sterilized instrument sets at the beginning of day t in inventory. $i = 0, \dots, S$

To be able to solve Equation 15 we need first to initialise our calculations by determining the fraction of the time that the OR storage is empty $\pi_0(S)$ or full $\pi_S(S)$. This is done in Equations 16 and 17. These two equations are constantly decreasing in S.

$$\pi_0(S) = \frac{P(D = 0)P(D \geq S)}{1 - P(D \geq S)P(D \geq 1)} \quad (16)$$

$$\pi_S(S) = \frac{P(D = 0)}{1 - P(D \geq S)P(D \geq 1)} \quad (17)$$

SYMBOL	DESCRIPTION
$\boldsymbol{\pi_0(S)}$	OR storage is empty at the beginning of day t+1
$\boldsymbol{\pi_S(S)}$	OR storage is full at the beginning of day t+1
$P(.)$	Probability of observing determined demand instance D
D	Observed daily demand for instrument sets
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR or being sterilized

Since Equation 15 seems to be abstract, we introduce Equation 18 and 19, which are a more detailed formulation of Equation 15. These equations can be recursively solved by increasing i from 1 to $\frac{S-1}{2}$. If S is even $\pi\frac{S}{2}$ is found using the normalization condition.

$$\pi_{S-i}(S) = \frac{1}{1 - P(D \geq S - i)P(D \geq i + 1)}\left(P(D = i)\left(1 - \sum_{k=0}^{i-1}\pi_k(S)\right) + P(D \geq i + 1)P(D = S - i)\left(\sum_{k=S+1-i}^{S}\pi_k(S)\right)\right) \quad (18)$$

$$\pi_i(S) = \frac{1}{1 - P(D \geq S - i)P(D \geq i + 1)}\left(P(D \geq S - i)P(D = i)\left(1 - \sum_{k=0}^{i-1}\pi_k(S)\right) + P(D \geq S - i)\left(\sum_{k=S+1-i}^{S}\pi_k(S)\right)\right) \quad (19)$$

Having calculated the steady state probability that in a given day there is a certain quantity of instrument sets on inventory at the beginning of the day $\sum_{i=0}^{S}\pi_i(S)$. We are able to determine the service level.

Determining the service level

Diamant et al. (2017) and Kapalka et al. (2016), define the service level as the steady-state probability that in any given day, the demand of inventory exceeds the demand. The authors introduce Equation 20 as one minus the probability of stockout. Each term is explained below. Nevertheless, it is important to mention that S represents the number of available reusable sets (no single instruments) in the system. System refers to the sets that are in use, on the storage warehouse or being sterilized, not accounting the ones which are being repaired. Therefore, this model tells you the service level when there are determined quantity of instrument sets in inventory.

$$\alpha = 1 - \sum_{i=0}^{S}\pi_i(S)P(D > i) \quad (20)$$

SYMBOL	DESCRIPTION
$\boldsymbol{\alpha}$	Service level
$\boldsymbol{i}$	Instrument sets on inventory at the MST at the beginning of the day t
T	Current day
$\boldsymbol{D}$	Observed daily demand for instrument sets
$\boldsymbol{P(D > i)}$	Probability of stockout (demand is bigger than the inventory on hand)
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR or being sterilized
$\boldsymbol{\pi_i(S)}$	Long run average fraction of the time that there are i instrument sets at the beginning of the day t . $i = 0, \dots, S$

After having formulated the service level, we introduce the cost that would help us to analyse the trade-offs of holding different levels of instrument sets in inventory along with the resulting service level.

4.4.2 Determining costs and base-stock level for SMAU scenario

In this section we provide the formulations necessary to calculate the costs involved to obtain an optimal base-stock level. These costs are: stockout costs, holding costs, and purchasing costs.

Stockout cost

Commonly, when a surgery cannot be performed on the scheduled date, the hospital is able to reschedule the patient's surgery. However, these changes generate stockout costs. These stockout costs consist of the extra overtime hours for supporting staff, administrative, and the cost of leaving the OR capacity without use. In other words, the stockout costs denotes the costs produced by delaying a surgery. The stockout cost is presented in Equation 21.

$$\mathrm{SC(S)} = \beta \sum_{i=0}^{S} \pi_i(S)\, E(D-i)^+ \qquad (21)$$

SYMBOL	DESCRIPTION
$\mathbf{SC}(\boldsymbol{S})$	Long run average cost of stockout events depending of S
$\boldsymbol{\beta}$	Stockout cost in € per patient not served
$\boldsymbol{E(D-i)^+}$	Expected number of patients not served
$\boldsymbol{\pi_i}$(S)	Long run average fraction of the time that there are i instrument sets at the beginning of day t . $i = 0, \dots, S$

Holding costs

Holding cost is a fundamental KPIs for this research, because it allows to measure the trade-offs of keeping a high service level, by maintaining a high number of instrument sets in stock (see Equation 22).

$$HC(S) = \frac{h * S * SP}{T} \qquad (22)$$

SYMBOL	DESCRIPTION
$\boldsymbol{HC(S)}$	Holding cost in € per day depending of S
$\boldsymbol{h}$	Fraction of the capital invested on instrument sets S dedicated to holding inventory
$\boldsymbol{S}$	Instrument sets available in the system either in the storage OR or being sterilized
$\boldsymbol{SP}$	The price in € per instrument set
$\boldsymbol{T}$	Life time of each instrument set

Purchasing costs

The purchasing cost for this model is analysed in the same way as in the FMAU scenario (see Equation 11).

Total cost formulation

Equation 23 shows the total costs produced by purchasing and keeping determined number of instrument sets. The first part represents the purchasing cost and holding cost, the second part the long run average cost of stockout events.

$$C(S) = \frac{S*SP}{T}\,(1+h)\; + \beta \sum_{i=0}^{S} \pi_i \, E(D-i)^+ \quad (23)$$

Determining the optimal base-stock level

The optimal base-stock level is determined in a straightforward way, by identifying the amount of instrument sets that generate the minimal total cost according to the desired service level.

After having described and adapted the mathematical model that we aim to use as tools to answer our main research question, we need to determine how the stochasticity of the demand can be simulated in order to provide a more realistic environment. Therefore, this is explained in the next section.

4.5 Monte Carlo simulation

As was mentioned in Section 3.5 Monte Carlo simulation is a widely-used method for estimating the value of an unknown quantity using the principles of inferential statistics, which are represented in this case per the distribution of the demand of instrument sets. This method draws the properties from the observed data which in this case is the demand of instrument sets during a determined time period, by generating random samples. In order to create a simulation model that provides an accurate representation of the demand behaviour, we need to verify and validate our model. This is explained in Section 5.6.

4.6 Models assumptions and limitations

These models do not include all the real-life aspects of the system, like surgeon preferences at the moment of choosing an instrument sets, neither that the instrument sets could break which produces that their absent from the system. For these reasons in this section we describe the assumptions that were taken into consideration in order to be able to apply the mathematical models found in the literature (see Chapter 3). These assumptions are divided in: common, FMAU, and SMAU assumptions.

Common assumptions

We assume the following:

- In both scenarios FMAU and SMAU, the demand of instrument sets is stationary, independent, and identically distributed (i.i.d).
- The reparation of the instrument sets is made per single instrument, and when one single instrument is broken it is replaced immediately by another one.
- No substitution occurs, so if an instrument sets is not available it is not replaced for another type of set that could accomplish the same tasks.
- The events are independent, and the sum of its probabilities is 1.
- If there is no inventory on hand, demand is backordered and filled at a later point in time when inventory has been replenished.
- The user is the one that specify the desired service level, according to the costs generated by different base-stock levels.
- When running the Monte Carlo simulation, the demand per day is random, but stationary (i.e. the mean and the variance do not fluctuate in the time because of seasonal effects or trends).
- The model does not take into account urgent patients, for this reason we use the observed data to create a random demand (generated by Monte Carlo simulation), which describes the behaviour of the demand of every type of patient (urgent or elective)

FMAU assumptions

- Sterilized instrument sets are available in the OR storage each morning after their use in the ORs.
- The Monte Carlo simulation produce random daily demand values that follow the normal distribution.

SMAU assumptions

- Sterilized instrument sets are available in the OR storage the second morning after their use in the ORs.
- The Monte Carlo simulation produce random daily demand values that follow the empirical distribution of the observed data.

4.7 Conclusion

In this chapter we combined the models found in the literature discussed in Chapter 3. To be able to model and answer the research question: "How can we create a model based on the found methodologies that helps to answer our main research question?"

Since there is not accurate information that identify the amount of time that it takes for instrument sets to comeback sterilized to the OR storage after their use in the OR. It was necessary to create a best-case scenario where the instruments are ready to be used (sterilized) in the OR storage after their use in the ORs called FMAU scenario and a worst-case scenario, where the instrument sets are available in the OR storage at the second morning after their use in the ORs, this last scenario rather than represent the worst-case scenario could exemplify the situation where CSA outsource sterilization services.

The FMAU scenario modelled using two different distributions: normal and empirical. If the demand follows a normal distribution and parameters such lead time and review period can be estimated. The (R,S) Inventory control policy can be applied. Nevertheless, some conceptual adaptations were necessary to be able to apply this policy. Inventory control policies are based on disposable supplies that go through a hierarchical supply chain. Since we are focused on reusable supplies, we needed to make different conceptual adaptations. First, we closed our scope to the single echelon supplies chain system which is confirmed by the next departments: warehouse, supplier, and consumer (see Section 2.6.1 & 2.6.2). These departments were adapted into our case study. The warehouse represents the OR storage, the supplier the CSA that provides sterilized instrument sets to the ORs (customers). Inventory control polices assume a normal distribution. Therefore if the demand follows a normal distribution, we are able to apply the formulations to find the base-stock levels of the (R,S). Since the costs formulations from the (R,S) inventory control policy is addressed for disposable supplies, we adapt these costs formulation to reusable supplies, which is the case of reusable instrument sets. Moreover, the service level performance is calculated by applying the CSL (see Section 4.3.2).

If the distribution of the demand does not fit a normal distribution and parameters such as lead time and review period are not reliable, we are not able to use the inventory control policies. For this reason, we created a model that uses the empirical distribution of the observed data. This model uses the random demand generated by Monte Carlo simulation model, which by setting a target service level, it obtains the amount of instrument sets needed to satisfy this service level (see Section 4.3.2). The costs formulation is performed in the same way that the FMAU for normal distribution demand does. The SMAU model was created by applying the Markov chain transition matrix, which helps to determine the average fraction of the time that there are certain number of instrument sets available at the beginning of the second morning. This allowed us to determine the service level and the costs involved, when having determined amount of instrument sets in the system (see Section 4.4). In order to produce random demand that follows a normal or empirical distribution, we created a Monte Carlo simulation model, which will help us to produce random daily demand based normal or empirical distribution. To analyse the trade-offs between service level and costs that involves having different levels of inventory.

After having identified and described the mathematical models suitable for finding the optimal base-stock level that minimizes the costs, while keeping a desired service level, we need to evaluate the functionality of our models by the creation of experiment designs. This is provided in the next chapter.

5 Experiment design

In this chapter we aim to design different experiments to test how many instrument sets we will require under different circumstances according to the determined service level. With these experiments, we aim to get insights into the performance of the current situation and what would be the optimal base-stock level of instrument sets under different scenarios and increases in demand.

The structure of this chapter is as follows (see Figure 28). Since there is a large quantity of instrument sets and each has a different demand behaviour, the selection of an instrument set type is required, this selection is performed in Section 5.1. After determining the instrument set to be studied, it is necessary to evaluate the demand distribution of this instrument to be able to choose one of the FMAU models (normal or empirical), which is discussed in Section 5. 2.To continue, in Section 5.3 an overview of the experiments is provided. In Section 5.4 the input data, output data, parameters, software used to create the present model, and the level of detail that this model can provide is identified and described. Since it is relevant to prove that the simulation model is a good representation of the real situation, it is verified and evaluate in Section 5.6. Finally, in Section 5.7, a conclusion of this chapter is presented.

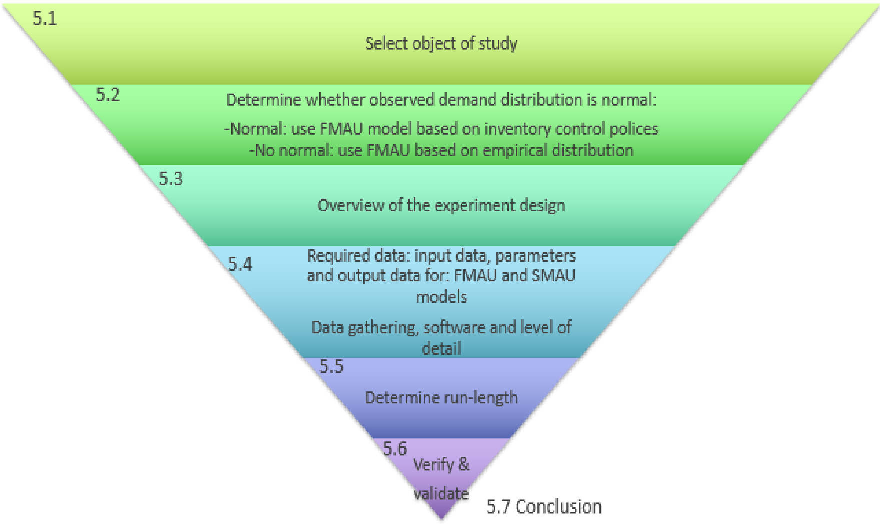


Figure 28 Experiment design structure. Based on Law (2017).

5.1 Selecting object of study

MST holds around 1000 different type of instrument sets. Therefore, in this section we aim to identify an instrument set that exemplifies the current problem in order to show the functionality of our model. The selection of our research scope is based on the arguments presented in the next paragraphs.

In this study, the focus is on the inventory management of instrument sets at the MST hospital. For the propose of this study we need to analyse the demand of the instrument sets. Normally, the procedure to determine which SKU are the most important to analyse in an inventory system, is applying an ABC inventory analysis. However, such a model accounts only for the cost without considering other important elements in the healthcare system such as storage space, demand variability, service level (Ehsan et al., 2018). Since the hospitals main goal is to provide a high-quality service care, any reduction of costs within a hospital should not compromise the health of the patient. Moreover, another important factor that does not allow the execution of an ABC analysis is related to the quality of the information. The availability of information such as the capital investment and demand of each type of instrument sets is not available or the data is unreliable. Nevertheless, to gain insights into this process, we will focus specifically on the laparoscopy instrument sets. We have chosen the laparoscopy set for the following reasons:

- It is frequently used within different kinds of surgeries, so the quantity of data allows to analyse better its demand behaviour.
- The treatment description is named after the instrument set, so it is easier to track in both systems used at MST: Steriline (Manage of instrument sets) and OR suite (Manage ORs surgery schedules)
- The purchasing cost of the laparoscopy set is around €13,000 and the MST stores 20 instrument sets in its OR storage, which represents a capital investment of around €260,000.
- It contains complex instruments difficult to sterilize, which makes this set category four (see Table).
- The instrument set is kept in a large container (53.5cmx25.5cmx9.5cm) which occupies a considerable amount of space in the OR storage.
- Laparoscopy instrument sets requirement per year during 2017-2018 was 1,200, where the maximal request of this instrument set was 12 and it just happened 3 days in the entire year.
- The service level related with this instrument set has been 100% from 2016-2017.
- On average there are 3.8 surgeries per day that required laparoscopy instrument sets

5.2 Determining demand distribution

In this case study, we explore two scenarios: FMAU scenario, where laparoscopy instrument sets return to the OR storage the first morning after the use in the ORs, and the SMAU scenario where the instrument set returns sterile to the OR storage the second morning, since the FMAU use different formulations according to the demand distribution. We must determine whether the observed demand follows a normal distribution or not. If the observed demand behaves like normal distribution, we use the model based on inventory control polices, otherwise the model based on empirical distribution. For this reason, it is important to determine first whether the observed demand of laparoscopy instrument sets behaves as a normal distribution.

A insightful way to determine if the observed demand follows a normal distribution, is by comparing the histograms of both observed and normal distribution. Figure 29, shows the red line which represents the normal distribution bell and the histogram of the observed data. As it is possible to see the normal distribution bell does not fit our observed data distribution.

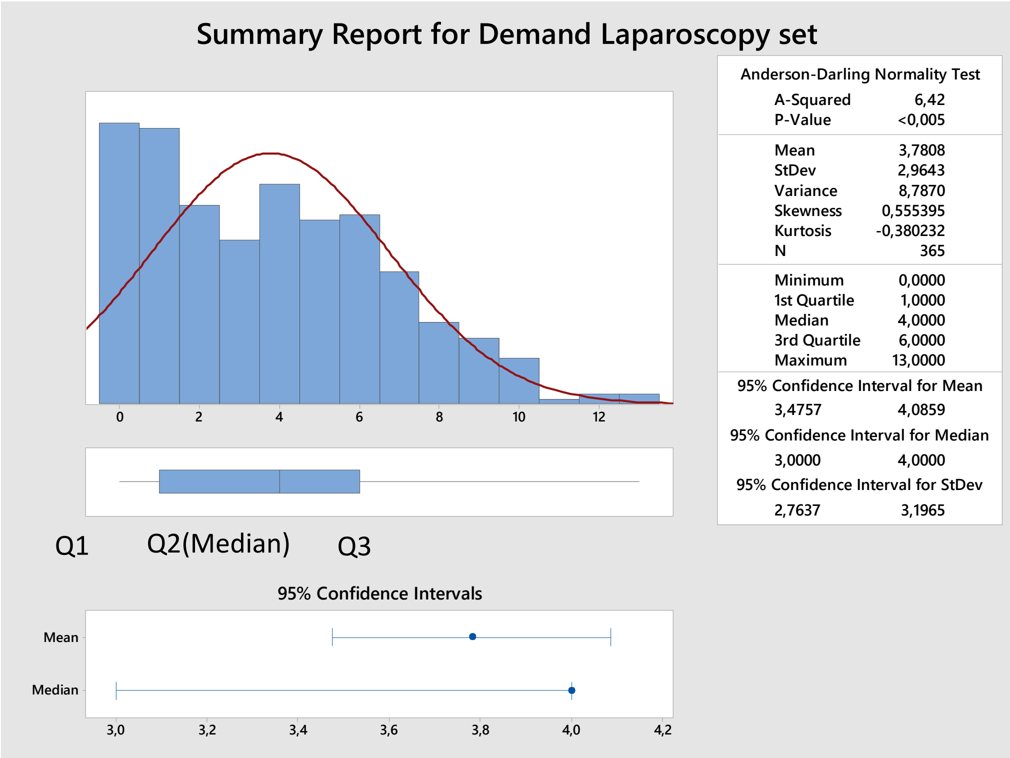


Figure 29 Statistics summary of observed and normal distribution of laparoscopy instrument sets. Sample of 365 days from 2017. Data extracted from Sterline in 2018.

To enhance our conclusion, we perform an Anderson-Darling normality test, which evaluates the p-value (see Table 10).

	Description
p-value	<.005
A	.05
Test:	H_0: The observed data follow a Normal distribution H_1: The observed data do not follow a Normal distribution
Test interpretation	As the computed p-value is considerably lower than the significance level α= .05. We can say that there is not enough evidence to assume that the observed distribution is normally distributed. Therefore, the risk to reject the null hypothesis H(0) while it is true is less than .5%

Table 10 Aderson-Darling normality test.

To finalize, we create a P-P plot (Probability-Probability) which compares the cumulative distribution of the observed and normal data (Figure 30). Since it is possible to see the major quantity of observations are out of the red line (normal distribution), which implies once again that the observed data cannot be represented by a normal distribution.

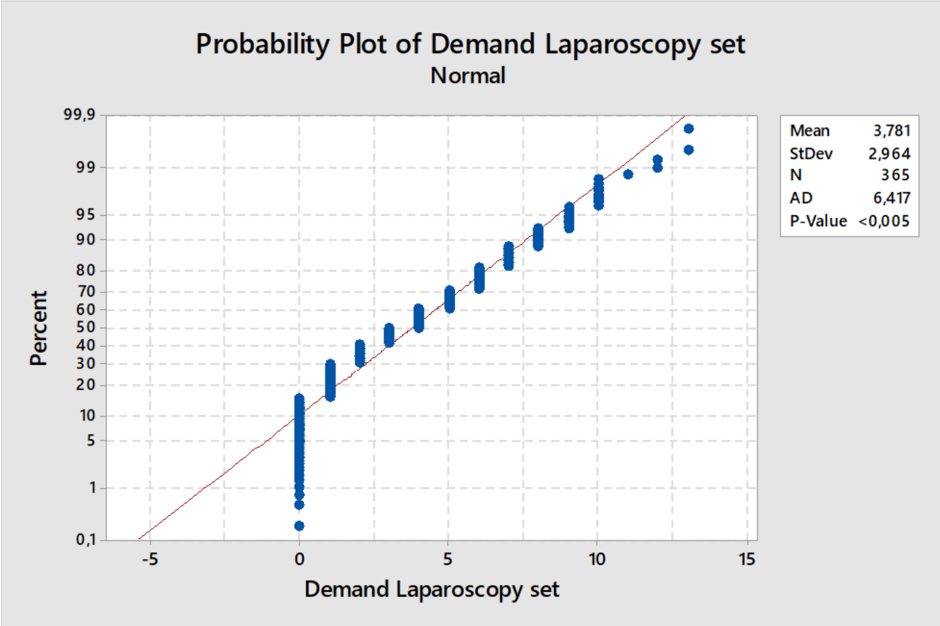


Figure 30 P-P plot, demand of laparoscopy instrument sets during 2017. Sample of 365 days from 2017. Data gathered from Steriline in 2018.

Now having enough evidence to assume that the demand of laparoscopy instrument sets does not follow a normal distribution, we can select the FMAU model designed for empirical data distribution.

5.3 Overview of experiments

The experiment design aims to define the input, parameters, output data and the number of runs that the simulation model (Monte Carlo simulation) needs to resemble the behaviour of the real system. Moreover, experiment design also aims to ensure that each step in the process of creating the proposed models be verified and validated to provide the best representation of the real system. Figure 31 provides us with a clear illustration of the use of the elements defined during the experiment design in the whole system.

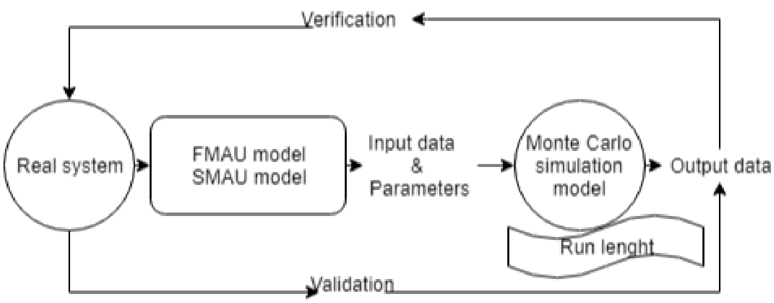


Figure 31 Overview of experiments design.

5.4 Required data

In this section we provide an explanation of the data required for the FMAU and SMAU. In Section 5.4.1 and Section 5.4.2 the definition of the input data and parameters required to run Monte Carlo simulation model is provided, while in Section 5.4.3 the identification and description of the output data expected from the simulation model is provided. In Section 5.4.4 the procedure to gather the input data is described. The software needed to program the mathematical models for each scenario and the simulation model described in Chapter 4, is introduced in Section 5.4.5 while in Section 5.4.6 we describe the level of detail that this model is able to research. To conclude, in Section 5.4.7 we describe the level of detail that our proposed model is able to reach.

5.4.1 Input data

The main objective of this study is to find a model that determines an optimal base-stock level that satisfies the demand. For this reason we select demand of laparoscopy instrument sets during the period of 2017 as our input data. This demand is represented by the orders raised for ORs when they require the sterilization of instrument sets. Since each instrument set must go through the sterilization process once it is opened in the ORs, each sterilization is considered as the demand.

In order to provide robustness to our model, we apply a probability transformation where we assume that the percentage increase in demand is uniformly distributed through each day from the year. Since the demand from 2016-2017 has increased by 8% in the year thereafter, we take increases of the demand of the same size. These increases are illustrated in Table 11.

Demand increments			
	Min.	Most likely	Max.
Stockout costs (€)	8%	16%	24%

Table 11 Yearly demand increase. Data based on demand increase from 2016-2017, Steriline 2018.

5.4.2 Parameters

In order to determine the optimal base-stock level for both scenarios we need to specify the parameters that are essential to analyse the performance of different base-stock levels. Since the MST does not have the exact measure of most the required parameters for the FMAU and SMAU models, we must estimate their values. These parameters are listed below:

- Quantity of Instruments in the system(S): this parameter is essential to determine the performance of the current situation of the laparoscopy instrument set. Therefore, after interviewing the instrument manager and consulting Steriline (database used for managing instrument sets) it was determined that MST holds in total 20 laparoscopy instrument sets in its inventory.
- Time to replace instrument set (T): the procurement of instrument sets occurs anywhere in a period of 5 years (Diamant et al., 2017), this period was confirmed by interviewing the instrument manager.
- Set price (SP): after several interviews with the CSD planner and the purchasing department we determined that the laparoscopic instrument set has a value of around €13,000 which includes 62 instruments that are hold together by a metallic tray of two levels which has a cost of around € 200 (already included in the total value).
- Holding % (h): normally holding costs between 15% and 35% (Heizer et al, 2008). Therefore, we present the increase according to the percentage cost of the inventory value as is shown in Table 12.

Annual inventory holding costs			
	Min	Most likely	Max
Cost as a percentage of inventory value	15%	26%	35%

Table 12 Annual inventory holding costs. Information based on Heizer et al.(2008). Operations Management page 480

Stockout costs (β): laparoscopy instrument sets are used in several type of procedures, and the cost of cancelling a surgery should be dependent of the type of surgery that has to be rescheduled. Nevertheless, the stockout cost is in the MST is not documented. Therefore, in this study we use an estimated proposed by Appavu et al. (2016). The authors estimate the cost of an unused operation room to be around €1,300 - €3,000 per hour not used. Since the average time that the laparoscopy instrument sets are in the operation room is 1.5 hours, we will set the stockout cost with the values shown in Table 13.

Stockout cost			
	Min	Most likely	Max
Stockout costs (€)	€1,000	€2,000	€3,000

Table 13 Stockout costs. Based on Appavu et al., 2016.

5.4.3 Output Data

The main output that we aim to achieve is the optimal base-stock level of instrument sets that satisfies a desired service level. Since we are interested on evaluate the trade-offs of having different base-stock levels, we consider service level, holding, purchasing and stockout costs as important output data to be evaluated at the moment of decide how many instrument sets should be purchased or hold in inventory.

5.4.4 Data gathering

The demand of instrument sets is gathered from Steriline, which is the database that controls and administrates the instrument sets. Since the data from Steriline is duplicated, we need to clean the data by comparing the data from Steriline with the data from ORsuite (database that schedules patients and ORs). This comparison needs to be performed in order to ensure that the instrument sets were really used in the ORs. To achieve this, we plan to use TABLEAU 2017. This program allows to connect patients from ORsuite and instrument sets from Steriline.

The demand gathered from these two systems is from the year 2017. This period is chosen because the information needed to perform this study is complete. Therefore, this study can be carried out based on the behaviour of the laparoscopy instrument sets demand during a whole year, meaning that the sample size of this case study is 365 days.

5.4.5 Software

We use VBA together with Excel spreadsheets to develop and run our discrete Markov Chain model and to create our Monte Carlo simulation for FMAU and SMAU models. This macro programming language is available in Excel. This programming tool is chosen because the MST has already MS Excel 2017 installed in its system, and the personal is already familiar with this software, which makes easier for the personal to manage the proposed models. The analysis of the demand distribution was performed through the use of MINITAB 2017, which is software that facilities the statistical analysis of data.

5.4.6 Level of detail

The FMAU for empirical distribution and SMU models do not take into consideration factors like the specific preferences from the patients, emergency situations, time of maintenance of the instrument sets nor the capacity of the staff necessary for each stage of the instrument set flow.

5.5 Determining the run-length

An important part of an experiment design is to determine the number of runs (run-length), that need to be performed by Monte Carlo simulation model. This is necessary, to ensure that the random demand generated by this simulation model represents as much as possible the behaviour of the observed demand. To achieve this, we compared the average demand of two run-length: 50 and 100. As is possible to see in Figure 32, the run-length that better defines the observed data (red line) is 100. This run-length shows the smallest difference between their means(µ) and standard deviations (σ). Therefore, we can conclude that performing 100 experiments (runs) we can ensure that the simulation model can provide us with data that represents the best the current demand behaviour of the laparoscopy instrument sets.

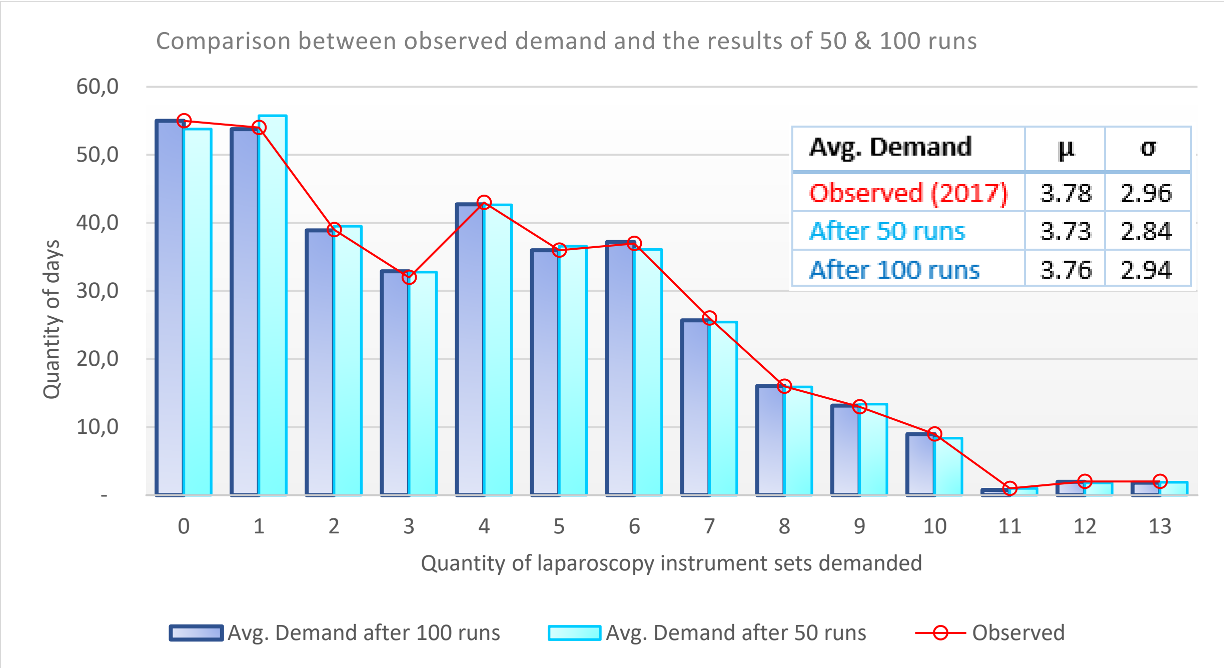


Figure 32 Comparison between the observed demand in 2017 of the laparoscopy instrument and different run-length configurations. Data gathered from Steriline in 2018.

5.6 Verification and validation

In order to know if our simulation model is an accurate representation of the real situation and if the assumptions of the conceptual FMAU and SMAU models have been well translated, we need to verify and validate our simulation model. This is fundamental, because future experiments can provide us with more reliable information. These two concepts are defined in Figure 33.

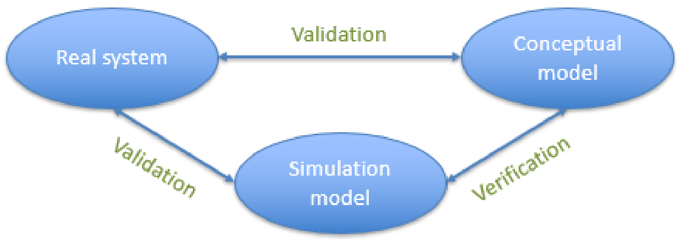


Table 33 Verification & validation cycle. Adapted from Law (2017).

Law (2017) defines verification as the process of determining whether the conceptual model is being correctly translated into a computer program, while validation is the process of determining whether the simulation model is an accurate representation of the system.

5.6.1 Verification

We verify both models by interviewing the staff from the CSD, in order to check if the data generated by our simulation was close to the real behaviour of the system. The staff was able to set their own parameters and the outputs coincided with their estimates. Moreover, we were also constantly debugging our simulation model, in order to find inconsistencies in the outputs. Additionally, we trace the mathematical formulation by disclosing the variables in order to be able to compare the on-hand calculations by the way the simulation model was calculating the required outputs.

Since the service level was not measured previously, but the annual complaint report from 2017 shows that the MST never cancelled a surgery due to not sterilized instrument sets on inventory, we determine that the service level in 2017 is 100%, which was proved to be true even in the SMAU model. Moreover, regarding specially to the SMAU model we verify the functionality of our model by introducing as input data the information provided by Diamant et al (2017) about a Canadian Hospital. The outputs of their model coincide with ours.

5.6.2 Validation

Validating our simulation model is fundamental to determine if it is an accurate representation of the reality. If it is valid then we can use it to make decisions without incurring to the costs and risks that experimenting with the real system involves. To validate our model, we use historical input data represented by historical demand from 2017. We compare the outputs from the real situation and the outputs from the average demand after 100 experiments using the Monte Carlo simulation model. Following the next approach shown in Figure 34.

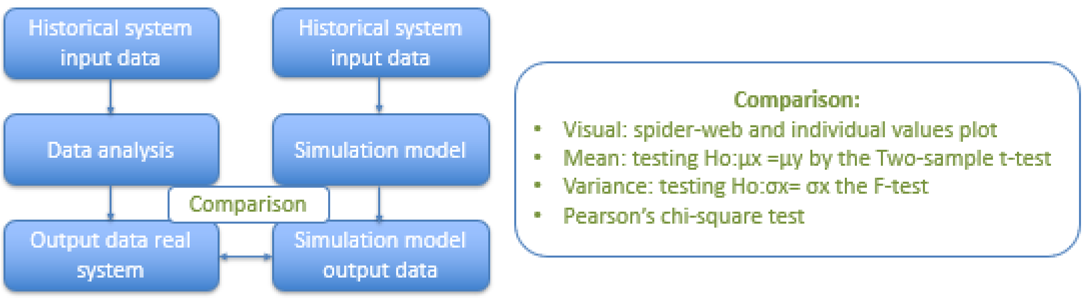


Figure 34 Comparison between real and modelled system. Based on Law (2015).

Visual comparison: the spider-web and the individual value plot Figure 35 shows the results of the average demand after 100 experiments performed by our simulation model. Since it is possible to observe in the spider-web plot the simulated demand represented (blue line) follows closely the real demand (red line). Moreover, the means shown in the individual value plot represented by a blue line, seems to be symmetric.

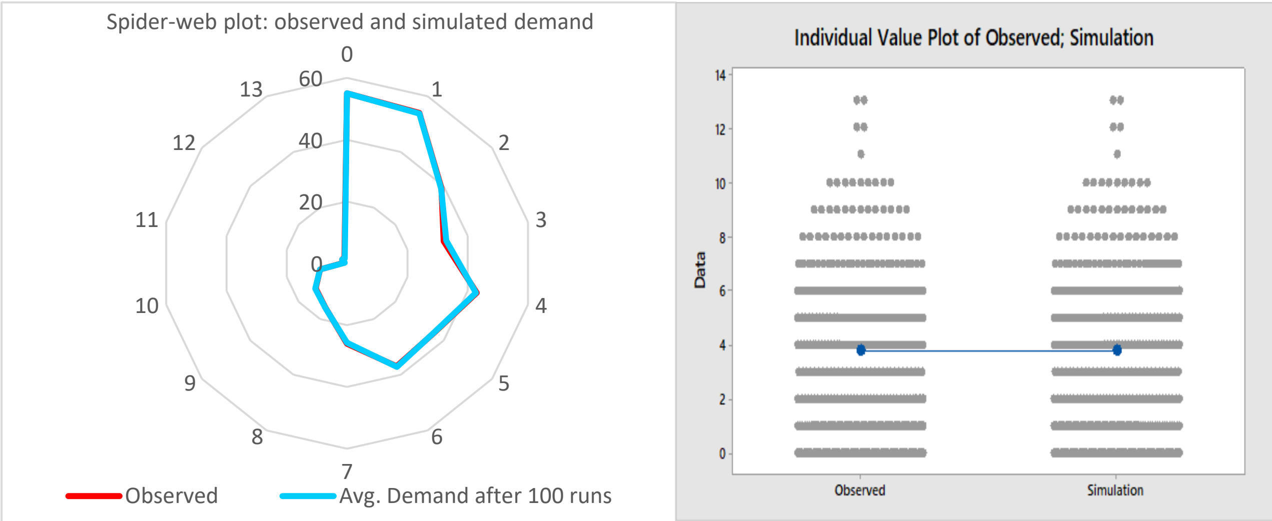


Figure 35 Spider-web and individual value plot observed vs. simulated demand. Data gathered from Steriline in 2018.

This visual exemplification seems to be a good approach to conclude that the simulated model is a good representation of the real situation. Nevertheless, it is important to compare variable parameters such as mean and variance. This comparison becomes a critical piece of information to determine if both systems behave similarly. Therefore, in the next paragraphs we perform such statistical comparisons.

Mean comparison: in order to enhance our findings we compare the means form the real (μ_x) and modelled system (μ_y). To achieve this we perform a t-test to tests the null hypothesis H_o:$\mu_x=\mu_y$ vs. H_1:$\mu_x \neq \mu_y$ by applying Equations 24 & 25. This test is shown in Table 14.

$$s_p = \frac{(n-1)\sigma_x^2 + (m-1)\sigma_y^2}{n+m-2} = \frac{(365-1)*2.96+(365-1)*2.96}{365+365-2} = 2.96 \quad (24) \qquad t = \frac{\mu_x - \mu_y}{s_p\sqrt{\frac{1}{m}+\frac{1}{n}}} = \frac{3.78-3.79}{\sqrt{\frac{1}{365}+\frac{1}{365}}} = -0.02 \quad (25)$$

Testing Ho: µx =µy -The two samples t-test : mean observed and simulated demand

	Description			
Parameters and method	t= t-value μ_x: mean of observed demand Laparoscopy set μ_y: mean of the simulated demand after 100 experiments s_p:polled variance σ_x^2 & σ_y^2sample variances x and y n & m: sample size form observed (n) and simulated demand (m) Difference: μ_x-μ_y			
Descriptive statistics	Sample	N	$\mu_{x\,\&\,y}$	$\sigma^2_{x\,\&\,y}$
	x=observed demand Laparoscopy sets	365	3.78	2.96

	y= simulated demand distribution		365	3.79	2.96
Estimation for difference	Difference	Pooled StDev	95% CI for Difference		
	-0.005	2.963	(-0.436, 0.425)		
Test	H_o:μ_x=μ_y vs. H_1:μ_x≠μ_y				
	T-Value	DF	P-Value		
	-0.02	728	0.980		
Test interpretation	Since the p-value=0.980 is bigger than α= .05, we do not have enough evidence to reject H_O. This means that we can assume that the means between both samples are equivalent, with a 95% certainty, that there is not a significant difference between the means of the observed and the average demand simulated by our model.				

Table 14 Two samples t-test Ho:μ_x=μ_y.

Variance comparison: to determine if our random sample demand from our simulated model differs produce a variance in its data, like the real systems does, we compare the variances between both models by applying the F-test represented in Equation 26 to test the Ho: $\sigma_y^2/\sigma_x^2 = 1$ vs. H1: $\sigma_y^2/\sigma_x^2 \neq 1$.

$$F = \frac{\sigma_y^2}{\sigma_x^2} = \frac{2.964}{2.961} = 1.0010 \quad (26)$$

Parameters	**F**: F-test or variance ratio test $\boldsymbol{\sigma_x^2}$: variance of observed demand Laparoscopy set $\boldsymbol{\sigma_y^2}$: variance of simulated demand after 100 experiments

The Ho states that the ratio between the standard deviations is 1. Because the p-values by Bonett and Levene, p-value=0.982 and p-value=.96 respectively (see Figure 36), are both greater than the significance level α =0.05 (see Figure), we fail to reject Ho. We do not have enough evidence to conclude that the standard deviations between the real and our model are different. The detailed F-test can be found in Appendix IV.

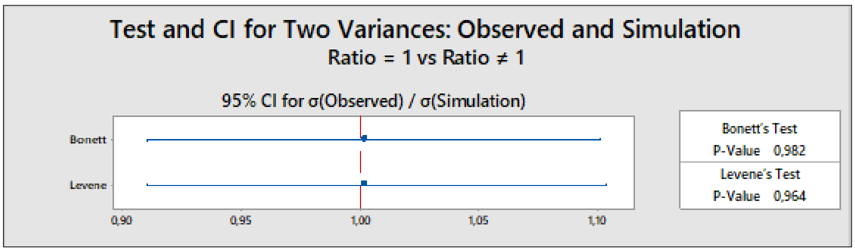


Figure 36 Test and confidence intervals α =0.05 from the observed and simulated demand. Data gathered from Steriline 2018.

Pearson's chi-square test (χ^2-test): another way to check whether our set of observations significantly defers from the simulated empirical distribution, we perform the Pearson's chi-square test. The idea behind this test, is to compare the cumulative distribution of both distributions by dividing the observed data into bins and to compare the number for occurrences per bins with the simulated empirical data. This is expressed in Equation 27 ant tested in Table 15 :

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \quad (27)$$

Parameters	$\boldsymbol{\chi^2}$: the Peron's cumulative test statistic $\mathbf{O}_{\boldsymbol{i}}$: the number of observed demand Laparoscopy sets $\boldsymbol{E_i}$: the number of simulated empirical demand Laparoscopy sets $\boldsymbol{n}$: the number of bins
Test	H_0: there is no difference between the distributions H_1 there is a difference between the distributions α=95% and DF=n-1=12 $\chi^2 - table$ DF $\chi^2 - data$ 21.03 12 .1108
Test interpretation	The $\chi^2 - data = .1108$ is lower than $\chi^2 - table$=21.03 Therefore, we can fail in rejecting Ho, in other worse we do not have enough evidence to assume that the random demand produced by Monte Carlo simulation differs from the observed demand.

Table 15 Chi-square test.

After observing the visual and statistical tests such as: t-test, F-test and the χ^2-test, we have enough evidence to conclude that our output data from our model resembles properly the real behaviour of the demand of laparoscopy instrument sets during 2017.

5.7 Conclusion

In this section we answer our fourth research question: "How should the experiments be designed?"

Since the MST is not measuring several KPIs, in this chapter we provided the parameters and the input data required to represent different changes in the demand. This with the object of finding the optimal base-stock level, through different demand increases. In order to verify and validate our model we apply different techniques such as: debugging, interviewing the staff and breaking down the code from the programmed models, to analyse their way of calculating the KPIs. Moreover, in this section we defined the laparoscopy instrument set as our test case instrument set.

The next chapter shows the results of the experiments designed.

6 Experiment results

In this chapter, the results from 20 different configurations (100 iterations each), obtained from experimental design, are analysed. The performance measurement and the evaluation between configurations is firstly based on the comparison between total costs and service levels to determine when the costs start decreasing and increasing while using different service levels. Secondly, it is based on the comparison between the holding and purchasing costs against the stockout costs. Since the main interest of this research is finding an equilibrium between service level and total costs, services levels lower than 97% were not considered, because lower service levels increase the total cost considerably.

In Section 6.1 an overview of the selection of the settings used to evaluate the results of various experiment configurations is given. In Section 6.2 the experiment results from FMAU scenario based on the empirical distribution model are analysed, while in Section 6.3 the results from SMAU are evaluated. Finally, in Section 6.4 a conclusion of this chapter is provided.

6.1 Settings of the experiments

Since the MST does not have the values of essential parameters for measuring the performance of the system, we select the most likely parameters found in Chapter 5 in order to find an optimal solution considering a fair comparison between service level and costs involved (see Table 16). Moreover, to evaluate the robustness of our model, we calculate several fluctuations in demand. More specifically, we assess the optimal number of instrument sets if the demand stays at the level of 2017, or increases with 8%, 16% or 24%. These percentages were chosen because the observed increase of the demand from 2016 to 2017 was 8%.

Parameters	*Values*
Period of study	2017
Object of study	Laparoscopy instrument set
Quantity of instruments in the system(S)	20 (current situation)
Set price (SP)	€13,000
Stockout cost (β)	€2,000
Holding % (h)	24%

Table 16 Values from the parameters found in Chapter 5.

6.2 Results for FMAU scenario

Since one of the purposes of this study is to gain insights into the performance of the current situation, while the current performance is currently unknown, we analyse the performance of the observed demand of the laparoscopy instrument sets under first morning after use (FMAU) scenario. In the current situation the hospital holds 20 laparoscopy instrument sets. Therefore, we analyse the costs and service level performance from the current number of instrument sets in order to compare them with different base-stock levels. This is done to see how the system will perform if the number of instrument sets is reduced. This procedure is described in Section 6.2.1. To analyse the robustness of the proposed system, we evaluate the number of instrument sets needed in case the demand increases. This process is explained in Section 6.2.2, while in Section 6.2.3 a sensitivity analysis is performed in order to evaluate how the outcomes of the model react when variating the input parameters. Finally, in Section 6.2.4 the determination of the optimal base-stock level is carried out.

6.2.1 Current situation

Table 17 shows the average outcomes of 100 iterations obtained from Monte Carlo simulation for empirical distributions. In this experiment we take the most likely stock cost of €2,000 and a holding percentage of 26%, in order to find an optimal solution considering a fair comparison between service level and costs involved. The current quantity of instrument sets has ensured a high service level of 100%, with €0 stockout cost. However, this comes with high hidden costs such as purchasing and holding costs which amount to €119,600. These hidden costs can already be reduced by 40% by having only 12 instrument sets on stock instead of the current 20 sets, while still maintaining a service level of 100%. However, the total costs with 12 instrument sets (€71,760.00) is higher than in case of having only 11 sets (€69,780.00). Therefore, the equilibrium between costs and service levels lies at 11 instrument sets. This quantity of instruments generates a cost reduction of 42% with still a desirable service level of 99% with just 0.1% of possible patients not served out of 1,380 surgeries performed during a year.

% increase in demand	# Sets	AVG. Service level	AVG. Safety stock	AVG. Stockout Probability	AVG. Stockout cost	Purchasing +Holding costs	AVG. Total	% difference between current situation and S*	Total AVG. demand
Current situation	20	100%		0.0%	€ -	€ 119,600.00	€ 119,600.00		
0%	12	100%	8	0.0%	€ -	€ 71,760.00	€ 71,760.00	40%	1380
	11	99%	7	0.1%	€ 3,836.00	€ 65,780.00	€ 69,616.00	42%	
	10	98%	7	0.2%	€ 6,291.79	€ 65,780.00	€ 72,071.79	40%	
	9	97%	5	1.2%	€ 33,779.70	€ 59,800.00	€ 93,579.70	22%	

Table 17 Annual cost comparison between number of instrument sets kept in stock. 1380 laparoscopy surgeries per year on average from 100 runs. Data from 2017 extracted from Steriline and ORsuite (2018).

6.2.2 Robustness of the model

To check the robustness of the model, we increment the demand to determine the optimal number of instrument sets kept in inventory with different percentage of increases of demand. Table 18 shows the comparison between the optimal solutions found in each experiment. It demonstrates that the minimal total costs are generated at a service level of 99%, in each increase of demand, except for the case of 8% of increased demand. In that case, the lowest costs can be found at a service level of 98%.

% increase in demand	# Sets	AVG. Service level	AVG. Safety stock	AVG. Stockout probability	AVG. Stockout cost	Purchasing +Holding costs	AVG. Total	% difference between current situation and S*
Current situation	20	100%		0.0%	€ -	€ 119,600.00	€ 119,600.00	
0%	12	100%	8	0.0%	€ -	€ 71,760.00	€ 71,760.00	40%
	11	99%	7	0.1%	€ 3,836.00	€ 65,780.00	€ 69,616.00	42%
	10	98%	7	0.2%	€ 6,291.79	€ 65,780.00	€ 72,071.79	40%
	9	97%	5	1.2%	€ 33,779.70	€ 59,800.00	€ 93,579.70	22%
8%	13	100%	9	0.0%	€ -	€ 77,740.00	€ 77,740.00	35%
	12	99%	9	0.2%	€ 5,840.89	€ 71,760.00	€ 77,600.89	35%
	11	98%	7	0.5%	€ 16,178.02	€ 59,800.00	€ 75,978.02	36%
	10	97%	5	1.1%	€ 34,077.74	€ 53,820.00	€ 87,897.74	27%
16%	14	100%	10	0.0%	€ -	€ 90,794.49	€ 90,794.49	24%
	12	99%	9	0.2%	€ 6,369.23	€ 71,760.00	€ 78,129.23	35%
	12	98%	8	0.7%	€ 21,820.07	€ 71,760.00	€ 93,580.07	22%
	11	97%	7	1.25%	€ 40,170.64	€ 65,780.00	€ 105,950.64	11%
24%	14	100%	10	0.0%	€ -	€ 90,794.49	€ 90,794.49	24%
	13	99%	9	0.1%	€ 1,900.28	€ 77,740.00	€ 79,640.28	33%
	12	98%	7	0.5%	€ 17,441.45	€ 71,760.00	€ 89,201.45	25%
	11	97%	6	1.0%	€ 33,964.27	€ 65,780.00	€ 99,744.27	17%

Table 18 Outputs of Monte Carlo simulation after 100 iteration of empirical random probability. Data from 2017 extracted from Steriline and ORsuite (2018).

As such, it seems that even with an increase of 8% compared to the situation of 2017, 12 instrument sets are still a good option for the base-stock level. Nevertheless, in case the demand increases by 24%, one extra instrument set is needed to ensure a 100% service level.

6.2.3 Sensitivity analysis

Given that we are interested in finding an equilibrium between costs and a desired service level, the outputs need to be evaluated. In order to provide a more detailed explanation of results, we analyse the most likely scenario of 16% increase of demand. Moreover, Table 18 shows a jump between sets from 14 sets with 100% service levels to 12 sets producing 99% service level. Therefore, it is also interesting to analyse the service levels from 95% to 100% with an increase rate of 0.5%.

Total annual cost versus service level

Figure 37 shows that if the system allows all the used instrument sets to be available again in the OR storage the morning after being used, and having 20 instrument sets in stock, the current service level is already 100%. Nevertheless, it generates the highest cost, because of the holding and purchasing costs. Conversely, having only 10 instrument sets in inventory while setting a low target level, increases the cost and risk of stockout events, producing almost the same cost of purchasing and holding as with 20 instrument sets. Therefore, the optimal number of instrument sets lies between 12 and 14. However, choosing the base-stock depends on the service level that the MST sets as a target. Figure 37 shows the same number of instrument sets have different total costs and service level. These differences are caused by the negative correlation between service level and the probability of stockout, which causes that any decrease in the service level or base-stock level produces an increase in the stockout probability and vice versa. Figure 38 shows this negative correlation. For instance, having 12 instrument sets in stock comes along with a risk of running out of stock 3 times out of 1,600 laparoscopy surgeries per year. This represents the 0.2% of patients not served due to the availability of the necessary instrument set. Therefore, with the information provided it is possible to affirm that with an increased demand of 16%, the hospital can serve 100% of the coming patients with 14 instrument sets. Nevertheless, the management needs to take into consideration the costs involved and the probabilities of stockout events in order to determine the service level that matches their goals.

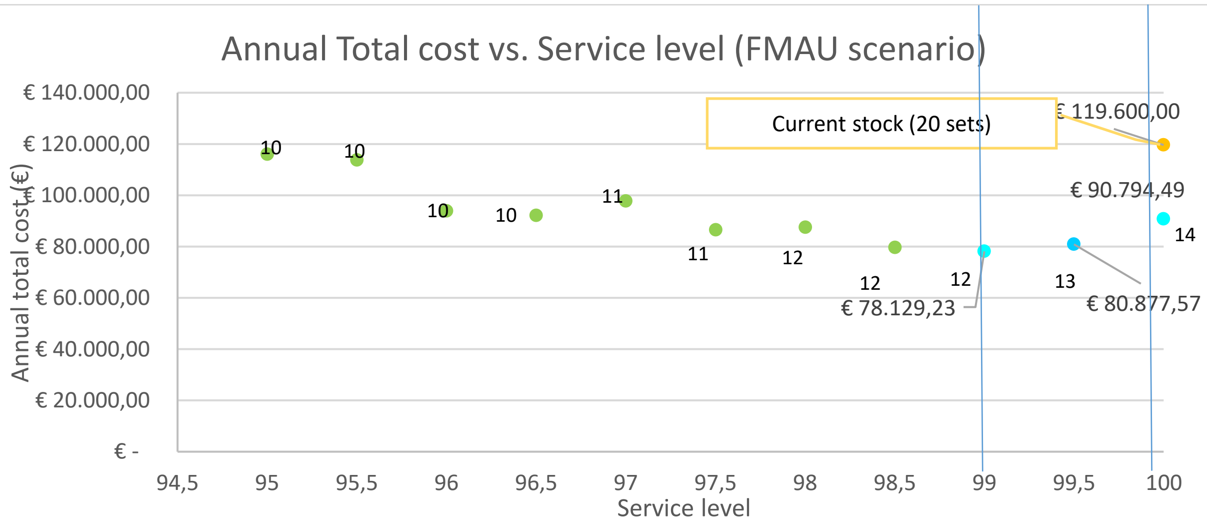


Figure 37 Total cost vs. Service level, considering a 16% of demand increase. Data from 2017 extracted from Steriline and ORsuite (2018).

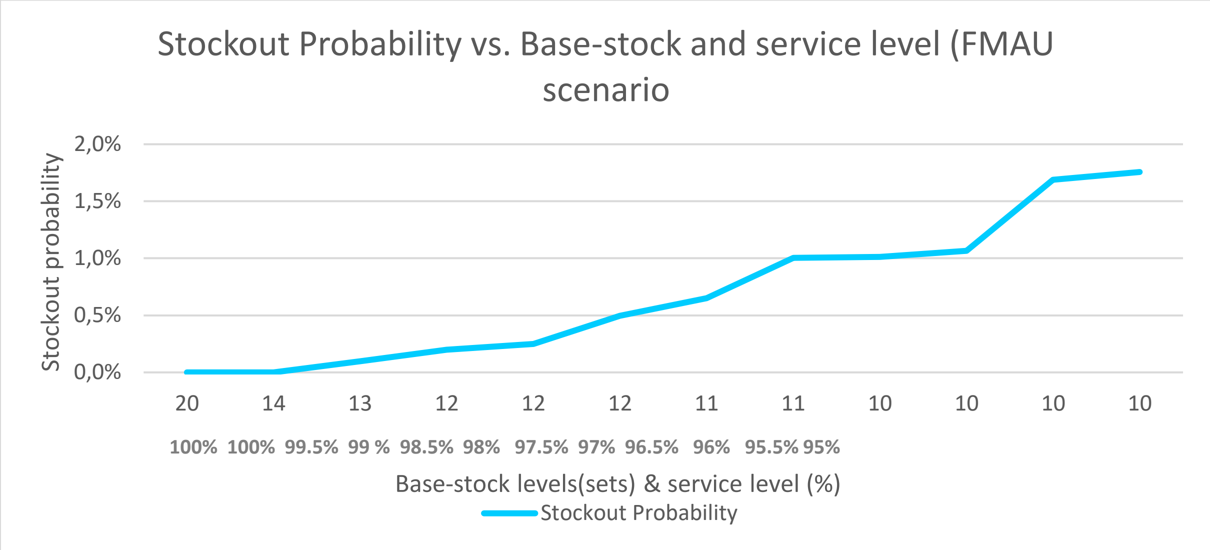


Figure 38 Stockout probability vs. Base-stock level and service level. Demand increase =16%. Data from 2017 extracted from Steriline and ORsuite (2018).

Base-stock level versus service level

Due to the variability in the demand, the ability to satisfy the coming demand depends directly from the base-stock level. Figure 39 shows that the number of instrument sets has increased, along with the service level. The figure also shows that the MST can serve the demand with 12 instrument sets targeting a service level from 98% until 99%. Even with an increase of 16% in the demand the MST can serve 100% of the demand with just 14 instrument sets, which means that it is possible to reduce 6 sets out of the 20 that the MST already holds.

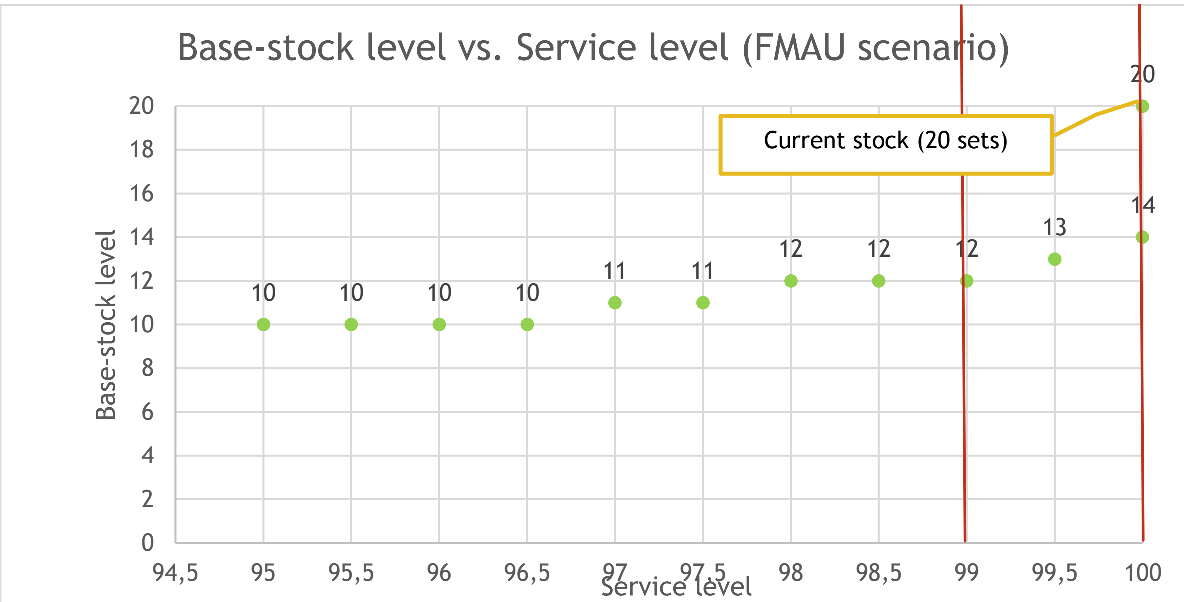


Figure 39 Base-stock level vs. Servicel level (FMAU scenario).Demand increase=16%. Data from 2017 extracted from Steriline and ORsuite (2018).

Single costs analysis

Figure 40 shows the trade-offs between having different service levels and the costs involved with each level. It demonstrates the interaction between, on the one hand the stockout costs, which increase as the number of instrument sets decreases, and on the other hand the purchasing and holding costs which decrease along with the number of instrument sets. Conversely, the total costs are less linear, as they first decrease when there are fewer instrument sets in stock. However, if there are too few instrument sets, the total costs increase again. This is because with few instrument sets, the stockout costs increase. Table 19 shows this more in detail. It demonstrates that the optimal number of instrument sets is 12, with a service level of 99%. In this case, the total costs decrease from €119,600.00 (20 instrument sets) to €78,129.23, which means a total cost reduction of 35%.

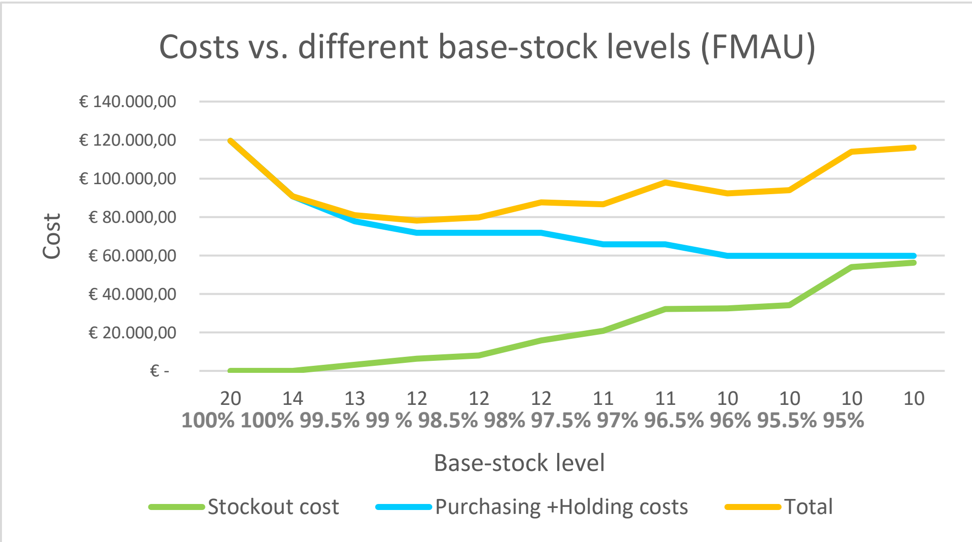


Figure 40 Cost vs. different base-stock levels. Demand increase=16%. Data from 2017 extracted from Steriline and ORsuite (2018).

# Sets	Service level %	Stockout Probability	Stockout cost	Purchasing +Holding costs	Total	between current situation and S*
20	100	0.000%	€ -	€ 119,600.00	€ 119,600.00	
14	100	0.000%	€ -	€ 90,794.49	€ 90,794.49	24%
13	99.5	0.098%	€ 3,137.57	€ 77,740.00	€ 80,877.57	32%
12	99	0.199%	€ 6,369.23	€ 71,760.00	€ 78,129.23	35%
12	98.5	0.249%	€ 7,959.23	€ 71,760.00	€ 79,719.23	33%

Table 19 Comparison between current situation and different levels of optimal (S) base-stock. Considering a 16% of demand increase. Data from 2017 extracted from Steriline and ORsuite (2018).*

6.2.4 Optimal base-stock level

Table 20 shows the optimal base-stock levels according to the increase of the demand. Therefore, according to the results of this experiment, the MST is holding more than the required number of instrument sets. It seems that even with an increase of 16% of laparoscopy surgeries, the MST can still maintain a service level of 100% if the inventory is reduced to 14 instrument sets, this is illustrated in Figure 41. This would lead to a reduction in total costs of 24% compared to the current situation (see Figure 42). In fact, the current 20 laparoscopy instrument sets held in stock have led to around €120,000 of purchasing and annual holding costs. With these expenses, the hospital could annually purchase 9 new laparoscopy instrument sets.

% increase in demand	# Sets	AVG. Service level	AVG. Stockout probability	AVG. Stockout cost	Purchasing +Holding costs	AVG. Total	% Cost reduction between current situation & S*
Current	20	100%	0.0%	€ -	€ 119,600.00	€ 119,600.00	-
0%	12	100%	0.0%	€ -	€ 71,760.00	€ 71,760.00	40%
	11	99%	0.1%	€ 3,836.00	€ 65,780.00	€ 69,616.00	42%
8%	13	100%	0.0%	€ -	€ 77,740.00	€ 77,740.00	35%
	12	99%	0.2%	€ 5,840.89	€ 71,760.00	€ 77,600.89	35%
16%	14	100%	0.0%	€ -	€ 90,794.49	€ 90,794.49	24%
	12	99%	0.2%	€ 6,369.23	€ 71,760.00	€ 78,129.23	35%
24%	14	100%	0.0%	€ -	€ 90,794.49	€ 90,794.49	24%
	13	99%	0.1%	€ 1,900.28	€ 77,740.00	€ 79,640.28	33%

Table 20 Optimal base-stock levels grouper per demand increases. Data from 2017 extracted from Steriline and ORsuite (2018).

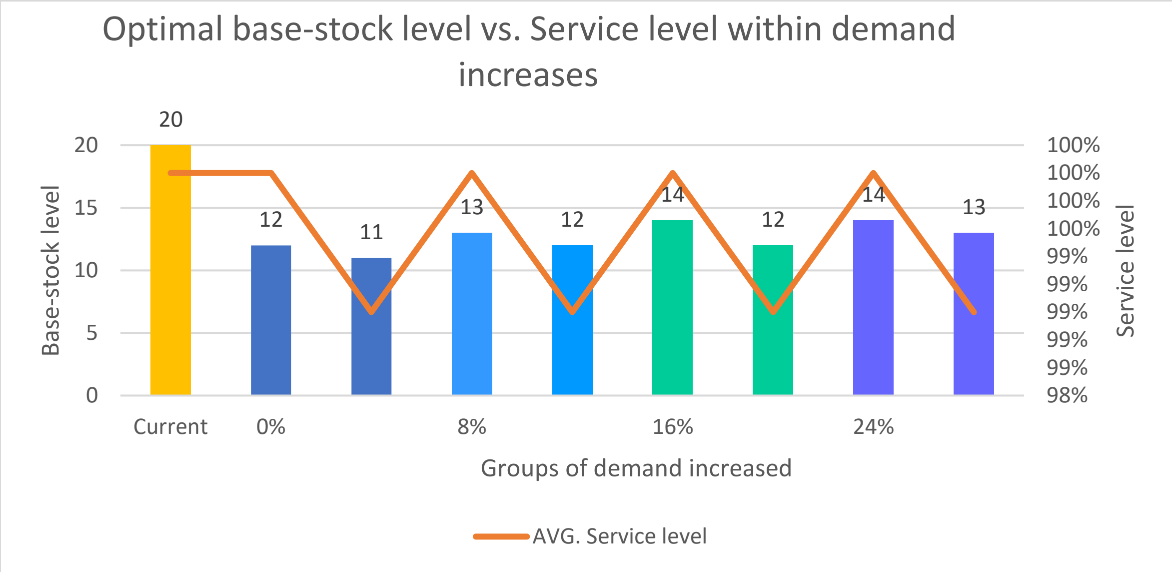


Figure 41 Optimal base-stock levels vs. Service levels grouped per demand increases(FMAU scenario). Data from 2017 extracted from Steriline and ORsuite (2018).

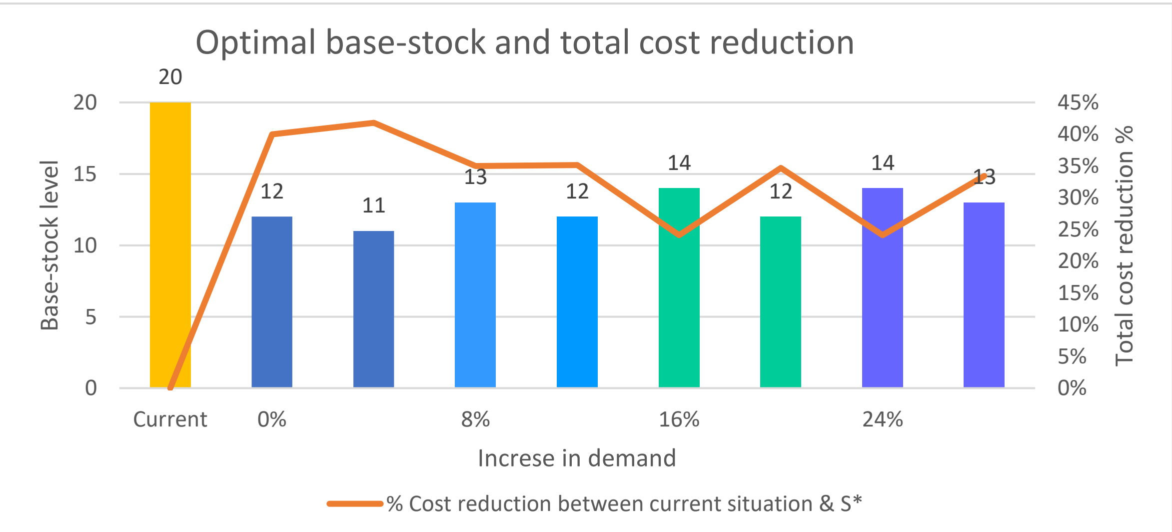


Figure 42 Optimal base-stock level and total cost reduction between current and optimal base-stock levels within demand increases (FMAU scenario). Data from 2017 extracted from Steriline and ORsuite (2018).

6.3 Results for SMAU scenario

The second experiment (SMAU) shows the *worst-case scenario* of this study, in which the time for an instrument set to return sterile after being used in the OR storage is two days instead of one. This case is also a representation of a situation in which the MST outsources the sterilization process. In order to analyse how the system performs in the current situation under the SMAU assumptions, we evaluate the outputs in Section 6.3.1, while in Section 6.3.2 we analyse the robustness of the model as was done for the FMAU scenario. In Section 6.3.3 a sensitivity analysis is performed in order to evaluate how the outcomes of the model react when variating the input parameters. Finally, in Section 6.3.4 the determination of the optimal base-stock level is carried out.

6.3.1 Current situation

Table 21 shows the results from the average demand after 100 Monte Carlo iterations. The current quantity of instrument sets (20) provides a service level of 99.8%. However, having 18 instrument sets can decrease the total costs with 3%, while still maintaining a high service level of 99.24%.

% increase in demand	# Sets	AVG. Service level	AVG. Stockout cost	Purchasing +Holding costs	AVG. Total	% difference between current situation and S*
Current	20	99.8%	€ 2,823.06	€ 119,600.00	€ 122,423.06	-
0%	18	99.24%	€ 10,957.34	€ 107,640.00	€ 118,597.34	(-)3%
	26	100%	€ -	€ 155,480.00	€ 155,480.00	(+)27%

Table 21 Annual cost comparison between number of instrument sets kept in stock. 1380 laparoscopy surgeries per year on average from 100 runs. Data from 2017 extracted from Steriline and ORsuite (2018).

Figure 43 shows the stockout costs versus the purchasing and holding costs. If the base-stock level decreases to 14 instrument sets, the dark-green line (holding + purchasing costs) and light-green line (stockout costs) reach an equilibrium. Nevertheless, in that case the service level is lower than 95%.

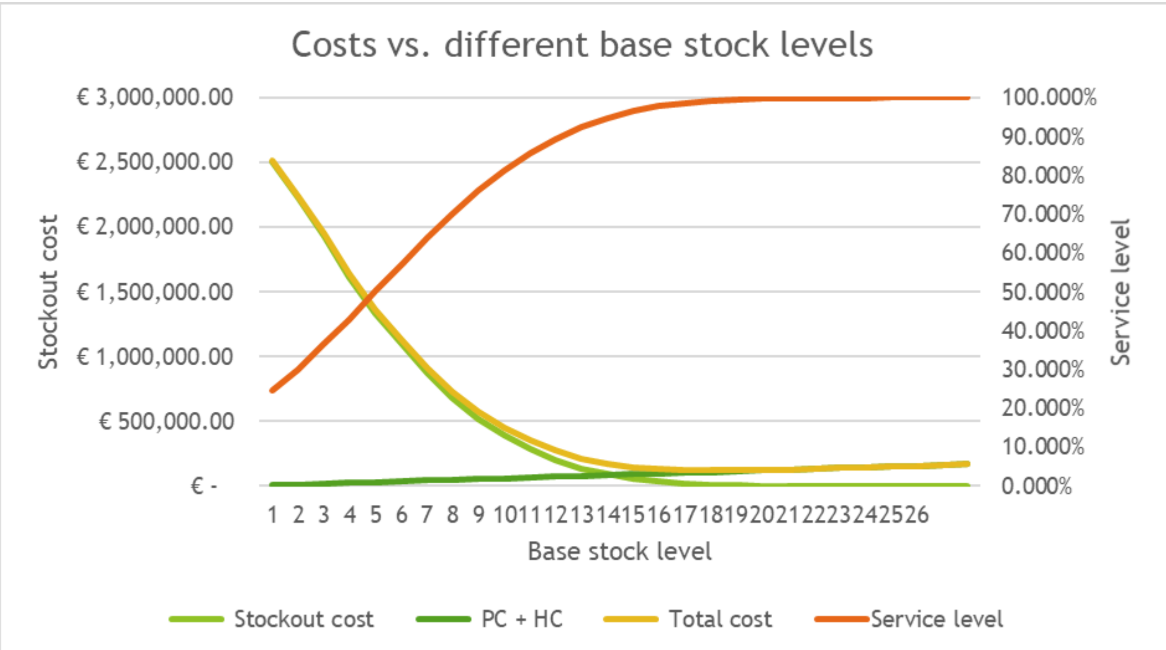


Figure 43 Costs vs. various base-stock levels from the current situation (SMAU scenario).

Figure 44 shows a more detailed view of the service level as well as the total cost trade-offs from base-stock levels higher than 14 instrument sets. The lowest total cost can be found at 18 instrument sets with a service level of 99.23%. In the current situation, the 20 instrument sets in stock with a lead time of 2 days, provide a service level of 99.79% (see Figure 27). However, the total costs start increasing when extra instrument sets are added to the inventory. This increase is caused by the purchasing and holding costs, which start to produce higher costs than the stockout costs, because the service level is already higher than 99%.

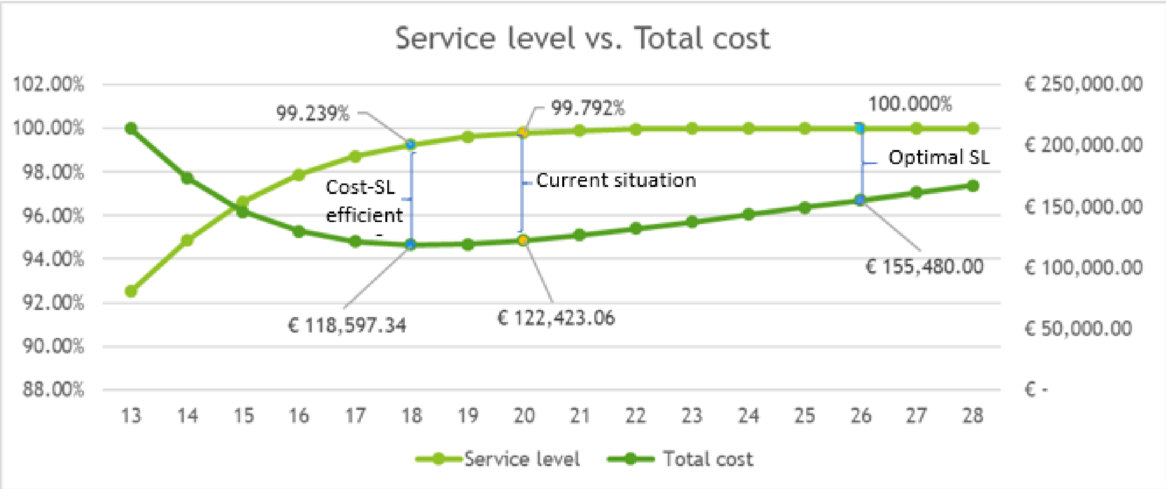


Figure 44. Service level vs. Total cost & base-stock level vs. Service level (SMAU scenario) of the laparoscopy instrument sets. Data from 2017 extracted from Steriline and ORsuite (2018).

6.3.2 Robustness of the model

As in the first scenario, the robustness of the model is tested with different increases in demand, in order to identify what would be the most suitable base-stock level. In Table 22 it is possible to see that 18 instrument sets can hold a high service level until 8% of increase in the demand. Nevertheless an extra instrument set is required if the demand increases with 16%. Similarly, if the demand increases with 24% also one extra instrument set is required to minimize the total costs, while keeping a service level of 99.2%. Also in this case we expect an increase of 12% of the total costs related to the total costs from 2017.

We expect to find a higher average stockout cost if the increase in demand happens. However, not in all the cases this is shown. This is explained by the average stockout costs being the product of the fraction of the time that a certain quantity of instrument set is expected to be in stock at the beginning of each day. When the demand increases, this probability decreases while the expected number of patients does the opposite. Therefore, the stockout costs decrease as the demand increases.

% increase in demand	# Sets	AVG. Service level	AVG. Stockout cost	Purchasing +Holding costs	AVG. Total	% difference between current situation and S*
Current	20	99.8%	€ 2,823.06	€ 119,600.00	€ 122,423.06	-
0%	18	99.24%	€ 10,957.34	€ 107,640.00	€ 118,597.34	(-)3%
	26	100%	€ -	€ 155,480.00	€ 155,480.00	(+)27%
8%	18	99.17%	€ 11,851.85	€ 107,640.00	€ 119,491.85	(-)2%
	26	100%	€ -	€ 155,480.00	€ 155,480.00	(+)27%
16%	19	99.5%	€ 6,287.14	€ 113,620.00	€ 119,907.14	(-)2%
	26	100%	€ -	€ 155,480.00	€ 155,480.00	(+)27%
24%	21	99.2%	€ 10,713.37	€ 126,537.93	€ 137,251.29	(+)12%
	28	100%	€ -	€ 161,460.00	€ 161,460.00	(+)32%

Table 22 Comparison between current situation and different levels of optimal (S) base-stock level. Empirical distribution. Holding cost h=.26 set price €13,000 and an increase of 16% from the demand of 2017.*

6.3.3 Sensitivity analysis

In order to analyse the most likely scenario we take an increase of 16% as an example for making a sensitivity analysis.

Service level versus base stock level

Figure 45 shows that a service level of 100% can be reached by holding 26 instruments in inventory. Nevetheless, tarjeting a 100% service comes along with high purchasing and holding costs. These costs surpass the stockout costs of having fewer instrument sets in inventory. This is explaned in the following paragraph.

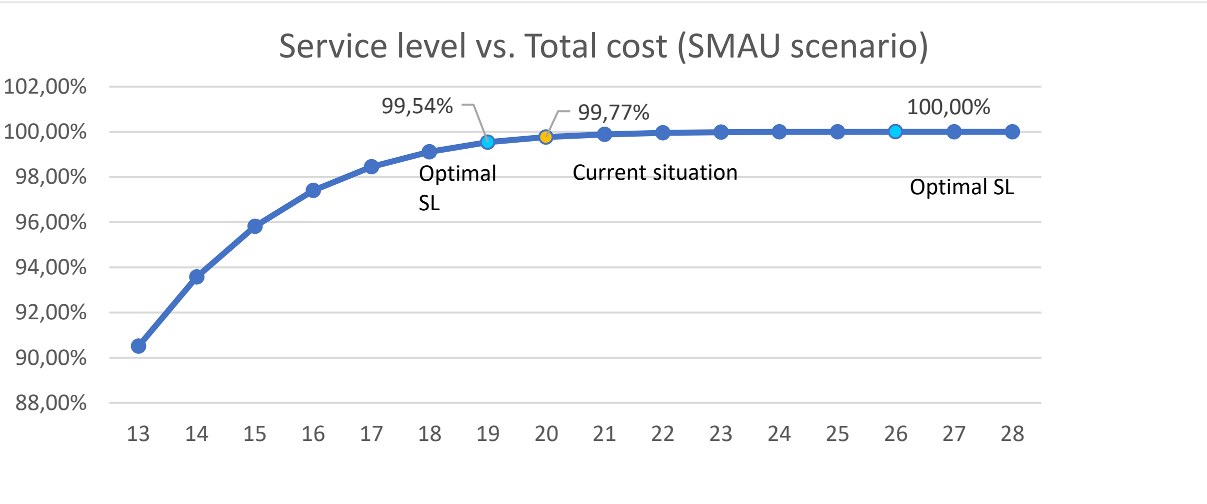


Figure 45 Service level versus total cost (SMAU scenario). Demand increase =16%. Data from 2017 gathered from Steriline and ORsuite (2018).

Costs versus various base-stock levels

The red line in Figure 46 shows the lowest boundary of the optimal solutions, which could be shown according to the desired service level. However, a higher number of instrument sets increases the total costs because purchasing and holding costs become more significant than stockout costs when having more than 19 instrument sets in stock.

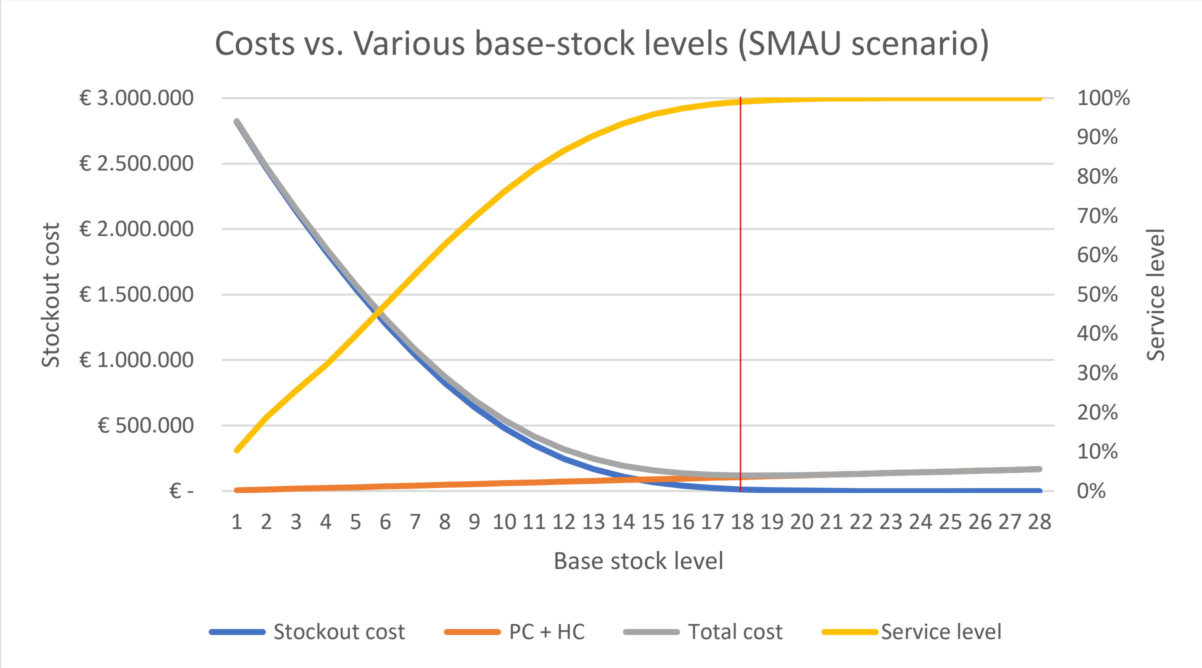


Figure 46 Costs vs. various base-stock levels. Demand increase =16%. Data from 2017 gathered from Steriline and ORsuite (2018).

Service level versus total annual cost

As shown in Figure 47, 19 instrument sets are the optimal cost saving while keeping a high service level. Fewer instrument sets could reduce the holding and purchasing cost, but the stockout probability events increase, creating an increase in stockout costs.

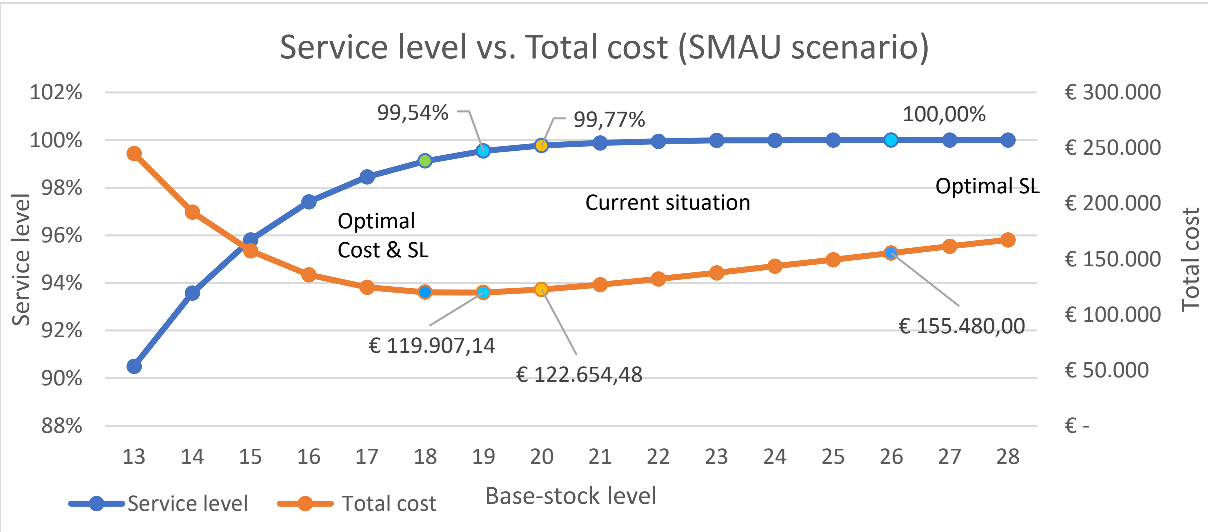


Figure 47 Service level versus total cos. Demand increase=16%. Data from 2017 gathered from Steriline and ORsuite (2018).

6.3.4 Optimal base-stock level

Table 22 in Section 6.3.2 demonstrates the optimal base-stock level in the SMAU scenario. It shows that even though the MST has more laparoscopy instrument sets in stock than necessary for a high service level, the difference between the current and optimal number of sets is lower than in the FMAU scenario. That is, the 20 instrument sets could ideally be reduced to 18 sets, which would lead to a service level of 99.24% (see Figure 48) and a total cost of €118,597.34. This represents a decrease of 3% of the total costs in the actual situation (see Figure 49). However, if the demand increases with 16% compared to 2017, the optimal base-stock level of laparoscopy instrument sets would be 19, leading to a total cost reduction of 2% (see Figure 49).

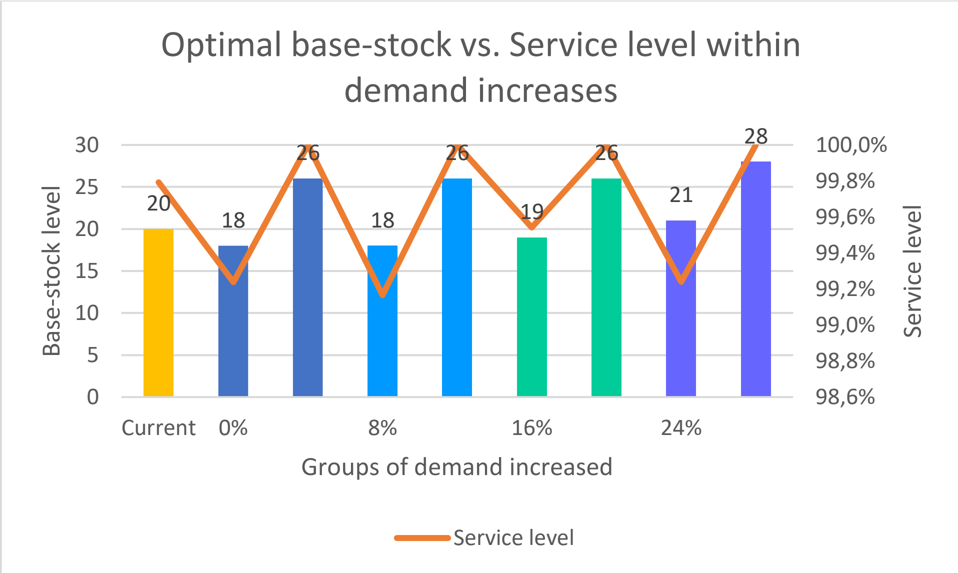


Figure 48 Optimal base-stock levels vs. Service levels grouped per demand increases (SMAU scenario). Data from 2017 extracted from Steriline and ORsuite (2018).

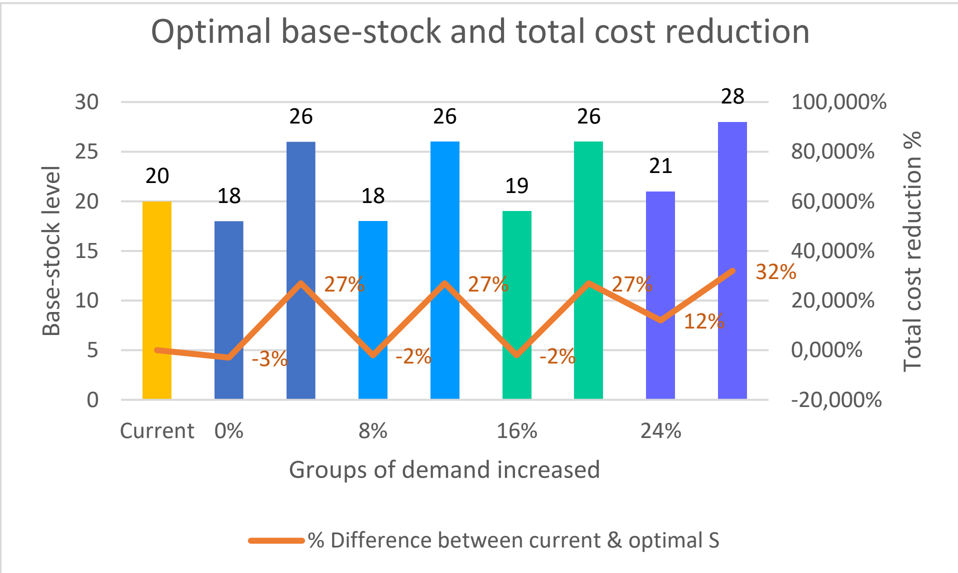


Figure 49 Optimal base stock level and total cost reduction between current and optimal base-stock levels within demand increases (SMAU scenario). Data from 2017 extracted from Steriline and ORsuite (2018).

6.4 Conclusions of experiment results

In this chapter we have analysed the results from the experiments designed in Chapter 5 in order to answer the sub question: *What are the results of the executed experiments?*

We answer this research question as follows. Instrument sets represent a high investment for each hospital. Nevertheless, the purchasing decision needs to be taken carefully. Even though it might seem that keeping a high number of instrument sets in stock will protect the hospital from any shortage, it comes with hidden costs, in the form of holding and purchasing costs. In case the demand increases with 16%, and that the instrument sets are ready in the OR storage in the beginning of the morning following their usage (FMAU), the optimal number of sets is 12, with a service level of 99%. However, if the instrument sets are ready the second morning after being used (SMAU), the optimal number of instrument sets is 19. In case the demand does not increase, and remains at the level of 2017, the optimal number of instrument sets is 11, leading to a cost reduction of 42% in the case of FMAU, and 18 instrument sets in case of SMAU, leading to a cost reduction of 3%.

With the results of this chapter, we have demonstrated that the evaluation of any purchase and inventory decision has to be taken carefully in order to be able to generate improvements in the system. Any improvement produced for the models proposed in this study cannot occur without an implementation plan. Therefore, in the next chapter we analyse the main activities that an implementation plan for these models must contain.

7 Implementation plan

This chapter describes the implementation strategies that need be taken into consideration in order to get the benefits that this purchasing and inventory decision model could provide to the users as a tool to guide them to take a well analysed purchasing and inventory decisions.

In Section 7.1 discusses reasons to oppose to the changes once being identified. In Section 7.2 we provide the actions that should be taken to achieve the implementation, after which we conclude this chapter in Section 7.3.

7.1 Factors against implementation

In order to implement this tool it is important to determine first the factors that inhibit the MST from achieving an improvement.

Uncertainty

The factors that could prevent to the decisions-makers from using this tool when the question arises of how many instrument sets should be purchased, is mainly based on the uncertainty of how the demand would behave. This, in its turn, creates fear across the staff of not having enough instrument sets available when it is required, placing the life of patients in risk.

Just-in-case practices

Until now the *just-in-case* practices have ruled the management of not just instrument sets, but also the disposable materials. The challenge that this practice entails, is that the absence of data shows the financial and clinical impact of these practices. After all, the most dangerous phrase in any business is: “We have always done it this way” CDV by Dr. Grace Murray Hopper.

7.2 Implementation actions

The first step to get the maximum benefits of this tool is by educating the staff through the information created by the model provided in this research.

Measure KPIs

In order to persuade the staff to implement this tool, it is important to start measuring the KPIs suggested in our literature review (see Chapter 3). This in order to generate data that best describes the environment modelled with the tool provided in this research. This will also help to identify the instrument sets that represent an area of improvement.

Communicate staff

An important factor to get the maximum benefits of this tool is to get the support of the physicians and OR assistance of each department, who are the ones that take the purchasing decision. This must start by sharing meaningful data with them. These data should be fuelled by cost benefit data and clinical aspects. The last aspect serves to show them that the proposed model is committed with providing a high-quality patient care while being cost-efficient.

Empower staff

Physicians and OR assistances never really needed to understand the financial aspects of running a hospital, nor did they have the financial stake in the hospital’s success or failure. Therefore, it is essential that these decision-takers are educated and empowered about how they can make a difference (Pfiedler, 2016).

Continuous improvement

Nothing can work in a long term if it is not improved constantly. Health care systems are constantly changing. Therefore, we need to be ready to adapt to any change in order to keep being competitive. A way to do this is by constantly measuring their current performance to identify and solve emerging problems in a proactive and preventive way. Figure 50 summarizes the involved steps to be taken in order to achieve the implementation of this model.

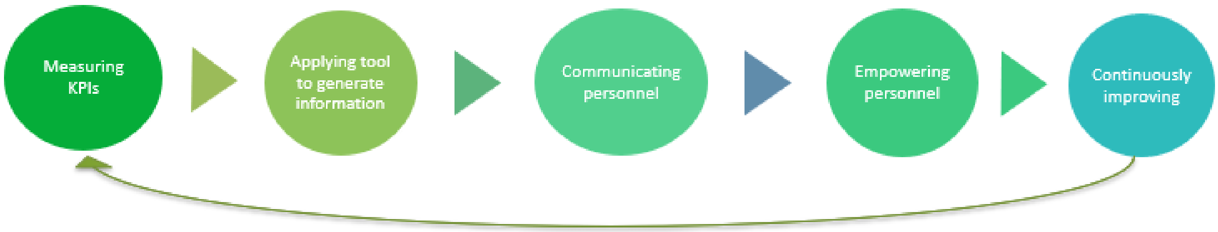


Figure 50 Implementation actions.

7.3 Conclusion

In this chapter we have answered **:** How can the MST implement the methodologies provided by this research? We observed that information is vital to persuade the staff to change their *just-in-case* practices. Therefore, our purchasing and inventory guide tool provides the staff with vital information about the cost-saving possibilities of finding an optimal base-stock level, while still providing a desired service level. This is the most important driver of any health care system and the cost reduction of any business.

The following chapter provides the conclusions, along with the recommendations and limitations of this case study.

8 Conclusions and recommendations

In this final chapter we conclude this study. Section 8.1 provides the final conclusions of this study based on the results found in Chapter 6, followed by the limitations faced in this study in Section 8.2. In Section 8.3 we provide recommendations for MST to improve their inventory system practices and for successfully implementing the model. In Section 8.4 we provide ideas for future research. Subsequently, in Section 8.5 we assess the academic relevance of this study and its results, after which we reflect on the process as a student in Section 8.6.

8.1 Answer to research question and sub questions

The overall research question of this project was: *How can we establish a target inventory level that minimizes the expected total cost over the lifetime of the reusable instrument sets while maintaining a high service level?* To be able to answer it, we decomposed it into sub questions. Therefore, first these sub questions are answered below, followed by the overall conclusion.

How is the MST currently managing the inventory of reusable instrument sets?

Currently, MST is not managing any inventory and purchasing methodology, which causes that the staff takes decisions based on *just-in-case* practices and experience, rather than analysing the behaviour of the instrument sets demand. This causes that the MST purchases more instrument sets than necessary and overstocks expensive and large assets in limited and expensive places such as the OR storage. This situation generates extra costs. Moreover, the CSD department is planning to reduce the number of shelfs used for instrument sets from 13 to 8, because the high locations of instrument sets within the closets violate ergonomic specifications (CSD planner, 2018). This means that it is necessary to reduce 38.4% of the locations for reusable instrument sets. Therefore, the urgency of finding a proper inventory system is clear, to be able to ensure that what is kept in the OR storage is used cost-efficiently. As such, overstocking for *just-in-case* reasons, does not lead to better results per definition.

Which KPIs are important to evaluate to determine an optimal base-stock level?

The MST has identified nor measured relevant KPIs that would enable it to determine the current performance of the inventory system in order to be able to compare and analyse the trade-offs of having various number of instrument sets in inventory, through our created models. Consequently, we found the need to determine and define these KPIs and metrics.

Since the main goal of this study was to determine the optimal quantity of instrument sets that should be kept in inventory, we selected the *base-stock level* as our main factor to be measured in various levels. Base-stock level is defined in the literature, as the number of SKUs (stock keeping units) that should be stored in inventory (Dhakar et al., 1994). Within the context of healthcare inventory a relevant KPI that is affected by changing the amount of instrument sets (base-stock level) is the *service level*. This KPI measures the probability of having enough instrument sets in inventory when they are needed. In other words one minus the probability of stockout (Diamant et al.,2017). Therefore, it was obvious to consider the *stockout costs* as one of our needed KPIs, which measures the costs generated when not enough instruments sets are available in inventory. Keeping expensive assets in expensive storage generates various costs like: housing costs, material handling, labour costs, obsolescence costs, and so forth. These costs all together are called *holding costs* (Melson et al., 1989). Therefore, we also included holding costs in the KPIs to be evaluated. Moreover, we included the *purchasing costs* of instrument sets in our model, because instrument sets represent a high investment in any hospital. MST invests around €4.5 million in reusable instrument sets and spends around €900,000 per year in purchasing disposable instruments, reparation services, and spare parts.

Which methodologies are found in literature suitable to determine an optimal base-stock level?

The problem that we solved during this study is related to the third question of the tray optimization problem (TOP) (see Section 3.3.1) , which is the only question out of the three that refers to sets and not to single instruments. The objective of this third question is to find the optimal base-stock level for reusable instrument sets. Nevertheless, as shown in Appendix I, only one optimization method was found related to the third TOP question. This method addresses our research question applying the discrete Markov chain transition matrix to find the optimal base-stock level. However, this method was created for situations in which the sterilization service is outsourced, causing the sets to arrive sterilized the second morning after their use in the OR storage. Therefore, we combined the literature research with data analysis to determine whether this model was suitable for our study. Through the data analysis we found that 85% of the instruments are available sterilized the next morning in the OR storage. Nevertheless, in some cases, sterilization may take one day extra. Therefore, we assumed that any instrument set is either available the first morning after use or the second morning after use. To account for both cases we proposed two separate models.

For the first scenario, in which the instrument sets are sterilized and available in the OR storage the first morning after their use (FMAU) in the OR, we found that the most suitable methodology to tackle this scenario was by applying the (R,S) inventory control policy. This policy aims to find the order-up to level S which is also called base-stock level. Nevertheless, inventory control policies are formulated for hierarchical supply chain system, which defines the flow of consumable supplies of non-reusable supplies. We needed to make some conceptual and mathematical adaptations. Moreover, these policies were based on supplies of which the demand follows a normal distribution. The latter is not always the case. Therefore, we found the need to create an FMAU model for a demand that follows a normal distribution and another model for a demand that does not fit this theoretical distribution.

For the second morning after use (SMAU) scenario, we made use of the previously mentioned model create by Diamant et al. (2017), which tackles the same research question under similar circumstances. The authors use the discrete Markov chain transition matrix to determine the fraction of the time that the instrument sets are available in inventory the second morning after being used in the OR. This probability allowed us to determine the stockout probability which can help us determining the service level, which represents the probability of no stockout.

To be able to simulate the daily demand we found Monte Carlo simulation to be a useful and reliable simulation model for generating random numbers according to any demand distribution.

How can we create a model based on the found methodologies that helps to answer our main research question?

In Figure 51, the used method is portrayed. The (R,S) inventory control policy turned out to be a good method to find the optimal base-stock level for the FMAU scenario when the observed demand follows a normal distribution. Nevertheless, some conceptual adaptations were made to be able to adapt this policy from a hierarchical supply chain system to a cyclical (see Section 4.3.1). For the case when the observed demand is not normal, we created the FMAU model based on the empirical distribution, which finds the optimal base-stock level by targeting a desired service level. For both FMAU models the formulations of the holding and purchasing costs normally calculated for consumables were adapted to reusable and long-life cycle assets.

The SMAU scenario was modelled by applying the methodology of Diamant et al., these authors tackle the same situation in a similar environment, applying the discrete Markov chain transition matrix.

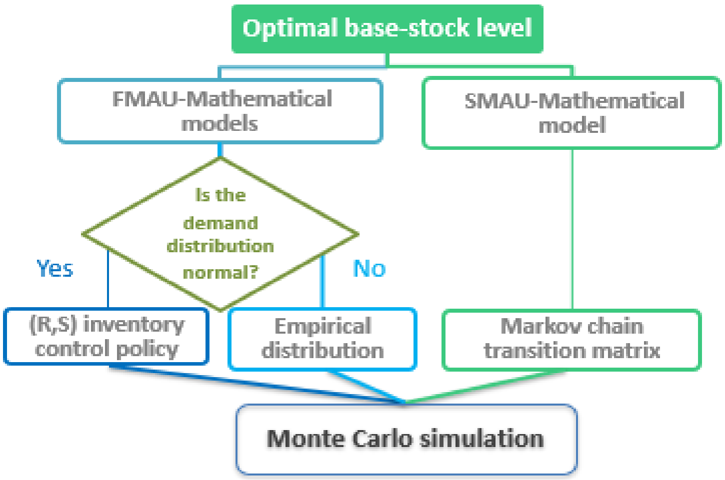


Figure 51 Methods to be used to find the optimal base-stock level.

How should the experiments be designed?

The main goal of answering this research question was to ensure that the right type of data was available to create a model that is able to find the optimal base-stock level; the main goal of this research. The design started with the selection of a type of instrument set (Figure 52 shows all the steps followed to create the experiments). Since there are around 1000 instrument sets types in the system, it was necessary to select one that better defined the current situation. This turned out to be the laparoscopy instrument set. The second step was to determine whether the demand distribution of this set was normal.

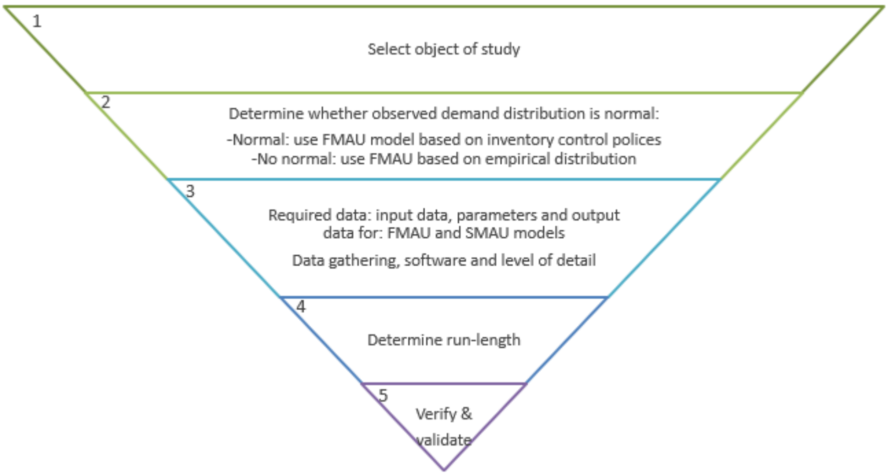


Figure 52 Experiments design structure

This was needed in order to select which of the FMAU models should be used. Since the p-value=.005 observed demand of the was considerably lower than α=.05, the H_O (observed data follows a normal distribution) was discarded. Therefore, the selected model was the FMAU based on the empirical demand distribution. The third step was to select the input data for both models (FMAU and SMAU) which in this case study is defined by the demand of laparoscopy instrument set during the complete year of 2017, resulting in a sample size of 365 days. Then the parameters needed for our model were defined as follows:

- Time to replace instrument set (T): Diamant et al.(2017) suggest that the purchasing of instrument sets takes place anywhere in period of 5 years.
- Holding % (h): holding cost from 15% - 35%
- Stockout cost (β): Appavu et al. (2016) suggest stockout costs per hour between €1,000-€3,000.

- Set price (SP) : €13,000
- Quantity of Instruments in the system(S): 20 laparoscopy instrument sets

Since we aim to obtain the base-stock level that minimizes holding, purchasing and stockout costs, while keeping a desired service level, we selected these costs and the base-stock level as our desired outputs. In order to analyse the trade-offs of having different base-tock levels we programmed the simulation model using MS Excel 2017. The input data was gathered from Steriline and ORsuite. The fourth step of our experiment design was to determine the number of runs needed to obtain reliable information from our Monte Carlo simulation model. The number of runs was obtained by comparing the means and standard deviation of various run-lengths. The result was 100 runs. The last step of the experiment design is related with the verification and validation of the system, which is mainly performed by consulting with the staff and experts the accuracy of the model. In the case of the SMAU model the results were verified using the data provided by Diamant et al. (2017), debugging and tracking coding mistakes was performed. The validation was performed by applying χ^2-test among others, which confirmed that the simulation model is a good representation of the real system.

What are the results of the executed experiments?

The model created during this research has demonstrated to be able to provide substantial and reliable information that shows the costs generated by the *just-in-case* practices. This model is able to show the trade-offs generated by increasing or reducing the number of instrument sets. Therefore, this model illustrates the involved risks, so guiding the user at the moment of deciding the number of necessary instrument sets for satisfying the demand without compromising the health of the patients. As previously mentioned, the experiments were based on the results obtained from the laparoscopy instrument sets. The MST has 20 instrument sets of this kind, which represents a capital investment of €260,000 (€13,000 per set). Apart from being an expensive asset, it also has large dimensions (53.5cmx25.5cmx9.5cm) that occupies a large space in an expensive storage (OR storage). From the observed performance of the instrument set in 2017, we determined that this set was already accomplishing 100% of service level, but with substantial costs, represented by their holding and purchasing costs. The maximum quantity of these 20 instruments sets was 13 and this only happened 2 times in 2017. The most frequent daily quantity of laparoscopy instrument sets request was 1, 4 and 3. Therefore, the MST was able to provide 100% service level with just 13 or fewer sets. Moreover, if we take into consideration the current situation under the assumptions of the FMAU scenario with 16% of increase in demand, the system can still reduce the instrument sets to 12, with a service level of 99%. This would mean a of decrease of 35% in costs compared to the current 20 of sets. In order to see what would happen in the worst-case scenario when the instrument sets arrive SMAU, which also represents the outsourcing of sterilization procedures, we analysed the SMAU scenario with 16% of demand increase. This configuration requires 19 instrument sets to provide a 99.5% of service level. In case the demand does not increase, and remains at the level of 2017, the optimal number of instrument sets is 11 (see Figure 42, Section 6.2.4), leading to a cost reduction of 40% in the case of FMAU, and 18, leading to a cost reduction of 3% in case of SMAU.

How can the MST implement the methodologies provided by this research?

MST needs to start identifying the KPIs (key performance indicators) which are considered vital for any purchasing and inventory control system. Moreover, with the use of the tool created in this study, the staff can experiment with a model that represents the real-life system, in order to be able to analyse and communicate to the staff the trade-offs of having different levels of instrument sets. If the staff is involved and constantly informed about the collateral effects of having more or fewer sets than necessary, the staff become problem owners. This could result in a change in employee mindset.

What is the conclusion of this study, and what are the recommendations for the CSD at MST?
As we have demonstrated in this study, the inventory level of instrument sets plays a crucial, yet largely ignored role in contemporary surgery planning and inventory management. Even though little attention has been given by scholars and practitioners, hospitals can save a large quantity of financial and physical resources. To determine the base-stock level, or ideal number of instrument sets, the discrete long run Markov Chain and the (R,S) inventory control policy have proven to be valuable and insightful tools for providing input into the simulation. The latter was done by making use of Monte Carlo Simulation, which allowed us to produce random numbers from an empirical distribution which could be transformed to represent different increases in demand while still representing the behaviour of the observed data. Hence, the combination of these three tools can contribute to a great magnitude in establishing a target inventory level which allows both to minimize costs and maintain a high service level.

As we have demonstrated in this study, the MST hospital would benefit financially from having a lower number of instrument sets for laparoscopy surgeries in stock. More specifically, if the hospital can ensure that all the instrument sets are sterilized and available in inventory each morning, the MST can ensure a 99.98% service level by holding just 11 instrument sets. Hence, it could do with 9 sets fewer than in the current situation, which means a cost reduction of 42%. Furthermore, taking into consideration an increased demand of 16%, 12 instrument sets are necessary to be able to provide a 99% service level.

The number of instrument sets for laparoscopy surgeries could even be reduced further if the CSD would work more closely together with the surgery planning department. In the current situation, this is not so much the case. In the few cases that all 13 instrument sets were being used at the same time or on the same day, several of the surgeries were diagnostics. Hence, it would be possible to schedule these diagnostics on different dates in which the demand of laparoscopy instrument sets was lower. Therefore, it is even recommendable that decision makers of the MST decide to reduce the number of laparoscopy instruments – and therefore the overall holding and purchasing costs – even further while maintaining a high service level. Nevertheless, we decided to model each scenario considering the actual planning in order to point out the importance of the instrument sets planning.

8.2 Limitations

There have been several occasions in which the decision for developing this model had to be made in such a way it that potentially could influence the outcomes of this research. These limitations were sometimes unavoidable. In this section we show the limitations of this research.

A first limitation of this report is found in the data. The research of this case started in the middle of 2018, but in order to have a full year of analysis, we made use of the demand of 2017 as our input data. This limits our results for analysing the real current behaviours of the demand of the previous year.

A second limitation for this model is that it does not take the failures of instrument sets into consideration. As the instrument management department saves a large amount of spare parts, if a single instrument breaks or needs maintenance, it is removed and replaced as soon as it arrives to the CSD. However, if there is no replacement for the broken instrument in the instrument management department storage available, the entire instrument set is removed from the OR storage until it is completed. This time is not considered in this research and could affect the outcomes of the model. For this reason, to tackle this problem, we model the worst-case scenario SMAU so the user can use this model when the instrument set which is being analysed tends to break often or need a periodic maintenance, so the sets are removed from the OR storage.

A third limitation is the reliability of the data. The lead-time and demand of the instrument sets is not documented very well by the MST. Therefore, we decided to create two possible scenarios: the best-case scenario 'FMAU' and the worst-case scenario 'SMAU'. We did this in order to provide the number of instrument sets that the system would require taking into consideration different lead-time environments. A further limitation related to the availability of the data is that the unavailability of the instrument sets prizes limited us from creating an ABC-analysis regarding important instrument sets that could provide a higher costs reduction. Nevertheless, we took the laparoscopy instrument set as a case study which resulted in a good example for proving the benefits of this decision supporting tool.

A final limitation of this research is that we have not considered the seasonality of the demand. There could be instrument sets that are in higher demand throughout the year. Nevertheless, our model does not take these trends into consideration and assumes that the demand is identically distributed during the year. For this reason, we decided to use the laparoscopy instrument set which does not show changes in demand during the year.

8.3 Recommendations

This section provides some recommendations related to inventory, utilization, planning and data of instrument sets problems, found during this research.

Inventory system

We recommend MST to follow the (R,S) inventory policy, which will provide the initial steps for getting a better control of the inventory. This would improve the communication between the CSD department and the ORs. Furthermore, it would provide more information about the real demand of each instrument set, which would help to improve the accuracy of the forecasted demand. Moreover, it would help to identify which instrument sets are most problematic.

Sterilization from just-in-case to just-in-time

If the hospital aims to use its resources more efficiently, the planning between patients and instrument sets is a 'must do'. On average 85% of the patients admitted to the ORs are elective, which means these patients are planned with two weeks in advance. The remaining 15% of patients is scheduled less than 24 hours before surgery (see Figure 5, Section 2.2.4). This means that 85% of the sterilization process could be planned in advance. Nevertheless, at the moment the CSD is sterilizing all the instrument sets that leave the ORs *just-in-case* they are needed (either there are used or not during the week) and allocates them in the OR storage, whereas they could clean and allocate them in a less expensive storage and plan their sterilization beforehand to have them ready in the ORs *just-in-time*. Planning instrument sets together with elective patients, could help to reduce unnecessary expenses:

- Reduction of the workload in the CSD;
- Reduction of instrument sets in the OR storage (less space needed, lower holding costs);
- Reduction of the uncertainty in the demand, which leads to a better estimation of the system's real needs;

- Reduction of instrument sets that occupy limited and expensive space in the OR storage;
- Reduction of double sterilization process due to out of date sterilization, which leads to a better conservation of instruments.

From a daily perspective, the major part of the elective patients are schedule at 8:00 AM, while the rest is spread from 9:00 to 15:00. This shows that the system has great planning capacity for instrument sets, since the patients that need to be attended with less than 24 hours are mainly arriving after the peak hours. Therefore, planning instrument sets together with elective patients, provides more capacity for attending unexpected demand.

Instrument sets utilization

Some identical instrument sets are used 100 times more than others, which leads to some instrument sets being sterilized without being used while others are used excessively. This situation is caused by the location of the shelfs on which the instrument sets are stored. The staff tends to choose the sets that are easiest to access, which are the sets located in the middle shelfs. In line with this, the prices of the instrument sets are not documented. Hence, the employees are unaware of the price of the instrument sets. This causes that surgeons order new instrument sets without being aware of the costs involved. It would benefit the MST to report openly about such costs with the staff involved.

Instrument set planning

Currently, the planning of elective surgeries is mainly driven by the surgeon a week before. However, they do not consider the instrument sets' availability for the coming week. Moreover, the absence of instrument sets is noticed only one day before of the planned surgery. Therefore, it is important to make a planning based on the demand for the coming weeks. Planning the instrument sets in advance together with the surgeries of elective patients will improve the availability of trays and lead to a more efficient use of resources.

Systems connection (Case number-instrument set)

An essential part of this improvement is based on the lack of connection between the data from Steriline and OR suite. Both systems need to be connected through the case number-instrument set. This connection is fundamental to determine the real demand of each instrument set and the time it takes in each part of its flow. With this information the present method could determine the current demand more accurately, as well as the lead-time of each instrument set during the year.

Reusable vs disposables

Purchasing of disposables instrument sets should be taking into consideration, since it comes with additional costs like ordering costs, holding costs and waste disposal costs. The MST has already invested in reusable instrument sets facilities and it has a high capital investment in reusable instrument sets. The price of disposable instrument should be lower than the sterilization price.

8.4 Future research

The purchasing and inventory decision tool provided in this research sets the initial steps for a better inventory and a guide of future procurement decisions. These decisions can now be supported with a tool that provides a diagnostic of the performance of the current situation, which was previously unknown and that can be compared with potential trade-offs and risks of underlying inventory management and purchasing strategies. Moreover, this tool can provide information about the number of instrument sets that would be required if the demand increases. Therefore, the users can estimate the benefits and disadvantages of removing or adding an instrument set in different demand contexts. This mathematical model can be extended to other product groups such as disposable materials, with just some modifications in the cost formulations from the normal distribution model, which in this case where adapted to reusable materials. Moreover, having information about the lead-time, holding and stockout costs could provide a more accurate inventory model and a better analysis of the trade-offs involved in any purchasing decision. Additionally, creating a simulation model of all the processes involved in the life-cycle of the instrument sets could provide information about the real capacity and limitations of the instrument sets supply system.

8.5 Academic relevance

As was observed through the literature review in Chapter 4 and the research strategy in Appendix I, only 25 articles were found related to inventory control management of reusable supplies. This number is even smaller for reusable instrument sets, because 4 out of the 25 provide optimization methods for reusable supplies, of which only one (Diamant et al., 2017) tackles the optimization of the base-stock level of the Tray Optimization Problem. However, as the authors of this paper make use of a second morning after use scenario (SMAU), their method was insufficient for accurately calculating the necessary base-stock of MST, whose instruments might return back sterilized the morning after being used. Therefore, we have created a method for calculating the base-stock level for instrument sets which are either sterilized the first morning after use (FMAU) or the second morning (SMAU). To come up with a solution for the FMAU model based on the inventory control policy (R,S) that formulates the base-stock level based on periodic review period, we focused on the single echelon inventory, which involves just one warehouse (see Section 2.6.1). However, this policy cannot be applied directly to reusable supplies for two reasons. The first is that any of the inventory control policies presented in Section 3.3.1 (see Table 7) are formulated for disposable supplies that go through a hierarchical supply, which means that the supplies never come back to the supplier. In the case of reusable instruments this process is cyclical, which means that the supplies return to the supplier to be sterilized and stay as fixed assets. As a result, the calculation of the base-stock level and costs is not the same as for disposables. The second reason is that these inventory control policies are addressed for a demand that follows a normal distribution, which is not always the case. Therefore, in order to tackle the first reason, we adapted the characters involved in the single echelon inventory system into a cyclical inventory system (see Section 4.3.1). Moreover, the costs were adapted to fixed assets, which involve depreciation costs (see Section 4.3.3). For the second reason, we created a model, where any theoretical demand distribution can be modelled through the use of Monte Carlo simulation and where the costs involved are calculated for fixed assets. This method has provided very relevant and accurate insights, allowing both policymakers of MST and scholars to make use of in future studies of base-stock levels of instrument sets in hospitals. Therewith, our study has both academic and practical relevance.

8.6 Student reflection on the master thesis process

Writing a master thesis is not an easy task, and in my case it was something that I had to do for the first time in my life, in another language, and educational and business environment. It is not just a project in which you have the challenge of testing and implementing that what you have been learning through your master’s in a real business environment; it is also a self-learning process. You have to learn how to be your own project manager.

The process of starting my master thesis was an ambiguous, long and difficult path, but I have to admit that without these three ingredients I would not have learnt as much as I have. I still remember my first meeting at the MST where I met Rob Lindeman, my supervisor in the MST. Immediately, I recognised that he was a visionary, always motivated and full of ideas, and seeing any problem as an opportunity for improvement. I sincerely admire that attitude, because it is always motivating to work with someone that is interested in making improvements in organizations in which the working culture is 'we have always worked in that way'. Nevertheless, there were already so many projects going on in the MST that I found myself swimming in a pool full of possible projects. From these projects, I had to pick one in which I could fulfil various requirements: a project which is interesting for the MST, related to my study's background, suitable for the time frame of a master thesis, and where I could find my place with the group of people that had already been working on the project for months. Rob offered me a project related to the reduction of costs in the OR department. I found this project very interesting, but still too broad for a master thesis. I tried to fit in three of the projects where Rob and I found that I could be of help: standardizing instruments, reduction of instruments and an analysis of reusable vs. disposable instruments. I was allocated in the CSD, where I met great people who were always able to help me through these projects. Unfortunately, these projects were already finished, too complex for the timeframe of a master thesis or not related to my master. I was constantly looking for ways to relate the topics to my master's and to reduce the scope of the topics in order to make them feasible for the time, which was each time shorter than I had available. A feeling that I was not able to even start properly with my thesis, was demotivating me. Nevertheless, talking with my supervisors and the great people that I met in CSD, I found my path through this difficult situation and I decided to create a project where I could make use of the things that I had already learnt during this process, and where I was not that dependent from the information that others could provide me. Through interviews with the CSD staff, I found that the project of reduction of instrument sets was performed by a consultancy company, and that the benefits and the methodology applied were not provided by that consultancy. Since one of the main interests of the MST was to reduce costs without compromising the patient safety, me and the planner of the CSD started looking for the prices of instrument sets. We found that it would be a great cost reduction if a methodology could help to support the MST to find a model which could help them to keep an optimal number of instrument sets, while keeping a desired service level. Before presenting this project with my supervisors, I needed to prove the need and the benefits that this project would represent. I started searching for suspicious and expensive instrument sets by analysing the data. We found that laparoscopy instrument sets are expensive and being overstocked. The MST has 20 instrument sets of this type and the maximum number of times that this was used during 2017 was 13 times in one day. This event only happened two days in the whole year. This showed that a method was needed to decide how many instrument sets should be held in inventory according to the demand fluctuations. With this information I could raise the interest of the MST, but I still needed to find a way to find a scientific method. Therefore, I immediately started my search for methodologies that could help me to address this problem, which had already been validated in the scientific world. Surprisingly, I could not find many academic studies related to inventory levels of reusable instrument sets. The few articles that I could find were related to single instruments but not to instrument sets. After searching on Google Scholar, Research Gate, as well as theses from other students, I found a scientific paper in which the same problem that I wanted to solve, was addressed. With this paper I could explain what I wanted to make and the benefits that this project could bring. After this, I started preparing a proposal for my supervisors in the university and the MST. Now, I had two important factors that a master thesis should contain: providing a project that could be interesting for the MST and being related with the Industrial Engineering and

Management (IEM) master. After seeing that both parties were enthusiastic about the project, I started again feeling motivated and encouraged to continue with my thesis.

Now looking back, I realize that through this experience I have learnt a lot about the professional environment in the Netherlands and I have to admit that I have become a more proactive and assertive person than I was before. Now, I feel more confident about my capabilities as an IEM professional. I come from a country where telling what you really need and want is not very polite, but being in the MST has taught me to become more direct at the moment of asking for help and for something that I need. I feel that this has been both a valuable and enjoyable experience that also allowed me to meet great people in the MST and the University of Twente.

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Appendix I Search strategy

The search was performed in Google Scholar, Scopus, and essay.utwente.nl until the 28th of November 2018. All eligible studies in English, were considered for this literature review. The search structure for Google scholar and Scopus is shown below:

Search structure Google Scholar: (“surgical instruments” OR “sterile instruments” OR “reusable instruments” OR “reusable surgical supplies” OR “surgical supplies” OR “surgical instrument trays” OR “instrument sets” OR “tray*” OR “instrument package” OR “instrument kit” OR “optimizing*” OR “hospital*”) AND (“inventory management” OR “supply management” OR “supply chain” OR “material management OR “sterilization logistics” OR “stockout-based substitution” OR “base-stock level” OR “optimization problem” OR “optimization methods”)

Search structure Scopus: (TITLE-ABS-KEY ((surgical instruments OR sterile instruments OR reusable instruments OR reusables surgical supplies OR surgical supplies OR surgical instrument trays OR instrument sets OR tray* OR instrument package OR instrument kit OR optimizing* OR hospital*)) AND TITLE-ABS-KEY ((inventory management OR supply management OR supply chain OR material management OR sterilization logistics OR stockout-based substitution OR base-stock level OR optimization problem OR optimization methods)))

An overview of the study selection is shown in Figure 53. In the identification stage, we introduced each of the combinations in the data base, which resulted in a large number of articles, journals and books. This was easily reduced by screening the titles and abstracts. The majority of the sources were more medical than supply management oriented. Moreover, several documents were duplicated. Therefore, the number of articles left was almost reduced by half. In the eligibility stage, we reviewed the abstracts more carefully, which allowed us to reduce the selection to 25 papers. However, 22 of these papers were only related with single instruments. These papers helped us to get to know more the logistic flow of reusable supplies within a similar environment than where this research was performed. Such is the case of two master theses performed in Academic Medical Centre, Amsterdam and the MST in Enschede and a study in HagaZiekenhuis in Den Haag. There were three articles which are related with reusable instrument sets, which were mainly used for creating an optimization model in this research: Diamant et al.(2017) and Fineman et al.(1978), and a literature report performed by Ahmadi et al. (2018). The latter was mainly used to track more literature related with inventory management and surgical supplies.

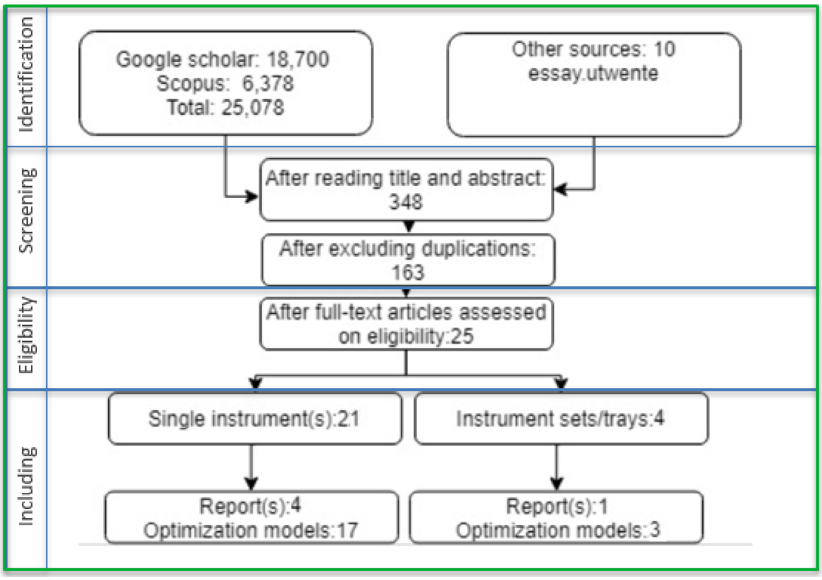

Figure 53 Search strategy process and results.

Table 23 shows an example of how the research query is performed, according to each of the combined keywords presented in Scopus and Google Scholar search structures.

Web search engine	Query	# of hits	Duplicated	# reviewed articles	# of articles used	single instruments	Instrument sets
Scopus	(TITLE-ABS-KEY(reusable surgical supplies AND inventory management))	6	4	2	1	1	
Google scholar	"reusable surgical supplies" AND "inventory management"	6		2	2	1	1

Table 233 Research query

Appendix II Detailed flow of reusable instrument sets

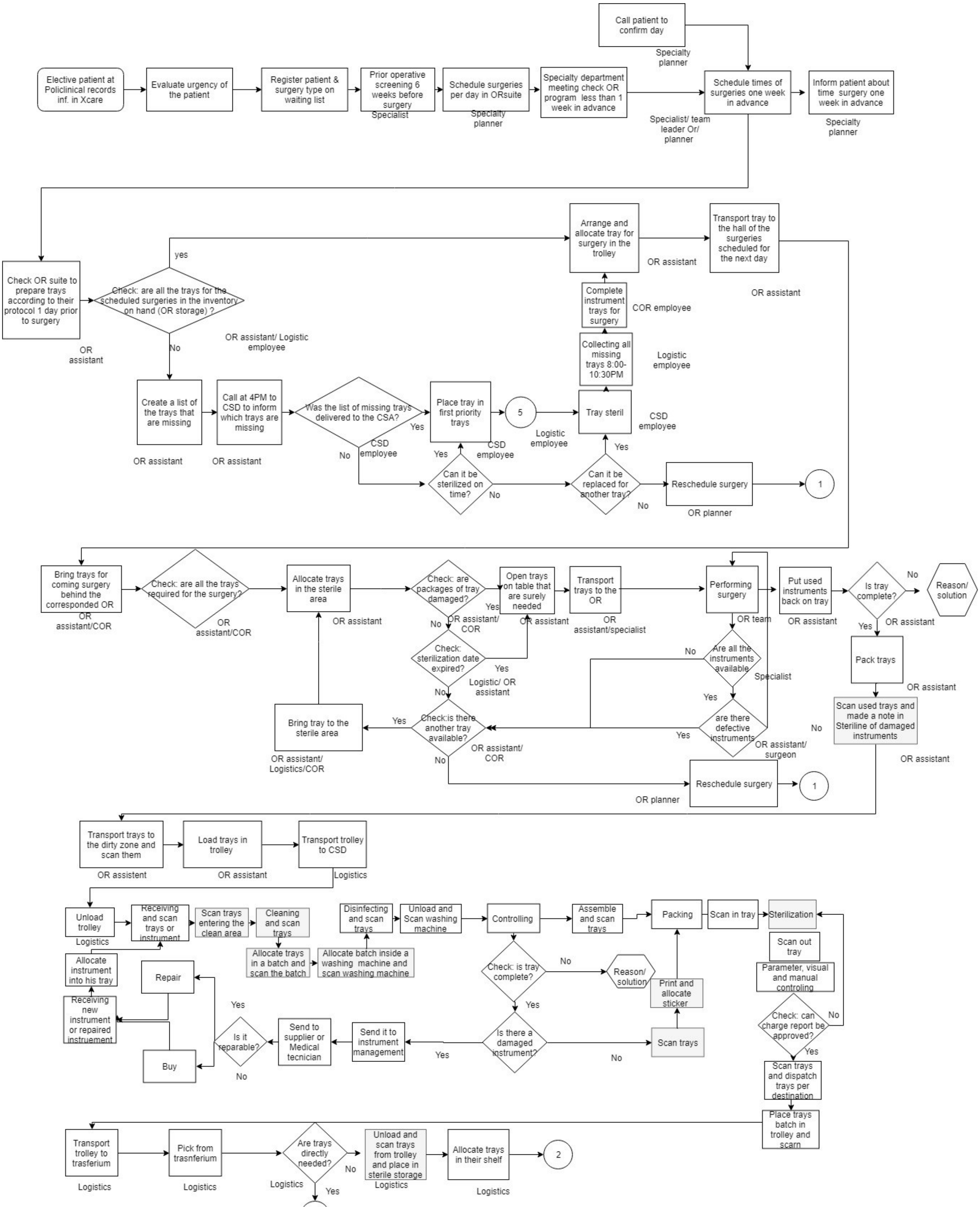

Figure 54 Detailed flow of reusable instrument sets. Based on interviews with the Coordinator and Planner from the CSD (2018).

Appendix III Integrating demand instances into the Markov transition matrix

$$\pi_j(S) = \sum_{i=0}^{S} \pi_i(S)p_{ij} \ \ for\ j = 0, \dots, S$$

$$\pi_j(S) = \sum_{k=0}^{S} \mathrm{k}(S)p_{kj} \ \ for\ j = 0, \dots, S$$

$$i + j - S\ So\ if\ we\ displace\ j\ then\ j = S - i$$

$$j = S - i$$

$$\pi_{S-i}(S) = \sum_{k=i+1}^{S} \pi_k(S)p_{k,S-i} \ + \ \pi_i(S)p_{i,S-i} + \sum_{k=0}^{i-1} \pi_k(S)p_{k,S-i}$$

First term

$$\sum_{k=i+1}^{S} \pi_k(S)p_{k,S-i}$$

Recall

$$j = S - i$$

$$k \geq i + 1$$

$$k + j \geq (i + 1) + j = (i + 1) + (S - i) = S + 1$$

$So\ k + j >$ S

So first part of demand transition matrix

$$p_{kj} \ = Pr(D = S - j) \ = \ Pr(D = i)$$

So we can replace $p_{kj} = p(D = i)$ into equation

$$\pi_{S-i}(S) = \sum_{k=i+1}^{S} \pi_k(S)p_{k,S-i} \ = Pr(D = i) \sum_{k=i+1}^{S} \pi_k(S)$$

Second term

$$\pi_i(S)p_{i,S-i}$$

$$i + j = S$$

$$i + \ S \ - \ i \ = S$$

So $p_{i,S-i} = Pr(D \geq i)$

$$\pi_i Pr(D \geq i)$$

Third term

$$\sum_{k=0}^{i-1} \pi_k(S) p_{k,S-i}$$

Recall

$$j = S - i$$

$$k \leq i - 1$$

$$k + j \leq (i-1) + j = (i-1) + S - i = S - 1 < S$$

$So\ k + j$ < S

So first part of demand transition matrix

$$p_{kj} = p_{k,S-i} = 0$$

So if can replace $p_{k,S-i} = 0$ into equation, shows that it is not possible to have less than S units running in the system.

Adding each term we obtain $\pi_{S-i}(S)$:

$$\pi_{S-i}(S) = \pi_i(S) Pr(D \geq i) + Pr(D = i) \sum_{k=i+1}^{S} \pi_i(S)\ for\ i = 0, \dots, S\ (3)$$

Appendix IV F-test

	Description
Method:	σ_1: standard deviation of Observed Demand Laparoscopy set σ_2: standard deviation of Empirical Distribution Ratio: σ_1/σ_2
Descriptive statistics	see table below

Variable	N	StDev	Variance	95% CI for σ
Observed Demand Laparoscopy set	365	2.964	8.787	(2.779, 3.179)
Empirical Distribution	365	2.961	8.767	(2.747, 3.176)

Estimation for difference

F Ratio	95% CI for Ratio using Bonett	95% CI for Ratio using Levene
1,00112	(0.910, 1.101)	(0.910, 1.104)

Test

Null hypothesis	H_0: σ_1 / σ_2 = 1
Alternative hypothesis	H_1: σ_1 / σ_2 ≠ 1
Significance level	α = 0,05

Method	Test Statistic	DF1	DF2	P-Value
Bonett	0.00	1		0.982
Levene	0.00	1	728	0.964

Test interpretation

Since our F ratio falls between the two critical intervals from Bonet (0.910, 1,101) and Levene (0.910,1.104), our decision is to fail to reject Ho. Moreover, the p-values from Bonett and Levene tests is lower than α = 0,05 we have enough evidence to assume with a 95% of confidence that that the two true variances are equal.

Appendix V Model of FMAU and SMAU

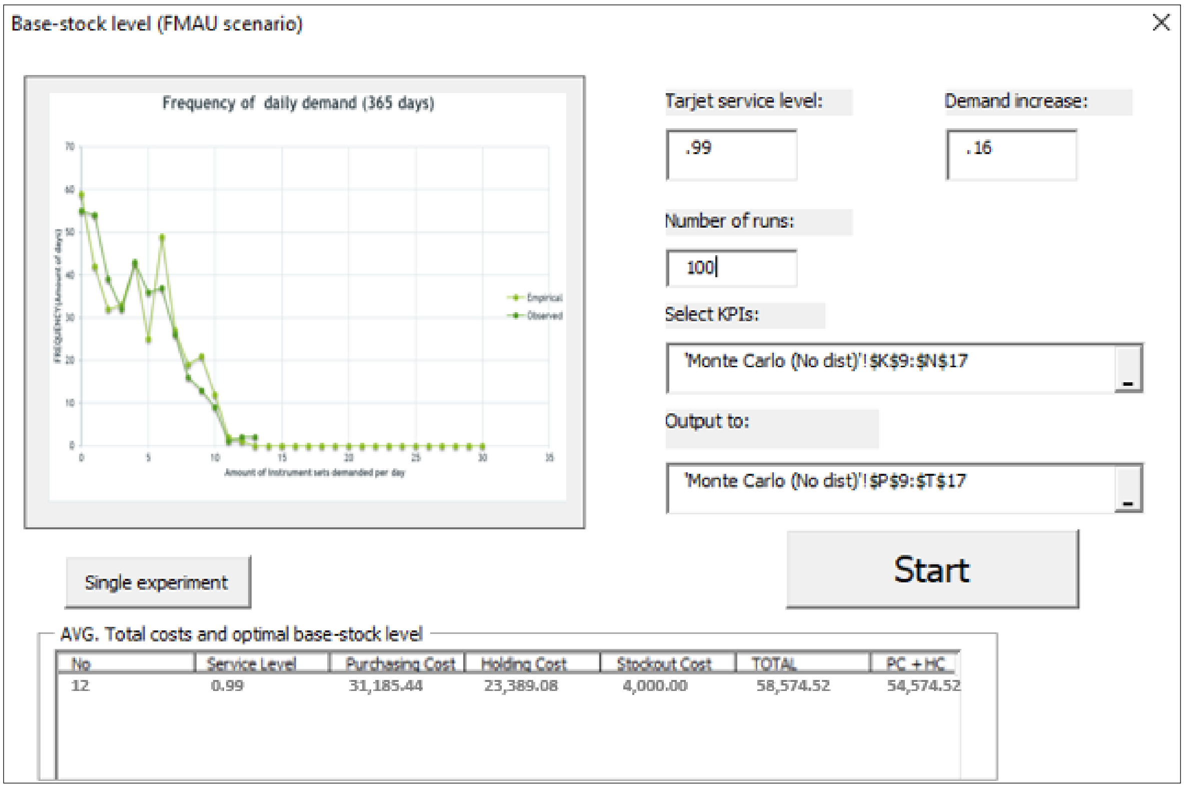

Figure 55: Screenshot of base-stock level (FMAU scenario)

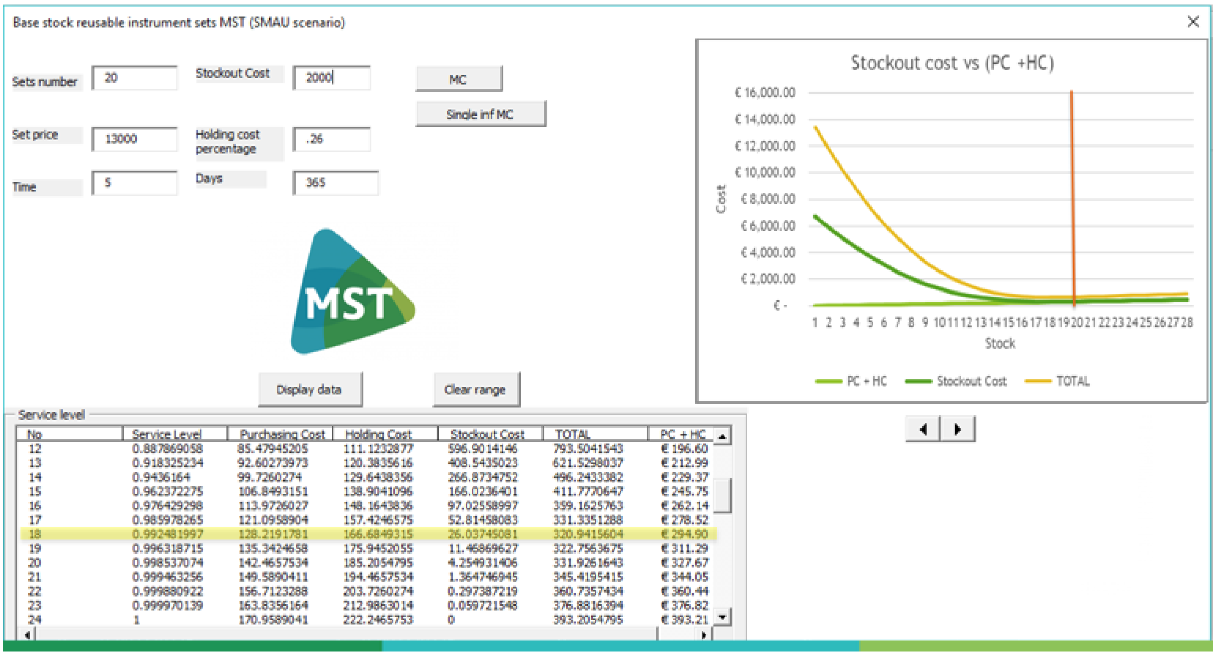

Figure 56: Screenshot base-stock level (SMAU scenario)