TÉCNICO LISBOA

Combining Discrete Event Simulation with Multicriteria Decision Analysis:

A Decision Support Methodology to Improve Efficiency in the Cath Lab

Paulina Gabriela Lima da Rocha

Thesis to obtain the Master Science Degree in

Biomedical Engineering

Supervisors: Professor Mónica Duarte Correia de Oliveira

Professor Lino Manuel Ribeiro Patrício

Examination Committee

Chairperson: Professor Agostinho Cláudio da Rosa

Supervisor: Professor Mónica Duarte Correia de Oliveira

Members of the Committee: Professor João Carlos Da Cruz Lourenço

November 2019

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Preface

The work presented in this thesis was performed at SIEMENS Healthineers (Lisbon, Portugal) during the period March-September 2019, with research being done with application to the Cath Lab at *Hospital Espírito Santo de Évora*. The work was supervised by Prof. Mónica Duarte Correia de Oliveira from Instituto Superior Técnico, by Dr. Filipa Matos Baptista from SIEMENS Healthineers and by Prof. Manuel Ribeiro Patrício from *Hospital Espírito Santo de Évora*. This work was developed also with the scope of the EIT Health MSc Technological Innovation in Health.

Acknowledgements

I would like to thank Professor Mónica Oliveira for the attention she always had with me over the last months, for all the questions answered, for the so organized and effective way of work and, for encouraging me and showing that I was capable. I would also like to thank Professor Lino Patrício, for the confidence and interest shown since day one and for all the wisdom advices and, to the whole team of the Cath Lab, in special to nurse Marisa Serrano who helped me tirelessly.

Filipa Baptista, I will be forever grateful for the opportunity. Also, for all the accompaniment, attention and constant advices. Finally, for allowing me to join such a wonderful team. Mafalda, Manuel, Carlos, Nuno and Vera made this chapter easier.

Additionally I would like to thank my friends, those of long standing, and those of short, those who entered IST with me and those who entered adventures with me, to all who entered and left my life in the meantime and to all who accompany me in faith.

To my family, with me since ever, I thank the love and the support.

I would also like to thank my sister, Lhalha, for being my support, my love and my strength. She helped me get where I am today. Plus, I would like to thank her for bringing Pedro and Teresinha to this amazing journey.

To my grandfather, Abel, wherever he is, I thank him for making me so strong.

Finally, I would like to thank my parents, this thesis was written for them and thanks to them. The life goal has been achieved.

Abstract

Cardiac Catheterization Laboratories (Cath Labs) are pressured to be efficient in economic and operational terms. Regularly, in an attempt to improve the efficiency in these units, managers make decisions without any objective foundation.

This thesis develops a new approach, called MultiSim, that aims to support laboratory management in the implementation of efficiency improvement measures. MultiSim proposes, through a sociotechnical approach, combining Discrete Event Simulation (DES) with Multicriteria Decision Analysis (MCDA) in an integrated format.

The methodology framework starts with the structuring of efficiency challenge in the Cath Lab workflow. Then, based on the principles of multicriteria analysis, a set of criteria to appraise the efficiency in the Cath Lab workflow is defined. In a decision conference, improvements in these criteria are assessed by the Cath Lab team, which also helps create a sense of common purpose among the team members. The simulation model is then built to evaluate the operational impact of alternative measures in a quick and costless way. To conclude, within viable measures, MultiSim prioritizes those that best incorporate the perspective of efficiency of Cath Lab workflow key players who especially valued improvements in 'Agility between procedures' and 'Efficiency of admission process', in that order of preference. The first requires a proper allocation of responsibilities among team members and the second, a better pre exam assessment and hiring of a full-time administrative assistant.

MultiSim has achieved its main objective: align a multidisciplinary team towards a common goal and advise on future efficiency improvement measures.

Keywords: Improve Efficiency; Cath Lab; Decision Support Model; Multicriteria decision analysis; Discrete Event Simulation; MultiSim.

Resumo

Os laboratórios de hemodinâmica são pressionados a ser eficientes tanto a nível económico como operacional. Regularmente, numa tentativa de melhorar a eficiência destas unidades, os conselhos de gestão tomam decisões sem qualquer tipo de fundamento objetivo.

Esta tese desenvolve uma nova abordagem, denominada de MultiSim, que visa apoiar a gestão do laboratório na implementação de medidas gerenciais. O MultiSim propõe, através de uma abordagem sociotécnica, a fusão dos princípios da análise multicritério com os da simulação.

A metodologia começa com a estruturação do desafio de eficiência no laboratório. Depois, com base nos princípios da análise multicritério, são definidos critérios para avaliar a eficiência do fluxo de trabalho no laboratório. Numa conferência de decisão, melhorias nesses mesmos critérios são avaliadas por colaboradores do laboratório, o que cria um sentido de propósito comum dentro da equipa. Segue-se então a simulação, construída para avaliar o impacto operacional de medidas alternativas de forma rápida e a custo zero. Para concluir, das medidas viáveis, o MultiSim prioriza aquelas que melhor incorporam a perspetiva de eficiência de quem trabalha no laboratório, que mostrou valorizar a “Agilidade entre procedimentos” e a “Eficiência do processo de admissão”, nesta ordem de preferência. O primeiro exige uma alocação adequada de responsabilidades entre os membros da equipa e, o segundo, uma melhor avaliação pré-exame e a contratação de um assistente administrativo a tempo inteiro.

O MultiSim alcançou o seu principal objetivo: alinhar uma equipa multidisciplinar em prol de um objetivo comum e aconselhar sobre futuras medidas de melhoria da eficiência.

Palavras-Chave: Melhoria de Eficiência; Laboratório de Hemodinâmica; Modelo de Apoio à Decisão; Análise de Decisão Multicritério; Simulação Discreta de Eventos; MultiSim.

Table of Contents

List of Figures

List of Tables

Abbreviations

ABS - Agent Based Simulation

CC - Cardiac Catheterization

CI - Confidence Intervals

CPL - Cardio pneumology

DALY - Disability-Adjusted Life Years

DES - Discrete-Event Simulation

DM - Decision Maker

DSS - Decision Support System

ES - Enterprise Services

ED - Emergency Department

EU - European Union

GDP - Gross Domestic Product

HESE - Hospital Espírito Santo de Évora

ICU - Interventional Cardiology Unit

KPI - Key Performance Indicator

MACBETH - Measuring Attractiveness by a Categorical Based Evaluation Technique

MCDA - Multicriteria Decision Analysis

PCI - Percutaneous Coronary Intervention

SH - SIEMENS Healthineers

UDAIC - Unit of Digital Angiography and Interventional Cardiology

Chapter 1 Introduction

For any organization, service quality and excellence come as a priority, even more in healthcare sector where the main focus is the provision of health, which is not a physical good. Moreover, healthcare managers are daily pressured to improve quality and decrease costs hence, every day they are forced to look for further efficiency gains [1]. These gains usually imply organizational changes and consequently, decision making.

Though, decision making is something that managers tend to have difficulties to do rationally, when unaided. However, decisions are often made with base on previous experience or trial and error methods, using heuristic or intuitive approaches to simplify complexity. The problem is that, in those cases, important information is many times ignored [2], which is why decision support tools are so important as they allow a rational and transparent priority setting. However, even in situations where decisions are made in a coherent way, there is another obstacle: the implementation of changes. Managerial changes are often met with resistance due to the risks and uncertainties they are associate with [3] hence, a main concern when improving a healthcare system should be with gain the confidence of stakeholders and administrative boards.

The current study addresses the aim of Hospital Espírito Santo de Évora (HESE) to improve the efficiency in its Cardiac Catheterization Laboratory (shortly referred to as Cath Lab) workflow. Cath Labs are, per se, complex systems characterized by unpredictable stressful days and high complexity cases [4]. Also, the costs associated with the procedures performed in there are high which, considering performance-related pay and prospective budgets, increase pressure in these units to be as productive and efficient as possible.

So, after presented to the problem, the challenge of the study was to develop a solution to support healthcare managers set priorities. Since the study makes part of a project from the SIEMENS Healthineers (SH) Enterprise Services (ES) team, the developed methodology should also be in accordance with their principles. SH ES team is characterized for being disruptive in its approaches, that look to forward improve and optimize workflows, clinical outcomes and patient experience, while reducing costs. For SH ES team, it is important to create value beyond the product and so, the methodology should be developed in a perspective of promoting value-based healthcare. Adding to this, as this dissertation is being elaborated within the scope of an EIT Health MSc in Technological Innovation in Health, it aspires to present an innovative and generalizable solution.

Considering all the aforementioned, we then propose a new approach, called MultiSim, which aims to support healthcare managers set priorities and improve efficiency in this specific Cath Lab, and others with similar challenges and concerns. The framework is developed with base in a sociotechnical approach in order to mitigate the referred barriers to the implementation of managerial changes. MultiSim suggests the use of simulation, an effective tool to replicate and explore possible changes in healthcare sector, combined with Multicriteria Decision Analysis (MCDA), which allows evaluation and prioritization of improvement measures, in an integrated format. These two techniques constitute the core of the technical component of the approach, which will be strongly allied with a social component, which involves stakeholders and workflow key players in the analysis of processes and in the evaluation of managerial changes.

The methodology framework starts with the structuring of the challenges to efficiency in the Cath Lab with the support of groupwork sessions and interviews. These first social steps are the pillars of the model and hence, very important for its success. Once challenges and respective improvement objectives are defined, MultiSim methods start to be. In this stage, principles from MCDA and from simulation techniques are applied, in accordance with a number of axioms that describe transparent choices, including completeness, transitivity, and independence [5]. These methods are implemented with the support of decision conferencing and smaller meetings, which ensure decision making is made under an organized and structured way, that considers all and different pints of view. Then, the last and final step, is the culmination of all and also the innovative feature of MultiSim. Because, if before one could only prioritize managerial actions without knowing their operational effects or, in the other side, if before one to see in advance the reaction of systems against different configurations but could not choose between viable options, with MultiSim, those problems do not exist anymore. MultiSim allows the construction of a model in close collaboration with Cath Lab stakeholders and workflow key players that, not only measures the performance of the system against alternative improvement measures, but that also evaluates at what extent these improvements add value to the efficiency in the Cath Lab, again, considering final users points of view.

Regarding the technical component, this simple approach is expected to cover the current needs and, relatively to the social component, it proved to be of extreme importance by ensuring engagement with stakeholders since day one and also showing workflow key players that their opinion matters.

This thesis starts with a contextualization regarding health in Portugal and the relevance of cardiac diseases on it. This introduction is complemented with a presentation of HESE and its services, specially the Interventional Cardiology Unit. Then, a literature review of the use of MCDA, Simulation and moreover, the combination of both in healthcare is presented. From that point, the methodology framework is described and implemented. Finally, the main aspects of the approach are discussed, and the key conclusions are summarized.

Chapter 2 Context

2.1 Key challenges in the Portuguese health spending and needs

One of the main challenges of public health units is to guarantee health assistance objectives with the lowest cost [6]. Thus, an analysis on the national health expenditures was developed with the aim of understanding the position of Portugal, in an economic perspective, relative to the other European countries.

By 2018, the current health expenditure increased 5.1% from 2017 in nominal terms and reached the value of 18 345.1 million euros, corresponding to 9.1% of the Gross Domestic Product (GDP), as shown in table 1. These values put Portugal in line with the European Union (EU) average of current expenditure on health in GDP (8.4%) [7]. However, the current health expenditure nominal rate of change is having a higher increment than the GDP, hence the fundamental problem then is how to contain the rhythm of growth of health care expenditures, within the intended assistance and protection objectives in the disease [6].

Table 1 Current health expenditure and GDP (2015-2018) [7].

	2015	**2016**	**2017 (Provisory)**	**2018 (Preliminary)**
Current health expenditure				
Value (10^6 €)	16 132.2	16 853.8	17 456.5	18 345.1
Nominal rate of change (%)	3.3	4.5	3.6	5.1
% of GDP	9.0	9.0	9.0	9.1
Per capita (€)	1 557.5	1 630.3	1 694.8	1 784.8

Though efforts are being made in order to eliminate inefficiencies in National Health System, there will come a time where opportunities for waste reduction will become exhausted and healthcare managers will be pressured to deliver quality care while facing rising costs and lower reimbursements hence, it is important to start looking for further efficiency gains. In that sense, changes are being implemented such as performance-related pay and prospective budgets, where the more efficient the public institution is, the more money it gets. These incentive strategies proved to be effective on promoting efficiency among health institutions, who increasingly look for alternatives that support them improve their performance [1].

Considering the described economic scenario of health in Portugal, an important next step is to understand the state of Portuguese population health itself. A study of the Global Burden of Disease [8] states that in Portugal, circulatory diseases have a major impact in morbidity, disability and premature death accounting for 15.82% of the burden of disease (measured by disability-adjusted life years (DALYs)) in the country in 2017, which is, again, in line with the EU (18.36% DALY).

Adding to this, also in 2017, *Instituto Nacional de Estatística* [9] corroborates the aforementioned stating that the main causes of death, in Portugal and in the EU, were diseases of the circulatory system and malignant neoplasms (figure 1). Particularly in Portugal, these two together represented 54.4% of the deaths, from where 29.4% corresponds to diseases of the circulatory system.

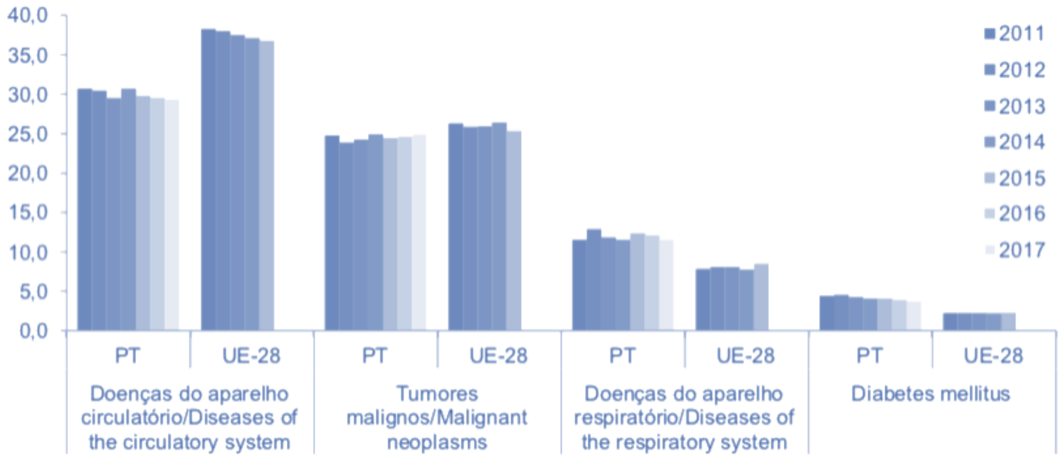


Figure 1 Deaths by some causes of death, Portugal 2011-2017 and EU-28 2011-2015 (% of total) [9].

Regarding the geographical distribution of the mortality rate of the main cause of death in the country, by NUTS III, data revealed that, during the year of 2017, the frequency of deaths caused by diseases of the circulatory system, was higher in the districts of Beja, Évora, Portalegre and Bragança with a rate of 420 to 514 death per 100k habitants [9], as depicted in figure 2. Thus, it is valid to consider these latter areas as targets when it comes to improve Interventional Cardiology Units (ICU).

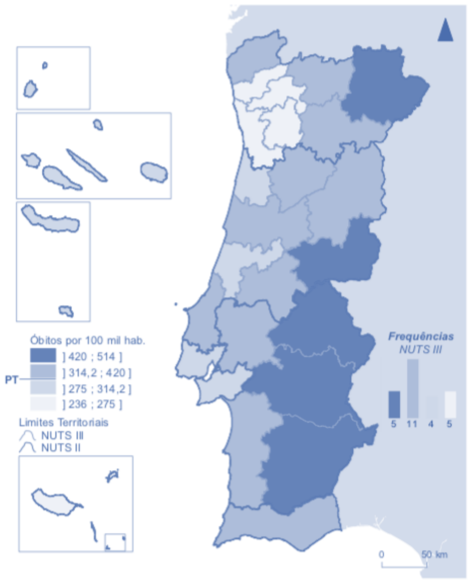


Figure 2 Distribution of the mortality rate of diseases of the circulatory system, by NUTS III, 2017 [9].

A study from the Portuguese Society of Cardiology revealed that Alentejo registered 2588.76 of Percutaneous Coronary Interventions (PCIs) per million inhabitants in the year of 2018, putting this region above all the others as shown in figure 3 [10].

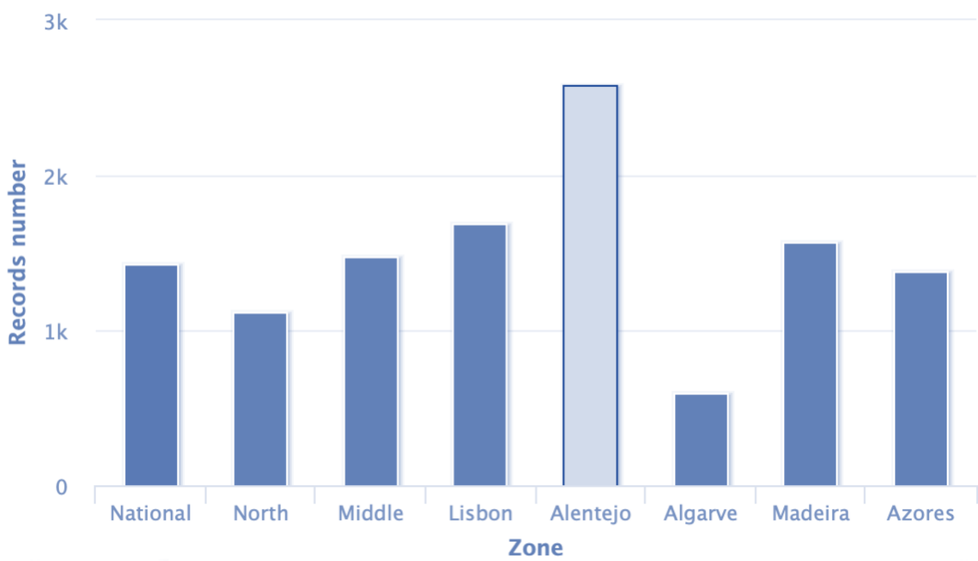


Figure 3 Records number of PCIs per Zone per Million of Inhabitants in 2018 [10].

Taking in account the current global impact of diseases of the circulatory system and focusing on the national scenario, one cannot help but highlight Alentejo region, as it includes the districts where the frequency of deaths caused by diseases of the circulatory system is higher and presents the highest number of PCIs per Million of Inhabitants. Despite the impact that circulatory diseases have on this region, it only has one Cath Lab, able to perform invasive cardiac techniques, and it is located in HESE, Évora. This puts HESE in a prominent place regarding the delivery of cardiac care.

Bearing in mind all the aforesaid, overcoming the daily challenges faced by the Cath Lab, also common to other labs and, described in the literature and in section 3.3, comes as a priority. The latter point, allied with the continuous interest of the Coordinator of Interventional Cardiology from HESE, Prof. Dr. Lino Patrício, in improve healthcare delivery in this region gave rise to the purpose of the current study: increase efficiency in HESEs' Cath Lab contributing to the enhancement of cardiac health in Alentejo.

2.2 Objective

The present study intends to develop methodologies to support Cath Lab managers in the implementation of managerial actions to improve efficiency in its clinical pathways. With that aim, the following section contextualizes and characterizes HESE and the Cath Lab, an essential step to understand what their objectives and main challenges to achieve them are.

Chapter 3 Description of the Entity

This chapter starts by briefly presenting HESE as a Central Hospital of Alentejo and, it is also given an explanation about the unit in which the Cath Lab is inserted and how it is organized. Afterwards we describe the characteristics of the pathologies treated in the Cath Lab and the two procedures used for it and, to conclude, the main challenges faced by a Cath Lab at a daily basis are listed.

3.1 Hospital do Espírito Santo de Évora

There have been more than 500 years since HESE serves the population from Alentejo, being under guardianship of the state since April of 1975. The hospital is located in the city of Évora and its direct area of influence corresponds to the Central Alentejo (NUT III), and the indirect area of influence to the rest of Alentejo, as represented in figure 4. The unit works as Central Hospital of the region and hence, many valences of regional character are located there, which is the case of the Cardiology Service the only one performing hemodynamics interventions, around 1000 per year [11].

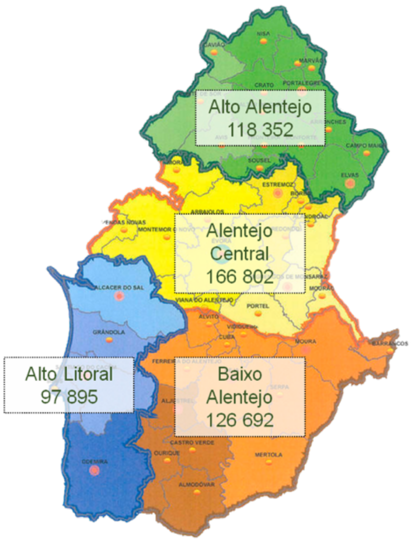


Figure 4 Map of Alentejo with the four municipalities that constitute it, and respective number of inhabitants [11].

Within the hospital, the unit responsible for such procedures is the Unit of Digital Angiography and Interventional Cardiology (UDAIC) which was inaugurated in June of 2009, with the mission of responding to the needs of the population from Alentejo region in several areas [12]. In fact, statistics say that from 2009 to 2017 the percentage of deaths due to circulatory system diseases decreased from 39.9% to 29.7% [13], which might be related with the opening of the lab.

Ever since its opening, UDAIC has been in operation 12 hours a day (from 8:00 a.m. to 8:00 p.m.) on weekdays and, also in permanent prevention regimen since December of 2012, for emergencies of patients with acute myocardial infarction. In a near future, and attending to the population needs, HESE will increase its capacity with the inauguration of a new Cath room and from there UDAIC will count on with two angiographs.

As UDAIC is a multidisciplinary unit, it involves the areas of Interventional Cardiology, Interventional Nephrology and Vascular Surgery, which are organized according to figure 5. An important fact to refer is that 80% of UDAIC's time is used for interventional cardiology [12].

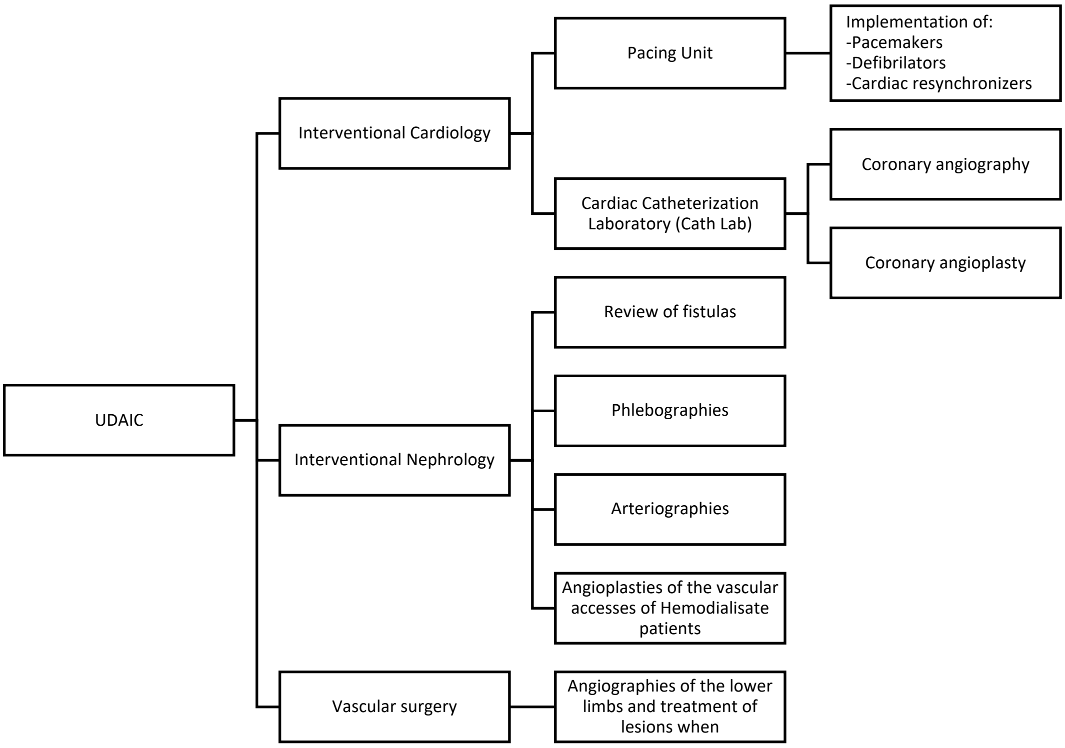


Figure 5 UDAIC organizational chart with its constituent areas principal procedures performed in each of the latter [12].

As the current study is developed in close collaboration with the coordinator of the Interventional Cardiology Unit, its main focus will be on the Cath Lab, which is mainly dedicated to the performance of coronary angiographies and angioplasties.

3.2 Pathologies treated in Cath Lab

Heart´s arteries can become blocked or narrowed progressively, as shown in figure 6, from a buildup cholesterol, cells or other substances (plaques) (American Heart Society 2015). These plaques decrease the caliber of the arteries and hence, the quantity of blood that reaches the heart decreases. Such occurrence can cause chest pain when performing efforts (*angina pectoris*), shortness of breath or, in some cases, no symptoms are registered. If the blood flow in the coronary arteries diminishes drastically it can result in an acute myocardial infarction also referred as ‘heart attack’ [15] and, in extreme cases, lead to death.

Figure 6 Illustration of the decrease in blood flow in the arteries due to the diminishing of their caliber. This is caused by plaque formation in their walls [15].

The Cath Lab performs the diagnosis and/or treatment of obstructions of the arteries that irrigate the heart in a process called Cardiac Catheterization (CC) that allows the examination of the inside of heart’s blood vessels using a thin hollow tube called Catheter. Therefore, a CC has two main goals [15]:

1. <u>Diagnostic:</u> diagnosis of coronary disease through an angiography, where one is able to visualize the vessels using a special type of X-rays called angiograms.
2. <u>Therapeutic:</u> to dilate obstructed arteries, opening arterial blockages, allowing blood to flow freely to the heart in a process called angioplasty.

These procedures are typically used to evaluate and treat conditions as [16]: coronary artery disease; hemodynamics in the right and left side of the heart; left ventricular function; cardiac arrhythmias; valvular heart disease; pericardial and myocardial diseases; congenital heart diseases; and heart failure.

Regarding the team who performs the procedure, it is usually constitute by an interventional cardiologist with assistance from radiologic technologists and nurses. Even though these exams can be executed with minimal or moderate sedation with the help of a local anesthetic, in a case where deep sedation or general anesthesia is necessary, anesthesia services might be required [16].

3.2.1 Arterial Access

CC starts with the placement of an ‘introducer’, a tube that is fixed in the artery, through which the Catheter is introduced. The arterial access is usually made on a femoral artery (located in the groin) or on a radial artery (on the forearm/wrist).

The radial access was first described in 1989 and since then its use has been increasing in comparison to the transfemoral access. This increment is due to several advantages such as: reduced mortality and stroke rate, decreased major bleeding and lessened access site complications [17]. Adding to this, radial access procedures enhance patient comfort, reduce post-procedure bed rest and eventually length of hospital stay [16].

3.2.2 Coronary Angiography

After the placement of the indroducer, the angiography is perfomed with the Catheter being threaded through the blood vessels into the heart. At the same time, a dye visible by X-ray is injected and a series of X-rays is taken. On the X-ray, one is able to see if there are any narrowed areas or blockages in the coronary artery. The patient might feel a hot, flushing sensation from the dye [18].

If, during the angiography, a coronary disease is diagnosed, the physician should decide whether it is possible to dilate the obstructed artery immediately by performing an angioplasty, or whether it should be performed posteriorly. In some cases, medication is enough to solve the blockage [15].

3.2.3 Coronary Angioplasty

If an angioplasty is performed, it can be completed by placing a stent to keep the artery ‘opened’, and in that case, it can be named as a PCI. A stent is a small metal mesh tube, placed post-angioplasty, that highly reduces the risk of another blockage [18].

After the treatment is done, the intensity of pain decreases, and symptoms are relieved immediately.

The patient recovery time will then depend if the CC used a femoral or a radial access. For the first case, patient should remain laying down without moving the leg that has the introducer until it is removed, usually less than 6 hours later. These patients are normally admitted (for no longer than one or two days) and have to stay in rest, at least, until the day after the intervention. If the CC is made through radial access, patient is able to move earlier and can go home on exam day.

3.2.4 Complications associated to Cardiac Catheterization

CC procedures are relatively safe, presenting a risk of complications minor than 1%, and a risk of mortality of 0.05% [19]. Although, the complication rate depends on multiple aspects that include demographics of the patient, vascular anatomy, comorbid conditions, clinical presentation, the procedure being performed and the experience of the operator [16].

3.3 Key challenges of the Cath Lab at HESE

Cath Labs are very unpredictable places that deal daily with high pressure situations [4] and, the Cath Lab under analysis is no exception. The volume and complexity adjacent to the cases that arrive, the multidisciplinary and magnitude of the team inside the Cath room, the use of advanced and continuously evolving technologies and, the coordination and precision required to perform CCs, make Cath Lab a unit hard to manage [20]. Besides all the referred challenges concerning the management of a Cath Lab, every hemodynamic unit has its own efficiency challenges, which are more easily detected through approaches to the lab team [21].

Thus, with the aim of addressing the key challenges to efficiency of the Cath Lab at HESE, the following sections include a literature review about methods used to support healthcare systems improve their performance. Since the present study has its focus on improving the efficiency in the Cath Lab workflow, the literature review will mostly concern models used to aid decision making process regarding the implementation of improvement measures and also models that help forecast the impact of those measures.

Chapter 4 Literature Review

A concept that allows to measure the performance of a company is productivity, as it is described as being the output obtained from a certain input. Strongly allied to this is the term efficiency, that corresponds to the maximum output attainable from a certain input, which is the main goal of any process [22].

Nowadays, as health care systems are being pressured financially with decrease of reimbursement, a valuable tool for practitioners and managers might be improvements in efficiency. Although, this can be a hard task for Cath Labs, as these are characterized by its high acuity, complexity, and often unpredictable schedule.

Thus, and in order to enhance patient's clinical pathway since the moment he enters the ICU until the moment he leaves, one needs to identify and eliminate any operational inefficiencies that are compromising it, taking in account the patient safety and satisfaction, employee fulfillment and retention, and overall quality of care [21].

However, although there are many different ways of analyzing and improving healthcare systems, the current lack of vision and leadership of the healthcare managers and health authorities becomes a challenge. Allied to this, is the lack of willingness to redesign processes in order to increase efficiency and quality [3]. Nevertheless, literature presents some successful approaches that have been already implemented in Cath Labs worldwide, some of which are described below.

Starting with Venkatadri et al. (2011), the study suggests the use of the six-sigma method combined with Discrete Event Simulation (DES). The focus of the study is to create a baseline simulation model that reflects the existing Cath Lab system, develop alternative scenarios and then study performance measures against the alternative scenarios proposed, so that most feasible change can be selected and suggested for implementation. To note that the development and analysis of alternative scenarios was supported by a survey that aimed to capture the views of each type of personnel on some of the operational improvement activities. The study presents positive results regarding patient turnaround time and overall procedure end time in Cath Lab as they met the study objectives [23].

Also, Stepaniak et al. (2014) experimented a way of improving the Cath Lab efficiency using a statistical model that helps understanding the stochastic behavior of Cath Lab procedures. Authors suggest the use of a lognormal model to manage the variation in treatment duration that exists as they defend that the efficient use of the Lab strongly relies on estimated case durations and, lognormal models make procedure times become more predictable through a more accurate estimation of the duration of the latter. The application of the suggested approach resulted in less overtime and in a reduction in the number of cancelled patients, supporting the assumption that Cath Lab procedures are well-modelled by lognormal models [24].

Another method, proposed by Agarwal et al. (2016), studies the impact of of lean six sigma implementation on improving the efficiency and the patient throughput, in the context of a busy, tertiary-care Cath Lab setting. The lean six sigma is based on the eradication of redundant non-value-added activities and intends to eliminate any operational inefficiencies that do not contribute to improve productivity. The researchers used a stream map to have a consistent view of the workflow and study what were the inefficiencies of the process. Also, founded in the lean six sigma principles, the improvement was made in a continuous way with the team meeting regularly to study the changes in the workflow and to make further amendment. Another relevant fact pointed out as one of the reasons of success was the team being composed of physicians, healthcare managers, department administrators and nursing staff, all of whom key players in the workflow under analysis. This approach was recognized as a very useful tool to improve several measured metrics, such as: turnaround time, physician downtime, on-time patient arrival, on-time physician arrival and on-time start [25].

In 2018, Reed et al. presented congruence model as a useful tool to address operational efficiency. The referred model takes in consideration the perspectives of the different elements that compose systems' operations, and which are interconnected to one another. The implementation of the method is based on the analysis of these elements, the interrelationships between them, and diagram them. By using the Congruence Model, one is able to assess whether the Cath Lab key elements are aligned with its strategy or not. The model defends that both, the technical–structural and the social component of the Cath Lab should be congruent [26].

Considering that, as already stated, one of the main challenges to redesign process in healthcare systems is many times the willingness of their managers and collaborators to perform it, we decided to focus on techniques that give special attention and promote the evolvement of stakeholders in their development. Thus, looking to the methods used in the Cath Lab, one would highlight Venkatadri et al. (2011) as the study that best meets the social aims of the present study. Venkatadri et al. (2011) wants to 'study performance measures against the alternative scenarios proposed' likewise, our study intends to study the performance of the Cath Lab against different improvement measures. In addition, the referred study also gives a prominent role to stakeholders and promotes their participation in the change process. The only thing that Venkatadri et al. (2011) does not consider, and that we think that can add value to the decision making process, is to complement DES with MCDA principles to allow further tradeoff studies aware of the importance that each of those improvement measures represent to stakeholders. Therefore, and in order to explore how DES and MCDA can be used to improve healthcare systems with a similar complexity to Cath Lab, the following subsections describe the state of the art regarding hospital management decision making using MCDA, simulation and the combination of both.

4.1 A review of Multicriteria Decision Analysis, Discrete Event Simulation and the combination of both in healthcare systems

4.1.1 Multicriteria Decision Analysis models in healthcare systems

Health care systems are characterized as complex when it comes to decision making, since these kinds of systems usually involve confronting trade-offs between multiple, often conflicting objectives [5]. This makes priority setting of interventions in healthcare systems difficult and many times resources are not used to an optimal extent, as decision makers tend to use heuristic or intuitive approaches to simplify complexity [2].

But, at some point arises the need of a structured, rational and explicit approach to set priorities. And, even though many approaches have been developed, most of them do not consider simultaneously all criteria that are relevant to decision makers, contrary to what happens with a MCDA model, defined by [27] as

> *both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option.*

The development of an MCDA model makes use of a sociotechnical approach, which improves communication within the organization, develops shared understanding of the problem and generates a sense of common purpose [28]. This guarantees the integration of the concerns and values of the people who best know the system and are directly related to management decision. For example, in a healthcare context, MCDA models have been used for shared decision making between patients and doctors in the evaluation and selection of therapies, treatments, and health care technologies. With this, one is considering distinct perspectives in the decision making process while capturing the full impact of an intervention [29]. Nevertheless, some disadvantages might arise, considering the gain complexity of the model and the time taken to complete it [30].

There are different types of MCDA approaches that can be applied in healthcare which include value measurement, outranking and goal programming, all depicted in figure 7. However, the first one is typically the most used because it is based on Multi-Attribute Value Theory, different from AHP [5], and hence, is in accordance with a number of axioms that describe transparent choices, including completeness, transitivity, and independence [31]. Adulin et al. (2014) also highlights the fact that value measurement approach is very flexible and supports the capture of subjective and objective aspects of a decision [32].

MCDA	Value Measurement models	Additive Aggregation or Weighted Sum Method E.g. MACBETH
		Analytic Hierarchy Process (AHP)
	Outranking models	Elimination Et Choix Traduisant la Realité (ELECTRE)
		Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE-GAIA)
	Goal, aspiration or reference models	Goal programming
		Heuristics
		Meta-heuristics

Figure 7 Classification of MCDA methods [30].

Although MCDA methods have been applied in numerous settings, in healthcare, their application only increased since 2011.

Adulin et al. (2014) conducted a literature review to identify studies using MCDA techniques within the areas of healthcare and involving the participation of decision makers. The review comprehended English language studies published from 1980 until 2013 and concluded that a total of 66 citations respected the considered criteria. These techniques are mostly applied, to disease diagnosis and treatment, followed by priority setting, Health Technology Assessment (HTA) and formulary management [32].

A more recent review performed by Oliveira et al. (2019) focused on identifying studies that referred the use of MCDA in HTA. The study included 129 journal articles, published between 1990 and 2017, from which 56% were published between 2015 and 2017. This review stated that in 42% of the reviewed articles the health technology focus was on pharmaceuticals. Regarding the type of study, 36% of the studies developed models to evaluate health technologies in practice Other studies would include analysis of MCDA implementation issues, proposed frameworks to support MCDA in HTA implementation, and exploration modeling approaches. This review also highlights the use of social processes, stating that a great majority of the studies (85%) reported the use of participative methods and 70% adopted face-to-face approaches for model-building, which comprises decision conferences and workshops. Other social methods involve questionnaires/surveys and interviews, for example. When it comes to criteria weighting, the most used procedures, by decreasing order of frequency of use, are AHP, quantitative swing weighting, point-scaling, 100-point allocation, and MACBETH [33].

Bearing in mind literature review results that refer the ability that MCDA methods have to contemplate stakeholders' preferences in a transparent way that returns simple outputs (Oliveira, Mataloto and Kanavos, 2019) and, considering all the advantages previous described regarding the alignment of MCDA with Multi-Attribute Utility Theory (Von Neumann and Morgenstern, 1947), one can conclude on the utility of such methods to address Cath Lab challenges to efficiency.

4.1.1.1 Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH)

Focusing now on an additive aggregation method, in 1994, Bana e Costa et al. described MACBETH as an interactive approach, that makes use of qualitative judgements about differences in attractiveness of one action over another, to help an individual or a group quantify the relative preferability between these [34].

This approach uses a simple protocol of question-answer that involves only two options for each question. The DM is asked to compare pairwise options through a qualitative judgment of the difference of values of the attractiveness of one action over another action to help an individual or a group to quantify the relative preferability of different actions [35]. The scale for the judgments is given to the DM as no difference, very weak, weak, moderate, strong, very strong and extreme [36].

MACBETH method allows to derive preference scales or value functions and scaling constants in many public and private applications of multicriteria additive value analysis [37]. It has been applied in public policy analysis, prioritization of projects, resources allocation and conflict management, human resources evaluation and management, total quality management, between others.

For the application of MACBETH there is a software, M-MACBETH [36], that supports the evaluation process. M-MACBETH can be very useful for group decision making, as it helps interactive group learning of a problem and enables to incorporate hesitation in choosing between two or more categories of difference in attractiveness. Moreover, this software offers features that allow to check the consistency of the judgements and can even suggest ways of resolving these [38].

In the literature, and regarding the application of MACBETH in healthcare, one can find many studies recommending its use however, none of them happen in a Cath Lab. In 2008, Pinheiro et al. resorted to MACBETH to develop a multicriteria model that would help in decision making for the diagnosis of Alzheimer's disease. MACBETH enabled the building of a ranking of the questions that are most relevant for the diagnosis of the referred disease [39].

On its turn, Moraes et al. (2010), developed a model with the aim of improving the use of the healthcare equipment through its better management. As authors define health technological process as the interaction between human resources and healthcare technology used in delivering patient's healthcare, they defend that Clinical Engineering should address the difficulties found by the workflow key players in the decision making of a health technological process, at different levels. Thus, the study uses MACBETH approach in its evaluation phase to obtain local cardinal scales, compensation scales and an evaluation, which then help to define benchmarks and identify opportunities of improvement [38].

Also, Oliveira et al. (2012) developed a *multicriteria model to allocate human resources in community care programmes,* a social-technical process that makes use of a MCDA in a decision conferencing. The MACBETH approach and its software were used to construct the multicriteria evaluation model allowing the measurement of benefit values (through the building of value functions and criteria weights). The decision conferencing allowed to get a consensus on how to proceed forward to achieve the initial goal. At the end, the model proved to be useful for a transparent prioritization of interventions in healthcare sector and aided a group of health centers to select programmes and redesign its information system [40].

In 2014, Rodrigues suggests the use of MACBETH, also in a healthcare context, this time to build a population health index, a formal assessment tool, that takes in consideration the concerns and strategic objectives of different stakeholder groups and the multiple dimensions of the health of a population (health determinants and outcomes). Hence, this study offers a way, using MACBETH, of evaluate population health in its multiple dimensions, aiding the health sector on its management and planning [41].

Later, in a study developed in 2016, Carnero and Gómez suggested the integration of Markov chains with MACBETH to make rational decisions on asset management in healthcare organizations. The model was applied to aid the selection of a set or combination of maintenance policies in four dialysis subsystems of a healthcare organization [42].

It is important to notice that, the aforementioned studies represent a small sample of a number of them reporting the use of MACBETH to support decision making in healthcare contexts.

4.1.2 Simulation Models in healthcare systems

According to [43, p. 7], simulation can be defined as

> *the process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behavior of the system and/or evaluating various strategies for the operation of the system. Thus, it is critical that the*

model is designed in such a way that the model behavior mimics the response behavior of the real system to events that take place over time.

In fact, healthcare simulation is an active area of research and practice [44] as it permits to explore scenarios of decision making from different stakeholders or practitioners [45] and successfully address managerial problems. The use of simulation tools enables managers of healthcare organizations to evaluate the efficiency of current practices, identify needed resources and, through a what-if analysis comparing different scenarios, predict the impact of managerial changes and therefore determine optimal system configuration [46]. Hence, enhancing patient flow and reducing healthcare delivery costs.

Back in the 1960s and 1970s there were a lot of barriers to the successful implementation of simulation models in healthcare. These barriers included the lack of economic incentives, no vested authority, non-quantifiable data, dehumanizing formulations, and no commitment to follow up, plus it was difficult to balance the conflicting objectives of physicians, nurses, hospital administrators, boards of directors, and other health-care professionals [44]. However, the use of simulation models in medical research and health service management has increased as researchers propose these models as a way to control costs and increase efficiency (Rohleder et al., 2011).

One can find several circumstances where simulation models were used in the healthcare sector that include: improvement of the patient flow at an outpatient orthopedic clinic [47], evaluation of average patient duration and queue length in emergency department (ED) considering human errors [48], improvement of an ED [49], redesign of a medication administration process [50], between others.

Mielczarek and Uzialko-Mydlikowska (2010) developed a review of the application of computer simulation modeling in the healthcare sector addressing the three main types of simulation: DES, Monte Carlo simulation and the System Dynamics approach. Stochastic simulation is usually represented by the first two, and more recently by Agent-Based Methods (ABM) [45], and deterministic simulation is generally associated to the third one. The authors reviewed a total of 168 papers published between 1999 and 2006 in peer-reviewed journals and in the proceedings from recognized international conferences. From those they excluded review-type, methodological papers and the ones where the simulation approach was not clear, then being able to classify a total of 156 papers [51]. This study revealed that simulation methods are mostly applied in the health and care systems operations area (51.28% of the papers). Moreover, 76 out of 156 classified papers that address this area are supported by the DES model [51].

In 2015, also Almagooshi performed a review of the challenges and trends of simulation modelling in healthcare. In the review, the author included only DES and ABM mentioned in papers published between 2008 and 2015. The paper refers to these two methods as the 'best practices in designing and developing simulation models in healthcare' and laments the fact that the knowledge regarding them is dispersed throughout the computing and operational research literature. The author also states a tendency towards a common graphic interfaces [45].

When it comes to the simulation software, even though models can be built using a variety of computer tools, one can verify a trend towards mixed approaches combined into one complex platform [51], which is the case of Simul8, Arena and ProModel computer packages for DES [52].

Considering that, in the present study, simulation aims to show everything that happens to the patient during its passage at the Cath Lab, DES seems to be the best type of simulation to use since: time-to-event is best described stochastically rather than with fixed time intervals; individual pathways through the model are influenced by multiple characteristics of the entity; one wants to study the effect of different managerial actions [53]. Hence, DES and its implementation are further explained and detailed in the following section.

4.1.2.1 Discrete Event Simulation

DES is one of many different tools and methods used in the analysis and improvement of healthcare systems, whose use has increased in recent years [44]. The fact that it allows hospital administrators or clinic managers to evaluate the efficiency of existing systems, to ask 'what if?' questions, and to design new system operations, makes it an appealing methodology for analysis and research modelling. Moreover, DES can also be used as a predicting tool to assess the impact of managerial changes on patient clinical pathway, study staffing levels and physical capacity and study complex relationships among different system variables [54].

Kuntz et al. (2013) points evaluation of alternative healthcare systems (as workflow, staffing) as the type of decision DES best suites, since it represents time in a continuous scale and simulates not only an individual at time, but also its interactions with other individuals and within the health system. The mentioned paper recommends the use of DESs for patient scheduling and admission rules, patient routing and flow schemes [55].

Regarding Simul8 software, it is considered one of the favorite simulation tools among engineers as it provides an easy-to-use DES package. Simul8 allows to build accurate, flexible, and robust simulations in a quick and costless way, hence supporting different kinds of decisions. Besides that, Simul8 has features that permit to obtain results such as machine and resource utilization, overtime requirements, and other standard analysis results. Which are very useful when assessing effectiveness of schedules [56].

Brenner et al. (2010) used Simul8 to manage patient flow inside emergency rooms. Through the use of the simulation model authors could find out optimal numbers of staffing and material resources plus evaluate any potential benefits of operational actions. The referred paper points out that another benefit from the study is its applicability to other emergency departments [46].

In 2012, Monks et al. similarly used Simul8 to evaluate the benefit from reducing delays in the emergency stroke pathway in a large district hospital. The choice of DES is based in the fact that these kinds of pathways present a wide variation in arrival-to-treatment times depending on hospital workload, clinical decision making, between others. The study defends that 'modeling alone is not enough to achieve change within healthcare systems' and therefore appeals the inclusion of stakeholders and workflow key players to reach an agreement on the forward actions to take [57].

Attending to the success and benefits reported by the reviewed studies, which were applied to systems with similar levels of complexity similar to the Cath Lab, Simul8 will be selected in the methodological proposal.

4.1.3 Combining Discrete Event Simulation with Multicriteria Decision Analysis

Literature does not present many studies where MCDA is combined with other Operational Research / Management Science methods to problem structuring and analysis, as most of the times the first is not seen as an integral part of problem-solving methodologies, but a set of tools only applicable to certain categories of a problem [58]. Though, there is a strong belief that MCDA approaches can be very useful and enriching in different situations where decisions aim at attaining multiple objectives.

Combining, for example, simulation with MCDA allows to, not only obtain the performance of the system against different alternative measures (with simulation), but also to convert each performance into value scores (through MCDA). Adding to this, the previous combination enhances the engagement with final users/customers and allows systems to be evaluated considering more than only the operational aspects, thereby turning decision making more inclusive and trustful [59].

As said by Belton and Elder (2013),

> *'Simulation provides the link between decision space and solution space (discovery), whilst multicriteria analysis provides the link between solution space and value space (clarification and explication)'.*

In fact, Belton and Elder (2013) proposed combining DES with MCDA to support the management of a regional UK airport, more specifically the allocation of check-in desks to airlines. Even though authors verified its utility, they suggested that, contrary to what they did, it could have been useful build the multicriteria model first and only then the simulation model, which would permit relevant criteria to be straight forward considered and integrated in the building of the simulation [58].

On its turn, Barros Brito et al. (2012) presents the case study of a steel company who wants to establish a new plant in the country, an example of a complex and multifaceted logistics system.

The study aims to size the company's own vessel fleet and determine the storage area assigned to two types of iron ore. A Decision Support System (DSS) that merges DES and MCDA was developed so that the DES model would help to represent the real system and on evaluating its performance according to the criteria defined in the multicriteria model. In further steps, he DES model allowed the analysis of alternative configurations of the system, whose results underwent a multicriteria analysis that would support determine the 'best' configuration [59]. Contrary to the previous in this study MCDA was performed after the results of the DES model were obtained.

From analyzing each of the models individually and then as a complement of each other, the literature review helped corroborate the advantages of combining DES with MCDA in an integrated format. The first one is that, a hybrid model helps to approach enterprise systems and decision makers. The second is that, approaches like this consider criteria that are many times ignored in decision making processes and so, the hybrid model creates an opportunity to make decisions based on technical and practical fundamentals, with criteria and weights that are well defined by experts giving credibility to the decision making process [59]. Combining these two models is also a way of surpassing the limitations of each of them, such as being able to evaluate scenarios considering more than one criterion or to use a wider range of possible classifications or to see the operational impact of changes. Moreover, and since our problem comprises a Cath Lab that aims to be more efficient through the improvement of its clinical pathways, it is important that key players of the workflow get to be involved in the process of developing the improvement strategy, ensuring the success of its implementation. Since MCDA and simulation are both characterized by a strong use of participatory methods, as described before, these models are quite compatible with what is intended.

To summarize all that was said, as the results of simulation models mainly concern performance measures that help DMs see if the implemented managerial changes affected the performance of the Cath Lab or not, MCDA comes as a natural extension of it that integrates these performance measures the efficiency objectives of the Lab. Even though, one could not find any applications of this combination in healthcare systems, bearing in mind all the advantages described before, of either systems independently and combined, the suggestion of combining MCDA with simulation arises as a good and feasible approach to improve efficiency in the Cath Lab and other similar logistics systems.

Chapter 5 Methodological Framework

According to the Head of the HESE Cath Lab and lab stakeholders, the demand for Cath Labs is expected to increase and, since the procedures performed within it are associated with considerable costs [60], improving efficiency in Cath Labs is a priority.

From the scope of project and the objectives of the Cath Lab under study and, bearing in mind the results of the developed literature review, this chapter describes a proposal of a methodological framework to improve efficiency in healthcare units, starting with HESEs' Cath Lab case, but having the potential to be adapted and used in other similar contexts.

From the literature review, one could conclude that combining in an integrated way MCDA with simulation can be an effective and valid tool for decision making in complex logistics systems [59], as the features of MCDA models might help overcome some of the limitations of DES models and vice versa. Nevertheless, these models have been widely used in healthcare but independently and not very frequently complementing one to another.

From that, the current study proposes combining MACBETH method with DES in a methodological framework that integrates both of their technical and social components, with particular emphasis on the latter. This framework aims to equip Cath Lab managers with a more a complete and more reliable tool that, through measurable criteria, shows at what extent the Cath Lab performance meets their goals.

The intuition behind building a framework that gives special importance to the social component comes from the belief that a close collaboration with workflow key players results in better outputs with right breadth and depth of detail, as they themselves represent a diversity of viewpoints regarding the systems' efficiency and hence, have their own different objectives and preferences [5] [28]. Other advantages that come from social approaches include allowing multidisciplinary groups to develop a shared understanding of the issues, generate a sense of common purpose, and gain commitment in the way forward and confidence in the results provided by the model [28].

To conclude, this framework arises as a solution to bridge the gap between data, processes, information and Cath Lab stakeholders and DMs.

The following sections comprise an explanation of the phases that make part of the designing, implementation of methods and, testing and validation of MultiSim approach. In the section of each phase, the steps that make up its technical and social components are thoroughly described.

5.1 Decision Support Methodology

The methodology framework can be divided in three distinct phases, all of them composed by a technical and a social component, as illustrated in figure 8.

Phase 1 comprehends the structuring of the Cath Lab efficiency problem, which includes collecting all the information and data needed for the development of the study and an exhaustive definition of the scope of the problem and objectives with of board members of the Cath Lab.

Then, during Phase 2 MCDA and DES techniques are used to construct MultiSim model. In this phase, the social component has great participation and highly affects the quality of the technical component.

To conclude, Phase 3 comprises the conclusion of the study through the presentation of the results of MultiSim. Moreover, this final phase intends to obtain the validation of the proposed Decision Support Methodology.

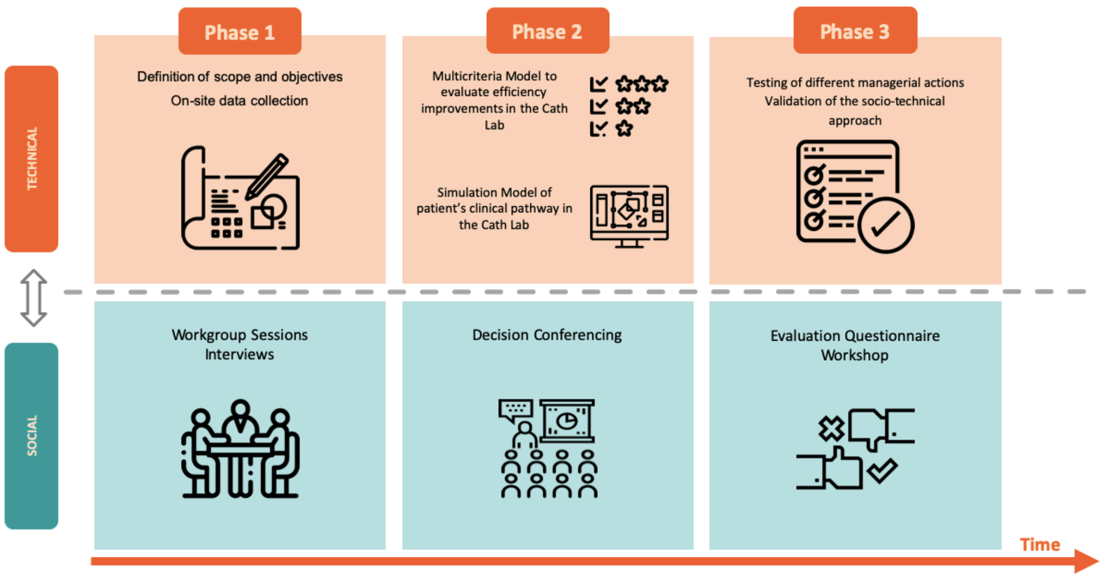


Figure 8 MultiSim components set within a sociotechnical structure.

The same steps of figure 8 above are presented in detail in figure 9.

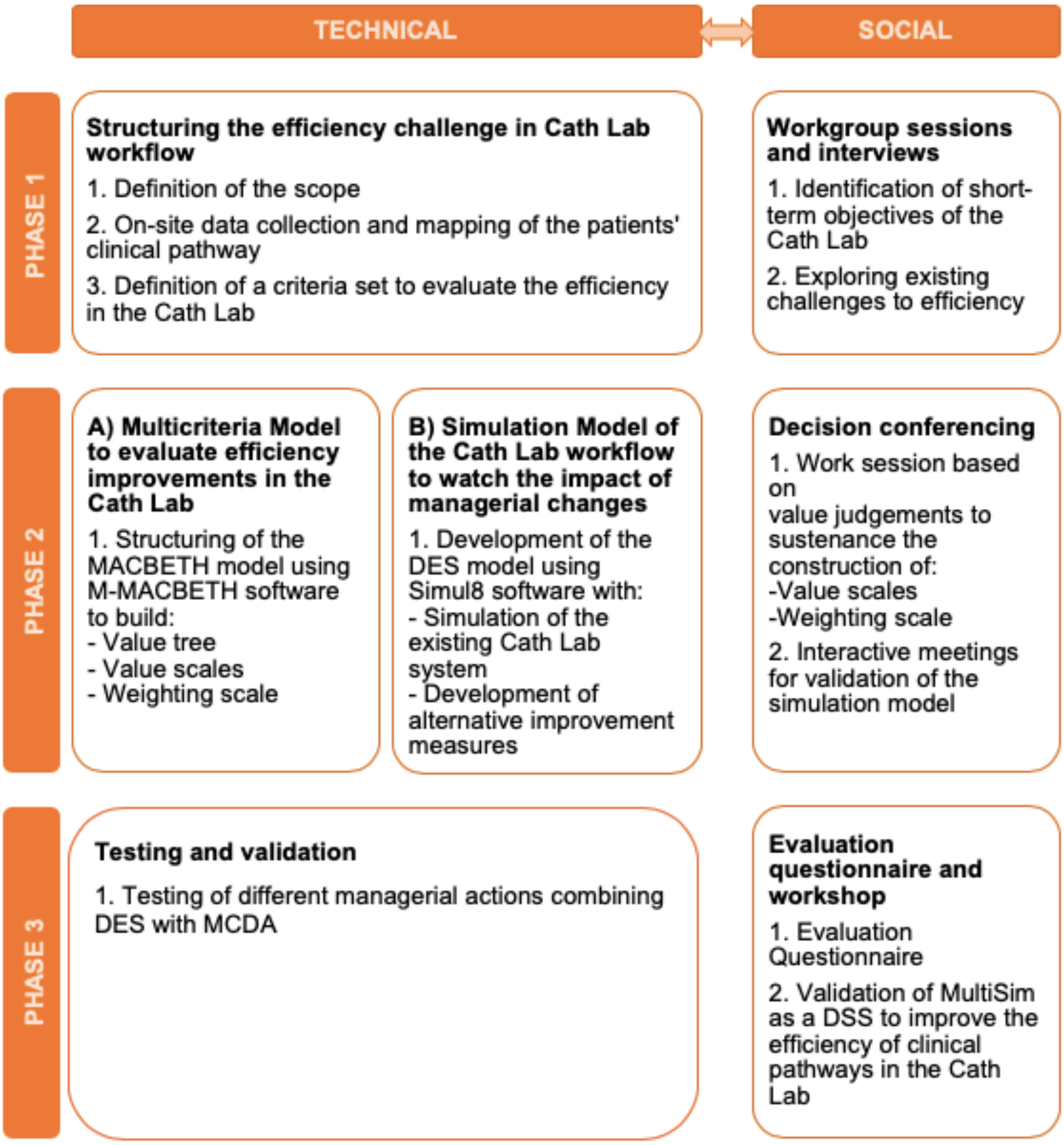


Figure 9 Detailed MultiSim components detailed within a sociotechnical structure. MultiSim is composed by three phases, all of them with a technical and a socio component that interact between each other.

5.2 Phase 1: Structuring the efficiency challenge in Cath Lab workflow

Phase 1 can be seen as the pillar of the approach since, its well-structuration results in a well-founded model that meets the objectives of the stakeholders. This phase aims to gather all the relevant information necessary to implement further steps of the methodology in the following phases.

Thereby, Phase 1 will focus on defining the scope of the problem, collect important data to its resolution and, to conclude, define the criteria set that best represents the efficiency in Cath Lab workflow. The descriptors of performance for each criterion should also be defined and validated by the workflow key players [5].

The outputs of the current phase, as well as the relationships between them, are illustrated below, in figure 10:

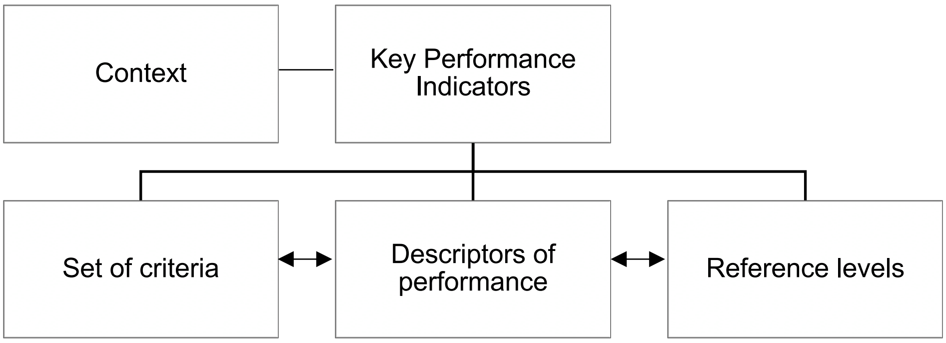


Figure 10 Flowchart of the outputs of Phase 1 and the relationships between them.

5.2.1 Phase 1 - Technical Component

The technical component of Phase 1 comprises the structuring of the models to be used, described by [61] as essential in a decision aid methodology.

<u>1. Definition of the scope</u>

MultiSim model requires a well-defined context of the system to be appraised, in this case, the Cath lab. To do so, data regarding the functioning of HESEs’ Cath Lab, its utility for the community, resources and management must be gathered in other to better understand its position and context, as well as what are its strong and weak points.

<u>2. On-site data collection and mapping of the patients' clinical pathway</u>

To further steps it is important to identify patients' ‘trajectories’ through the Cath Lab when they have to undergo an exam. One can associate this to the concept of clinical pathway which, second Kovalchuk et al. (2018) is defined as the ‘typical care paths for a certain group of patients’ [62].

Mapping the patient’s clinical pathway allows to collect important information on the main steps and procedures applied during care process, as well as which resources are associated to them. Some examples of important mapping information are hours and days of operation, floor plan with the patient’s path and, which professional take which tasks and where.

Therefore, visits to HESEs’ Cath Lab are mandatory to observe and understand the process flow and the functioning of the system, as well as to identify, include and study all sub-processes involved [23] and hence, conclude on which are the critical points that most influence the efficiency of patient's clinical pathway [53].

<u>3. Definition of a criteria set to evaluate the efficiency in the Cath Lab</u>

Considering the future multicriteria evaluation, it is necessary to define the set of criteria that best evaluates the impact of alternative managerial actions in the efficiency of the Cath Lab workflow. To do so, the first step is to identify and select the Key Performance Indicators (KPIs) that best reflect the performance of the Cath Lab in terms of efficiency. These indicators should then be summarized into different criteria according to the improvement targets of the study. On their turn, the different criteria (improvement targets) can be organized in areas of concern [41]. It is important to distinguish the difference between criteria and KPIs, as the first are associated to the notion of value and the second to the notion of performance and hence, criteria improvements should be evaluated only regarding the notion of importance, ignoring value trade-offs underlying additive aggregation models [63], which is referred to as the most common mistake [64]. Therefore, KPIs represent the performance of the lab and criteria the value added to its efficiency, which is what is being assessed.

Ugwu and Haupt (2007) emphasizes the importance of adequate understanding and knowledge of KPIs as one of the first steps towards successful institutional transformations, and efficient decision making [65]. KPIs, are important sources of information about administrative, operational and clinical levels and, focus on the aspects of organizational performance that are the most critical for the current and future success of an organization [66]. Hence, these should be seen as a strategic assessment tool that supports healthcare managers achieve excellence and, knowledge discovery and assessment [3].While developing the study and research on the most adequate KPIs, one must keep in mind the scope of the project, which is evaluating the performance of a healthcare unit, where healthcare outcomes are more important than financial outcomes and, therefore, intangible assets are more important than tangible [3]. Adding to this, most of the selected metrics should be of operational nature, as the model evaluates a process.

Once KPIs are defined, assessing existing knowledge and future needs will also help establish evaluation criteria [3]. The evaluation set of criteria needs to be assessed against several characteristics that include [27]:

- Completeness: all important criteria must be included;
- Redundancy: duplicate or unimportant criteria should be removed;
- Operationality: criteria must be clear enough to be assessed. Furthermore, is important to refer criteria are operationalized through descriptors of performance that often take the form of indicators, and turn criteria more comprehensible in the segment of what was previously explained;

- Mutual independence of preferences: preferences associated with the consequences of the options are independent of each other from one criterion to the next;
- Double counting: effects should not be double-counted, or it is given more weight in the final overall decision than they deserve;
- Size: guarantee that the structure is no larger than it needs to be;
- Impacts occurring over time: ensure that all assessments of criteria are made on the same basis.

Once a valid set of criteria is obtained, the next step consists of assigning descriptors of performance to each criterion to make them operational for evaluating the attractiveness of options [67]. Oliveira et al. (2012) defines a descriptor of performance as ‘a measure of the extent to which the criterion can be satisfied, from a most attractive to a least attractive level of performance’, this is, an ordered set of plausible performance levels. A descriptor of performance can be a quantitative indicator or a qualitative scale [40].

The creation of the descriptors consists of fixing two levels which correspond to the best and worst levels of performance, thus limiting the range of performance in that criterion. Then, a fixed and small number of intermediate equally spaced levels should be demarked and tested using M-MACBETH, which is why this step can be seen as introductory to the implementation of the multicriteria model in Phase 2 [68]. The different reference levels of performance that compose the descriptor correspond to levels of accomplishment for the KPI that measures de performance of a criterion.

The next step is to define, for each of the descriptors reference levels, which can be denominated with different terms, such as ‘Target’ and ‘Base’ [68], ‘Best’ and ‘Worse’ and, as ‘GOOD’ and ‘NEUTRAL’ which is best suited to this study. The ‘GOOD’ level corresponds to a level that has an unquestionably attractive benefit and should be looked to as a ‘goal’, as this is the level of performance envisaged by managers, that when achieved indicates there is no improvement need in the respective criterion [68]. The ‘NEUTRAL’ level is neither attractive nor unattractive in terms of need for improvement, a minimally satisfactory level that can surely be improved, in the Cath Lab might regard the *status quo*. The reference levels may not be necessarily the most and least attractive levels of the descriptor, although it can happen [40].

Having this step well accomplished is the first step to, posteriorly, be able to comparison and evaluate different performances.

5.2.2 Phase 1 - Social Component

As already stated, the technical steps highly depend of the inputs given by stakeholders in the social component of Phase 1. The whole approach is developed with base on the objectives and challenges described by the stakeholders in this phase, which makes it really important to start creating engagement with DMs and to develop a tool that meets their needs.

1. Identification of short-term objectives of the Cath Lab

Initial meetings are useful to understand which policies are already being implemented and the restrictions to the implementation of others, as well as to identify stakeholders' main ends-objectives and means-objectives and their relationships.

Therefore, this step starts with a kickoff meeting with hospital administrators, boards of directors and the coordinator of the interventional cardiology, where the two methods contemplated in the framework are presented, detailed and discussed, as well as the fundamentals of this new innovative sociotechnical methodology, which combines both of them [28].

2. Exploring existing challenges to efficiency

Following the initial meetings, individual interviews with a small group of collaborators associated with the day-to-day work permits them to mobilize their intimate knowledge of what is being done and what could be done [28].

Some of the questions posed for discussion should be: How to obtain a more efficient Lab? How to assess the benefits of the managerial changes and implications of them? What are the best managerial measures in the light of the objectives? [69] What are the biggest challenges to efficiency at this moment? What would you change in the Cath Lab? What makes you unhappy in your daily at the Cath Lab?

Additionally, these individual interviews will also contribute to know the patient's clinical pathway in the Lab and the tasks associated to each of the members of the workforce, giving important inputs for the conceptualization of the simulation model.

The interviewed must be incentivized to think strategically, and not become bogged down in how activities are usually carried out [28].

5.3 Phase 2: Implementing the MultiSim methods

Healthcare systems are complex thus, any operational changes in these organizations are hard to implement and need to be well structured and substantiated. The suggestion of combining simulation with MCDA, in an integrated format, intends to mitigate this complexity. Simulation will allow to dynamically model the current state of the system, as well as several 'what if' scenarios, helping to understand what the main problems and possible solutions are. However, simulation models' output is tangible and, as referred before, decision making in healthcare systems should often rely on intangible data and that is where MCDA complements DES and vice versa [59].

Phase 2 consists of implementing the decision support methods represented in figure 11, being considered the central point of the proposed framework. This phase is supported by two interactive software, M-MACBETH and Simul8.

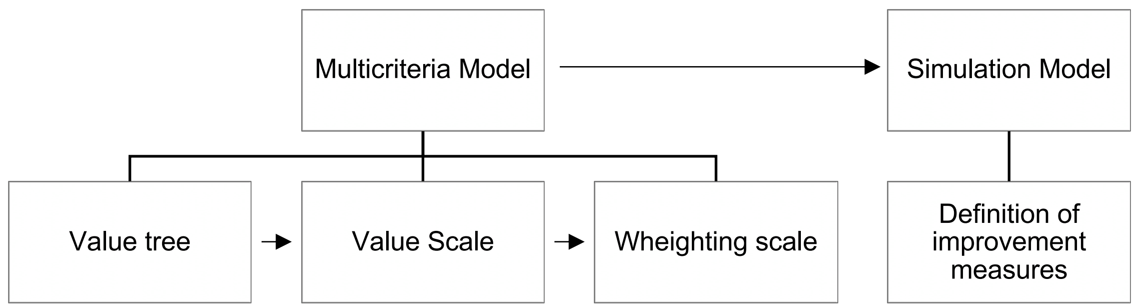


Figure 11 Flowchart of the outputs of Phase 2 and the relationships between them.

5.3.1 Phase 2 - Technical Component

As the present methodology proposes the combination of two different decision support methods, this section is organized in the steps that make up each of the two separately.

1. Multicriteria Model to evaluate efficiency improvements in the Cath Lab

The multicriteria model is used in Phase 2 to build value and weighting scales, and posteriorly in Phase 3, for evaluation of managerial changes. The model is built based on the criteria set and descriptors of performance, defined in Phase 1.

In Phase 2, the multicriteria model will help to evaluate improvements in the considered criteria with base on the additive value approach selected, MACBETH. One choose MACBETH approach since it has been successfully applied in several healthcare contexts and has proven to be effective to avoid common scoring and weighting pitfalls in a wide variety of real-world cases reported in the literature [69].

Regarding the computational model it is developed with the support of M-MACBETH tool, an interactive and visual way of evaluating criteria and alternative options. It is important to retain that the implementation of the computational model is performed on-spot, during the decision conference.

Important to note that, to implement an additive method, which is the case of MACBETH, one must ensure preference independence between criteria, this is, the evaluation of the performance of a criterion should not depend of the performance of other criteria. In such circumstances, criteria should be redefined to meet the requirements of additive methods or clustered into a single criterion [70]. Once all the criteria correspond to the requirements, further, in Phase 3 (section 5.4.1), value scores are assigned to the consequences of an improvement on all the evaluation criteria and multiplied by the respective criteria weight. The obtained products are summed across all the criteria as follows [28]:

$$V(imp.measure) = \sum_{j=1}^{n} w_j v_j(imp.measure) \;\; with \; \sum_{j=1}^{n} w_j = 1 \; and \;\; w_j > 0, \; and \; \begin{cases} v_j(GOOD_j) = 100 \\ v_j(NEUTRAL_j) = 0 \end{cases} \quad (1)$$

This is, considering a set of n criteria, w_j represents the relative attractiveness (weigh) of criterion j and v_j is a cardinal criterion-function that quantifies the local attractiveness of the option in the criteria j. On its turn, $V(imp.measure)$ measures the overall attractiveness of an improvement measure that belongs to the set under consideration, previously defined.

1.1 Value tree

As said in Bana e Costa and Beinat (2005), the construction of a value tree gives a visual overview of the various concerns at hand in an hierarchically organized way by level of specification [67]. That said, the value tree should be organized, in descending order in the tree hierarchy, by concern areas, criteria related to them and, finally, the KPIs that these criteria represent and summarize in the form of descriptors.

1.2 Value scales

The evaluation of each of the criteria starts by qualitatively judging differences of attractiveness within it. From there, one is able to quantify the attractiveness of the performance levels that constitute each criterion through the construction of validated value scales and value functions.

MACBETH approach uses a scale with seven categories of qualitative difference of attractiveness: null, very weak, weak, moderate, strong, very strong and extreme [34]. Each criterion judgment matrix must be filled with the differences of attractiveness between pairs of levels of performance using the MACBETH scale, with the least attractive performance level highlighted in the selected cell's column and the more attractive one in the cell's row. It is not necessary to fill all the cells in the matrix considering that, if the ranking of performance levels is validated, filling in the last column corresponds to compare each of the performance levels with the least attractive one; and filling in the diagonal above the main diagonal of the matrix corresponds to compare each pair of performance levels that are consecutive in the ranking [36]. So, if the previous mentioned cells are filled, the rest will then be filled by transitivity and a complete judgement matrix is obtained. It is important to refer that, in case of reluctance, doubt or discord, instead of a qualitative judgement, a range of judgements can be selected, which is very helpful in a group decision making context. The rest of the cells are filed by transitivity and any inconsistencies must be solved and validated.

From the judgement matrices, one gets value scales for all the criteria and, for the criteria with quantitative levels of performance, also value functions. As these scales respect the M-

MACBETH judgments, they allow the conversion of performances into scores. Nevertheless, it is important to guarantee that any necessary adjustments are made to the value scale before it is validated, details of this process are provided in Bana e Costa et al. (2010) [71].

1.3 Weighting scale

Having the value scales validated, the next step consists of obtaining the weights of the evaluation criteria. To do so, criteria should be ranked in terms of their overall attractiveness [36] this is, their improvements of going from the 'NEUTRAL' to the 'GOOD'. Then, and similarly to what was made in the construction of the value scales, the weighting matrix must be filled with qualitative judgements about the relative attractiveness of the evaluation criteria this is, the differences of attractiveness between the considered pairs of levels of performance based on the MACBETH approach scale. Here, once again, it is only necessary to obtain judgements to fill in the last column of the matrix that classifies the difference of attractiveness of having a certain criterion at the 'GOOD' level and all the others in the 'NEUTRAL' one [36]. The rest of the cells are filed by transitivity and any inconsistencies must be solved and validated. Having the matrix filled, coefficient weights for each criterion are built. Any necessary adjustments are made to the weighting scale before it is validated.

At this point it is already possible to evaluate the contribution (weight) of each of the considered criteria to the efficiency in the Cath Lab workflow, which will be posteriorly important to define, classify and prioritize managerial actions.

2. Simulation Model of the Cath Lab workflow to watch the impact of managerial changes

The development of a simulation model allows to evaluate the state-of-the-art of Cath Lab and thus, consider possible changes. It is important that the model mimics patient's clinical pathway as much as possible so that reliable results are obtained.

When it comes to the quality of the model, it heavily relies on a good data collection and mapping of the system. The mapping of staff workflow and patient's clinical pathway was performed on Phase 1, where the current workforce configurations and facilities in the hospital were determined.

From this point, the simulation model should be developed following the steps below (figure 12), proposed by Venkatadri et al. (2011):

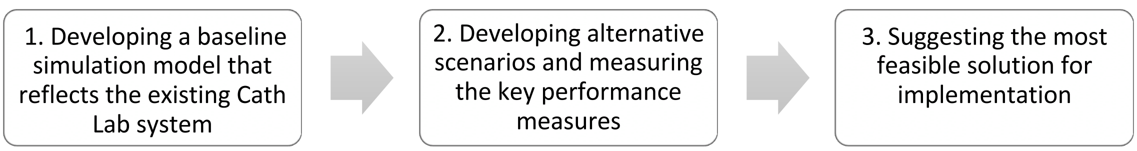


Figure 12 Three main stages that constitute the simulation based approach [23].

At the current phase the focus should be on steps 1 and 2, since MultiSim suggests step 3 to be performed in Phase 3 through combining results from simulation and MCDA.

2.1 Simulation of the existing Cath Lab System

DES was already referred to as an effective tool for analyzing healthcare systems and to improve its performance and patient satisfaction [48]. However, its success depends of the elaboration of a well-structured conceptual model, which is a representation of the real system elaborated from the mapping performed in Phase 1.

As described by Law (2009), more important than an exhaustive description of the system, the conceptual model should explain the response of the system to problems addressed in the study, such as challenges to efficiency [72]. Some of the topics that should be addressed in the conceptual model are [72]: i) a process-flow/system-layout diagram; ii) detailed descriptions of each subsystem and how they interact; iii) what simplifying assumptions were made and why; iv) limitations of the model; v) and summaries of model input data.

It is essential that all the information gathered and presented in the conceptual model is detailed and clear enough so that it can be seen as a draft that supports the building of the computer simulation.

In order to define appropriate distributions and estimate the parameters for each activity of the workflow, one should have gathered enough information and historical records in the mapping step of Phase 1. Though, when there is no data for an activity, inputs may be elicited from personal working in the Cath Lab, considering that these inputs are subject to a range of biases and so, additional questions must be made in order the compare elicited values with empirical data [53].

Then, and based on the conceptual model, the computerized model must be designed on a computer using a simulation software. Literature presents many options of commercial simulation-software packages [72] that support the designing of the Cath Lab layout and workflow, though considering the use of DES, Simul8 seemed as the more appropriate tool to use in this case. The computational model prosecutes demand according to its configuration which, again, is based on the results of the mapping and conceptualization process. The configuration includes variables such as numbers of doctors, nursing and reception staff, treatment rooms, capacity of waiting areas and, produces different performance measures such as throughput, waiting times, number of patients who attended the service, staff and equipment utilizations, between others [52][46].

Once the computer model is completed, it must be verified and validated in order to ensure its results accuracy with the real system. Any errors or discrepancies with reality must be evaluated and eliminated to ensure the model represents reality as much as possible [48].

To evaluate the accuracy of the model one must prove that the conceptual model is an accurate representation of real system and therefore the computerized model is reliable as well [48]. The model can be evaluated using statistical tests or mathematical procedures, which include graphs of the model and system behavior data, confidence intervals or hypothesis tests [73]. Moreover, the model must be also checked with professionals from the lab, who will confirm the accuracy of the results.

<u>2.2 Development of alternative improvement measures</u>

With the DES model one can detect causes of inefficiency in the lab [47] and, from that, support DMs in designing alternative 'what-if' scenarios, which represent the implementation of different managerial changes focusing on the short-term objectives of the lab and their immediate importance to it [49]. Likewise, the MCDA model helps identify improvements considered important for the workflow key players, that can be implemented without dramatically altering the existing system and should, therefore, be considered at this step.

For any 'what-if' scenarios, which in the current case represent improvement measures and managerial changes in the lab, there should be a description of what the inputs and outputs of the simulation are going to be. Thus, one can view any changes associated to each of the improvement measures as inputs and the resulted impact from these as outputs, which can be, for example, time patient spends in the system, queue lengths, delays, as outputs [48].

5.3.2 Phase 2 - Social Component

<u>1. Decision conference</u>

The social process has a key role during Phase 2 as it allows to not only assess the validity of the evaluation criteria, but also prioritize improvement measures in them considering workflow key players and stakeholders judgements. A decision conference is defined in ([28], p. 54) as

> *a gathering of key players who wish to resolve important issues facing their organization, assisted by an impartial facilitator who is a specialist in decision analysis and works as a process consultant (Schein 1999), using a model of relevant data and judgements created on-the-spot to assist the group in thinking more clearly about the issues" [28].*

Therefore, the decisions conference aims to evaluate, on-the-spot and with the support of M-MACBETH tool, the multicriteria model developed in the technical component of the current phase. The evaluation of the model considers the inputs from a group composed by different positions, points of view and responsibilities and, hence, concerns and perspectives.

Through a simple and intuitive protocol of questions about differences in attractiveness between different improvements and doing nothing to change the efficiency in the Cath Lab, participants evaluate the contribution of these improvements for the efficiency in the Cath Lab. For this task, voting tools are frequently used in order to promote and support consensus in the process of building the model. The present study proposes the use of a new tool for decision conferencing, which is Mentimeter*,* a voting tool that allows participants do an individual evaluation of the model in their personal phones. The individual judgements are then discussed by the group and revised through an interactive and learning process, until collective judgements, agreed by all the participants, are obtained [69].

In 2014, Bana e Costa et al. suggested the layout of the conference room to be as the one illustrated in figure 13, where eye-to-eye contact between participants is ensured, as well as visual access to computer-projected information. It also suggests the use of two screens to allow participants to visualize both, factual data and the computer-based model, created on-the-spot, thus incorporating objective data and group judgements [69].

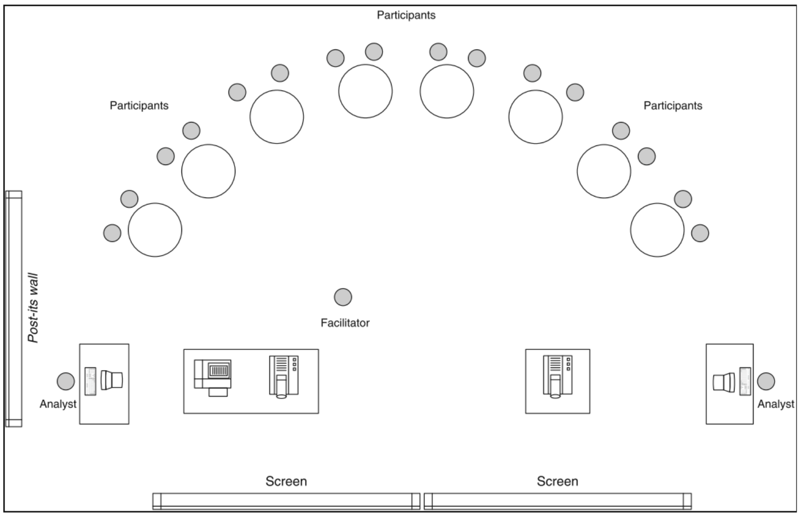


Figure 13 Layout of the decision conferencing room proposed by [69]*.*

It is important that the facilitator takes a constructive approach, enhancing the client's learning ability of the problem at hand and promoting client-facilitator interaction. The facilitator should follow Schein (1999) principles of intervention in order to always try to be helpful, stay in touch with the current reality, and ensure that 'it is the client who owns the problem and the solution' [74].

Regarding the agenda of the decision conference, it should start with a brief explanation of what a decision conference consists of and what is intended from it. And here it is important to ensure that all participants are in agreement with what was proposed and explained and, aware of the conference objectives. Having this, the next steps will support the building of value scales and criteria weights, as described below.

1.1 Value scales

In order to build value scales, participants should be asked questions, for each evaluation criteria, such as ‘For the improvement of workflow efficiency, going from: [Level A] to [Level B] is of [MACBETH category selected by the participants] importance’. To this question, each participant gives an individual judgement and all individual results are presented on the screen. The group must then discuss their different points of view and, unanimously, decide their final group judgement.

From the group judgements, a value scale is obtained, which must be reviewed with participants and, if there is the case, adjusted in the allowed intervals to the best of their opinion. From there, one is able to quantify the attractiveness within each criterion.

1.2 Weighting scale

After all value scales are obtained, it is time to get the weighting coefficients of criteria through qualitative judgements of their overall attractiveness. To do so, participants must rank the improvements of going from the ‘NEUTRAL’ to the ‘GOOD’ level in all the criteria in terms of overall attractiveness answering to questions such as ‘Suppose that all the criteria are at the Neutral level. If you could improve only one of them, which one would it be?’. And, as they respond, the criteria already ranked must be removed. Mentimeter then presents the calculated ranking from participants individual rankings and the group must decide if they agree with it and do any adjustments if necessary.

Having the criteria ranked, participants must classify the difference of attractiveness of these same improvements, according to MACBETH scale, like it was made with value scales, answering questions as ‘What is the attractiveness of improvement [name the improvement]?’. Once again, and similarly to what was made with value scales, the group must discuss their individual points of view and, unanimously, decide their final group judgement.

During the decision conference it is important to emphasize and notify participants that the judgement corresponds to the attractiveness of the improvement of a criterion for efficiency effects and not the criterion itself.

2. Interactive meetings for validation of the simulation model

According to Sargent (1998), the operational validity determines if a model’s output behavior is accurate enough regarding its purpose and applicability. Validation techniques can be either subjective or objective though, a combination of both is usually applied [73]. Following the accentuate social component of the proposed framework, when the model is completed, a ‘Face validity’, as called by Azadeh et al. (2016), is performed. This technique is one of the most efficient validation techniques, where a small group of professionals from the Cath Lab are asked about the accuracy of the logic in conceptual model and whether the computerized model behavior is reasonable or not [48].

Notwithstanding, throughout the development of the simulation model, interactive meetings and workgroup sessions with this specific group are crucial, not only to create engagement, but also to guarantee the success and acceptance of the model [49].

5.4 Phase 3: Testing and validation of MultiSim

From Phase 2, one obtained a model of the existing system and possible improvement measures were evaluated, considering Cath Lab collaborators inputs. So, in Phase 3 the goal is to implement these improvements in the simulation model and, not only learn about their impact on the performance of the Cath Lab, but also understand which improvement measure better suits the aims of the Cath Lab.

As described by Belton and Elder (2013) [58],

> *Simulation provides the link between decision space and solution space (discovery), whilst multicriteria analysis provides the link between solution space and value space (clarification and explication).*

That said, Phase 3 is the conclusion phase, where results are obtained, but more important than that, where MultiSim approach is recognized by Cath Lab stakeholders as a valid DSS to help them achieve their short-term objectives.

The current phase is structured as shown below, in figure 14.

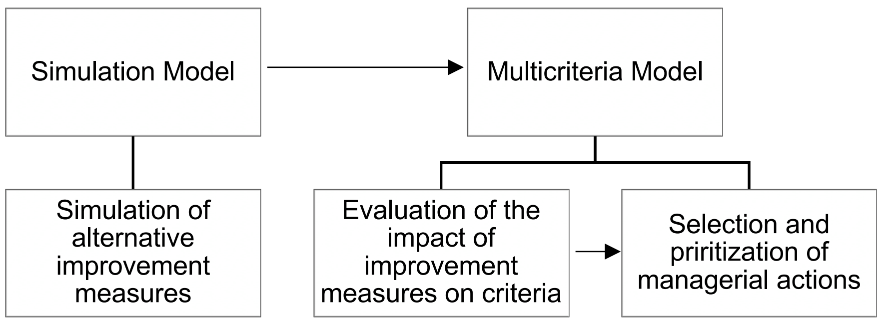


Figure 14 Flowchart of the outputs of Phase 2 and the relationships between them.

5.4.1 Phase 3 - Technical Component

<u>1. Testing of different managerial actions combining DES with MCDA</u>

After validating the baseline model, the new scenarios, proposed to improve the workflow efficiency in the Cath Lab, are tested. The alternative improvement measures are simulated with support of DES in order to learn about the operational performance of the system in different configurations. After that, is when MACBETH technique is applied to the DES results considering decision conference judgements over the decision criteria and its appraisal of priorities [59]. MACBETH, being an additive aggregation model, returns the degree to which one decision option is preferred over another by constructing and comparing numerical scores (overall attractiveness) [30]. It is important to refer that the use of additive aggregation requires weights to satisfy the trade-off requirements [61], which is accomplished through their normalization so that it is possible to interpret the weight of individual criterion as a proportion of the total weight. From this step results a recommendation of what improvement measure should be implemented first.

5.4.2 Phase 3 - Social Component

1. Evaluation questionnaire

As the current phase aims to, at the end, obtain a combined model to assist Cath Lab managers to improve the efficiency of its workflow and, considering the whole approach is supported with participatory methods, an evaluation questionnaire can be very useful to evaluate the benefit and applicability of MultiSim. Therefore, a simple and intuitive evaluation questionnaire should be built and sent to all stakeholders and workflow key players to obtain feedback about the used techniques and the obtained results. Such questionnaire can also help conclude about needed adjustments and the validity of MultiSim.

2. Validation of MultiSim approach as a DSS to improve the efficiency of clinical pathways in the Cath Lab

All results obtained so far should be synthetized, presented and discussed in a workshop with the main stakeholders. The workshop includes briefings of recommendations, drawing attention to the trade-offs that are being made or that can be made [5], so that, as said by Baltussen and Niessen (2006), 'good performance on one criterion can in principle compensate for weaker performance on another' [2].

Besides of confirming results, the workshop also aims to validate the proposed framework and, if management sees this new way of prioritizing managerial actions as helpful, may then take steps in order to institutionalize the process and use it for future organization restructuring projects [28].

One expects MultiSim to be easily replicable in many other Cath Labs or healthcare units, across Portugal and the world. This framework goes beyond what has been done in healthcare contexts and proposes combining DES and MCDA, both successfully implemented in healthcare units, in an integrate format to improve the performance of the Cath Lab. Therefore, this new format includes features that none of the already mentioned methods have when performed independently consequently, filling existent gaps of DES and MCDA. MultiSim also promises to have very positive repercussions on the success of the implementation of management changes as this model lays on a sociotechnical approach that promotes engagement with stakeholders and key players of the workflow since step 1.

Chapter 6 Implementing the MultiSim Methodology

This chapter comprises the implementation of the methodological framework previously presented and described. It starts with the baseline of the problem which define the key concerns of the Cath Lab and challenges to efficiency. From that, a set of evaluation criteria is defined in cooperation with stakeholders. Improvements in the defined criteria are then evaluated, in a decision conference with all workflow key players, regarding the importance of improvement changes in each of them. Once the multicriteria evaluation is concluded and validated, improvement measures considering the obtained results are tested with a simulation, also built in close collaboration with stakeholders.

6.1 Structuring the efficiency challenge in Cath Lab workflow

The following sections describe the steps took, in a first approach to stakeholders and Cath Lab team members, to understand the main challenges to a more efficient workflow and at what extent do these compromise Lab managers objectives.

6.1.1 Definition of the objectives and concerns of the Cath Lab

To start structuring the problem and developing MultiSim it was very important to be aware of the Cath Lab context, infrastructure, challenges and short-term objectives. In that sense, exploratory interviews played an important complementary role in understanding professionals' perspectives and needs. These interviews were performed according to the concept of value-focused thinking, where the first focus is on the identification of objectives and then of alternatives to achieve them [75]. The interviews were divided in two rounds: the first was focused on getting a scope of the Cath Lab and what were the management short term objectives. These groupwork sessions counted with the participation of the coordinator of the interventional cardiology, members of the board of administrators and hospital managers. The second round consisted of individual interviews to members from workforce such as nurses, technicians and cardiologists and, intended to realize the inefficiencies of the patient clinical pathway from the eyes of professionals who deal daily with them and also to know what their main concerns were. During the meetings it was clear the commitment of professionals in contributing to the improvement of the Cath Lab, which is fundamental in a framework that highly relies on social inputs.

Regarding the inputs obtained from each round, in the first round, the group referred that a main goal for the institution, and considering the opening of a new Cath Lab, is for HESE to become a reference cardiology center, capable of meeting all cardiological needs in the Alentejo region, under a value-based healthcare model. Though, for this to be accomplished, stakeholders admit the need of some system restructuration and there is when the second round of interviews plays a key role.

In second round, at the end of the exploratory interviews, one could summarize all that was said in four main concerns: defective pre exam assessment, bad external referral, accumulated administrative tasks and, lack of human resources. Regarding pre exam assessment, the fact that it is defective requires all scheduled outpatients to arrive at 8 am, regardless the time at which the exam is going to be performed, so that nurses can check if they meet essential requirements to perform the exam. Concerning bad external referral, what happens is that many times incorrect referrals result in delays in the UDAIC service since patient might need a different treatment from what was prescribed by the external unit. At third, technicians and nurses stated that administrative tasks consume a lot of their time as there is no administrative employee fully dedicated to UDAIC, only partially. This creates the need of certain tasks to be performed twice, first as a draft by lab staff and then introduced in the computer system by the administrative assistant. Another very claimed problem was the lack of human resources however, this topic revealed great disagreement between professionals, as some defended it, and others did not. The latter argued that the problem was not the lack of human resources but the lack of cross-over between activities or versatility of professionals who refuse to perform tasks that go beyond their responsibilities. To conclude, all these inputs constitute an important start up to suppress Cat Lab key challenges and support improvement of its efficiency.

6.1.2 Data collection and mapping of patients' clinical pathway

Information gathered in interviews plus on-site mapping allowed to understand the way the Cath Lab is organized, as well as the entire clinical pathway of its patients.

The UDAIC opening hours is from 8 am to 8 pm, although it is allocated to hemodynamics only on Tuesdays, Wednesdays (morning only) and Fridays as presented in table 2:

Table 2 Weekly distribution of the laboratory by the three areas that operate in it, with highlight to the hours allocated to hemodynamics.

	Monday	Tuesday	Wednesday	Thursday	Friday
8am - 2pm	Pacing Unit	Hemodynamics	Hemodynamics	Vascular surgery	Hemodynamics
2pm - 8pm	Pacing Unit	Hemodynamics	Nephrology	Pacing Unit	Hemodynamics

Table 3 describes hemodynamics team members and distribution per shift :

Table 3 Cath Lab team composition, team members distribution per shift and shift hours.

Team members	Number in the team	Number per shift	Shift hours
Interventional cardiologist	4	3 (4 on Tuesdays and Fridays, 10am-6pm)	Non defined
Radiology technician	7	1	8am – 2pm 2pm – 8pm
CPL technician	6	2	8am – 3pm 3pm – 8pm (extra hours)
Nurse	9	2 (3 on Tuesdays and Fridays, 10am-5pm)	8am – 3pm 2pm – 9pm
Administrative officer	1	1	Part-time

On its turn, figure 15 illustrates UDAIC's plan and the clinical pathway followed by patients who undergo a CC. From patients' clinical pathway, one could highlight four main moments: Admission, Preparation, Procedure and Recovery, following described.

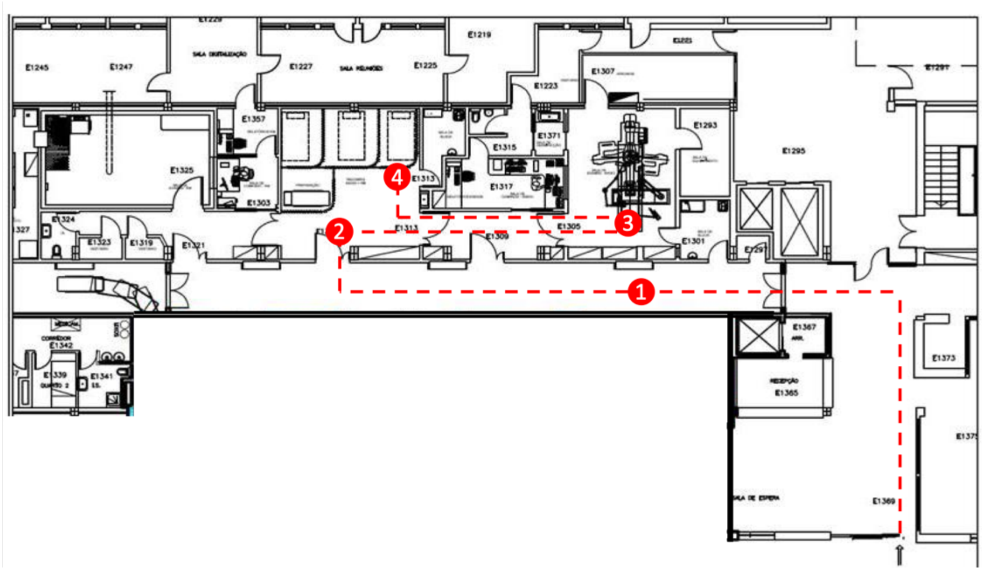


Figure 15 UDAIC's plan and the clinical pathway followed by patients who undergo a CC. The four moments highlighted are: (1) Admission, (2) Preparation, (3) Procedure and (4) Recovery. Regarding the clinical pathway, outpatients start in (1), inpatients in (2) and primary patients in (3).

1. Admission: All four scheduled outpatients arrive at 8 am. One nurse is responsible for doing the admission, which consists of: i) check the patient's presence; ii) and verify if the patient meets the necessary requirements for the exam, such as blood tests. If patient meets the requirements, enters the Prep Room to start Preparation if not, the exam can be rescheduled or delayed.

2. Preparation: In the Prep Room, patient changes clothes in a change box. Then, a nurse explains the procedure and clarifies any doubts of the patient or the accompanying person. The next steps will include: i) measurement of vital signs; ii) vein puncture and fluid administration; iii) and EHR registration. Once these three steps are completed, patient must sign a consent form and wait for being taken to the Cath Lab.

3. Procedure: In the Cath Lab, patient is asked to lie in an x-ray table with a mattress and is connected to an ECG machine for heart rhythm monitoring. Patient's vital signs, such as blood pressure and blood oxygen levels are monitored as well. The procedure can last between 30 minutes to a few hours, depending on the procedure being performed and how long it takes. Regardless of whether it is an angiography or angioplasty the following steps are taken: i) the skin of either groin, collarbone or neck is cleaned with a special solution; ii) local anesthetic is administrated by injection to numb the puncture site; iii) and a dye passes through the Catheter to take a series of x-rays.

   In case of angioplasty: i) the Catheter is directed until its tip reaches a narrow or blocked section of coronary artery; ii) and the balloon on the end of the Catheter is gently inflated so that it squashes the fatty plaques (or deposits) against the artery wall. Often, a stent is inserted to reinforce the walls of the artery. Once the procedure is completed, the catheter is removed, and patient goes back to the Prep Room.

4. Recovery: Already in the Prep Room patient has to wait until homeostasis process is complete. Then, an explanation about specific care to take the days after is given. How long patient stays in the recovery room or even hospitalized depends of the procedure, if there are any complications during it and if the puncture is radial or femoral, as shown in table 4:

Table 4 Recovery duration depending on the procedure, puncture site and if there are any complications.

	Angiography	Angioplasty
Radial	4-5 hours	1-2 hours + 24-48 hours hospitalized in HESE
Femoral	4-6 hours	1-2 hours + 24-48 hours hospitalized in HESE
If there are complications	1-2 hours + 24-48 hours hospitalized in HESE	1-2 hours + 24-48 hours hospitalized in HESE

For inpatients these times are slightly different for angiography, since HESEs' inpatients stay for about 45 minutes in recovery in Prep Room and then leave to their hospital room and inpatients from external units stay around 60 minutes in recovery before leaving again for the external unit.

6.1.3 Definition of a criteria set to evaluate the efficiency in the Cath Lab

It is difficult to define which criteria to include in the evaluation and to find appropriate indicators for performance measurement, but the two previous sections helped on this task. Having the objectives and concerns defined, the analysis of patient's clinical pathway in detailed aided to identify the performance indicators that were sources of operational inefficiencies related with medical service delivery, logistics or administrative services [76], which could and should be improved, such as the turnaround times and delays on the startup of the day. Then, indicators were organized and summarized in evaluation criteria, according to the main objectives and concerns of the Cath Lab. It is important to keep clear that, while KPIs appraise the performance of the Cath Lab, criteria evaluate its workflow efficiency.

So, starting with the KPIs, table 5 lists the indicators identified and selected and, associated metrics that must be measured in the system (real or modeled) in order to allow KPIs measurement.

Table 5 List of the KPIs summarized in the four criteria and the metrics that allow their measurement.

Criterion	KPIs associated	Definition	Metrics for calculation
1. Efficiency of admission process	Patient check-in duration	Time taken for the process of registering the patient, usually performed by a nurse.	Patient arrival time Preparation time
	Extra time for patient preparation	Time taken for the patient be in the right conditions to do the exam, in case fasting was not properly made or if there is the need of doing blood tests.	Preparation time
	Door-to-needle time (outpatients)	Time since the patient arrives until the procedure begins.	Patient arrival time Procedure start time
2. Compliance with schedules	On-time lab start	Time at which the first procedure of the day starts.	Procedure start time
	Delays due to emergency cases	Delays due to the occurrence of emergency cases (primary exams).	Number of emergency cases
3. Agility between procedures	Turnaround time	Duration between the exit of the preceding patient and the arrival of the next scheduled one.	Procedure start time Procedure end time
4. Human resources training	Time spent on training courses, research and meetings	Time invested in activities to develop the team's capabilities.	Time spent on other tasks

Table 5 also presents the link between the KPIs and the decision criteria that evaluate the efficiency in the Cath Lab workflow. We now present each criterion and what is intended in it:

1. <u>Efficiency of Admission Process:</u> Improve the time it takes from check-in to the beginning of the procedure, considering any extra time needed for patient preparation.
2. <u>Compliance with schedules:</u> Improve the punctuality of the Laboratory in the first procedure of the day, considering that it should start at 8:30 am (0 minutes delay).

3. Agility between procedures: Improve the efficiency captured by turnaround times, which corresponds to the average duration between the conclusion of a procedure (hemostasis) and the beginning of the next scheduled one.
4. Human resources training: Improve the capacity of the available human resources by promoting weekly training courses.

Once the criteria were validated by stakeholders, the next step consisted of associating descriptors of performance to them. The descriptors of performance were structured through several equally spaced reference levels of accomplishment that permit to assess the Cath Lab performance in each criterion [68]. Since the descriptors of performance are seen as the objective part of the model, they were built to be sources of unambiguous factual information for the elaboration of value judgements [68].

Concerning the configuration of the descriptors of performance, for each criterion two reference levels were defined, the ‘GOOD’ and the ‘NEUTRAL’ level. The ‘GOOD’ was set as a goal level of performance for the lab, with base on what managers ambitioned and also considering exemplary performances from other Cath Labs. The ‘‘NEUTRAL’’ was set as the status quo, this is, the current state of the Cath Lab in that criterion based on data provided.

All the criteria and respective descriptors of performance are listed in table 6, with reference levels of each of them identified. Three of the descriptors are five-level quantitative performance scales and one is a four-level qualitative performance scale.

Table 6 List of the four evaluation criteria and respective descriptors of performance. Each descriptor of performance has the 'GOOD' and 'NEUTRAL' levels identified.

Criterion	Descriptor of performance
1. Efficiency of admission process	1. Have an administrative fully dedicated to UDAIC (calls and check-in) and a nurse doing pre exam assessment **GOOD** 2. Have an administrative fully dedicated to UDAIC (calls and check-in) and no nurse doing pre exam assessment (patient assessment right before the exam) 3. No administrative fully dedicated to UDAIC but a nurse doing pre exam assessment 4. No administrative fully dedicated to UDAIC and no nurse doing pre exam assessment (patient assessment right before the exam) **NEUTRAL**
2. Compliance with schedules	1. 0 minutes **GOOD** 2. 10 minutes 3. 20 minutes 4. 30 minutes 5. 40 minutes **NEUTRAL**
3. Agility between procedures	1. 10 minutes 2. 20 minutes **GOOD** 3. 30 minutes 4. 40 minutes **NEUTRAL** 5. 50 minutes
4. Human resources training	1. 120 minutes 2. 90 minutes **GOOD** 3. 60 minutes 4. 30 minutes 5. 0 minutes **NEUTRAL**

6.2 Implementing the MultiSim methods

MultiSim approach makes use of two decision support techniques: MCDA and DES, which were employed in that order. The multicriteria evaluation process was performed in a decision conference environment and the simulation was developed throughout several workgroup sessions. We now present how each approach was applied and the results obtained from it.

6.2.1 Decision conference to evaluate efficiency improvements in the Cath Lab

The decision conference took place in HESE and counted with the participation of 17 professionals that included cardiologists, nurses, CPL technicians, radiology technicians, operational assistants and hospital managers. In the room there were also a facilitator guiding the group throughout the conference and a decision analyst giving support and manipulating the computer software. The decision conference was held in Portuguese to ensure that all questions were clearly understood and, for three hours participants questioned, discussed and contributed constructively for the evaluation of possible improvement measures.

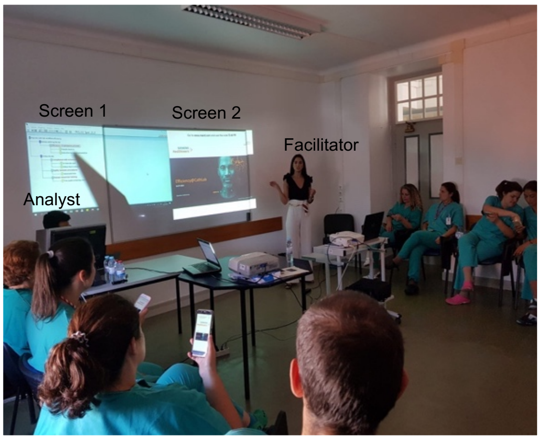


Figure 16 Left image: Two screens were used, so that participants could visualize both, factual data and the computer-based model. Also, in the room there was a facilitator (on the right) and a decision analyst (on the left). Right image: Room layout with 'U' shape ensuring eye-to-eye contact between all participants as well as visual access to computer-projected information. It also suggests the use of two screens to allow participants to visualize both, factual data and the computer-based model.

The room layout respected the one suggested by [69] (figure 16, Right image), with all participants having eye-to-eye contact and direct visual access to two displays (figure 16, Left image), one projecting the M-MACBETH software and the other displaying the decision conference protocol questions and, also the results from individual judgements.

The work session started with a brief explanation of the project being developed and the impact of diseases of the circulatory system in the region of Alentejo. Also, a very simple example of a multicriteria model built with M-MACBETH was shown so that participants could better understand the concepts underlying this type of models and how improvement measures should be seen.

Then, and to start the presentation of our model, MultiSim was presented, as well as the set of evaluation criteria, already defined in section 6.1.3, in the form of a value tree (figure 17) built with the support of M-MACBETH. Hierarchically, the tree starts with the two areas of concern, passing through the criteria and ending with the performance indicators.

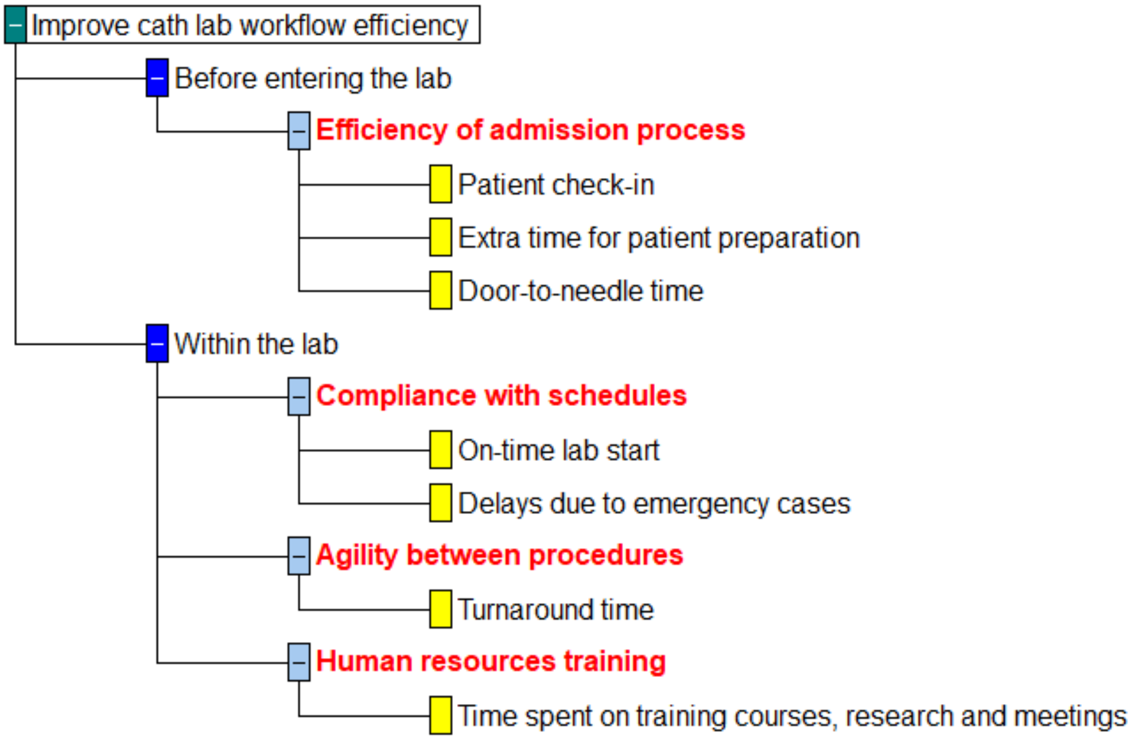


Figure 17 Value tree structure underlying the Improve Cath Lab workflow efficiency model – From top to bottom, 'Before entering the lab' and 'Within the lab' areas of concern, decomposed by efficiency objectives (criteria) and KPIs within the objectives (in the M-MACBETH DSS).

6.2.1.1 Building of value scales

After all the criteria were adequately presented and explained, the next step consisted of collecting qualitative judgements to build value scales for each of the criteria. Each criterion had a group of questions, all structured the same way, to fill the last column and the diagonal above the main diagonal of the judgement matrix. In each question, participants were asked to give a judgement that would complete the sentence 'For the improvement of the efficiency in the Cath Lab workflow [proposed improvement measure] is of [MACBETH scale judgement] importance', like in the slide presented in figure 18. After all participants had given their individual assessment, results were projected so that they could discuss which collective judgment would best integrate all their individual qualitative judgments. Here it was important to listen and understand the justification of non-majority judgments and try, with the participants, reach a consensus that did not exclude or ignore anyone's point of view.

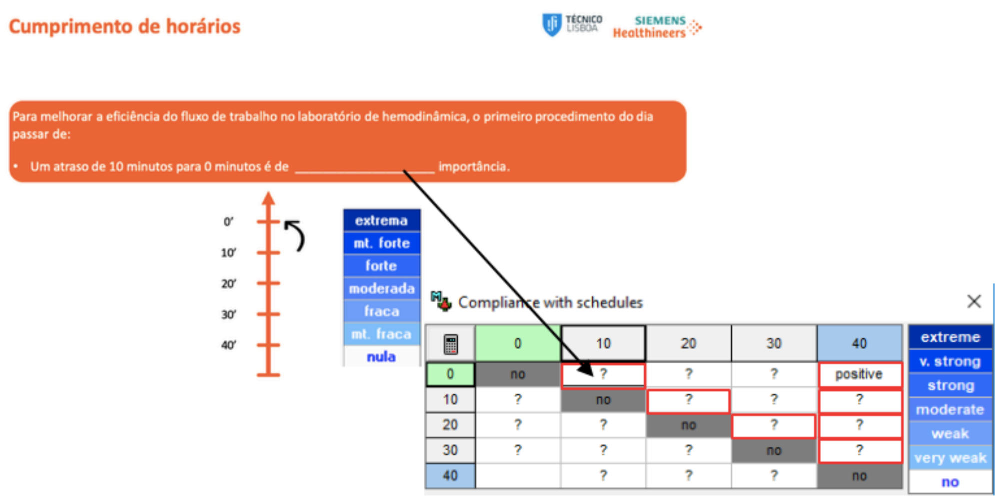


Figure 18 Question regarding the Compliance with schedules criterion in the first part of the conference. First, the performance levels are presented and then it was asked, for the improvement of efficiency in the Cath Lab workflow, to evaluate the difference of attractiveness between some levels.

Once the criteria judgement matrices were filled, value scales were built, which allowed to quantify the attractiveness within each criterion. Additionally, for the criteria with quantitative performance levels ('Compliance with schedules', 'Agility between procedures' and 'Human resources training'), value functions were also constructed. Every value scale was presented to the participants and, if needed, differences in the scale scores were collectively adjusted in the allowed intervals, while maintaining the compatibility with the matrix of judgements. Only then, value scales were validated.

The main conclusions retained from this first part are now presented as well as the value scales and functions, validated by all the participants, for each of the criteria.

<u>1. Efficiency of admission process:</u>

The results of the evaluation of improvements in efficiency of admission process are presented in figure 19.

Efficiency of admission process

	Both	Administrative	Nurse	None	Current scale
Both	no	strg-vstr	positive	extreme	100
Administrative		no	mod-strg	strong	64
Nurse			no	strg-vstr	46
None				no	0

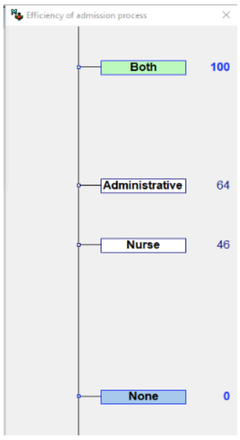


Figure 19 Judgements matrix (left) and value scale (right) obtained for the criterion 'Efficiency of admission process' (in the M-MACBETH DSS).

The group was reticent about the pre exam evaluation and also concerned if duplication of tasks would continue to happen in the case of having a fulltime administrative assistant and a nurse. Though most of the participants opinion was that an administrative assistant would have more impact in the efficiency of the Cath Lab, than the nurse doing the pre exam assessment, as they defend that an administrative assistant with a well-structured check list is able to do a pre exam assessment good enough to avoid most of the delays. Nevertheless, participants agreed that pre exam assessment performed by a nurse was an added value improvement, especially for patients in special conditions and for whom the call following the general guidelines may not be enough to do an accurate appraisal.

Another widely discussed topic in this criterion was the preparation of 4 patients simultaneously by 2 nurses, as all the outpatients are scheduled for 8 am and arise at that time. Here it was difficult to get to a consensus, as some participants saw no impact on the efficiency in the Cath Lab, but on patient satisfaction. On the other hand, some have seen here an opportunity for improvement, since preparing only one or two patients at a time leaves the nurses free for other specific tasks. In sum:

Current state: Pre exam assessment call does not exist, and admission of the patient is performed by a nurse.

Short term target: Have a full-time administrative assistant that does a pre exam assessment call following a well-structured checklist (guideline) and the admission of patients. And then, later and with less urgency, have a nurse performing a pre exam assessment appointment for patient with special needs.

2. Compliance with schedules

Regarding compliance with schedules, the performance level scale was adjusted and rounded as participants felt that the attractiveness difference between 10 minutes and 20 minutes delay is similar to the attractiveness difference between 20 minutes and 30 minutes delay, as shown in figure 20, contrary to what was initially proposed by the software. Therefore, the value function obtained presents the two sections mentioned as approaching a linear function, since the performance levels of this quantitative criterion are equally spaced and considering that the differences in attractiveness are similar.

Compliance with schedules

	0	10	20	30	40	Current scale
0	no	weak-mod	positive	positive	vstrg-extr	100
10		no	mod-strg	positive	v. strong	82
20			no	mod-strg	strg-vstr	55
30				no	mod-strg	27
40					no	0

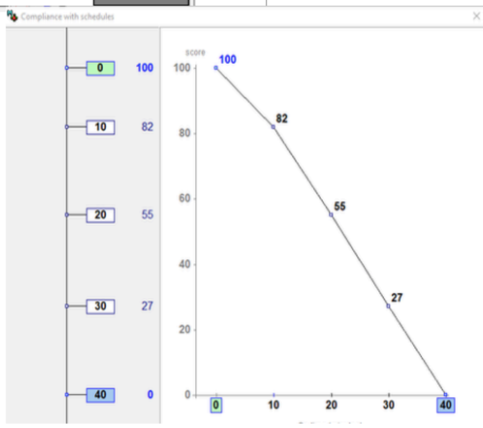


Figure 20 Judgements matrix (left), value scale (middle) and value function obtained for the criterion 'Compliance with schedules' (in the M-MACBETH DSS).

One should take special attention to the fact that participants realized that improving the compliance with schedules from 40 minutes to 30 minutes is more important and relevant (moderate-strong) than improving it from 10 minutes to 0 minutes (weak-moderate), as the first has a bigger impact in the workflow efficiency and, this is also shown by the difference in slope presented between these two intervals in the value function.

It was suggested, in order to guarantee that the first procedure of the day starts at 8:30 am, to have always a hospitalized patient prepared at 8 am in case there is any delay in admission/preparation of the first ambulatory patient of the day or even to decree that the day starts with an hospitalized patient to ensure punctual start up. In sum:

Current state: First procedure of the day starts with a delay around 40 minutes.

The following flowchart (figure 21) shows the time, estimated by key players, it takes to admit, change clothes and prepare a patient. Considering this, and assuming that the patient is punctual and arrives at 8 am, procedures could never start at 8:30 am as the Cath Lab aims them to.

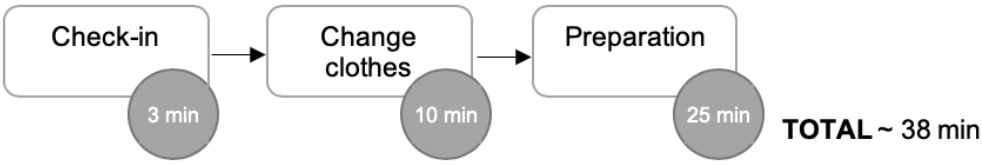


Figure 21 Flowchart of the patient's various steps until reaching the Cath Lab and the respective times estimated by key players.

Short term target: Start the first procedure of the day less than 10 minutes late.

<u>3. Agility between procedures</u>

Once again, likewise in the previous criterion, performance level score was adjusted and rounded as participants felt that the attractiveness difference between 20 minutes and 30 minutes average turnaround is similar to the attractiveness difference between 30 minutes and 40 minutes average turnaround, as illustrated in figure 22, contrary to what was initially proposed by the software. The value function obtained presents these two sections as approaching a linear function, since the performance levels of this quantitative criterion are equally spaced and considering that the differences in attractiveness are similar.

Agility between procedures

	10	20	30	40	50	Current scale
10	no	moderate	positive	positive	vstrg-extr	137
20		no	strong	positive	v. strong	100
30			no	strg-vstr	v. strong	50
40				no	mod-strg	0
50					no	-37

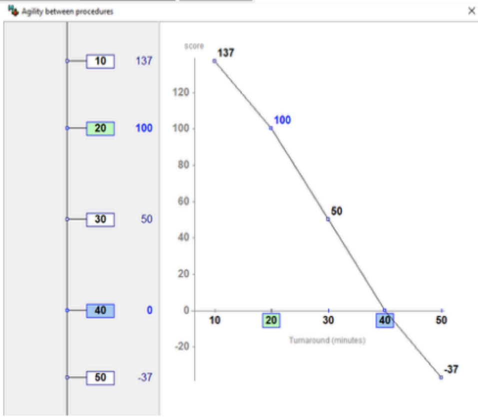


Figure 22 Judgements matrix (left), value scale (middle) and value function obtained for the criterion 'Agility between procedure' (in the M-MACBETH DSS).

The majority of the participants defended that having a turnaround time below 10 minutes would result in loss of quality. So, it was important to remember the model was not only considering 10 minutes but also the other values comprehend between 20 minutes and 10 minutes, such as 17 minutes, referred by [76] as an achievable goal.

The improvement from 50 minutes to 40 minutes, in the perspective of the participants, does not add much value to the efficiency in the Cath Lab, as these are punctual situations that happen less frequently and whose delay is often caused by third parties (stretcher transport, urgent patients transportation, etc.). In sum:

Current state: Average turnaround of 35 minutes.

Short term target: Reach a turnaround time of 20 minutes.

4. Human resources training

Concerning human resources training, the value function obtained has a concave behavior as the time allocated to training increases (figure 23).

Human resources training

	120	90	60	30	0	Current scale
120	no	weak	positive	positive	mod-vstr	109
90		no	moderate	positive	strg-vstr	100
60			no	strong	v. strong	81
30				no	strong	45
0					no	0

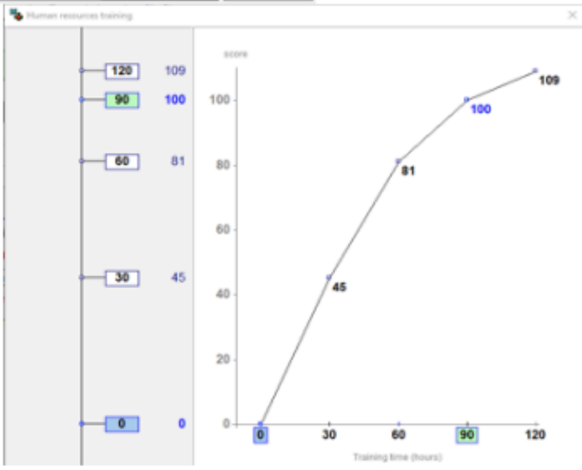


Figure 23 Judgements matrix (left), value scale (middle) and value function obtained for the criterion 'Human resources training' (in the M-MACBETH DSS).

From 60 minutes onwards, the function presents a less pronounced growth with a decrease in marginal gains, resulting from some disadvantages pointed out by the participants regarding the practice of longer sessions, such as the loss of time and efficiency.

Therefore, in a short-term perspective, a weekly 60 minutes session dedicated to workshops, training, feedback sessions, etc., might be the most advantageous. In sum:

Current state: Professionals do not dedicate any time of the week to training or team building.

Short term target: 60 minutes weekly session.

6.2.1.2 Building of weighting scale

After building value scales for each of the criteria it was then time for the last part of the decision conference: criteria weighting. This step starts with the ranking of improvements of going from the 'NEUTRAL' to the 'GOOD' level in all the criteria in terms of their overall attractiveness. Therefore, participants were shown the slide of figure 24 and asked the question 'Suppose that the Cath Lab workflow is at the blue level in all criteria. If you could improve only one of them, which would it be?’. In their personal phones, using Mentimeter, as they chose an improvement measure, in the next position of the ranking that improvement could no longer be chosen again.

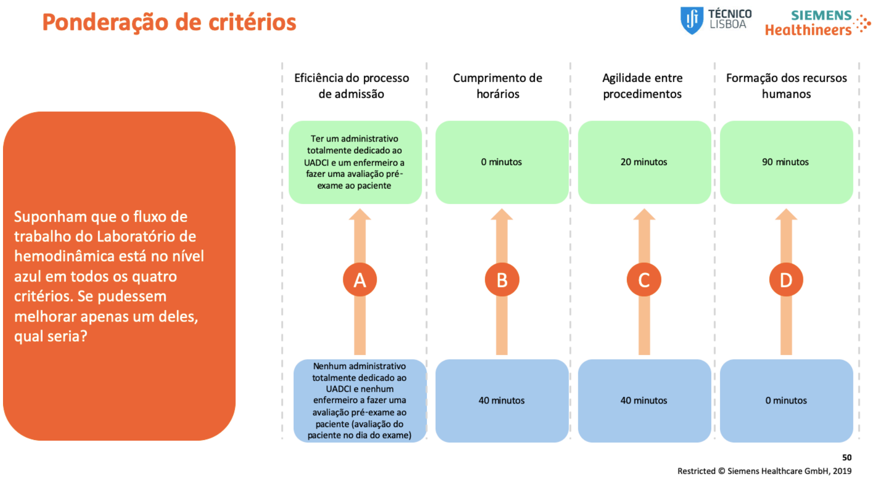


Figure 24 At left it is the question where the surgeons chose the ranking of the improvements (named from A to D) from the ‘NEUTRAL’ (blue) to the ‘GOOD’ (green) level.

After all participants did individual rankings, one could obtain a collective ranking automatically calculated by Mentimeter and depicted in figure 25, which was validated by all. ‘Agility between procedures’ and ‘Efficiency of admission process’, by that order of preference, occupied first and second place of the weighting ranking.

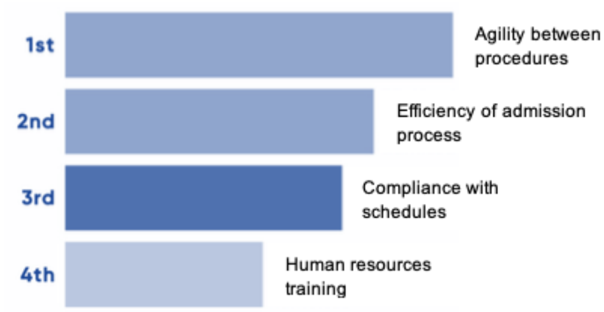


Figure 25 Ranking obtained for the weight of the criteria.

The next and final step consisted of qualitatively judging differences of attractiveness of the same improvements described in figure 24, with participants being asked questions such as ‘What is the attractiveness of improvement [letter correspondent to the improvement measure]?’, as illustrated in figure 26, so that judgements to fill the last column of the weighting matrix could be obtained. The rest of the cells were filled by transitivity.

Figure 26 Example of how the difference of attractiveness was asked, this example for the 'Efficiency of admission process' criterion.

Once the matrix was filled with consistent judgements, criteria weights were quantified through the building of a MACBETH weighting scale that was adjusted and validated by participants, giving rise to the final scale depicted in table 7.

Table 7 Normalized weights obtained for each of the criteria using M-MACBETH.

Criterion	Priority	Normalized Weight
Agility between procedures	1	36
Efficiency of admission process	2	29
Compliance with schedules	3	19
Human resources training	4	16
Sum		100

As referred before, 'Agility between procedures' was the criterion that participants collectively believe improvements of are more important and will have the greatest impact on the efficiency of the Cath Lab workflow, therefore obtaining the highest weight (0.36), followed by 'Efficiency of admission process' (0.29). Thereby, one should look to forward improve 'Turnaround time', 'Patient check-in', 'Extra time for patient preparation' and 'Door-to-needle time' KPIs in the simulation.

It is important to refer that any inconsistencies that emerged, while building the scales (value and weighting), the software would suggest ways of resolving them and, again, participants should in group decide how to solve them [36].

Mentimeter proved to be a very useful tool to support the building of collective judgements, by streamlining the individual evaluation process and allowing participants to visualize the group results in a quick and instantaneous way. And, when needed, it also helped to hold a second vote for the same judgement.

6.2.2 Simulation model of the Cath Lab workflow

The following subsections comprise the steps of building the simulation model of the Cath Lab workflow. For that, we start with the elaboration of the conceptual model demonstrating the basic structure of the existing system and respective validation. This is followed by the development of the computational model and, again, its validation. At the end, proposed alternative improvement measures are described.

6.2.2.1 Conceptual model of the existing Cath Lab system

Every day the Cath Lab receives patients from different provenances: outpatients, inpatients from HESE, inpatients from referral hospitals and primary patients. The clinical pathway of the patient depends on its provenance however, the current study has its main focus on outpatients. These patients' clinical pathway follows the steps presented in the flowchart below (figure 27). The difference for inpatients and primary patients is that the first go straight to 'Patient preparation' and the second to 'Exam'.

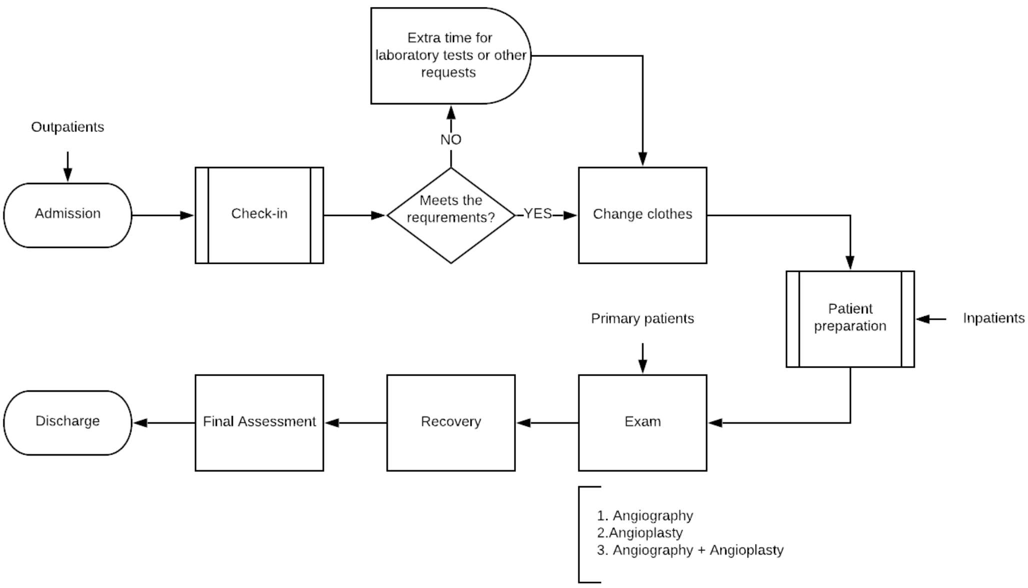


Figure 27 Flowchart of patients' clinical pathway in the Cath Lab. Patients have different starting points depending on their provenance.

The model should run for three days a week, Tuesdays and Fridays from 8 am to 9 pm and, Wednesdays from 8 am to 3 pm. Regarding the arrival times, outpatients are all scheduled for 8 am (four on Tuesdays and Fridays and, three on Wednesdays), inpatients from referral hospitals should start arriving to the Cath Lab between 11 am and 12 am and, HESEs' inpatients around 12 am. Primary patients can arrive at any time of the day, though the simulation model will only consider arrivals during the opening hours.

The simulation model considers patients going under one of the following three types of procedure: angiography, angioplasty or both of them. The type of procedure that patients undergo follows the probability distributions in figure 28.

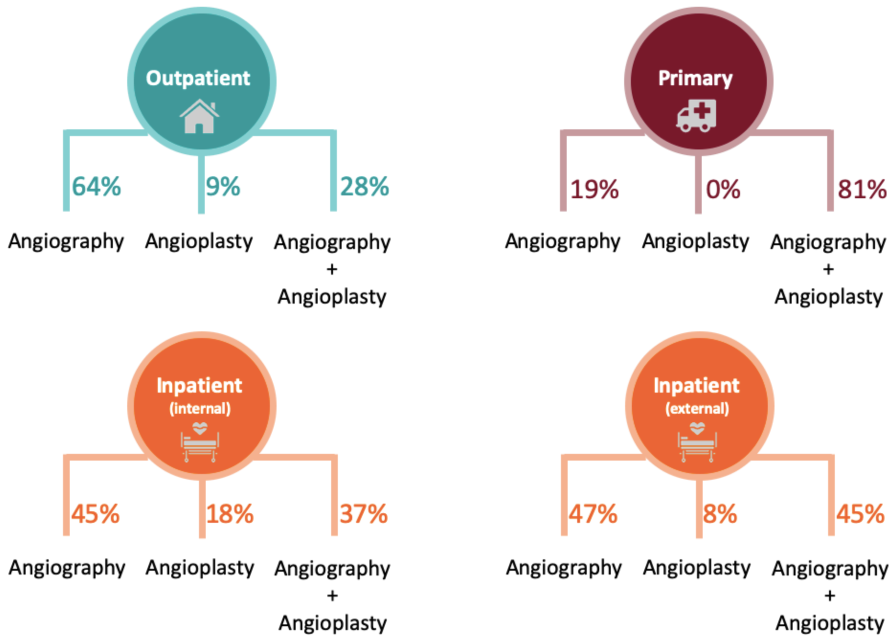


Figure 28 Probability profile distributions of the type of procedure performed, according to the provenance of the patient (values deduced from the laboratory database).

<u>Patients' clinical pathway:</u>

Starting with the clinical pathway of outpatients, 25% (value elicited) of the scheduled patients has to be rescheduled for different reasons, not even entering the system. The remaining go to the admission station which is assisted by a nurse (patients going under angiography procedure usually have priority). This activity serves to the nurse to check patient's presence, explain the procedure and verify if the patient brought the required blood tests. If patient meets the requirements, continues to one of the two change clothes boxes if not, then must go to the laboratory, accompanied by a nurse or an operational assistant, and do the required blood tests, which takes approximately an average of 30 minutes to do. 50% (value elicited) of the patients do not meet the checklist requirements and need extra time for blood tests. Once requirements are met, patient goes to the change clothes boxes and changes to the pajama. An operational assistant assists this station, which takes an average duration of 10 min.

Then, patient enters to the Prep Room, which for inpatients is the first station. One nurse is assigned to this station and is responsible for preparing the patient for the exam, which consists of: i) verify if patients meets the requirements in a checklist; ii) do the trichotomy; iii) puncture the patient; iv) measure the vital signs; v) and apply serum. Still at this station, a responsibility term must be signed. The preparation of the patient takes an average time of 25-30 minutes.

Afterwards, the patient is transferred to the Cath Room where the exam is performed, which for primary patients is the first station. Every intervention requires the presence of three cardiologists, one nurse, one radiology technician and one CPL technician distributed between the Control Room and the Cath Room as described in table 8:

Table 8 Distribution of the team between the Cath Room and the Control Room to perform an exam.

Cath Room team	Control Room team
2 cardiologists	1 cardiologist
1 CPL technician	1 CPL technician
1 nurse	1 radiology technician

The processing time in the Cath Room depends of the type of procedure being performed and should be based on times collected from the database, below described in table 9:

Table 9 Average exam duration according to the type of procedure being performed.

Exam type	Exam duration (min)
Angiography	26
Angioplasty	60
Both	58

When the exam ends, patient is then transferred back to the Prep Room, waits until hemostasis is completed and stays in recovery. The time spent in recovery also depends of the provenance and type of procedure as shown in table 10.

Table 10 Average recovery duration according to patient's provenance ad type of procedure.

Provenance	Recovery duration (min)
Ambulatory	1. Angiography: 240 2. Angioplasty: 80 3. Angiography + Angioplasty: 80
Inpatient (HESE)	45
Inpatient (referral hospital)	80
Primary	80

It should be noted that these durations only concern the time the patient spends recovering in the Cath Lab consequently, outpatients who undergo an angiography stay longer in recovery since they are discharged after a final assessment performed by a cardiologist. Hospitalized patients who undergo an angiography continue hospitalized in their institution of provenance. Nevertheless, all the patients who undergo an angioplasty, independently from their provenance, continue or are hospitalized in HESE.

6.2.2.2 Validation of the conceptual model

The validation of the conceptual model was made at the time of its elaboration, as MultiSim is a methodology developed with stakeholders and not for stakeholders. Moreover, a simulation model is not just about indicators' values, it must truly mimic the reaction of the system to the different circumstances and that is why building the conceptual model with workflow key players is so important. Therefore, the model building was supported by several groupwork sessions and virtual meetings. These ensured the model to be in accordance with the existing system plus, in situations for which there was little or no information in the database, it allowed elicitation and discussion with stakeholders of what would be the most appropriate value. It should be noted that this process was truly enriching for the relationship stakeholder-developer, as stakeholders could better understand the methodology by participating in its implementation.

Another point that should be mentioned is that, since we built a very detailed conceptual model in collaboration with workflow key players, the computational model would be unlikely to not be in line with their expectations either. Thus, we guaranteed in advance the success of the next phase.

6.2.2.3 Computational model of the existing Cath Lab system

Once the conceptual model was confirmed, it was time to, with the help of the chosen software, Simul8, build a computational model representing the actual configuration of the Cath Lab. Simul8 is a user-friendly DES package that allowed the creation of a visual model of the Cath Lab by drawing objects directly on the screen. The objects used are listed below (table 11) [77]:

Table 11 Simul8 objects used in the simulation.

	Work Items – Temporary entities that flow within the system. The work item is the central object of the simulation, which in the current case is the patient.
	Work Entry Points - This is where Work Items enter the system. It is possible to have more than one Entry Point. The way work is feed in can be controlled by different statistical distributions and labels can be associated to the work items as they enter. In the existing system there are four entry points, which correspond to the four different provenances: Outpatients, Inpatients (HESE), Inpatients (referral hospital) and Primary Patients.
	Storage Bins – Place where work items wait until the necessary resources or work centers are available. Storage bins allow to prioritize work items through their label values. (For example, angiographies have priority to check-in and primary patients have priority to enter the procedure room)
	Work Centers – Place where work is performed on the Work Items. This works usually take time and might be performed by Resources that can either be machines (e.g. angiograph) or workers (e.g. cardiologist). Work Centers can collect work items from different places and give probabilities or specific routing out after processing. (E.g. change rooms, check-in station)
	Resources – These might be necessary for a certain work center to work. The availability of resources can be controlled through the use of shift patterns. (E.g. Cardiologists, Nurses, CPL technicians, Radiology technicians, Angiograph, Chairs)
	Work Exit Point – Where completed works leave the system, for example, when patients leave the Cath Lab.

The following scheme (figure 29) represents the simulation layout of HESEs' Cath Lab, where one can emphasize six main processes: i) Outpatient Admission; ii) Inpatient Admission; iii) Preparation; iv) Primary Patient Admission; v) Procedure; v) and Recovery. These latter will be described in detail thereafter.

<u>Computational implementation of HESEs' Cath Lab:</u>

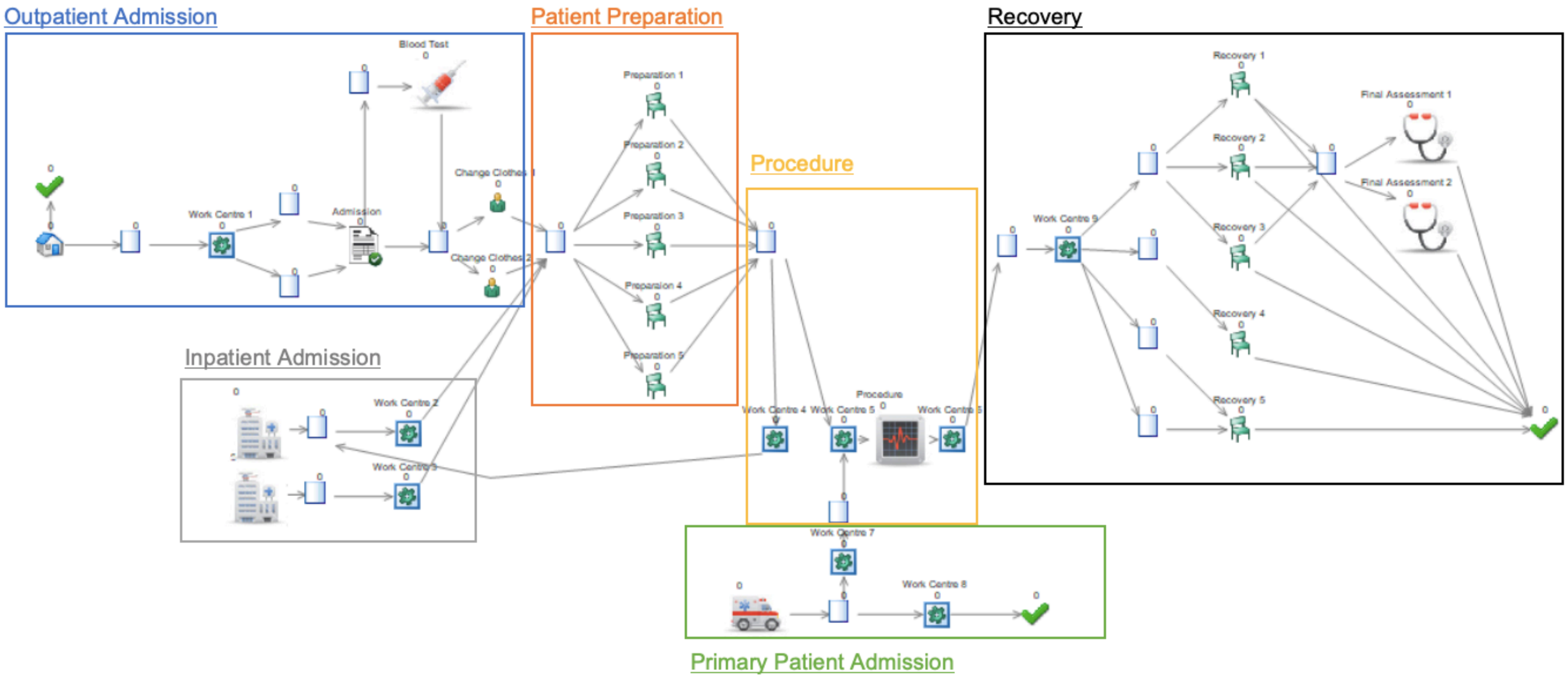


Figure 29 Computational implementation of HESEs' Cath Lab (in the Simul8 DSS).

i) Outpatient Admission

Figure 30 represents the admission process of Outpatients who enter in Work Entry Point A according to the arrival planner. At the same time Patient enters the hospital, a procedure type is tagged to it, according to Outpatient Distribution. Patient also is labeled as being Outpatient and gets a unique ID number. Patient can either proceed to the Admission or leave the system in Work Exit Point B, depending on the percentage discipline defined. If Patient proceeds, Work Centre 1 tags the day and time of arrival to Patient and routs it out according to the type of procedure assigned. Therefore, if Patient is going to do an Angiography goes to the Storage Bin C, if Patients is going to do an Angioplasty go to the Storage Bin D. The next step is described by Admission and depends on the presence of a Nurse. This station gives priority to Patients who come from Storage Bin C, once these Patients stay in recovery for a longer time.

After Admission, the Patient may either be sent to the Blood Test, accompanied by a Nurse or an Operational Assistant, or to the Storage Bin E to wait to change clothes, which occurs according to a percent Routing Out. When in Storage Bin E, Patients wait until a Change Clothes (Work Centre) and Operational Assistant are available to change clothes to then, move to Preparation.

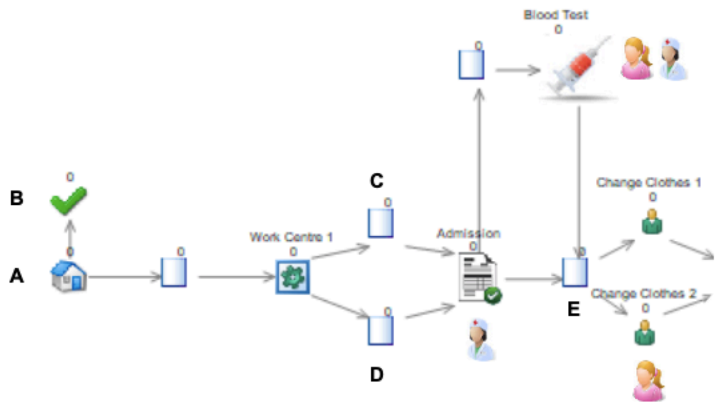


Figure 30 Outpatient Admission process in HESEs' Cath Lab (in the Simul8 DSS).

ii) Inpatient Admission

Figure 31 represents Inpatients Work Entry Points in the Cath Lab, which are two, one for inpatients from HESE (F) and one for inpatients from referral hospitals inpatients (G). Similar to what happened in Outpatient Admission, at the same time Patient enters the hospital, a procedure type is tagged to it according to the Internal Inpatient Distribution and External Inpatient Distribution, plus a unique ID number and the Patient type label (Internal Inpatient or External Inpatient). Work Centers 2 and 3 tag the Patient with the day and time of arrival before it proceeds to Preparation. The fictitious Storage Bin H receives Patients from F and also Inpatients whom exam has had to be rescheduled for lack of time.

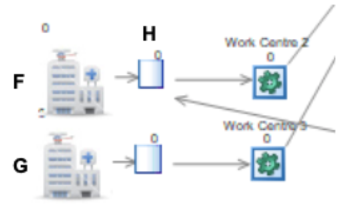


Figure 31 Inpatient Admission process in HESEs' Cath Lab (in the Simul8 DSS).

iii) Preparation

As it was previously explained, there are two possible routes leading Patients to Preparation process, which is depicted in figure 32. Once in the Prep Room, Patient enters a Storage Bin and waits until a Chair and a Nurse are available so that Preparation can be performed. After Preparation ends, Patients are referred to the Cath Room, where the Procedures are performed.

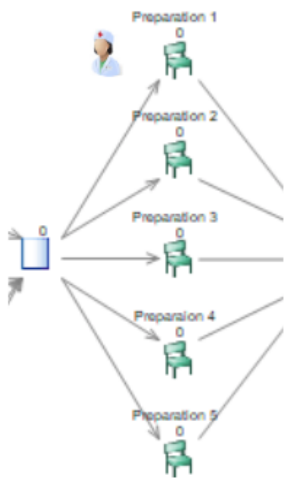


Figure 32 Preparation process in HESEs' Cath Lab (in the Simul8 DSS).

iv) Primary Patient Admission

The fourth, and last, Work Entry Point (I) introduces Primary Patients into the system, as illustrated in figure 33. Similarly, to the other Work Entry Points, Patient is tagged a unique ID number, the procedure type (according to the Primary Distribution) and provenance (Primary).

Acute cases can be directed to Work Centre 7 or to Work Centre 8, depending on the hours they enter the system. This is possible because Resource J is allocated to Work Centre 7 and is available only during working hours which means that any Work Items that arrive after the working hours are led to Work Exit Point K, leaving the system. The latter was defined, so that the system would only consider cases during working hours.

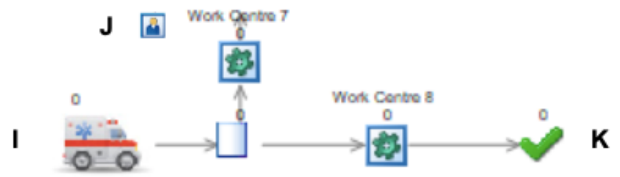


Figure 33 Primary Patient Admission process in HESEs' Cath Lab (in the Simul8 DSS).

v) Procedure

How the Procedure is processed in the simulation model is lustrated in figure 34 and starts with all out and inpatients flowing into the fictitious Storage Bin L. On its turn, and as refereed before, Primary Patients were led to the fictitious Storage Bin O, to wait for the procedure. Then, and again in order to process only patients during working hours, there is a Resource M associated to Work Centre 4 and a Resource N associated to Work Centre 5. Resource N is available until one hour before the closing hour, which is the limit time to start procedures. When Patient arrives to L after that time, is directed to Work Centre 4, as Resource M is available from that time on. When the Patient goes to Work Centre 4 is then directed to Storage Bin H, in order to be reschedule to another day (this usually happens to Inpatients as they are the last exams of the day).

A Patient that proceeds to Work Centre 5, can come from two routes, Work Entry Point I or Storage Bin L. This fictitious Work Centre records the Start Time of the procedure and leads patients to Procedure, which duration depends of Spreadsheet Procedure Duration. The following fictitious Work Centre 6 determines the Turnaround Time and records Procedure Duration. The next step will be the Recovery.

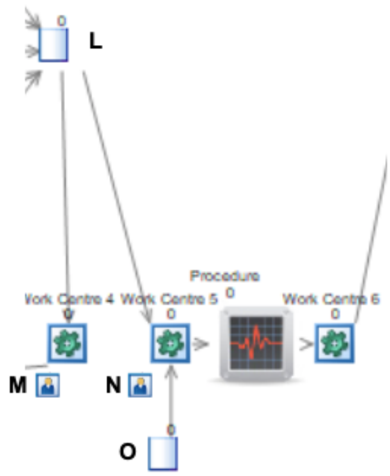


Figure 34 Primary Patient Admission process in HESEs' Cath Lab (in the Simul8 DSS).

vi) Recovery

The Recovery is shown in figure 35 and starts with fictitious Work Centre 9 directing the Patient to a fictitious Storage Bin according to its Provenance. Therefore, Outpatients are routed out to fictitious Storage Bin P, Inpatients from HESE are routed out to fictitious Storage Bin Q, Inpatients from referral hospitals and Primary Patients are routed out to fictitious Storage Bin R and, any Patient that arrives to Work Centre from 7 pm on is routed out to fictitious Storage Bin S to guarantee that no patients stay in the lab after 9 pm.

The duration of Recovery is defined in Spreadsheet Recovery Duration, according to the type of procedure and provenance of the Patient. In Recovery 1, 2 and 3 the Routing Out depends on the Type of Procedure, because a Patient who underwent Angiography needs to be directed to Final Assessment, before going to Work Exit Point U and, a Patient who underwent Angioplasty needs to be hospitalize, going straight to Work Exit Point U. If Patient is in Recovery 4 or 5, is because it is an inpatient and goes straight to Work Exit Point U.

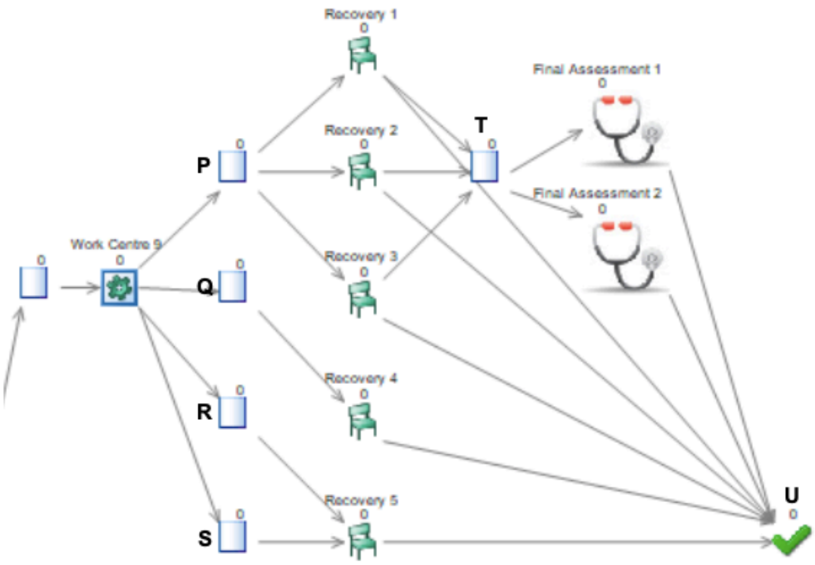


Figure 35 Recovery process in HESEs' Cath Lab (in the Simul8 DSS).

6.2.2.4 Validation of the computational model

In the system under study, it is possible that the analysis does not start with an empty system, for example, when the Cath Lab is not able to attend all patients of the day these are rescheduled to the next day. Also, elective inpatients from HESE and external units might enter the system at any day of the week and need to wait for one of the opening days. So, a way of contouring this situation is to run the model for some time prior to starting to collect results, what is called of a 'warm-up' period. Therefore, the system starts empty at the beginning of the warm-up period, though it is built up to the current state based on inputs that are continuously applied during the main analysis [53]. Karnon et al. (2012) states that warm-up period ‘helps validate the model by testing whether it is able to create realistic starting conditions’ [53]. To validate and calibrate the model one needs to set warm-up period and the results collection period. The current model uses a one-month warm-up period, which was defined after some research and attempts turning out to be enough for the parameters to stabilize, bearing in mind that there is not much ‘accumulated’ work from one week to another and even though there is, it does not stay in the system for more than a week. Regarding the results collection period it was also set for a month, taking in account the data available for comparison and aim of the model, where a month was enough to analyze results. These times helped and were enough to conclude the model was creating accurate conditions.

Another validation method was performed regarding for the average number of patients, from different provenances, that enters the lab per month. Since the model of the Cath Lab was built and run using a trial of one hundred seventy-one runs (value suggested by Simul8), for each run of the model, a set of results was produced. From the trials one could obtain average and standard deviations values, and therefore present the final results as Confidence Intervals (CI) that also inform on the reliability of the model. The current simulation used a 95% CI for the average results obtained from the trials, which means that 95% of CIs contain the real value. A comparison, regarding the number of patients who attended the lab, was performed to conclude if the real values were within the intervals returned by the model. From the analysis of the table, one can consider the model as valid, since all model intervals, except one, include the real values in 95% of the runs.

Table 12 Results obtained for the average number of patients, from different provenances, that enters the lab per month. Real stands for the real values, ‘Model’ for the values obtained from the model and ‘Variation’ for the percentage variation between the latter two.

	Average Number of Patients per Month		
Provenance	Real	Model	Variation (%)
Outpatients	30,92	[30,90 ; 31,73]	[-0,06 ; 2,62]
Inpatients (HESE)	25,00	[24,31 ; 25,92]	[-2,76 ; 3,68]
Inpatients (Referral)	13,25	[9,24 ; 10,97]	[-30,26 ; -17,20]
Primary	1,75	[1,51 ; 1,91]	[-13,71 ; 9,14]

One must emphasize that these were not the only validation methods applied, likewise in the conceptual model, several meetings with stakeholders took place within the development of the simulation, with all the inputs being validated by them. Then, once the computational model was concluded, a groupwork session to describe all the simulation functioning, steps and values was held and, stakeholders had space and were invited to give feedback and to propose changes to be further integrated. The continuous work that was developed from conceptualization to realization and visualization of the simulation model gave the model credibility and proved to stakeholders that all inputs from previous approaches, such as interviews and decision conferencing, were being considered. This not only creates engagement with stakeholders, but also gives them willingness to do more and better as they were able to see and understand the potential these decision support tools for future improvements.

Since both, objective and subjective, validations were achieved, one can confirm this model as an accurate representation of the real Cath Lab.

6.2.2.5 Input parameters

The input parameters were defined by stakeholders in workgroup sessions and from analysis of the available data. Table 13 lists the inputs common to all the simulated alternatives, centering on the actual demand and capacity of the lab:

Table 13 Input parameters of all simulated alternatives and respective values.

Parameter	Value
Places in the prep/recovery room	5
Angiographs available	1
Number of change clothes boxes	2
Planned demand	70 cases per month

Still, the simulation model also contemplates a number of variables that include:

<u>Rescheduled Outpatients:</u> Percentage of outpatients that have to be rescheduled for not meeting essential requirements. According to information given by stakeholders, around 30% of the outpatients ends up not doing the procedure on the scheduled day. Therefore, this percentage can vary if the right improvements are made.

<u>Blood Tests:</u> Percentage of patients that need to do blood tests, in case they did not do them in advance. Currently, this value goes around the 50% according to stakeholders.

Nurse Availability: Percentage of time nurses are available for their tasks in the workflow under analysis during working hours. Since no administrative assistant is fully dedicated to the lab, nurses perform most of the administrative tasks, which is reflected in an 80% availability to perform tasks that compete to them.

Administrative Assistant Availability: Percentage of time the administrative assistant is available to perform tasks in the workflow under analysis during working hours. Since, at his moment, the administrative assistant does not perform any task in patients' clinical pathway, its availability is of 0%.

Average Turnaround Time: Average duration between the exit of the preceding patient and the arrival of the next scheduled one to the Cath Room. In the existing system this value is around 35 minutes but, according to literature and stakeholders it can surely be improved.

Weekly Training: this variable represents the weekly time spent in activities to develop the team's capabilities. It can be represented by reducing the available time percentage of human resources to perform tasks of the workflow and see if it affects the performance of the Cath Lab.

6.2.2.6 Definition of different improvement measures

We now propose, in table 14, organizational changes to improve the performance of the Cath Lab regarding the KPIs of interest.

Table 14 Proposal of ways to improve the performance of the Cath Lab.

KPI	How can the KPI be improved?
Patient check-in duration	• Online platform for check-in; • Full-time (from 8am to 3 pm) administrative assistant doing the confirmation call according to a well-structured script with a checklist; • Nurse doing pre exam confirmation calls to patients with special needs (e.g. elderly people); • Schedule two outpatients at 8 am instead of four.
Extra time for patient preparation	• When the exam is prescribed, together with it blood analysis must be prescribed too to be made in the hospital, so they are registered in informatic platform;
Door-to-needle time	• Simplification of the pathway.
On-time lab start	• Electronic whiteboard/digital platform [76]; • Start the day with an inpatient from HESE.
Delays due to emergency cases	• Electronic whiteboard/digital platform [76].
Turnaround time	• Proper allocation of responsibilities among team members [76].
Time spent on training courses, research and meeting	• Promote multitasking.
	• Organize weekly sessions for training courses, workshops or discussion of different topic

Considering the proposals of table 14 and also the results obtained in the multicriteria evaluation, three improvement measures were elaborated for the laboratory, by way of example, and are described below. The inputs respective to these improvements are summarized in table 15.

<u>Improvement 1 – Improve the start-up of the day</u>

This managerial action focuses on improving the start-up of the day, not only through the admission of a full-time administrative (from 8am to 3 pm) to assure that check-in is not perform by a nurse, but also applying some changes in daily management and scheduling. The latter includes start the day with an inpatient from HESE, in order to guarantee that a patient is ready to start the procedure at 8:30 am, as with these patients a proper pre exam preparation can be ensured. Another change made here is to schedule two outpatients at 8 am instead of four and 2 at 10 am, for example, so that the nurses only have to prepare two patients at a time and consequently, patients spend less time at the lab. This improvement also proposes an enhancement of the current average turnaround times to an average of 25 minutes.

Improvement 2 – Improve pre exam assessment

Improvement 2 intends to enhance efficiency through preventing and decreasing the number of delays caused by a defective pre exam preparation. Consequently, the current improvement consists of i) having a full-time administrative doing the confirmation call following a well-structured script with a checklist for patients with no special needs; ii) and a nurse doing the confirmation calls to patients with special needs (e.g. elderly people) or even some physical appointments to guarantee the full compliance with requirements and proper pre exam preparation.

Additionally, to perform this improvement, it is important to allow some time for training, especially in an initial phase to understand what the core exam requirements are and how to verify them. Hence, the percentage of patients needing for blood tests decreases in until 70%, as well as the percentage of rescheduled outpatients in until 66%.

Improvement 3 – Improve staff training

The third improvement is a soft approach to all the short-term targets of the Cath Lab. Therefore, it suggests the admission of a full-time administrative assistant performing the admission of the patients and the confirmation calls. This action also aims to improve the turnaround to an average of 20 minutes and to introduce a weekly training session of 90 minutes that can be dedicated to workshops, research, teambuilding activities or feedback sessions in order to enhance team capacities. Moreover, to have better results on the daily start-up, this improvement proposes the day to start with inpatients from HESE.

Table 15 Input parameters for Improvements 1, 2 and 3.

Improvement	Rescheduled outpatients	Blood Tests	Nurse Availability	Administrative Assistant Availability	Average Turnaround Time	Weekly Training
1	20%	25%	90%	20%	25 min	0 min
2	10%	15%	80%	20%	17 min	60 min
3	15%	20%	90%	20%	20 min	90 min

Chapter 7 Results and Validation of MultiSim

This section aims to confirm MultiSim as an effective methodology to support healthcare DMs prioritize the implementation of managerial changes, knowing in advance their impact, in tangible and intangible terms, in the daily efficiency of the system. Therefore, the chapter stars by presenting the impact of the proposed improvement measures on the efficiency indicators. Then, the multicriteria evaluation allows to quantify the value added by each of the actions to the efficiency of the Cath Lab workflow. This culminates in a final result proposed by MultiSim. To end, the validation of MultiSim as a decision support methodology is presented.

7.1 Results of different managerial actions using MultiSim

One hundred seventy-one replications (of one month each) of the simulation model were run for each improvement described in section 6.2.2.6. The results are now shown in table 16 and thereafter described.

Table 16 Impact of the improvement measures in the efficiency KPIs.

	KPIs associated	Existing system	Improvement 1	Improvement 2	Improvement 3
1. Efficiency of admission process	Patient check-in duration	8 min	7 min	7 min	7 min
	Extra time for patient preparation	65 min	53 min	42 min	44 min
	Door-to needle time (outpatients)	187 min	125 min	107 min	109 min
2. Compliance with schedules	On-time lab start	35 min	27 min	29 min	21 min
	Delays due to emergency cases	2 cases/month	2 cases/month	2 cases/month	2 cases/month
3. Agility between procedures	Turnaround time	37 min	25 min	18 min	22 min
4. Human resources training	Time spent on training courses, research and meetings	0 min	0 min	60 min	90 min
Global impact	Average time in system	681.05 min	586.63 min	545.74 min	547.13 min

Regarding ‘Patient check-in duration’, there is no way of diminishing this time, but once an administrative assistant starts performing check-in, a nurse is available to spend those 7-8 minutes preparing the Cath Room for the patients. When it comes to the ‘Extra time for patient preparation’, more precisely to do blood tests, the simulation helped to realize how late a patient might start its procedure for not having the adequate blood tests done. This demonstrates the importance of increasing the percentage of patients coming to Cath Lab meeting all the requirements needed to undergo the CC. Though, this parameter highly depends of the quality of the information given to the patient and also of patient’s preparation in the days previous to exam day. About door-to-needle time, it is true that this indicator is especially valued in acute cases though, it should also be given more importance to it in elective cases. Door-to-needle time highly reflects the organization of patient’s clinical pathway and can be a source to detect any inefficiencies in the admission process. In fact, this indicator was very affected by the managerial changes with a decrease in until 43%

The on-time lab start can really be improved by starting with an inpatient from HESE. Concerning the delays due to emergency cases, they were a good surprise. First, because there are not as much emergency cases during working hours as thought and, therefore, the delays caused by these cases are few. Second, because the lab revealed to have a good response to these cases, and the conclusion is that, at this moment, they are not a concern.

Going on to turnaround times, these represent a key challenge in efficiency of the Cath Lab workflow. The bad performance of this indicator often results from the unavailability of professionals required for the procedure or from internal and external communication failures (in the case of referral hospitals). The fact is that, turnaround times are associated with all kinds of procedure and patient so, any improvements in this indicator have impact in all cases throughout the whole day.

Regarding the time spent on training, research and meetings, what could be emphasized here is that, once there is an investment in the training of human resources and encouragement to the cross-over of some tasks, workflow will become more fluid and tasks will be streamlined. Moreover, through simulation, one could see no negative impact for Cath Lab team spending one hour of the week in training. To conclude, the global impact of changes can be assessed through the average amount of time the patient spends in the Cath Lab, since the elimination of little inefficiencies all over the lab will always affect this indicator.

Looking at table 16, DMs can assume that either improvement 2 or improvement 3 are good options, with positive effects in the KPIs of interest, but DMs could never make a grounded and coherent decision between these two only looking at the indicator’s measurements. And that is exactly why MultiSim was proposed, to help decide which improvement measure should be applied first considering both, the performance of the system and the value added to efficiency in Cath Lab workflow. Thus, the final step of the decision making consisted of assigning scores to criteria in each of the three considered improvement measures, using the performance measurements obtained from the simulation and described in table 17.

Table 17 Table of performances of the improvement measures in the evaluation criteria.

	Efficiency of Admission Process	Compliance with Schedules	Agility Between Procedures	Human Resources Training
Improvement 1	Administrative	27 min	25 min	0 min
Improvement 2	Both	29 min	18 min	60 min
Improvement 3	Administrative	21 min	22 min	90 min

The performances were converted into scores with the support of M-MACBETH (figure 36) so that, from the sum of the scores of an improvement in each criterion, considering the weight of the latter, resulted an overall score for that improvement. And here, DMs were already able to rationally decide between Improvement 2 and Improvement 3, as Improvement 2 had the best overall score, meaning that this managerial adds more value to Cath Lab efficiency than Improvement 3 and should be the first to be implemented. Thus, improved turnaround times and, greater investment in pre exam assessment and preparation should be the next steps.

Table of scores

Options	Overall	Admission process	Scheduling	Agility	HR training
Imp 1	52.29	64.00	35.40	75.00	0.00
Imp 2	86.29	100.00	29.80	107.40	81.00
Imp 3	76.88	64.00	52.20	90.00	100.00
[all upper]	100.00	100.00	100.00	100.00	100.00
[all lower]	0.00	0.00	0.00	0.00	0.00
Weights :		0.2900	0.1900	0.3600	0.1600

Figure 36 Table of scores, obtained with support of M-MACBETH, of the proposed improvement measures (in the M-MACBETH DSS).

7.2 Evaluation questionnaire and validation of MultiSim

Stakeholders and workflow key players were invited to fill an evaluation questionnaire that aimed to:

1. Receive feedback about MultiSim and its applicability in healthcare context;
2. Understand if participants saw benefits in a tool, that allowed not only to see the operational impact of improvement measures but that also helped prioritize them according to the Cath Lab objectives.

The answers of 10 out of the 17 participants are now presented below, in tables 18 and 19.

Table 18 Answers to the evaluation questionnaire.

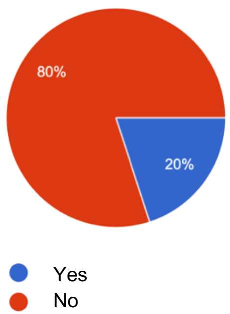
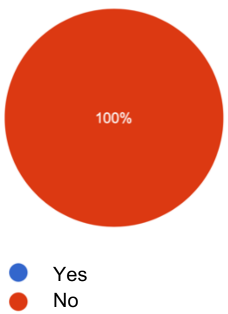
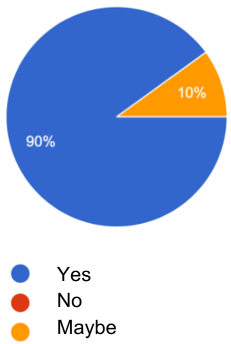
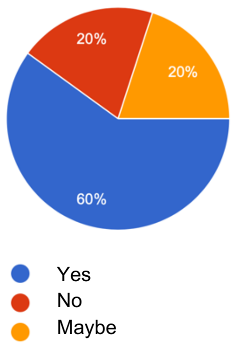
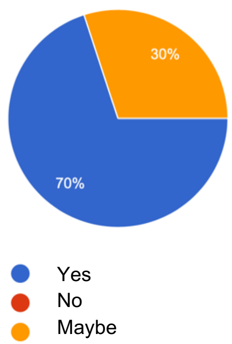
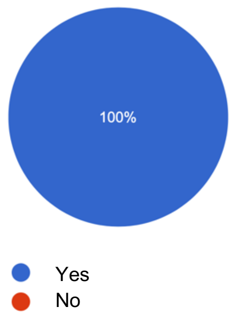
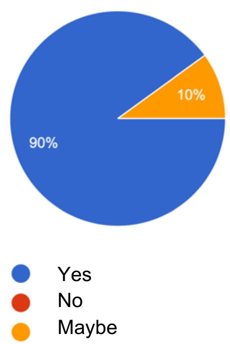
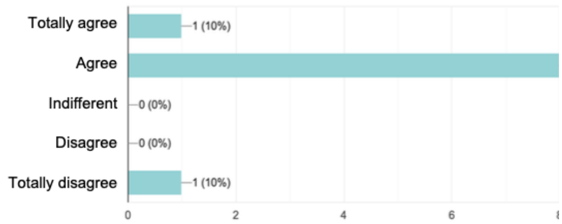
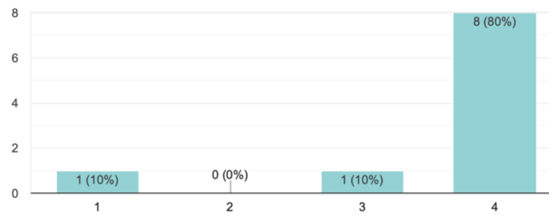
Question	1. Have you ever participated in a decision making regarding Cath Lab management?	2. Have you ever attended a decision conference?	3. Is decision conference a useful tool for improving lab workflow?	4. Do you think Mentimeter worked well?	5. Should Cath lab staff have more opportunities to express their views on possible management measures?	6. Are the results obtained regarding the prioritization of improvement measures feasible?	7. Besides prioritizing improvement measures, is it useful to know the operational impact of these on Cath Lab performance?
Answers							

Table 19 Continuation of the answers to the evaluation questionnaire.

Question	Answers
8. Indicate your agreement on: ‘The decision conference aligned opinions and created a common sense of purpose among the team.’	
9. From 1 to 5 in how much these initiatives encourage them to improve their performance?	

Regarding usefulness of the decision conference to improve the functioning of the Cath Lab, the feedback was truly positive, with participants referring aspects such as allowing to:

1. Optimize of tasks and detect problems;
2. Tackle a number of possible improvements as a team;
3. Emphasize important aspects to improve individual personal performances;
4. Improve interaction between team members in an environment where everyone’s points of view can be listened in an organized way;
5. Reorganize human resources and the lab through a dynamic and constructive meeting;
6. Generate greater acceptance to implementation of organizational changes;
7. Achieve a consensus in many aspects.

Concerning negative aspects, the answers can be generalized to time requirement and management. Also, since Mentimeter is an online tool, the fact that the room did not have wireless internet made it sometimes difficult.

To conclude, through the evaluation questionnaire, it is valid to confirm the usefulness and acceptance of this new approach which is the MultiSim. The prioritization results were 100% validated by participants and they also agreed with the added value of knowing in advance the operational impact of the alternative measures. Therefore, at this point, MultiSim has either its social and technical components approved, objectively and subjectively.

Chapter 8 Discussion

The main aim of the current study was to test if MultiSim could be applied in complex healthcare systems to aid managerial decision making, in this specific context, to support HESEs' Cath Lab improve efficiency in its workflow. Therefore, throughout the development of the study, the focus was in obtaining a well-structured methodological framework that would allow further studies to implement and improve it and, also get valid improvement measures to enhance efficiency in the Cath Lab evaluated with MultiSim.

8.1 Comparison of MultiSim with the Current Literature

In the literature review the management and improvement of healthcare units was studied, with special attention to what has been implemented in Cath Labs. Most of the reports define Cath Lab as a complex unit due to its unpredictable and stressful days. But though one could find ways of improving the performance of these units, there was another problem to solve, the resistance usually offered to the implementation of new organizational measures. And from that point, the focus was not only about improving the efficiency in the Cath Lab but, also in enhancing the willingness and confidence of stakeholders and key players to employ managerial changes. Therefore, the review targeted techniques that had strong social components, like MCDA and DES as the aim of MultiSim was not to develop these models, but to create a methodology that would combine their principles, with stress to the social approaches used by them.

MACBETH approach has been used in health sectors mostly to perform transparent prioritization of interventions and to support rational decisions on management, though there was no report of its application in Cath Labs. On its turn, simulation is an active area of research with a wide use in healthcare sector and there are studies reporting its success supporting the improvement of Cath Lab performance. Then, a literature review was performed to learn of studies that have combined both of them for a common purpose, improve the performance of a system. But there were few reports, what seems strange since a model that reunites features from simulation and MCDA is a model that allows systems to be evaluated considering more than only the operational aspects and, that turns decision making more inclusive and trustful [59]. From that point, MultiSim was developed based on a sociotechnical approach that used multicriteria evaluation and simulation to appraise the performance of the system regarding its improvement objectives.

MultiSim was successfully applied and there is no doubt that this framework has huge potential in healthcare sector. It should be highlighted the impact this methodology had in the team, as key players of the workflow participated, for the first time, in a decision making regarding Cath Lab management. And in a team where improvement is so appreciated, this kind of approach can only be enriching, for the consultant and the team. The feedback relative to the social component was astonishing and, in addition, the technical component also yielded viable results that were useful to support management members deciding the next steps to take.

8.2 Efficiency improvement in Cath Labs

MultiSim proposed, and the team agreed, the next steps should be improving agility between procedures and efficiency of admission process. This was achieved with an improvement measure that invested in the efficiency of admission process even before the arrival of the patient to the Cath Lab, which consists of avoiding all the delays caused by a defective pre exam assessment and preparation. With that aim, it is proposed hiring a full-time administrative assistant who performs the confirmation call following a well-structured script with a checklist. Besides that, and considering patients in specific conditions, or with special needs, it is proposed to be a nurse doing the confirmation call or, if needed, a physical appointment to guarantee the compliance with requirements. Considering that the administrative assistant now performs an extremely important task for Cath Lab efficiency, it is relevant dedicate some time for training, especially in an initial phase to understand what the core exam requirements are and how to verify them. Moreover, improvements in the agility between procedures are also suggested, as this was the number one criterion of the weighting scale, and an enhancement to 18 minutes, close to the one proposed by [76], is recommended, which results from a proper allocation of responsibilities among team members [76]. Out of curiosity, the turnaround time of 'Improvement 3' was improved to 18 minutes, but even in that case, 'Improvement 2' continued to be the measure preferred by Cath Lab management and workforce to improve Cath Lab efficiency. If the Cath Lab decided to move forward and implement this managerial action, it has in the study the arguments and objective values to support its implementation. Moreover, it already knows the position of the workforce key players regarding it, ensuring an easier acceptance of the changes.

8.3 MultiSim: Pros and Cons

MultiSim was, as already stated, highly grounded to the principles of sociotechnical approaches, which means that, every technical component of the approach had a strong social component allied to it and heavily depended of it.

The first part of the approach comprehends the structuring of the challenges of the Cath Lab to efficiency with a small group of stakeholders. Already in Phase 2 and Phase 3, the social group increased with the inclusion of all the Cath Lab team members. Stakeholders and workflow key players participation were a very enriching aspect of MultiSim as it addressed and included topics that would otherwise hardly be covered in an improvement study. A clear example of that is Human Resources Training criteria, which would probably never be considered as an important criterion in the scope of a study that aims to improve workflow efficiency. But, having stakeholders proposing it and further research revealed that, this criterion, difficult to simulate, was a fundamental piece of the puzzle, representing one of the biggest challenges to a continuous flow of tasks in the laboratory. In fact, although all elements of the team shown interest in participating in the improvement of the Cath Lab performance, there was not a sense of common purpose. This must be fought with organized workgroup sessions and MultiSim started the improvement of this aspect already during its implementation.

The success of the multicriteria evaluation was mainly due to the decision conference, an organized workshop that was valued by the vast majority of participants who, for 3 hours, actively participated in a constructive way. A fundamental step in this part was a clear explanation and exemplification of the technique, and how criteria should be seen. Participants were very aligned with the value focus thinking principles and most of the time voted thinking on the impact in efficiency and not on what was more important to them. More criteria could have been integrated but, considering this was a first approach to the Cath Lab and the implementation of MultiSim, one tried to keep it as simple as possible, summarizing all KPIs of interest in four main evaluation criteria. Also, in further applications of MultiSim a sensitivity analysis may be performed by changing the weights of the criteria and priorities, as well as through the generation of more improvement measures.

Regarding simulation, many limitations related to the software version made it difficult to build an accurate copy of the real system. Though, the computational model was not the main focus of the framework and therefore was not construct with deep detail as should in future applications. However, this very simple model was able to mimic the real system with a sufficient level of accuracy and achieved what was intended from it: create engagement with stakeholders and visualize the impact of improvement measures in the Cath Lab, in a dynamic and interactive way. In fact, the coordinator of the Cath Lab wants to make use of it to test human resources restructuration with the new Cath room. There are still plenty aspects that need to be improved to make this approach more embracing and reusable. To stress out that a barrier to the implementation of MultiSim was software related, since it was not easy to implement the approach using two distinct software tools. Also, the lack of information and of KPIs being measured was a challenge

To conclude, MultiSim approach had to be validated not only from the perspective of DMs, Cath Lab managers, but also from the perspective of the enterprise system, the SH ES Team. Regarding the latter, in the business environment, creating engagement with customers can be decisive to get their trust therefore, as MultiSim had a great focus on client engagement, the application of this methodology truly fits the aims of the enterprise side. For the SH ES team it is mandatory walking side by side with the customer and building solutions together, in a continuous and innovative way. So, all the methodology was developed with concern to these requirements and, at the end, was validated by SH ES Team as a new approach with potential to be further used in other projects. The success of MultiSim strongly relies on the knowledge shared by the three intervenient poles: academic, enterprise and healthcare provider. The main goal of this study was to learn about the applicability of MultiSim in healthcare systems and this goal was accomplished with the approval from the Cath Lab team and managers and, SH ES team. Therefore, and not disregarding all the limitations adjacent to the used methods, at this point one can say that MultiSim is a valid decision support methodology to support improve efficiency in the Cath Lab.

Chapter 9 Conclusion

The MultiSim approach does not necessarily indicate the best decision to make, but it aids DMs in process improvement and to prioritize interventions according to their short-term goals. Therefore, this approach comes as a support tool to promote coherent and grounded decision making within complex systems, like the Cath Lab. The social component is the strong and the key feature of MultiSim, since it is not limited to engaging with stakeholders, but with a wider group of participants, which include daily key players in the Cath Lab workflow. The participatory methods used in this approach, promoted improvement even during model building by creating a sense of common purpose and giving collaborators the opportunity for them to participate in the improvement of the system.

Regarding the employed techniques, simulation have already proved to be great to, in a dynamic and visual way, show the impact of managerial changes in a system. But even though its animated attributes help create engagement with the user, the lack of collaboration, during its development does not create the same engagement in practical terms, when it comes to perform the changes. This is, one can come over to stakeholders and present them an awesome simulation model, with an incredible performance but, is that achievable or is it just an appealing model to show off? Simulation is a great tool, though it can only evaluate alternatives as viable or not viable, since it does not contemplate intangible aspects of the systems. And here is when MultiSim arises as a solution, where multicriteria evaluation acts as an extension of simulation, allowing this approach to go beyond performance measures. Therefore, through the interaction between model developers and users/customers, MultiSim was able to, between different viable options advise on the ones that better fitted the concerns of the Cath Lab.

The most relevant improvements to the agility between procedures, require a proper allocation of responsibilities among team members [76], and enhancement of the efficiency of the admission process through a better pre exam assessment and hiring of a full-time administrative assistant.

To stress out that MultiSim revealed itself as a tool that adds value to decision making in healthcare contexts, from enterprise systems (providers) and DMs (users) point of view. The participatory methods allowed efficiency improvement to begin right with the implementation of the model, as a cohesive team aligned in the same direction is the first step towards an efficient system. Therefore, for HESE, this approach was very helpful to create a sense of common purpose among the team and mitigate some conflicts of interest it was facing. The SH ES team also saw in MultiSim a way of enhancing relationship with customers and truly valued the capacity of this model in showing customer results in advance, in a cost and timeless way. For all the aforementioned, MultiSim arises as an inclusive and innovative approach to decision making, that goes beyond the financial aspects and that considers the perspective of workflow key players, creating not only a better place to receive care but also to daily delivering it.

Chapter 10 References

[1] J. de Almeida Simões, G. Figueiredo Augusto, I. Fronteira, and C. Hernández-Quevedo, "Portugal Health System review," vol. 19, no. 2, 2017.

[2] R. Baltussen and L. Niessen, "Priority setting of health interventions: The need for multi-criteria decision analysis," *Cost Eff. Resour. Alloc.*, vol. 4, pp. 1–9, 2006.

[3] A. Berler, S. Pavlopoulos, and D. Koutsouris, "Using Key Performance Indicators as Knowledge-Management Tools at a Regional Health-Care Authority Level," *IEEE Trans. Inf. Technol. Biomed.*, vol. 9, no. 2, pp. 184–92, 2005.

[4] R. B. Siegrist, M. Gutkin, O. Levtzion-Korach, and S. Madden, *improving patient flow in the cath lab*, no. April. 2009.

[5] P. Thokala *et al.*, "Multiple Criteria Decision Analysis for Health Care Decision Making—Emerging Good Practices: Report 2 of the ISPOR MCDA Emerging Good Practices Task Force," *Value Heal.*, vol. 19, no. 2, pp. 125–137, 2016.

[6] P. P. Barros, "Health costs: Basic issues | Custos da saúde: Alguns princípios," *Acta Med. Port.*, vol. 26, no. 5, pp. 496–498, 2013.

[7] INE-Statistics Portugal, "Conta Satélite da Saúde 2016 – 2018Pe [Satellite Account for Health 2016 – 2018Pe]," Lisbon, 2019.

[8] IHME, "The Global Burden of Disease - 2017 data," 2017. [Online]. Available: https://vizhub.healthdata.org/gbd-compare/. [Accessed: 13-Mar-2019].

[9] INE-Statistics Portugal, "Causas de morte 2017 [Death causes 2017]," Lisbon, 2017.

[10] Portuguese Society of Cardiology, "Registo Nacional de Cardiologia de Intervenção [National Register of Interventional Cardiology]," 2018. [Online]. Available: https://registos.spc.pt/RegistosNacionaisSPC/Public/Login.aspx?ReturnUrl=%2FRegistosNacionaisSPC%2FDefault.aspx#. [Accessed: 13-Mar-2019].

[11] Hospital do Espírito Santo de Évora, "Área de influência [Area of Influence]," 2019. [Online]. Available: https://www.hevora.min-saude.pt/o-hospital/area-de-influencia/. [Accessed: 13-Mar-2019].

[12] Hospital do Espírito Santo de Évora, "Exames e Análises [Exams and Analysis]," 2019. [Online]. Available: https://www.hevora.min-saude.pt/servicos-clinicos/exames-e-analises/angiografia/. [Accessed: 13-Mar-2019].

[13] PORDATA-Database of Contemporary Portugal, "Óbitos por algumas causas de morte (%) [Deaths from some causes of death (%)]," 2019. [Online]. Available: https://www.pordata.pt/Municipios/Óbitos+por+algumas+causas+de+morte+(percentagem)-373. [Accessed: 13-Mar-2019].

[14] A. H. Society, "What is Coronary angioplasty?," *Am. Hear. Soc.*, 2015.

[15] Direção-Geral da Saúde, "Sobre o Cateterismo Cardíaco." 2018.

[16] Y. R. Manda and K. M. Baradhi, "Cardiac Catheterization, Risks and Complications," *StatPearls*, 2018.

[17] S. S. Jolly, S. Amlani, M. Hamon, S. Yusuf, and S. R. Mehta, "Radial versus femoral access for coronary angiography or intervention and the impact on major bleeding and ischemic events: A systematic review and meta-analysis of randomized trials," *Am. Heart J.*, vol. 157, no. 1, pp. 132–140, 2009.

[18] Mary Greeley Medical Center, "Cardiac Catheterization & Interventional Cardiology. Mary Greeley Medical Center." 2019.

[19] M. Tavakol, S. Ashraf, and S. J. Brener, "Risks and Complications of Coronary Angiography: A Comprehensive Review," *Glob. J. Health Sci.*, vol. 4, no. 1, pp. 65–93, 2011.

[20] S. S. Naidu *et al.*, "SCAI expert consensus statement: 2016 best practices in the cardiac

catheterization laboratory: (Endorsed by the cardiological society of india, and sociedad Latino Americana de Cardiologia intervencionista; Affirmation of value by the Canadian Associatio," *Catheter. Cardiovasc. Interv.*, vol. 88, no. 3, pp. 407–423, 2016.

[21] R. D. Anderson and M. R. Massoomi, "Efficiency Improvements in the Catheterization Laboratory: It's All About the Team ∗," *JACC Cardiovasc. Interv.*, vol. 11, no. 4, pp. 339–341, 2018.

[22] T. J. Coelli, D. S. P. Rao, C. J. O'Donnell, and G. Battese, *An Introduction to Efficiency and Productivity Analysis*. 2005.

[23] V. Venkatadri, V. A. Raghavan, V. Kesavakumaran, S. S. Lam, and K. Srihari, "Simulation based alternatives for overall process improvement at the cardiac catheterization lab," *Simul. Model. Pract. Theory*, vol. 19, no. 7, pp. 1544–1557, 2011.

[24] P. S. Stepaniak, M. A. S. Hamad, L. R. C. Dekker, and J. J. Koolen, "Improving the efficiency of the cardiac catheterization laboratories through understanding the stochastic behavior of the scheduled procedures," *Cardiol. J.*, vol. 21, no. 4, pp. 343–349, 2014.

[25] S. Agarwal *et al.*, "Impact of lean six sigma process improvement methodology on cardiac catheterization laboratory efficiency," *Cardiovasc. Revascularization Med.*, vol. 17, no. 2, pp. 95–101, 2016.

[26] G. W. Reed, M. L. Tushman, and S. R. Kapadia, "Operational Ef fi ciency and Effective Management in the Catheterization Laboratory," vol. 72, no. 20, 2018.

[27] J. Dodgson, M. Spackman, A. Pearman, and L. Phillips, *Multi-criteria analysis : A Manual. Department for Communities and Local Government: London*. 2009.

[28] L. D. Phillips and C. A. Bana e Costa, "Transparent prioritisation, budgeting and resource allocation with multi-criteria decision analysis and decision conferencing," *Ann. Oper. Res.*, vol. 154, no. 1, pp. 51–68, 2007.

[29] K. Marsh, T. Lanitis, D. Neasham, P. Orfanos, and J. Caro, "Assessing the value of healthcare interventions using multi-criteria decision analysis: A review of the literature," *Pharmacoeconomics*, vol. 32, no. 4, pp. 345–365, 2014.

[30] P. Thokala and A. Duenas, "Multiple criteria decision analysis for health technology assessment," *Value Heal.*, vol. 15, no. 8, pp. 1172–1181, 2012.

[31] J. Von Neumann and O. Morgenstern, "Theory of games and economic behavior, 2nd rev," 1947.

[32] G. Adunlin, V. Diaby, and H. Xiao, "Application of multicriteria decision analysis in health care : a systematic review and bibliometric analysis," pp. 1894–1905, 2014.

[33] M. D. Oliveira, I. Mataloto, and P. Kanavos, "Multi-criteria decision analysis for health technology assessment : addressing methodological challenges to improve the state of the art," *Eur. J. Heal. Econ.*, vol. 20, no. 6, pp. 891–918, 2019.

[34] C. A. Bana e Costa and J.-C. Vansnick, "MACBETH — An Interactive Path Towards the Construction of Cardinal Value Functions.," *Int. Trans. Oper. Res.*, vol. 1, no. 4, p. 489, Oct. 1994.

[35] J. Goldstine, C. M. R. Kintala, and D. Wotschke, "On measuring nondeterminism in regular languages," *Inf. Comput.*, vol. 86, no. 2, pp. 179–194, 1990.

[36] C. A. Bana e Costa, J.-M. De Corte, and J.-C. Vansnick, "M-MACBETH User's Guide," no. July, pp. 1–54, 2005.

[37] C. A. Bana e Costa, J.-M. De Corte, and J.-C. Vansnick, "On the Mathematical Foundations of MACBETH," in *Multiple Criteria Decison Analysis: State of the Art Surveys*, I. Springer Science + Business Media, Ed. Lisbon, 2005, pp. 410–442.

[38] L. De Moraes, R. Garcia, L. Ensslin, M. José, S. Maris, and D. Carvalho, "The multicriteria analysis for construction of benchmarkers to support the Clinical Engineering in the Healthcare Technology Management," vol. 200, pp. 607–615, 2010.

[39] P. R. Pinheiro, A. K. A. De Castro, and M. C. D. Pinheiro, "A multicriteria model applied in

the diagnosis of Alzheimer's disease: A Bayesian network," *Proc. - 2008 IEEE 11th Int. Conf. Comput. Sci. Eng. CSE 2008*, pp. 15–22, 2008.

[40] M. D. Oliveira, T. C. Rodrigues, C. A. Bana e Costa, and A. Brito de Sá, "Prioritizing health care interventions: A multicriteria resource allocation model to inform the choice of community care programmes. Advanced Decision Making Methods Applied to Health Care.," *Adv. Decis. Mak. Methods Appl. to Heal. Care.*, vol. 173, pp. 142–154, 2012.

[41] T. C. Rodrigues, "The MACBETH Approach to Health Value Measurement: Building a Population Health Index in Group Processes," *Procedia Technol.*, vol. 16, pp. 1361–1366, 2014.

[42] M. C. Carnero and A. Gómez, "A multicriteria decision making approach applied to improving maintenance policies in healthcare organizations," *BMC Med. Inform. Decis. Mak.*, 2016.

[43] R. E. Shannon, "Introduction to the art and science of simulation," in *1998 Winter Simulation Conference. Proceedings (Cat. No.98CH36274)*, 1998, vol. 1, pp. 7–14.

[44] M. M. Günal and M. Pidd, "Discrete event simulation for performance modelling in health care: A review of the literature," *J. Simul.*, vol. 4, no. 1, pp. 42–51, 2010.

[45] S. Almagooshi, "Simulation Modelling in Healthcare: Challenges and Trends," *Procedia Manuf.*, vol. 3, no. Ahfe, pp. 301–307, 2015.

[46] S. Brenner, Z. Zeng, Y. Liu, J. Wang, J. Li, and P. K. Howard, "Modeling and analysis of the emergency department at university of Kentucky Chandler Hospital using simulations," *J. Emerg. Nurs.*, vol. 36, no. 4, pp. 303–310, 2010.

[47] T. R. Rohleder, P. Lewkonia, D. P. Bischak, P. Duffy, and R. Hendijani, "Using simulation modeling to improve patient flow at an outpatient orthopedic clinic," *Health Care Manag. Sci.*, vol. 14, no. 2, pp. 135–145, 2011.

[48] A. Azadeh, M. Pourebrahim Ahvazi, S. Motevali Haghighii, and A. Keramati, "Simulation optimization of an emergency department by modeling human errors," *Simul. Model. Pract. Theory*, vol. 67, pp. 117–136, 2016.

[49] A. Goienetxea Uriarte, E. Ruiz Zúñiga, M. Urenda Moris, and A. H. C. Ng, "How can decision makers be supported in the improvement of an emergency department? A simulation, optimization and data mining approach," *Oper. Res. Heal. Care*, vol. 15, pp. 102–122, 2017.

[50] J. Vidal, R. Snyder, A. Tavakoli, B. Cai, and N. Huynh, "Application of Computer Simulation Modeling to Medication Administration Process Redesign," *J. Healthc. Eng.*, vol. 3, no. 4, pp. 649–661, 2012.

[51] B. Mielczarek and J. Uzialko-Mydlikowska, "Application of computer simulation modeling in the health care sector : a survey," vol. 88, no. 2, pp. 197–216, 2010.

[52] S. C. B. S. M. D. J. Viana, "TOWARDS THE HOLY GRAIL: COMBINING SYSTEM DYNAMICS AND DISCRETE-EVENT SIMULATION IN HEALTHCARE," *Sch. Manag. Univ. Southampt. Southampt. SO17 1BJ, UNITED KINGDOM*, vol. 84, pp. 487–492, 2013.

[53] J. Karnon, J. Stahl, A. Brennan, J. J. Caro, J. Mar, and J. Möller, "Modeling using discrete event simulation: A report of the ISPOR-SMDM modeling good research practices task force-4," *Med. Decis. Mak.*, vol. 32, no. 5, pp. 701–711, 2012.

[54] S. H. Jacobson, S. N. Hall, and J. R. Swisher, "Discrete-event simulation of health care systems," *Int. Ser. Oper. Res. Manag. Sci.*, vol. 206, pp. 273–309, 2013.

[55] K. Kuntz *et al.*, "Decision and Simulation Modeling in Systematic Reviews," *Ahrq*, 2013.

[56] K. H. Concannon, K. I. Hunter, and J. M. Tremble, "Proceedings of the 2003 Winter Simulation Conference S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, eds.," pp. 1488–1493, 2003.

[57] T. Monks, M. Pitt, K. Stein, and M. James, "Maximizing the population benefit from thrombolysis in acute ischemic stroke: A modeling study of in-hospital delays," *Stroke*, vol. 43, no. 10, pp. 2706–2711, 2012.

[58] V. Belton and M. Elder, “Integrated MCDA: A Simulation Case Study,” pp. 347–359, 2013.

[59] T. Barros Brito, R. C. dos Santo Silva, E. F. Capovilla Trevisan, and R. C. Botter, “Discrete Event Simulation Combined with Multiple Criteria Decision Analysis as a Decision Support Methodology in Complex Logistics Systems,” 2012.

[60] C. J. Cooper *et al.*, “Effect of transradial access on quality of life and cost of cardiac catheterization: A randomized comparison.,” *Am. Heart J.*, vol. 138, no. 3 Pt 1, pp. 430–6, 1999.

[61] C. A. Bana e Costa and J. Vansnick, “Applications of the MACBETH approach in the Framework of an additive aggregation model. Journal of Multi-Criteria Decision Analysis, 107-114.,” vol. 6, no. July 1995, pp. 107–114, 1997.

[62] S. V. Kovalchuk, A. A. Funkner, O. G. Metsker, and A. N. Yakovlev, “Simulation of patient flow in multiple healthcare units using process and data mining techniques for model identification,” *J. Biomed. Inform.*, vol. 82, no. May, pp. 128–142, 2018.

[63] C. A. Bana e Costa and M. D. Oliveira, “A multicriteria decision analysis model for faculty evaluation,” *Omega*, vol. 40, no. 4, pp. 424–436, 2012.

[64] R. L. Keeney, “Value Focused Thinking: A Path to Creative Decisionmaking,” *Har-vard Univ. Press. Cambridge, Massachusetts*, 1992.

[65] O. O. Ugwu and T. C. Haupt, “Key performance indicators and assessment methods for infrastructure sustainability-a South African construction industry perspective,” *Build. Environ.*, vol. 42, no. 2, pp. 665–680, 2007.

[66] D. Parmenter, *Key Performance Indicators: Developing, Implementing, and Using Winning KPIs*. Wiley, 2015.

[67] C. A. Bana e Costa and E. Beinat, “Model-structuring in public decision-aiding,” *London Sch. Econ. Polit. Sci.*, pp. 1–43, 2005.

[68] C. A. Bana e Costa, M. C. Carnero, and M. D. Oliveira, “A multi-criteria model for auditing a Predictive Maintenance Programme,” *Eur. J. Oper. Res.*, vol. 217, no. 2, pp. 381–393, 2012.

[69] C. A. Bana e Costa, J. C. Lourenço, M. D. Oliveira, and J. C. Bana e Costa, “A Socio-technical Approach for Group Decision Support in Public Strategic Planning: The Pernambuco PPA Case,” *Gr. Decis. Negot.*, vol. 23, no. 1, pp. 5–29, 2014.

[70] C. A. Bana e Costa, J. C. Lourenço, P. Manuel, and J. C. Bana, “Development of reusable bid evaluation models for the Portugese Electric Transmission Company Working paper the Portuguese Electric Transmission Company,” *LSE Res. Online*, 2007.

[71] C. A. Bana e Costa, J.-M. De Corte, and J.-C. Vansnick, “MACBETH (MEASURING ATTRACTIVENESS BY A CATEGORICAL BASED EVALUATION TECHNIQUE),” 2010.

[72] A. M. Law, “How to build valid and credible simulation models,” *Proc. - Winter Simul. Conf.*, pp. 24–33, 2009.

[73] R. G. Sargent, “Verification and Validation of Computer Simulation Models,” *Evaluation*, 1998.

[74] E. H. Schein, “Process Consultation Revisited Building the Helping Relationship Ten Principles as the Essence of Process Consultation,” 1999.

[75] R. L. Keeney, “Value-focused thinking: Identifying decision opportunities and creating alternatives,” *Eur. J. Oper. Res.*, vol. 2217, no. 1992, pp. 00004–00005, 1996.

[76] A. Krishnaswamy *et al.*, “Operational Efficiency and Productivity Improvement Initiatives in a Large Cardiac Catheterization Laboratory,” *JACC Cardiovasc. Interv.*, vol. 11, no. 4, pp. 329–338, 2018.

[77] D. W. Mcgregor and M. J. Cain, “An Introduction to SIMUL8,” 2004.