Optimization of surgery allocation to operating rooms in a post-pandemic context

Helena Montenegro
Faculdade de Engenharia da Universidade do Porto
Porto, Portugal
up201604184@fe.up.pt

Juliana Marques
Faculdade de Engenharia da Universidade do Porto
Porto, Portugal
up201605568@fe.up.pt

***Abstract*—The return to normal after a general close down of services such as surgeries is characterized by a large number of surgeries that were put on-hold and that need to be scheduled. It is critical to optimize the allocation of surgeries to operating rooms, reducing the average waiting time and possible casualties. In this study, different policies of allocation of operating rooms to surgeries in a hospital will be discussed.**

Keywords—Surgery, Allocation, Waiting Time, Operating Rooms

I. Introduction

A. Context of the Application Domain

Currently, the world is going through the COVID-19 pandemic, which has resulted in many services being reduced to a minimum. Surgeries are included in this group, having most of them been postponed, except in urgent cases. The pandemic is starting to slow down, and each country is getting ready to slowly go back to normal. But when we do go back to normal, the surgeries that were postponed during the pandemic need to be rescheduled, which results in a very high volume of surgeries that need scheduling. To reduce casualties to a minimum, it is critical to properly allocate resources such as operating blocks to surgeries, minimizing the surgeries' waiting time.

When it comes to surgeries, each hospital contains operating rooms that can be used to perform surgeries of any type. These rooms need to be prepared for each surgery, with activities that englobe bringing equipment to the room, sterilization of the equipment, and the whole environment, among others. A hospital also contains medical staff, such as surgeons, which perform surgeries in their respective areas of expertise.

B. Problem Statement

The return to normality after a pandemic, which has temporarily shut down services such as surgeries, is characterized by a high volume of surgeries that need to be scheduled. In this context, it is critical to optimize the allocation of resources to these surgeries and the respective scheduling, with the goal of minimizing waiting time. Since the resources that compose an operating block, such as operating rooms and medical staff, are limited, it is crucial to study different approaches to overcome these limits, such as transfer of surgeries between hospitals and methods to optimize the allocation inside each hospital.

C. Motivation to Tackle the Problem

The COVID-19 pandemic has been a real challenge for society. The process of going back to normal is reassuring, but scary since many things can go wrong if the population is not careful. One of these things includes the scheduling of surgeries. If this process is not carefully considered, there might be casualties that could be avoided. In this context, we want to provide a mechanism to test what are the best procedures to apply to surgeries scheduling and respective resource allocation that will allow minimizing waiting time and casualties.

D. Research/Simulation Questions & Hypothesis

In this paper, we want to answer the following questions:

- Is the transfer between hospitals a viable solution to overcome the limits in resources in a hospital? If so, what heuristics can be used to make the decision of when a surgery should be transferred?
- Inside a hospital, what contributes to the overall optimization of average waiting time?
- Does an increase in operating rooms help hospitals increase their capacity to respond to patients' surgery needs in a desirable time frame? What about an increase in surgeons?

E. Expected Contributions

With this paper, we expect to contribute to:

- Health system, by providing information about whether establishing a policy of transfers between hospitals would improve the actual response to surgeries in this situation of pandemic.
- Society, by optimizing the surgery scheduling process which results in a reduction in waiting time which is critical in the context of post-pandemic.
- Hospitals, by optimizing the allocation of surgeries to operating blocks.

F. Aim and Goals of the Project

This project has the aim of optimizing the allocation of surgeries to operating rooms and with the more specific goal of minimizing the waiting time for surgery, providing information about different heuristics that can be used in this process.

II. Literature Review

The allocation of surgeries to operating rooms, with the goal of minimizing waiting time, as well as of maximizing operating room usage, has been approached in many articles. However, most of them do not consider extreme situations, where surgeries need to be done in mass, such as the one we are living in right now. In a situation with mass surgeries, if a hospital is overwhelmed, reallocation of surgeries to another hospital should be considered. These are some situations that have not been considered in many articles that approach this subject.

Article [1] studies a method for scheduling surgeries where first the operating rooms are divided into two-time blocks per day which are assigned to surgeons and then the surgeons assign the respective surgeries to the existing time blocks. The simulation system in this article calculates the scheduling for one week, having all the surgeries that cannot be done in that week removed from the system. It also assumes that the operating rooms always have the equipment necessary for the surgeries, independently of the type of surgery. It does not consider, this way, the costs of adapting the operating rooms according to the surgery.

Article [2] studies the allocation of resources to surgeries, including not only operating rooms but also medical staff. It does not consider a high number of surgeries known a priori, resulting from an event such as a pandemic, nor does it consider that surgeries can move between hospitals.

Article [3] also studies the method used in the article [1], where operating rooms are allocated first to surgeons and then the surgeons' time blocks are allocated to surgeries.

Article [4] studies the allocation of surgeries to operating rooms specialties in two stages. The first one, surgery priorities are evaluated based on patient age, surgery types, estimated surgery durations and delayed days using regression technique without considering specialties. In the second scenario, the proposed priority-based surgery scheduling optimization model considering operating room specialties is solved using the discrete harmony search (DHS) algorithm. Also as the article [1], It assumes that the operating rooms always have the equipment necessary for the surgeries, independently of the type of surgery, so, it does not consider, this way, costs of adapting the operating rooms according to the surgery or even the possible reallocation of an operating room adapted to one medical specialty to another for a certain time period.

In general, all the methods simulated in these articles are applicable to normal situations, to optimize the process of scheduling surgeries allocating them to operating rooms. However, they do not consider scenarios of rupture, like in a post-pandemic context, where the flow of surgeries that need to be done is much bigger.

TABLE I

GAP ANALYSIS

	Surgeries known a priori	*Surgery urgency*	*Allocation across different hospitals*
[1]	X	X	
[2]		X	
[3]		X	
[4]	X	X	
Our Approach	X	X	X

III. METHODOLOGICAL APPROACH

The system was modelled using the multi-agent programmable modelling environment: **NetLogo**. It receives as input, data read from CSV files that contains surgeries, hospitals and surgeons, the heuristics to be applied, and the number of operating hours in which the operating rooms operate. The system outputs the results of the allocation in the format of CSV files, one for each operating room, with the resulting schedules for the surgeries and all the respective information.

To analyse and compare the different scenarios, the following metrics were used:

- Average waiting time.
- Maximum waiting time.
- Average preparation time.
- Maximum preparation time.
- Average transfer cost.
- Number of transfers.
- Average surgery per day per surgeon.
- Average surgeon time occupancy rate.
- Average surgery per day per operating room.
- Average operating room occupancy rate.

A. Entities of the System

The system contains the following entities:

Hospitals:

- **Role:** Hospitals contain operating rooms and surgeons.
- **Attributes:**
  - Identifier (string).
  - Coordinates (pair of integers).
  - Type (public or private).
  - The number of operating rooms (integer).

Operating rooms:

- **Role:** Operating rooms are allocated to surgeries.
- **Attributes:**
  - Schedule (bidimensional array, where each row is a day that contains the surgeries that will occur).
  - Hospital to which it belongs to (string).

Surgeons:

- **Role:** Surgeons perform surgeries.
- **Attributes:**
  - Identifier (string).
  - Medical Specialty (string).
  - Schedule (bidimensional array, where each row is a day that contains the surgeries that will occur).
  - Level of expertise (novice, veteran or expert)
  - Hospital to which it belongs to (string).

Surgeries:

- **Role:** Surgeries are scheduled at a certain time block and operating room and allocated to a surgeon.
- **Attributes:**
  - Urgency Degree (integer from 1 to 3).
  - Medical Specialty (string).
  - Type of Surgery (big, medium or small)
  - Head surgeon (string).
  - Operating Room to which it's allocated (string, to be calculated during the execution of the system).
  - Day in which the surgery is scheduled (integer, to be calculated during the execution of the system).
  - Starting time of the surgery (integer, to be calculated during the execution of the system).
  - Duration (in minutes).
  - Preparation time (in minutes).

B. Assumptions and Premises

Before we go into detail about the existing operating policies and the model of the system, let's take a look at some assumptions that were made about the system:

- The surgeries to be scheduled are known a priori.
- Other than the head surgeon, all the medical staff needed for the surgery does not need to be allocated specifically to a surgery. There is always enough staff available during the operating rooms' hours.
- There are always enough beds in the hospital for the patients to stay after the surgeries.
- The cost of transferring a surgery to a private hospital is bigger than to a public hospital.
- The cost of transferring a surgery between hospitals depends on the distance between these.
- The surgeon allocated to a surgery needs to be of the same medical specialty as the surgery.
- Rest days are not considered. The waiting time considers the number of working days that the patient needs to wait to have surgery.

C. Operating Policies

The model starts by ordering all the existing surgeries by their urgency. Then, for each surgery three main decisions are done, in the following order:

- Decision of whether the surgery should be transferred, and which hospital should perform the surgery if so. This contains the following heuristics:
  - **No transference between hospitals:** The hospital to which the surgery is associated will perform the surgery.
  - **Transference depending on waiting time:** The surgery might be transferred if its waiting time in the original hospital is much bigger than in other hospitals.
  - **Transference depending on surgeon occupation:** The surgery might be transferred if the surgeons of a hospital are much more occupied with surgeries than in other hospitals.
  - **Transference depending on the number of surgeries:** The surgery might be transferred if the original hospital has a very high number of surgeries when compared to other hospitals.
- Decision of which surgeon will perform the surgery. For this, the following heuristics exist:
  - **Surgeon occupancy:** The available surgeon who has the freest time will perform the surgery.
  - **Surgeon occupancy and degree of expertise:** The surgeon chosen to perform the surgery has the freest time and the highest degree of expertise.
- Decision of which time block of which operating room the surgery will be allocated to. For this, the following heuristics exist:
  - **Waiting Time:** The time block chosen will be the earliest one available.
  - **Preparation Time:** The time block chosen will be the one with the least preparation time.

D. Data sources

The data used for the simulations was synthetic, since there isn't much information about the surgeries that exist in this period of post-pandemic. As such, we created data for input in the simulation system, enough to overload the hospitals, which is enough to compare between the different heuristics used. The results cannot be compared, however, to the real world, since for that, more realistic data should be used, if there is access to it.

IV. IMPLEMENTATION

We developed the simulation using **Netlogo**. We defined operating rooms as patches and the remaining entities as turtles of different breeds.

During the setup of the simulation system, the data regarding hospitals, surgeries and surgeons is read from CSV files and the respective patches and turtles are built.

The allocation process starts with ordering the existing surgeries by urgency so that urgent surgeries are allocated first. Then, each surgery is allocated to an operating block in three steps:

1. Check if the surgery should be transferred to another hospital if its current hospital is overloaded according to the chosen heuristic.
2. Allocate a surgeon to perform the surgery according to a heuristic.
3. Allocate the surgery to an operating room according to a heuristic.

After all surgeries are allocated to an operating block, the results can be seen in the canvas, which shows the surgeries being performed in the respective schedules. During this step, the metrics used to analyse the system are also calculated and displayed.

To understand in more detail how the allocation process is done, let's analyse the implementation of each step.

A. Surgery transfer between hospitals

At the beginning of the allocation process for surgery, the system checks whether the surgery's hospital is overloaded, and if there is another hospital with more resources available that could perform the surgery. The transfer of surgery between hospitals is associated with a transfer cost which is calculated with the following formula:

$$\boldsymbol{Transfer\ Cost} = \sqrt{(\boldsymbol{x1} - \boldsymbol{x2})^2 + (\boldsymbol{y1} - \boldsymbol{y2})^2} + \mathbf{10} * \boldsymbol{Private}$$

Where:

- (x1, y1) and (x2, y2) are the coordinates of hospital 1 and hospital 2, respectively.
- Private is 1 if hospital 2, to which the surgery is transferred to, is private, and 0 otherwise.

To make the decision of whether a surgery should be transferred and to where, there are 4 heuristics:

- **None:** The surgery is never transferred. It is performed in its original hospital regardless of whether this hospital is overloaded or not.
- **Waiting Time:** The decision of whether a surgery should be transferred takes into consideration its waiting time in the original hospital and in the remaining ones. The system obtains the minimum number of days that a surgery must wait in each hospital, taking into consideration both operating rooms' and surgeons' availability. If there is another hospital where the minimum number of days that a surgery must wait is less than half than in the original hospital and that has already allocated at least half of its surgeries, then the surgery is transferred.
- **Surgeon Occupancy:** The decision of whether a surgery should be transferred takes into consideration the availability of the surgeons of the same specialty as the surgery in the original hospital and in the remaining ones. The system obtains the occupancy time of the surgeons of each hospital of the same specialty as the surgery. If there is another hospital where the surgeons' occupancy time is less than half than in the original hospital and that has already allocated at least half of its surgeries, then the surgery is transferred.
- **Number of Surgeries:** The decision of whether a surgery should be transferred takes into consideration not only the availability of resources in the hospitals but the number of surgeries in need of resources. The system obtains the number of surgeries to be allocated and that have been allocated, as well as the number of operating rooms that are available in the hospital. If there is another hospital where the average of surgeries to be allocated per operating room is less than half than in the original hospital and that has already allocated at least half of its surgeries, then the surgery is transferred.

In all heuristics, if more than one hospital satisfies the condition that allows a surgery to be transferred, then the hospital chosen, to where the surgery will be transferred, is the one with the least transference cost.

B. Allocation of the surgeon to surgery

After the hospital on which the surgery will occur has been decided, the surgery is allocated to a surgeon. All surgeons of the hospital, that have the same medical specialty as the surgery, are compared according to the following heuristics:

- **Occupancy:** The chosen surgeon has the least occupancy time, which means he has the most available time out of all surgeons.
- **Occupancy and Expertise:** The chosen surgeon has the least occupancy time as well as the highest level of expertise. The expertise levels vary from 1 to 3. Higher levels of expertise mean that a surgeon takes less time to perform surgeries. The formula that is minimized in this heuristic is the following, which mixes both the surgeon's occupancy time as the level of expertise:

$$\boldsymbol{Occupied\ Time + 0.25 * Occupied\ Time * (3 - Expertise)}$$

After the surgeon is picked, the duration of the surgery is calculated according to the surgeon's expertise and the surgery's type. The duration has a base time of 180 minutes for big surgeries, 120 minutes for medium-sized surgeries, and 60 minutes for small surgeries. An expert surgeon can diminish the surgery duration by 20 minutes, while a new surgeon takes more 30 minutes to conclude a surgery.

C. Allocation of the operating room to surgery

After the surgeon has been selected, the only thing left is to allocate a time block of an operating room to perform the surgery.

In this process, each operating room analyses its schedule to obtain all available time blocks. In this process, the operating rooms will also calculate the time that it would take to prepare for the surgery (the surgery's preparation time) on each day with the following formula:

$$\boldsymbol{Preparation\ Time = Equipment * Previous\ Surgery + 20}$$

Where:

- Equipment is the time it takes to bring the equipment needed for the surgery to the operating room, according to the surgery's type: big surgeries need 40 minutes, medium-sized surgeries need 20 minutes and small surgeries need only 10 minutes.
- Previous Surgery is 0 if there is a surgery of the same type and specialty allocated on the same day to the operating room. If so, the equipment needed for the surgery is already in the room. This variable is 1 if there was no previous surgery on the same day that needs the same equipment.

The surgeon that will perform the surgery also analyses his own schedule to see the available time blocks. The operating rooms compare their respective schedule with the surgeon's, to obtain the time blocks in which both the surgeon and the operating room are available, and remove all the time blocks which are smaller than the surgery's preparation time plus duration because the surgery won't fit in these time blocks. Having obtained all the time blocks in which the surgery can occur, the best one for each operating room is selected to be compared with other operating rooms. The best schedule is decided using the following heuristics:

- **Minimize preparation time:** The best time block contains the best preparation time, which results in allocating surgeries of the same type and specialty to the same operating rooms when it is possible.
- **Minimize waiting time:** The best time block is the earliest one available.

After the operating room has been decided, the surgery is added to its schedule and to the surgeon's schedule.

V. RESULTS

We executed the simulation system with 2 main scenarios:

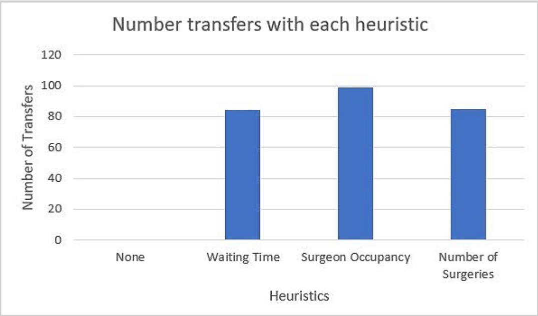
- A scenario where the number of hospitals, resources, and surgeries is small, to see how the system would work in a normal context.
- A scenario where there is a high amount of surgeries that need to be allocated to operating blocks, representative of a post-pandemic situation. In this scenario, one of the hospitals is overloaded, while others do not have as many surgeries. This scenario contains three hospitals, with 3, 2 and 1 operating rooms respectively, and where all surgeons and surgeries belong to three medical specialties. The total of surgeries in this scenario is 250.

In both these scenarios, the system was executed with all the different heuristics, to analyse which heuristic would work best in this task of allocation, and also by changing the number of surgeries, surgeons and operating rooms available, to see how the metrics change with these.

A. Hospital Transfer Heuristics

The main goal of analysing different heuristics to decide if a surgery should be transferred to other hospitals is to understand whether transferring surgeries between hospitals is a viable solution to overcome the limitations in hospitals' resources in a post-pandemic context.

First, we can see in this chart how many surgeries, out of a total of 250 surgeries, were transferred using the different heuristics:

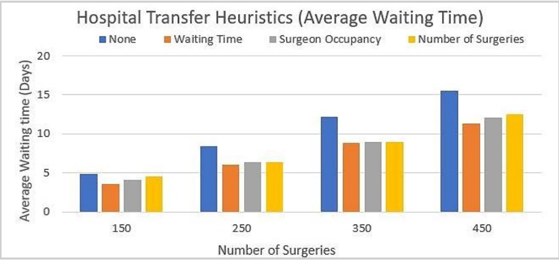


We can see here that the heuristic that takes into consideration the occupancy rate of the surgeons' time leads to more transfers, while the other two heuristics, that consider waiting time and existing number of surgeries per hospital respectively, lead to around the same amount of transfers.

Let us analyse how heuristics affect the different metrics.

1) Average Waiting Time

In this graph, we can see how the different heuristics affect the average waiting time, with a rising number of surgeries:

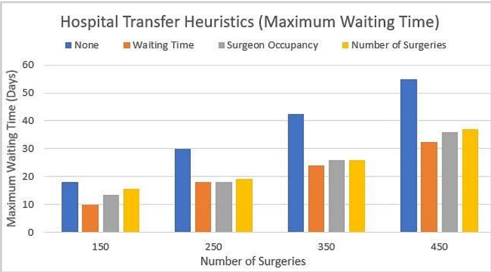


We can see that the average waiting time is much greater when there are no transfers between hospitals when compared to other heuristics. As the number of surgeries rises, the discrepancy between the average waiting time when there are no transfers, and when there are, also rises. This suggests that transferring surgeries between hospitals reduces waiting time and that it is indeed a viable solution to tackle the lack of resources in an overloaded hospital.

Between the different heuristics that allow transfers, the one that considers a surgery's waiting time seems to have slightly better results when it comes to average waiting time.

2) *Maximum Waiting Time*

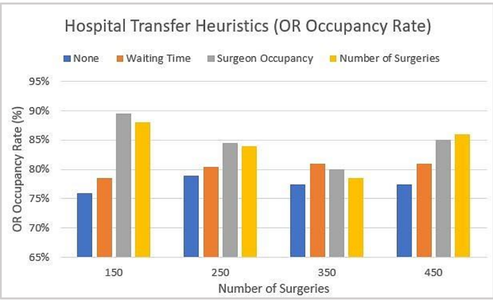
In this graph, we can see how the different heuristics affect the maximum waiting time, with a rising number of surgeries:



This graph is similar to the previous one, but it is even more apparent the rising discrepancy that occurs between the heuristic "None" and the remaining heuristics when the number of surgeries goes up. For 450 surgeries, the maximum waiting time reaches 55 days, not considering rest days. These results also support the conclusion that transfers between hospitals should be considered as a viable solution to overcome limitations in resources in overloaded hospitals. It is also apparent that the waiting time heuristic is slightly better than others, as we could conclude while analysing the average waiting time.

3) *OR Occupancy Rate*

In this graph we can see how the different heuristics affect the ORs occupancy rate, with a rising number of surgeries:

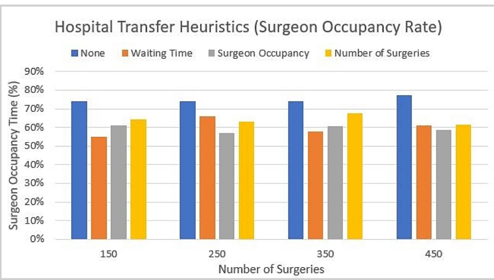


When there is no transfer between hospitals, the operating room occupancy rate of the system is lower, since there are free operating rooms in hospitals with fewer surgeries that are not being used. This suggests bad management of the operating rooms and accounts for a loss in cost for the hospitals that pay for the operating rooms to be operating during the whole operating hours.

Transfers of surgeries contribute to better management of operating rooms with higher occupancy rates. The heuristic that considers the surgeon occupancy seems to have better results overall when it comes to operating room occupancy, but, depending on the number of surgeries, the other heuristics also present similar or sometimes better results.

4) *Surgeon Occupancy Rate*

In this graph we can see how the different heuristics affect the surgeons' occupancy rate, with a rising number of surgeries:

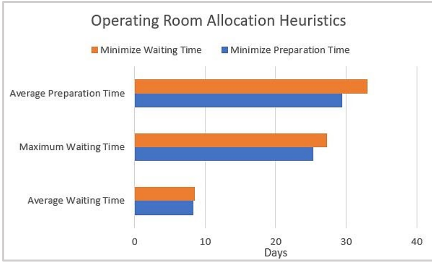


When there are no transfers, the surgeons are more occupied with surgeries, in general. The other heuristics present similar results in terms of the surgeons' occupancy time.

Looking at all the metrics evaluated to measure the different heuristics used to decide transfers between hospitals, we can conclude that transfers allow for better management of resources and significantly reduce waiting time for surgeries. In the context of post-pandemic, it is worth to develop mechanisms that facilitate transfers and communication between hospitals to overcome limitations in resources in overloaded hospitals and minimize waiting time, as well as potential casualties that occur from a surgery not being done in time.

B. Operating Room Allocation Heuristics

The main goal of analysing operating room allocation heuristics inside hospitals has as goal the minimization of waiting time locally, in each hospital.

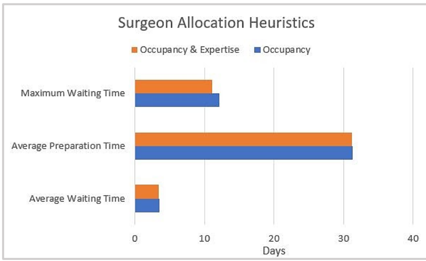


Looking at both heuristics implemented, the minimization of preparation time, which results in a higher volume of surgeries of the same type and specialty being allocated to the same operating rooms, seems to have slightly better results, when it comes to average and maximum waiting time, than the greedy approach of minimizing each surgery's waiting time.

To note in this chart, that the average preparation time is not counted in days, but in minutes.

C. Surgeon Allocation Heuristics

The main goal of the analysis of the surgeon allocation heuristics serves to also minimize the waiting time locally, in each hospital.

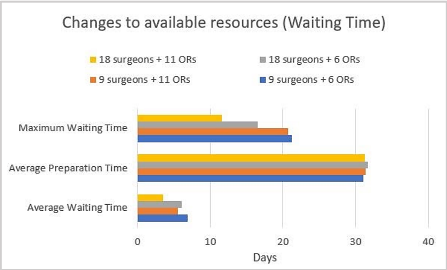


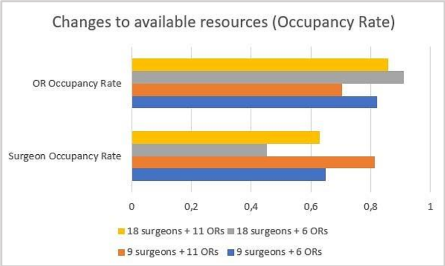
Looking at the chart, the heuristic that takes into consideration both the occupancy of a surgeon as well as the level of expertise results in a slightly better average and maximum waiting time. This might be because surgeons with higher levels of expertise, who take less time to perform surgeries, are prioritized in the process of allocation, which results in a decrease in surgeries duration, leaving bigger time blocks where other surgeries can fit.

To note in this chart, that the average preparation time is not counted in days, but in minutes.

D. Changes in resources (surgeons and ORs)

In this subsection, the goal is to find out how increases in operating rooms or surgeons would affect the system and if adding more of these resources would be a solution to improve the hospital's capacity to respond to all surgeries in a timely manner.





Looking at these charts, we can see that:

- When we increase the number of surgeons while maintaining the number of operating rooms, the average, and the maximum waiting time decrease since there are more surgeons available, which allows more surgeries of the same specialty to be done at the same time. Also, for this reason, the OR occupancy rate gets higher. The surgeon occupancy rate also decreases since the surgeries are distributed between more surgeons. This suggests that adding surgeons is a viable solution to improve waiting time during surgery allocation, if the resources to do so exist. However, the decrease in the surgeon's occupancy rate to less than half percent suggests that surgeons are not being managed properly.
- When we increase the number of operating rooms while maintaining the number of surgeons, the average waiting time decreases, since there are more ORs available, which allows more surgeries to be performed at the same time. Also, for this reason, the surgeon occupancy rate gets higher. The OR occupancy rate decreases since the surgeries are distributed between more ORs. This suggests that adding operating rooms is also a viable solution to improve waiting time during surgery allocation, however, the decrease in OR occupancy rate suggests that the rooms are not being used to their full capacity, which results in higher costs from the hospital's point of view.
- Finally, by increasing both surgeons and ORs, the maximum and the average waiting time both significantly decrease, which suggests that an addition to ORs is more significant if accompanied by an addition of a surgeon, and vice-versa. On top of this, OR occupancy rate increases, and the surgeon occupancy rate only decreases slightly, which suggests better management of these resources, with lower costs for the hospitals.

Overall, we can conclude that additions to either operating rooms or surgeons do contribute to increasing a hospital's capacity to respond to surgery needs in a timely manner, but additions of operating rooms are only fully useful if accompanied by additions in surgeons, and vice-versa.

VI. Related Work

The project we developed is considerably different from the articles and simulations that regard surgery allocation to operating blocks. We created and tested new heuristics and we developed a project to test the scenario of post-pandemic, which has not been very studied in the scientific community yet. As such, we have found no other works that could be used to compare the results.

VII. Conclusions

Considering all the tests and data, we were able to gather a few concrete conclusions.

Firstly, regarding the transfers between hospitals, we can conclude that transfers allow better management of resources and significantly reduce waiting time for surgeries. In the context of post-pandemic, it is worth to develop mechanisms that facilitate transfers and communication between hospitals to overcome limitations in resources in overloaded hospitals and minimize waiting time, as well as potential casualties that can occur.

Secondly, regarding minimization of average waiting time in each hospital, locally, the minimization of preparation time, which results in a higher volume of surgeries of the same type and specialty being allocated to the same operating rooms, seems to have slightly better results in operating rooms' allocation. The best option, during times of overcrowding of surgeries in hospitals, is to allocate surgeries of the same specialty and type to the same ORs in the same days. In the case of surgeon allocation, the best results were obtained taking into consideration both the surgeon's occupancy as well as the respective level of expertise, because surgeons with higher levels of expertise, who take less time to perform surgeries, are prioritized in the process of allocation, which results in a decrease in surgeries duration.

Thirdly, regarding the hospital's resources, we can conclude that additions to either operating rooms or surgeons do contribute to increasing a hospital's capacity to respond to surgery needs in a timely manner, but additions of operating rooms are only fully useful if accompanied by additions in surgeons, and vice-versa.

VIII. Future Work

In the future, the system could be expanded by considering:

- all the medical staff needed to perform a surgery.
- post-surgery services, such as beds and rooms available for the patients to stay after surgery.
- real data.

IX. Acknowledgment

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