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[181010] Hospital Resource Planning: A Case-Based Application for Surgical Services of a Colombian Hospital

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1. Abstract

For strategic decision making, the implementation of Hospital Resource Planning (HRP) is important to allow efficient resource management, identify those resources which are causing bottlenecks, improve patient flow, and provide timely treatment and reduce costs. This project proposes and develops an application that implements a quantitative HRP model for the elective surgical service for a Colombian Hospital by using a Genetic Algorithm with stochastic demand scenarios as solution method. The application takes into account its impact on tactical and operative scheduling of surgical resources for elective surgeries, this impact is reflected in the interaction with a scheduling tool.

The main purpose was to analyze the most suitable investments to minimize the total tardiness by increasing the current capacity of the hospital. The application developed used demand scenarios generated from data given by the Colombian Hospital to get a robust solution in order to consider the potential demand increasement. Besides, the proposed application can also be used as a diagnostic tool between the current situation and the proposed investment through the tardiness measure, which is considered as the main key performance indicator (KPI) to take into account.

Initially the critical resources and KPIs were defined based on the literature and the requirements of the Colombian Hospital's Staff. The earnings per procedure (EPP) were calculated in order to measure the amount of money that the hospital would get at the end of the evaluated time period in the initial and proposed shituations. Then, a historical data analysis was realized based on the surgeries made in the Colombian Hospital, in order to generate the demand forecast.

The application was developed implementing a Genetic Algorithm (GA) with demand forecast scenarios based on stochastic simulation in order to identify the resources combination to minimize the tardiness given the hospital demand historical behavior, its budget and restrictions. The GA has an internal improvement algorithm in order to guarantee a better O.F. with the lowest possible investment. Then, What-If-Analysis were made in order to explore the effects on the tardiness by two situations proposed by the Colombian hospital, where some input parameters were modified as the scheduling rule for surgeries assignation and a potential 10% reduction of the recovery time per surgery.

Finally, the HRP applicative was executed generating the investment proposal, where the KPIs between the initial situation and the simulated demand forecasts were compared in order to evaluate the impact of the given solution for the Colombian Hospital.

Keywords: Hospital Resource Planning, surgical schedule, software application, quantitative model, demand scenarios, key performance indicators, tardiness.

2. Justification and problem statement

2. 1. Justification

The growing demand of health care services in Colombia and particularly for surgeries in the past few years has increased the complexity to manage them efficiently in hospitals and other health care institutions. For instance, the Ministery of Social Protection (Ministerio de la Protección Social (2017)) reported an increment of 45.41% in 2017, only for cardiovascular surgery from 2009 to 2015. One of the biggest issues in surgical services can be seen in patients' waiting times that according to Siciliani and Hurst (2005) can generate several consequences including deterioration in health status, prolongation of suffering and uncertainty. Waiting times are associated with inappropriate techniques for surgeries planning, along with the absence or lack of synergy (before, during and after) of adequate resources. It is essential to bear in mind surgery resource availability to carry out any surgical procedure, and because of that Hospital Resource Planning (HRP) becomes fundamental.

Based on Guerriero and Guido (2011) Hospital Resource Planning is the development of several procedures acting to maximize utilization of available resources, identify those which are causing bottlenecks to improve patient flow, and provide timely treatment and reduce costs. As depicted in Figure 1, hospital decisions are divided into strategic, tactical and operative. Fanti et al. (2013) state that the strategic level is related to the long-term (years) decisions of the healthcare system concerning its location, structure, department planning, and dimensioning in relation with facility and resource needs. Neyshabouri (2016) affirms that tactical level decisions aim to identify and develop a master surgery scheduling, for instance, the assignation of the surgery blocks to different specialties, where blocks are time ranges of varying lengths. Each surgical specialty team decides on the number of patients to operate on in its assigned block . The assignment is generated to meet the total hours demanded by each specialty (Li et al. 2017).

The master plan or schedule is usually made based on the experience of specific staff members, resulting in feasible planning (under their criteria). However, most of the time, these schedules leave aside other possibilities considering quantitative arguments focused on optimization, and therefore, the different variables and overall objectives affecting this planning are not fully considered. And last, operative decisions involve day-to-day scheduling of patients, divided in to scheduling requests that arrive before the appointment and reacting to events that could not have been foreseen (Marynissen and Demeulemeester 2016). The dotted line is Figure 1 refers to the scope of this project, which is confined to the strategic level, since HRP related decisions tackle long-term investments, as infrastructure, specialized equipment, personnel and other high cost resources. In particular, this project focuses on HRP for surgical services.

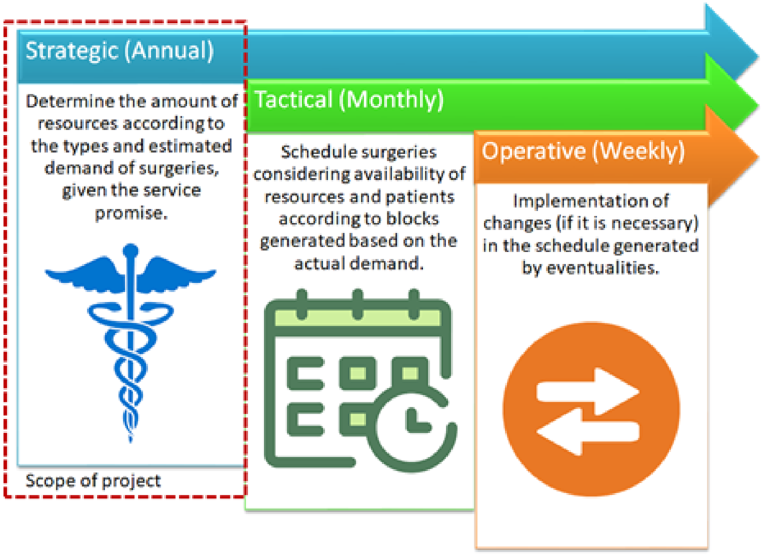
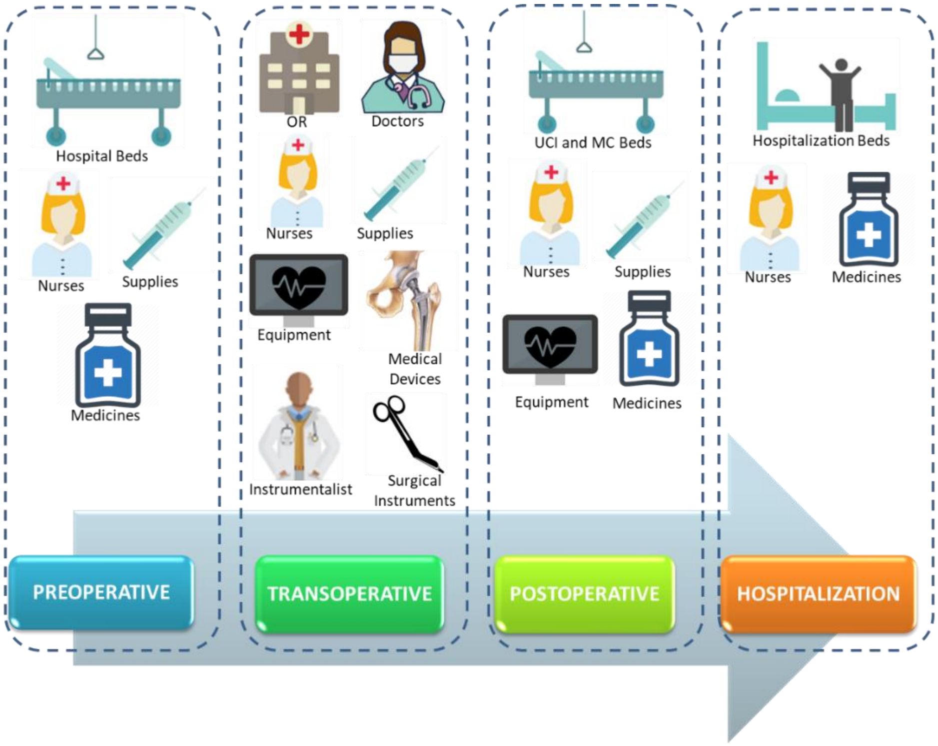


Figure 1.Hierarchical decision- making based on van Ostrum, Bredenhoff, and Hans 2010

To implement HRP, as seen in Figure 2, it is necessary to consider several types and amount of resources required in the pre-surgical, trans-surgical, post-surgical and hospitalization phases (Dubois 2001). Given the capacities of these resources, the strategic level determines the flow of patients within the hospital. The absence of a least one resource within any phase may affect the functionality of tactical and operative levels, compromising the schedule, patients' waiting times and surgical services capacity, therefore the complexity of the HRP is to determine the right amount of such resources based on the demand and the service promise.



ICU: Intensive Care Unit - MC: Medium Care

Figure 2.Resource need based on surgical step inspired on Dubois 2001

2.2. Problem Statement

Considering the requirement of financial stability, the hospital's service promise, and some of the main characteristics of the surgical resources such as high cost, difficulty in their immediate acquisition, useful life time, maintenance, among others; the need for proper resource management arises. For instance, Penn, Potts, and Harper (2017) reported that operating rooms and surgeons are among the most expensive resources in any hospital. However, these are not necessarily the critical resources that may limit the management.

Given the aforementioned conditions, the need to develop an application to implement a HRP model from a quantitative perspective is evident in order to identify and manage the critical surgical resources, looking to increase capacity of the hospital and to minimize tardiness (defines as the total difference between the scheduled date and the maximum theorical realization date of the surgical procedure). The main purpose is to allow a better flow in the surgical schedule. The main outcome of the proposed application is the suggestions for the appropriate investments, so the management can decide on hospital resources acquisition based on their budget and other strategic criteria. The HRP proposal in this project will be based on a case study for a Colombian Hospital.

3. Literature Review

In hospital resource management different approaches have been observed through different methodologies to deal with strategic decisions. For instance, Fanti et al. (2013) proposed a strategy to evaluate the performance of hospitals depending on the availability of their resources to minimize the patients' waiting times using an Unified Modeling Language tool and a timed Petri net (PN) model to take decisions about the available resources in relation with the workflow hospital protocols. As well, Schmidt, Geisler, and Spreckelsen (2013) used a mixed-integer linear programming solver (SCIP) and three heuristic strategies to develop a decision support system for admission planning and bed assignment, taking into account the treatment of shared resources. All the approaches were evaluated with a realistic discrete- event simulation. The outcomes were the ratio of successful assignments and dismissals, the computation time, and the model's cost factors. Applying the proposed decision support system, a reduction in more than 30% in the patient dismissal rate was achieved. Similarly, Holm, Lurås, and Dahl (2013) presented a generic discrete-event simulation model of patient flow through the wards of a Norwegian general hospital. The model was applied in order to reallocate the hospital beds among the wards. For each ward, arrivals were modelled with Poisson-distributions with time-varying intensity, length of stay was modelled as beta- distributions, using a combination of subject matter experts' evaluations and empirical data. The output of the model is a matrix, with statistics on the utilization of different hypothetical numbers of beds for each ward, this matrix was fed into an allocation algorithm, which distributes the available beds among the wards in an optimal way. The main results showed that when bed distribution is optimized, the share of crowding patient nights is reduced from 6.5% to 4.2%.

Later, Choi and Wilhelm (2014) implemented a non-linear stochastic programming model with different adaptations taking in to account the capacity allocation to minimize the consequences (cost due to penalties) for any patients who are not accommodated in the schedule and for planning extra hours in the operating room, achieving a better frame for master surgical scheduling in the medium term. Also, Belciug and Gorunescu (2015) proposed a complex analysis of the resource allocation in a hospital department by integrating, in the same framework, a queuing system, a comportamental model, and an evolutionary-based optimization. The authors presented a simulated application to explore the effects on the resource utilization through systematic changes to improve hospital bed usage. The evolutionary approach reported the number of beds to get the minimum healthcare cost. Also, it was observed that the delay probability is mainly sensitive to the change of the mean service time, and it is not significantly affected by the relative changes of the number of beds and arrival rates.

Finally Burdett and Kozan (2016) analyzed a hospital capacity model with a multi-objective approach using variants of the standard epsilon-constraint method and a pareto optimal patient case mixes. Therefore, it was possible to provide a plan to determine the number of patients the hospital should attend of each type and how to treat them (theoretical capacity). In addition, Spratt and Kozan (2016) generated master surgical schedules that adhere to staff and equipment restrictions while ensuring patients treatments in a timely manner. The authors proposed a mixed-integer nonlinear programming (MINLP), and solve the model with hybridized metaheuristics, such as simulated annealing (SA) and reduced variable neighborhood search (RVNS). The adaptive SA and hybridize SA with RVNS greatly improved the solution quality, maximizing the number of surgeries performed during the planning horizon, concluding that those metaheuristics have potential to be applied to complex hospital scheduling problems on a large scale.

In conclusion, there has been approaches to the scheduling and use of resources for surgery at tactical and operational levels, however the strategic level has not been studied in depth. From this literature review, the following aspects will be considered: resources used in surgical procedures, optimization techniques used to schedule surgeries and KPIs. Thus, the following research questions can be proposed: *what are the aspects that should be considered to implement an application for a quantitative HRP model for the surgical service?*

4. Objectives

The general objective is to propose and develop an application to implement a quantitative Hospital Resource Planning (HRP) model for a fourth level Colombian Hospital in order to improve their surgical Resource management for elective surgeries, in order to minimize the total tardiness. This general objective can be divided into the following specific objectives:

- Define the critical resources involve in the surgical procedure, that will be considered into the HRP model.
- Propose a quantitative model for HRP.
- Develop and implement an application using a quantitative technique for solving the proposed model
- Define demand scenarios to validate the proposed model and determine the economic impact of the resulting strategic decisions.

4.1 Design statement

This project proposes an application for surgical resource planning, with restrictions focused on the relationship of surgical resources, their characteristics and hospital information related to surgeries scheduling, the main objective is to minimize the total tardiness (total difference between the scheduled date and the maximum theorical realization date).

The aim of this application is to suggest the investment on critical surgical resources through a quantitative model or algorithm. Indeed, the application will provide an estimation of the appropriate investments to increase surgical capacity, but the final investment decisions will be taken by the management, analyzing the viability of such investments. The application used a simulation to improve the solution with demand scenarios generated by historical data given by the hospital, in order to verify the impact of the proposed resource investment, by comparing the current and the proposed KPIs values.

4.2 Design requirements:

- The application must be able to interact with scheduling techniques, to visualize the effect of strategic decisions in a tactical/operational time horizon.
- The application must identify the quantity of critical resources to acquire through the simulation of stochastic demand scenarios.
- The amount of critical resources given by the application should be feasible by considering as input the hospital budget and other criteria.
- It is necessary to measure the effect in the scheduling caused by the variation in the amounts of proposed resource investment through total tardiness as KPI.

4.3 Standard accomplishment:

The methodology used in this project is described by the ISO 13053-1 for the quantitative methods in process improvement. This methodology typically comprises five phases: Define, Measure, Analyze, Improve and Control ("ISO 13053-1, Quantitative Methods in Process Improvement — Six Sigma — Part 1: DMAIC Methodology" 2011).

In this project the control phase was not executed, because the solution provided is an investment proposal in the acquisition of resources as a HRP for the strategic decisions making. Therefore, considering that the development time horizon of the project is shorter than the HRP execution (if carried out), there is no way to follow up the implementation.

4.4 Design constraints:

The application only modifies the surgical resources associated with the care of elective patients, who are defined as patients for whom the surgery can be planned in advance (Cardoen, Demeulemeester, and Beliën 2010).

- Not all the resources required in the different phases of the surgeries were used, their selection was based on the information gathered through the literature review and the resources considered critical by the Colombian Hospital of the study case.
- The application used a scheduling technique, so it didn't include the design of a new scheduling technique.
- Once the critical resources were defined, they couldn´t be added or replaced by any other resource that has not been contemplated in the initial selection.
- The viability of the proposed resource investment depended on the budget willing to invest, given by the Colombian Hospital.
- The execution of the proposed resource investment was determined by the financial and operative management of the Colombian Hospital.
- The development of the project was limited to the information provided by the Colombian Hospital, however, if the required information was not available, hypotheses were made.

5. Methodology

This methodology comprises five phases: Define, Measure, Analyze, Improve and Control. Each is stage is explained below.

a. Define

In this phase, the critical resources to be considered in the application were selected taking into account those reported in the literature and the requirements of the Colombian Hospital's staff. Also, the KPIs were defined to determine the implementation effect of the HRP and finally the quantitative technique to develop the application was defined, as described below.

The Master Surgery Schedule can be seen as the engine that drives the hospital. Therefore, it is very important for decision makers to have a clear image on how the demand of several resources is linked to the surgery schedule, so the impact of critical resources can be taken into consideration. Critical resources share the following features: they are limited in capacity, they are expensive, and their consumption pattern depends on the master surgery schedule (Belien, Demeulemeester, and Cardoen 2006).

To Define the critical surgical resources, which were considered into the HRP model, a literature review was made. Based on Guerriero and Guido (2011) the OR department is a key hospital resource, as 60–70% of all hospital admissions are caused by surgical interventions and it has been estimated that it accounts for more than 40% of the total expenses of a hospital. Likewise, Belien, Demeulemeester, and Cardoen (2006), established that all situations happening inside the operating room dramatically influences the demand for resources throughout the rest of the hospital. Additionally, after surgery, a patient most of the time occupies a cubicle and requires nursing services for recovery. Consequently, the demand patterns for these resources are highly dependent on the operating room schedule.

Furthermore, in order to identify the critical resources, several meetings were held with hospital staff (the Colombian hospital of the case study) to gather information. According to this, the following resources were selected: operating rooms, medical devices (Microscope, Intensifier, Harmonic scalpel, Sonicision and Arthroscopy towers) and recovery cubicles.

Given the need to evaluate the solution's impact of the HRP application, Key Performance indicators were used, the KPI'S taken into account were:

-Tardiness (defined as the total difference between the scheduled date and the maximum theorical realization date).

$$Tardiness = \sum_{\forall i \in I} (scheduledDate_i - TheoricalDate_i)$$

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Equation 1.Tardiness

I: Set of surgeries in one-month horizon.
$ScheduledDate_i$**:** Assigned date by the scheduling tool given the hospital's critical resources for surgery *i.*
$TheoricalDate_i$**:** Execution date suggested by the hospital for surgery *i.*

-Percentage of utilization of recovery cubicles

$$Percentage\ of\ utilization\ of\ recovery\ cubicles = \sum_{\forall dc \in C} \sum_{\forall d \in D} \sum_{\forall i \in I} \frac{Recovery_{idc} * Periods_i}{TC}$$

Equation 2.Percentage of utilization of recovery cubicles

I: Set of surgeries in one-month horizon.
D: Set of days of the planning horizon.
C: Set of recovery cubicles.
$Recovery_{idc}$**:**1, if the surgery *i* was assigned in the cubicle *c* on the day *d;*
0, if not.
$Periods_i$**:** Periods required by the surgery *i* in a recovery cubicle.
TC: Total available periods in the recovery cubicles, a period is 15 minutes.

-Percentage of budget invested.

$$Percentage\ of\ budget\ invested = \sum_{\forall r \in R} \frac{BudgetInvested_r}{TotalBudget}$$

Equation 3. Percentage of budget invested

R: Set of critical resources
$BudgedIndveted_r$**:** Amount of money invested in the resource *r*.
$Total\ budget$: Total amount of money available to invest by the hospital.

-Profit given by the scheduled surgeries.

$$Profit\ given\ by\ \ scheduled\ surgeries = \sum_{\forall i \in I} Scheduled_i * UVR_i * \$16.000 * 4\%$$

Equation 4.Profit given by the scheduled surgeries

I: Set of surgeries in one-month horizon.
$Scheduled_i$**:** 1, if surgery i was scheduled by the application.
UVR_i**:** units of relative value for the surgery *i.*
$\$ 16.000$: Colombian value of one UVR.
4%**:** Estimated percentage of surgery profit suggested by the hospital.

Finally, the quantitative technique selected was a genetic algorithm (population-based metaheuristic) based on evolutionary computation, because the configuration of the problem required discrete variables with a high level of complexity. In addition, it was evidenced in the literature that this algorithm yields good results, for example, as proposed by Belciug and Gorunescu (2015), who used a genetic algorithm which provided an effective management of bed occupations and resources utilization.

All applications (HRP and scheduling tool) were developed in Visual Basic for Applications taking all data from Microsoft Excel Sheets. The choice of the programming environment was made based on the Hospital requirements, hospital personnel's skills and the software's low complexity. Likewise, within the HRP programming, the minimum quantity required for each critical resource and the maximum amount allowed (upper and lower limits) were taken into account as a restriction, guaranteeing that all possible solutions are feasible.

b. Measure

The second phase of this methodology considers measuring the initial situation, given by the actual resource quantity of the hospital and an EDD (Earliest Due-Date) scheduling method, set on an application developed in Microsoft Excel Visual Basic made by Alejandro Rivera, Camilo Zuleta and Angela Moreno (2018).

Once the HRP model was implemented, the KPIs were measured again in order to identify the impact of the application, the analysis made by the results of these measures are reported in section 6. On other hand, the earnings per procedure (EPP) were calculated in order to measure the amount of money that the hospital would get at the end of the evaluated time period in the initial and proposed situations. The EPP was calculated using the UVR`s (units of relative value), which according to the directing council of the institute of social insurance (2001) grades the procedure according to its complexity and resources requirements, each UVR has a monetary value and procedures have different amounts of UVR`s representing the total amount of money involved in each procedure, where the hospital indicated that the 4% of this total are the earnings after all the cost, expenses and outflows of money. Total earnings for the evaluated time periods were calculated by adding the amount of procedures made by their respective UVR`s, value of one UVR and % of earnings for the hospital.

c. Analyze

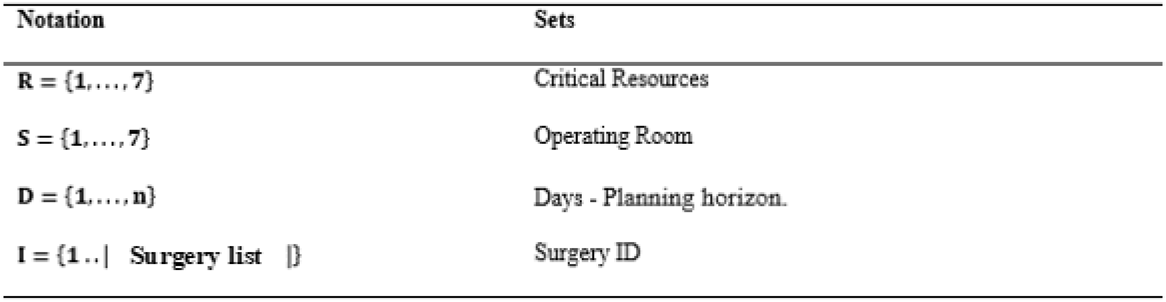
In this third phase is a historical data analysis is shown based on the surgeries made in the Colombian Hospital and the linear programming model to represent its initial situation.

An analysis of the historical data provided by the hospital was carried out to estimate the average length of patient stay in recovery cubicles. The data was composed by records of the six previous months, each month had the daily information of time periods in the recovery cubicles depending on each type of surgery.

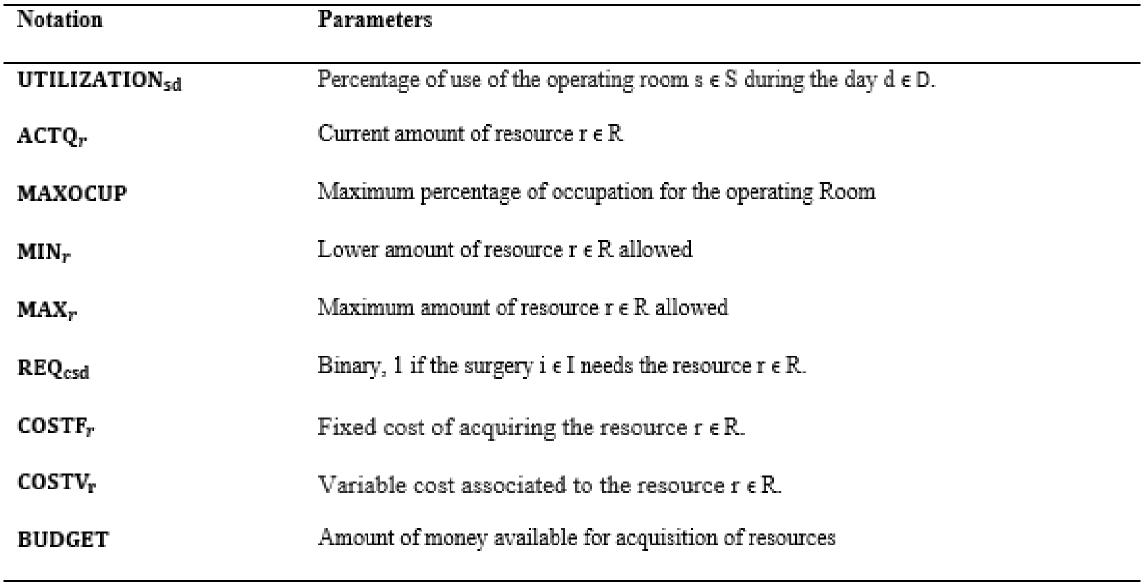
Data debugging was also performed excluding the procedures with atypical or incomplete information resulting in a reduction of 17.33% from initial data, then the different surgeries were assigned to one of the 220 defined categories of procedures done in a previous capstone final project (Alejandro Rivera, Camilo Zuleta and Angela Moreno, 2018) to obtain the expected value in order to use it as an input parameter for the development of the application. Afterwards, an analysis was made between the surgery and recovery times for the 220 categories of procedures in order to identify if there was correlation between the recovery time and the surgery time. To do so, the correlation and determination coefficients were calculated and given their value, the regression was used to estimate the relationship between these two variables. Results of this analysis are reported in Annexed 2.

Subsequently, records of 22.000 surgeries made since 2015 were analyzed by determining the amount of surgeries per category made in periods of one month, in order to identify and select the three categories with the biggest participation in the periods and study their increasement in the course of each of the 18 time periods of one month. The dependency of the amount of surgeries per category with the time period was analyzed with the correlation and determination coefficients as well, and the regression was used to make a forecast of the amount surgeries of the three selected categories in 5 years for the generation of the demand scenarios. Results of this analysis are also reported in Section 6.

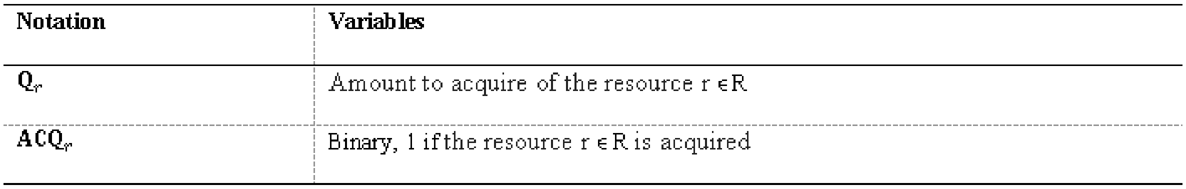
Additionally, a mathematical model using linear programming was developed as the first approach in order to identify variables, parameters given by the Colombian Hospital staff and restrictions of the problem described below:



Notation	**Sets**
$\mathbf{R = \{1, \dots, 7\}}$	Critical Resources
$\mathbf{S = \{1, \dots, 7\}}$	Operating Room
$\mathbf{D = \{1, \dots, n\}}$	Days - Planning horizon.
$\mathbf{I = \{1 .. \mid \text{Surgery list} \mid\}}$	Surgery ID



Notation	**Parameters**
$\mathbf{UTILIZATION_{sd}}$	Percentage of use of the operating room s ϵ S during the day d ϵ D.
$\mathbf{ACTQ_r}$	Current amount of resource r ϵ R
$\mathbf{MAXOCUP}$	Maximum percentage of occupation for the operating Room
$\mathbf{MIN_r}$	Lower amount of resource r ϵ R allowed
$\mathbf{MAX_r}$	Maximum amount of resource r ϵ R allowed
$\mathbf{REQ_{csd}}$	Binary, 1 if the surgery i ϵ I needs the resource r ϵ R.
$\mathbf{COSTF_r}$	Fixed cost of acquiring the resource r ϵ R.
$\mathbf{COSTV_r}$	Variable cost associated to the resource r ϵ R.
$\mathbf{BUDGET}$	Amount of money available for acquisition of resources



Notation	**Variables**
$\mathbf{Q_r}$	Amount to acquire of the resource r ϵR
$\mathbf{ACQ_r}$	Binary, 1 if the resource r ϵ R is acquired

The effect HRP solution is reflected with the use of a scheduling tool, therefore the objective function is still the same as the presented in the project found in appendix 7 (Alejandro Rivera, Camilo Zuleta and Angela Moreno, 2018) where its function was minimize the total tardiness of the scheduled surgeries, recalling the OF definition as the total difference between the scheduled date and the Execution date suggested by the hospital of the surgical procedure, if the surgery is realized the day or before of its due date, the tardiness for this procedure would be zero.

$$MAXOCUP \geq \sum_{\forall s \in S} \sum_{\forall d \in D} UTILIZATION_{sd} - M\,(ACQ_1)$$

$$MAXOCUP \leq \sum_{\forall s \in S} \sum_{\forall d \in D} UTILIZATION_{sd} + M\,(1 - ACQ_1)$$

Equation 5. Constraints for the maximum percentage of use for the operating rooms

$$Q_r \geq (MIN_r);\ \forall r \in R$$

$$Q_r \leq (MAX_r);\ \forall r \in R$$

Equation 6. Boundaries constraints for the resource acquisition

$$\sum_{\forall r \in R} Q_r * COSTV_r + \sum_{\forall r \in R} ACQ_r * COSTF_r \leq BUDGET$$

Equation 7. Budget constraint

Given the problem complexity and considering the requirement of a complementary scheduling tool, it was determined that an exact method was not suitable for finding a solution on a realistic case, consequently approximate methods were taken as alternatives.

d. Improve

The implementation of a genetic algorithm (GA) with demand forecast scenarios based on stochastic simulation in the application was made in order to identify the resources combination to minimize the tardiness given the hospital demand historical behavior, its budget and restrictions. The GA has an internal improvement algorithm in order to guarantee a better O.F. with the lowest possible investment.

Then, What-If-Analysis were made in order to explore the effects on the tardiness by two situations proposed by the Colombian hospital, where some input parameters were modified as the scheduling rule for surgeries assignation and a potential 10% reduction of the recovery time per surgery**.**

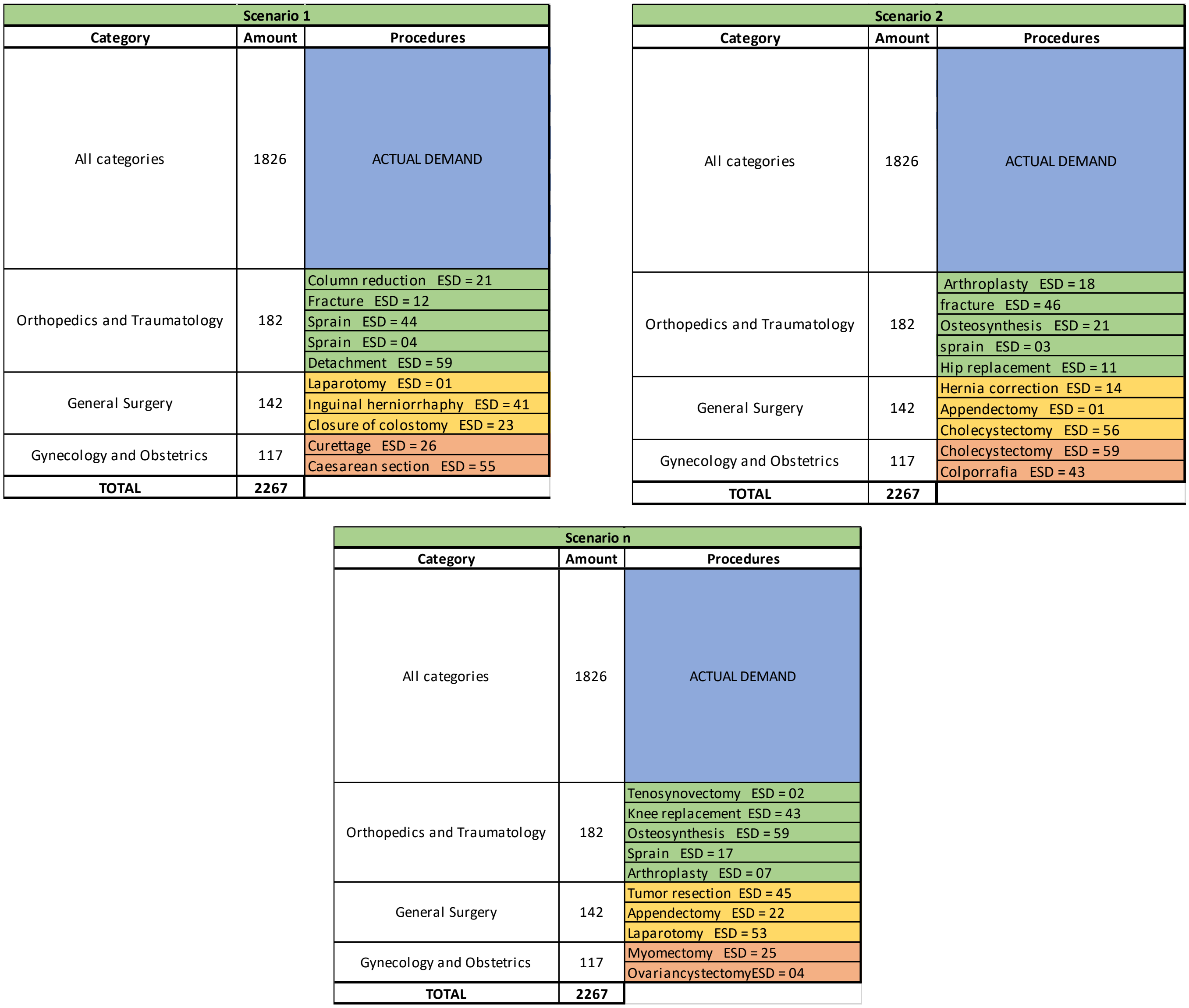
The application is focused on optimization technique, which can be approached by different methods according to Gara Miranda Valladares and Coromoto León Hernández (2012) the exact methods find the optimal solution, but it is only viable to apply them at very small instances of the problem. On the other hand, approximate methods handle specific knowledge of the problem to obtain high quality solutions without needing an excessive computational effort compared to the exact methods. Given the aim to find a combination of resources that support demand scenarios and adapts to the stochastic optimization concept, an approximate method was selected because it allows to take into account the implicit variability within the use of demand scenarios.

The different scenarios used in order to identify the best critical resources to acquire are designed by defining the surgeries demand forecast in 5 years by the three categories with the biggest participation. Orthopedics and Traumatology; General Surgery; and Gynecology and Obstetrics were increased with a composition of 182, 142 and 117 respectively, resulting in 441 surgeries added to the actual demand of 1826 surgeries.

Once the forecast quantity gave the size of the scenarios (2267 surgeries) and the composition of the supplementary surgeries, the first scenario was made from the actual demand of 1826 surgeries, 182 random selections of the procedures executed in Orthopedics and Traumatology, 142 of the executed in General Surgery and 117 of the executed in Gynecology and Obstetrics, and for the each of the 441 added surgeries an execution suggested date was assigned randomly between the scheduling period of one month.

From the scenario ***1*** to the scenario ***n*** in the simulation the same process was implemented, where the variation between all of them are the procedures selected randomly from the respective category and the execution suggested date assigned randomly as well to each surgery added. It is important to remark that there was no variation in any scenario the amount of surgeries added (441) or the amount of surgeries per category compounding the **addition** ass seen in the example below.

*ESD= Execution Suggested Date



Scenario 1		
Category	**Amount**	**Procedures**
All categories	1826	ACTUAL DEMAND
Orthopedics and Traumatology	182	Column reduction ESD = 21
		Fracture ESD = 12
		Sprain ESD = 44
		Sprain ESD = 04
		Detachment ESD = 59
General Surgery	142	Laparotomy ESD = 01
		Inguinal herniorrhaphy ESD = 41
		Closure of colostomy ESD = 23
Gynecology and Obstetrics	117	Curettage ESD = 26
		Caesarean section ESD = 55
TOTAL	**2267**	

Scenario 2		
Category	**Amount**	**Procedures**
All categories	1826	ACTUAL DEMAND
Orthopedics and Traumatology	182	Arthroplasty ESD = 18
		fracture ESD = 46
		Osteosynthesis ESD = 21
		sprain ESD = 03
		Hip replacement ESD = 11
General Surgery	142	Hernia correction ESD = 14
		Appendectomy ESD = 01
		Cholecystectomy ESD = 56
Gynecology and Obstetrics	117	Cholecystectomy ESD = 59
		Colporrafia ESD = 43
TOTAL	**2267**	

Scenario n		
Category	**Amount**	**Procedures**
All categories	1826	ACTUAL DEMAND
Orthopedics and Traumatology	182	Tenosynovectomy ESD = 02
		Knee replacement ESD = 43
		Osteosynthesis ESD = 59
		Sprain ESD = 17
		Arthroplasty ESD = 07
General Surgery	142	Tumor resection ESD = 45
		Appendectomy ESD = 22
		Laparotomy ESD = 53
Gynecology and Obstetrics	117	Myomectomy ESD = 25
		OvariancystectomyESD = 04
TOTAL	**2267**	

Figure 3. Demand scenarios example

As seen in the graph below initially for step one of the simulation a number of 6 (n + n) scenarios was set with an n = 3, the first 3 (# scenarios-n) scenarios were evaluated to obtain the mean 1 and deviation 1 of the tardiness, then the mean 2 and deviation 2 were obtained evaluating the other 3 scenarios with the initial 3, the deviation 1 and 2 were compared, if a variation smaller than the 1% between the deviations was observed the simulation was finished, if not, the step two modify the total number of scenarios in 9 (2n + n), to obtain the new mean 1 and deviation 1 the first 6 (# scenarios-n) were evaluated, therefore, the new mean 2 and deviation 2 was obtained with all 9 scenarios, the comparison between the deviations was made once again to determine if convergence was identified, if not, the same process of step one and two was made to any step needed varying the amount of scenarios in (#step*n)+n.

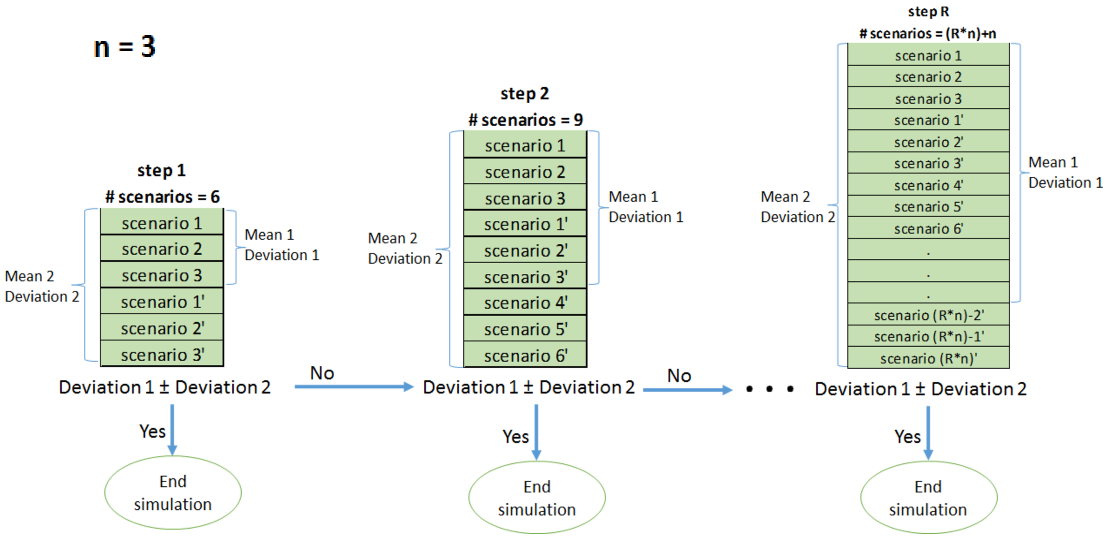


Figure 4. Simulation steps

Once the simulation was finished, the (#step*n)+n scenarios were executed three more times in order to evaluate if the deviation was converging to the first simulation value with a 3% (or less) difference, to determine if the amount of scenarios was significative for the simulation, if not this same process was executed with 2*((#step*n)+n) scenarios successively until convergence was accomplished. This simulation was made four times, the first one was made with the EDD, the second time with the Genetic Algorithm, then with the SPT (What If 1), and finally, the fourth time with the reduction of recovery time in cubicles (What If 2) with EDD.

As soon as the scenarios are generated, the Genetic Algorithm works with the parameters shown in the Table 1 and starts with the creation of the population where the first chromosome is the actual resources amount of the Colombian Hospital, then, five chromosomes are added, for each gen a random number is generated between the actual amount of the respective resource (lower bound) and the maximum possible amount of acquisition (upper bound), these limits were set through meetings with the Colombian Hospital staff.

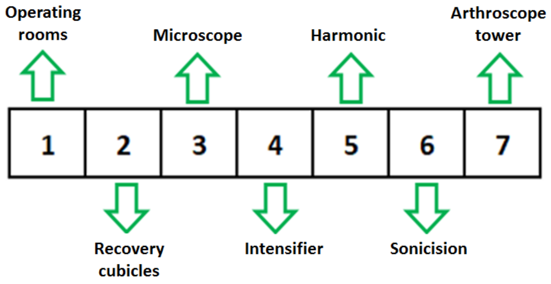


Figure 5.Chromosome representation

Once the population is created a scheduling tool is executed in order to verify the impact in the surgery assignation reflected on the objective function, where the chromosome with the best O.F , the probability of becoming a parent is assigned to each chromosome, probability given by the quotient between the individual fitness and the population fitness (sum of all the individual fitness).

The selection technique applied was the Roulette Wheel selection, which is explained as the expected value of an individual is that fitness divided by the actual fitness of the population. Each individual is assigned a slice of the roulette wheel, the size of the slice being proportional to the individual's fitness. The wheel is spun N times, where N is the number of individuals in the population. On each spin, the individual under the wheel's marker is selected to be in the pool of parents (Sivanandam and Deepa 2007).

Then the Genetic Algorithm create Six offspring using a single point crossover, where two mating chromosomes are cut once at corresponding points and the sections after the cuts exchanged. Here, a cross-site or crossover point is selected randomly along the length of the mated strings and bits next to the cross-sites are exchanged (Sivanandam and Deepa 2007).

For each chromosome its respective investment cost is calculated taking into account the established budget given by the hospital.

Subsequently a random number was generated, if this was lower than the mutation probability an increase of one unit was made in a randomly selected resource considering its lowest and upper limits previously set, finally a random son is selected and replaced with the chromosome with the best O.F. saved at the beginning.

After setting the new population the scheduling tool is used again, this process is made as many times as generations established in the programming. The Genetic Algorithm, as shown in the Annexed 10, was implemented to identify the best chromosome for each demand forecast scenario. Considering the hospital budget, an improvement algorithm was made and executed each time once the Genetic Algorithm (HRP) finalized, in order to guarantee a better O.F. with the lowest possible investment as shown in the Annexed 10.

Parameter	value	Method
Generations	4	-
Population	6	-
Crossover method	-	Point crossing
Parents selection method	-	Roulette rule
Mutation probability	0,4%	-

Table 1.Genetic algorithm parameters

Additionally, the application has two different options, which can be applied at the same time, these options allow the realization of **What-If-Analysis** for different situations requested by the hospital with the objective of identifying the impact of the HRP in conjunction with internal hospital decisions.

The first option consists in ordering the surgeries realization by the Shortest Processing Time rule, in order to identify if this rule can increase the quantity of procedures realized and analyze the performance of the recuperation cubicles. Additionally, verify if the minimization of the waiting and realization time of the surgery can beneficiate the O.F. taking into account its dependence on the realization date and also if minimizing the amount of time between the realization of the first and last procedure can be beneficial for the objective function, as described below.

An example of the shortest processing time (SPT) scheduling method is shown below, initially eight different surgeries arrived in a certain order in one day with their respective processing time, understood as the number of periods required for the execution of surgery , each surgery received an identification as Si (i =arrival order) as shown in the Figure 6; then, the surgery with the shortest processing time was set as the first one and so on until the surgery with the longest processing time is set as the last surgery to be done. Once the surgeries are ordered as the Figure 7. they were assigned to one of the three possible operating rooms (OR) in a certain time period, as seen in the Figure 8. where the surgery S1 (first in the order) was assigned to the OR 1 in the first time period, the surgery S4 was assigned to the OR 2 in the first time period because the OR 1 was occupied until the S1 was finished, this process of assignation was used for all the surgeries.

Surgeries arrival order

Figure 6.Surgeries arrival order example

Shortest Processing Time order

Figure 7.Surgeries ordered by shortest processing time

Scheduling example by SPT

Figure 8. Scheduling example by SPT rule

In the second option, the recovery time in the cubicles required by the procedures is reduced by 10 %, this situation is focused on modeling a possible improvement made by the hospital staff in the recovery area with the objective of identifying the potential benefits in the tardiness with administrative decisions to improve the staff productivity.

6. Results

In the results section are shown the critical resources' unitary acquisition effect on the O.F. (Figures 9 to 15), the individual increase was made for all the resources until a O.F. stabilization was observed. Later, on the Figure 16 the two critical resources with the biggest effect evidenced are shown in order to identify a potential acquisition combination with a bigger impact on the O.F. ; and last, the HRP application results are presented as a proposal for the Colombian Hospital.

A simulation was made in order to provide a solution based on different demand scenarios (forecast). The simulation was performed with different scheduling tools (EDD and Genetic Algorithm). Also, it was taken into account both What-if analysis. The simulations' results are in the Tables 2 to 7.

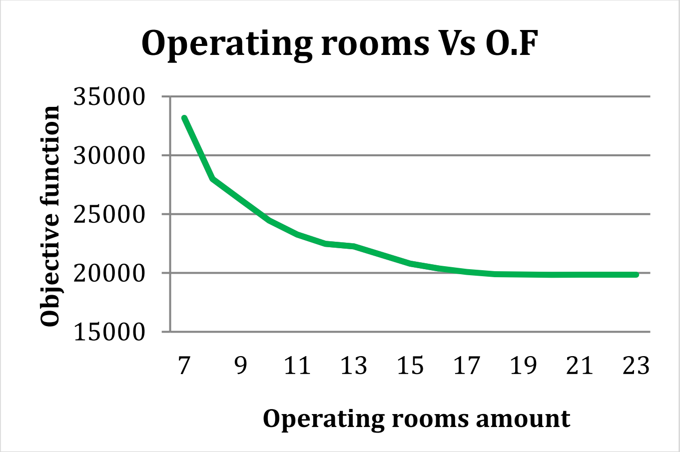


Figure 9.Operating rooms Vs O.F

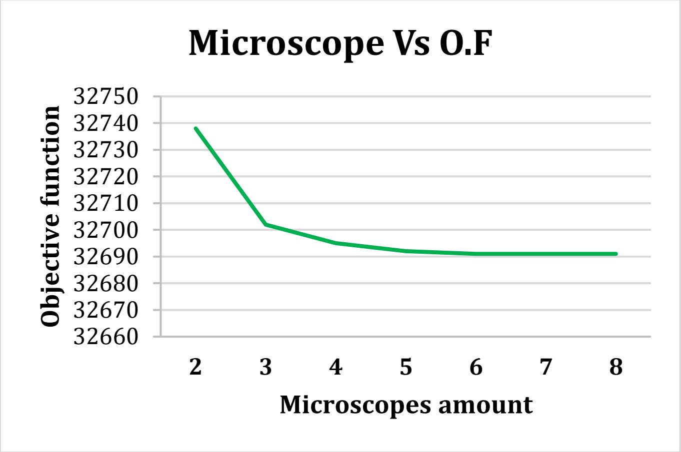


Figure 10. Microscope Vs O.F

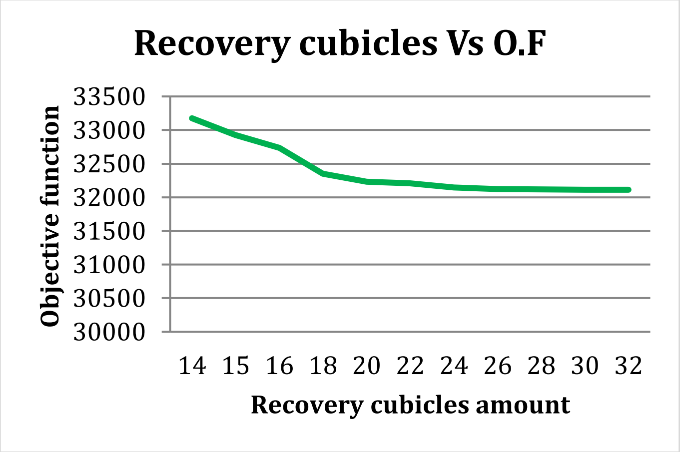


Figure 11. Recovery cubicles Vs O.F

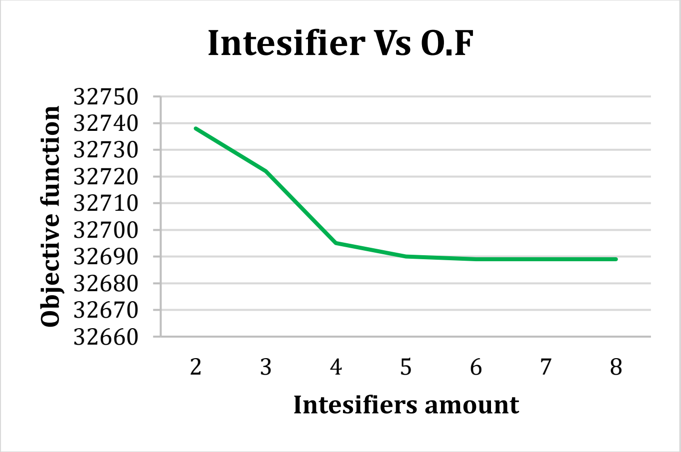


Figure 12.Intensifier VS O.F

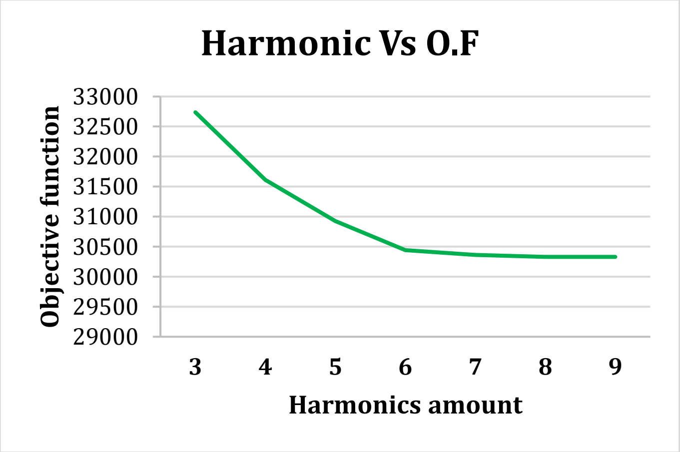


Figure 13.Harmonic Vs O.F

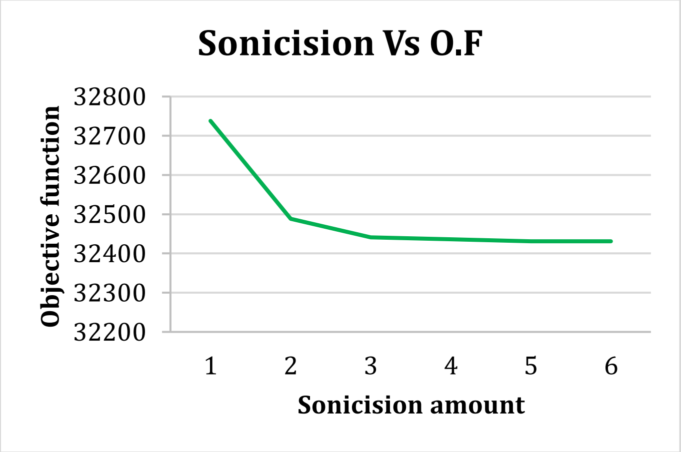


Figure 14. Sonicision Vs O.F

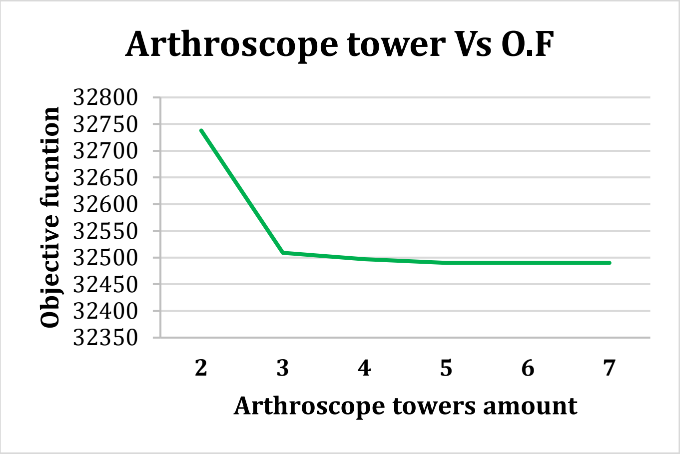


Figure 15. Arthroscope tower VS O.F

The O.R. and the Recovery Cubicles were the resources identified with a more significative impact and were selected for evaluating their combinations to reach a O.F. with a lower value.

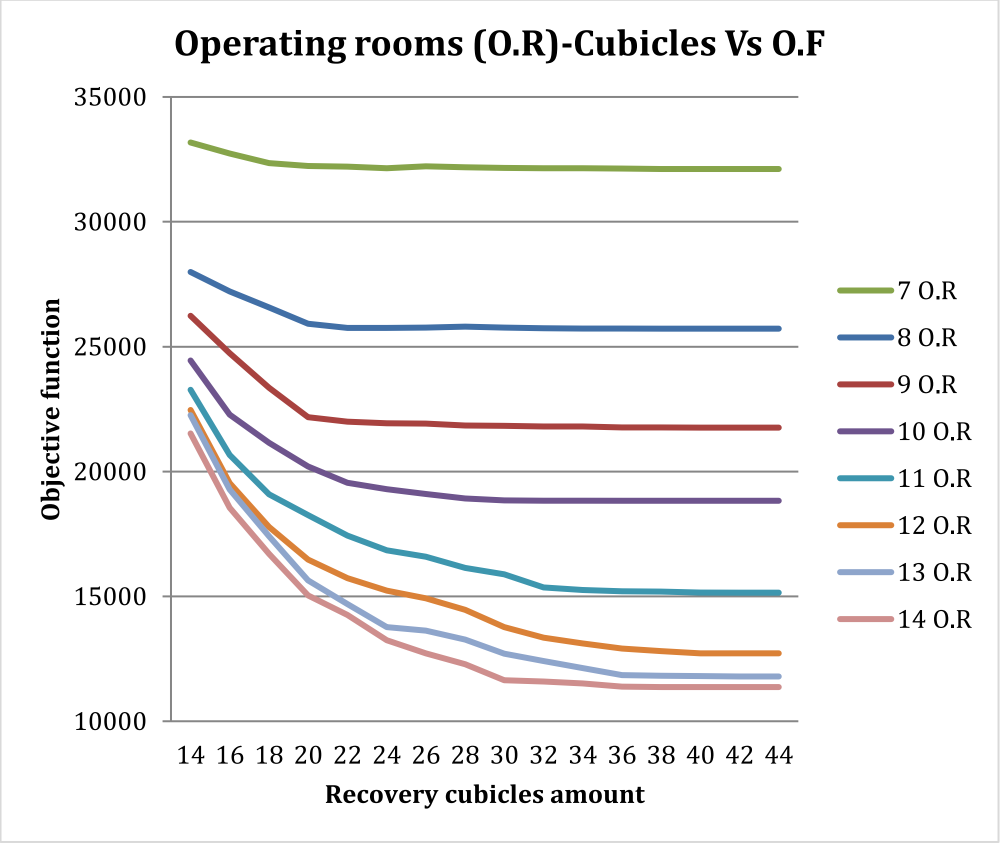


Figure 16. Operating rooms-Cubicles Vs O.F

The resource combination with the lowest O.F. through all the combinations made is composed of 14 O.R., 38 Recovery Cubicles, 2 Microscopes, 2 Intensifiers, 3 Harmonics, 1 Sonicision, and 2 Arthtoscopes Towers, with a O.F. of 11369 for a one-month scheduling horizon.

When the simulation was initiated using the EDD scheduling tool, it took five steps to start showing that 18 scenarios were a representative quantity in order to evaluate the deviation´s convergence, then 18 scenarios were executed three more times and their deviations were compared with the 18 scenarios from the simulation, resulting in the variations showed below:

Tardiness EDD				Simulation 18 scenarios	#1 18 scenarios	#2 18 scenarios	#3 18 scenarios
Mean				15.661,2777	15.668,9444	15.668,9444	15.670,1111
Deviation				109,0743	106,4338	106,3438	107,8866
Variation				-	2,4208%	2,5033%	1,0889%
Mean Interval				95% confidence	(15.607,03-15.715,52)		
Resource	Operating Rooms	Recovery Cubicles	Microscope	Intensifier	Harmonic	Sonicision	Arthroscope Tower
Amount	8	22	2	2	5	1	2
Computational Time						84 Mins	

Table 2.Tardiness EDD simulation

The simulation was also executed with the Genetic Algorithm scheduling tool, it took six steps to shows that 21 scenarios were a representative quantity in order to evaluate the deviation´s convergence, then 21 scenarios were executed three more times and their deviations were compared with the 21 scenarios from the simulation, resulting in the variations showed below:

Tardiness Genetic Algorithm				Simulation 21 scenarios	#1 21 scenarios	#2 21 scenarios	#3 21 scenarios
Mean				14.941,8571	14.941,8095	14.970,3333	14.937,7619
Deviation				146,9416	146,7287	144,4332	148,4357
Variation				-	0,1449%	1,7071%	1.0168%
Mean Interval				95% confidence	(14.874,97-15.008,75)		
Resource	Operating Rooms	Recovery Cubicles	Microscope	Intensifier	Harmonic	Sonicision	Arthroscope Tower
Amount	8	23	2	2	5	2	2
Computational Time						129 Mins	

Table 3.Tardiness Genetic Algorithm simulation

The What-If-Analysis 1 was made using the EDD scheduling tool, which allows to change the EDD method to the SPT method, otherwise, the Genetic Algorithm don't allow a scheduling method because its logic. The What-If-Analysis 1 required 21 scenarios in order to approach deviation convergence, later on the simulation was executed three more times and their deviation was compared with the first simulation executed as shown in the Table 4below:

Tardiness SPT				Simulation 21 scenarios	#1 21 scenarios	#2 21 scenarios	#3 21 scenarios
Mean				18.097,9048	18.075,000	18.049,9524	18.120,4289
Deviation				114,9322	113,6213	115,5343	114,4252
Variation				-	1,14068%	0,5239%	0,4411%
Mean Interval				95% confidence	(18.045,59-18.150,22)		
Resource	Operating Rooms	Recovery Cubicles	Microscope	Intensifier	Harmonic	Sonicision	Arthroscope Tower
Amount	8	20	2	2	5	2	2
Computational Time						65 Mins	

Table 4.Tardiness SPT simulation

The What-If-Analysis 2 was executed with the EDD scheduling method by request of the Colombian Hospital to evaluate the impact of the described reduction with the actual scheduling method. 12 scenarios given by 3 steps were needed in order to identify deviation convergence, the results of the comparison with three more executions of the simulation are shown below:

Tardiness EDD with WI 2				Simulation 12 scenarios	#1 12 scenarios	#2 12 scenarios	#3 12 scenarios
Mean				15.717,8333	15.718,0833	15.717,8333	15.719,0012
Deviation				120,4352	120,4654	120,4352	120,7249
Variation				-	0,0251%	0,0000%	0,2405%
Mean Interval				95% confidence	(15.641,31-15.749,35)		
Resource	Operating Rooms	Recovery Cubicles	Microscope	Intensifier	Harmonic	Sonicision	Arthroscope Tower
Amount	8	19	2	2	5	1	2
Computational Time						48 Mins	

Table 5.Tardiness EDD with WI 2 simulation

As seen in the tables above the best results are given by the Genetic Algorithm, therefore its resources amount were selected as the investment proposal for the Colombian Hospital.

In order to identify the impact of the possible combinations between the actual demand, the demand forecast, actual resources quantity, proposed resource quantity, what ifs characteristics and scheduling rules, ten mean values of the tardiness were compared:

Combination	Demand	Resource Quantity	Scheduling Rule	What if	Tardiness
1	Actual	Actual	EDD	-	19.608
2	Actual	Actual	Genetic Algorithm	-	18.696
3	Simulated	Proposed 1	EDD	-	15.661,2777
4	Simulated	Proposed 2*	Genetic Algorithm	-	14.941,8571
5	Actual	Proposed 2*	EDD	-	13.697
6	Actual	Proposed 2*	Genetic Algorithm	-	13.009
7	Simulated	Proposed WI1	SPT	1	18.097,9048
8	Simulated	Proposed WI2	EDD	2	15.717,8333
9	Actual	Actual	SPT	1	20.966
10	Actual	Actual	Genetic Algorithm	1	20.956
11	Actual	Actual	EDD	2	17.996
12	Actual	Actual	Genetic Algorithm	2	17.927
13	Actual	Proposed 2*	SPT	1	15.6697
14	Actual	Proposed 2*	Genetic Algorithm	1	14.993
15	Actual	Proposed 2*	EDD	2	19.293
16	Actual	Proposed 2*	Genetic Algorithm	2	18.493

Table 6.Tardiness comparison

Proposed 1: resource combination given by the demand forecast simulation and the EDD scheduling tool.
Proposed 2*: resource combination given by the demand forecast simulation and the Genetic Algorithm scheduling tool.
ProposedWI1: resource combination given by the demand forecast simulation and the EDD scheduling tool adapted to SPT.
ProposedWI2: resource combination given by the demand forecast simulation and the EDD scheduling tool adapted to the 10% reduction on the recovery time.

Based on the results of the tardiness comparison the resources proposed as a solution are given by the combination 4 (Proposed 2*) considering the use of the demand forecast simulation and the Genetic Algorithm scheduling tool provided by Alejandro Rivera, Camilo Zuleta and Angela Moreno (2018).

The amount of resources proposed was set on the scheduling tool (EDD and Genetic Algorithm) with the actual demand (1826 surgeries) with the purpose of evaluating the impact of the proposal immediately implementation to identify how the tardiness and the KPIs behaved from now (Combination 1,2 and 4) to the strategic point of decisions taking of five years (Combination 5 and 6).

KPIs Combination	Tardiness	Utilization % of Recovery Cubicles	% of Budget Invested	Profit Given By Scheduled Surgeries
1	19.608	57,94%	0,00%	$98.818.560
2	18.696	60,30%	0,00%	$99.377.280
4	14.941,8571	72,46%	67,00%	$128.065.920
5	13.697	43,81%	67,00%	$130.646.720
6	13.009	57,44%	67,00%	$134.212.800

Table 7. KPIs Comparison

7. Conclusions and recommendations.

Given the interaction requirement of the HRP Application with scheduling techniques, it was linked with the tools developed in (Alejandro Rivera, Camilo Zuleta and Angela Moreno, 2018), first with the EDD technique, which is an approximation of the actual process used in the Colombian Hospital and second, the Genetic Algorithm developed without surgeon, schedule and operating room restrictions. the second technique showed improvements in the scheduling performance.

With the HRP application´s KPIs, it was concluded that the best results are obtained by linking Genetic Algorithm scheduling tool with the HRP application, given its bigger cost/benefit relation with monthly earnings of $128.065.920 and % of invested budget of 67,00%

Two What If analysis were implemented by hospital requirement (applied to EDD and Genetic scheduling techniques), in the first analysis it was used a SPT dispatch rule, which generated a bigger O.F., and in the second one, a 10% reduction was applied to the recovery cubicles times, which resulted in a smaller O.F. (both compared with the initial situation O.F.). Therefore, it is recommended to apply actions in order to manage the implementation of the What-If-Analysis 2.

The simulation in the HRP application was carried out with 5 years forecast demand stochastic scenarios, obtaining a robust solution (amount of critical resources to invest), where the proposed combination of resources to acquire generates the lowest tardiness against any possible demand (according to forecast) in the time horizon considered.

The proposed amount of critical resources to acquire are 1 Operating Room, 7 Recovery Cubicles, 0 Microscopes, 0 Intensifiers, 2 Harmonics, 1 Sonicision, 0 Arthroscope Towers for a total amount of 8, 23, 2, 2, 5, 2 and 2 respectively. The investment value is $1.340.000.000 COP, reducing the actual Tardiness state in 33,65% from 19.608 to 13.009, and projected the tardiness in 5 years to mean interval with 95% confidence.

It is recommended to realize the classification of categories and procedures with medical knowledge criteria in order to achieve results with a bigger accuracy and similar to reality. Sometimes even when the procedures are the same, they can vary depending on the body part of application, for example an ablation in the finger is different in the amount of resources needed than in an arm ablation.

The need of a HRP application is fundamental for the Colombian Hospital, considering that different resources investments can required a bigger amount of money and still, not be beneficial for the O.F.; achieving the same or a smaller tardiness value compared with the O.F. given by the resulting with the acquisition proposal

8. Glossary

Below are the most relevant set of concepts for the development of this project, and their respective definitions:

Application: computer program designed to execute tasks or processes, allowing the user to perform their work more effectively. It consists of a set of inputs, information processing logic and the deployment of specific results through an interface. (Hernández et al., n.d.).

Demand scenarios: is to evaluate and to forecast the volume of demand in the future based upon some scenarios analysis.(Suryani et al. 2010)

Elective patients: patients for whom the surgery can be planned in advance. (Cardoen, Demeulemeester, and Beliën 2010).

Hospital Resource Planning: is the development of several procedures acting to maximize utilization of available resources.(Guerriero and Guido 2011).

KPI: Real-time monitoring of processes based on key business metrics, also known as key performance indicators (KPI). (Wetzstein, Ma, and Leymann 2008).

Master surgery scheduling: cyclic timetable that defines the number and type of available operating rooms, the hours that operating rooms will be open, and the surgical groups or surgeons available for each operating room block. (Blake, Dexter, and Donald 2002).

Patients' waiting times: The time between the hospitalization date and the surgery date. (Guerriero and Guido 2011).

Quantitative technique: tools, augmentation of production, maximization of profits, minimization of costs, and production methods can be oriented for the accomplishment of certain pre – determined objectives. (Vardhaman Mahaveer Open University 2014).

Surgery blocks: pre-defined time intervals that allow the assignment of surgeries according to the estimated time of this. (Li et al. 2017).

Surgical procedure: Surgery is a medical treatment performed by a surgeon to remove or repair a part of the body affected. It's sometimes called an operation or surgical resection. (Cancer Council Australia 2016).

Surgical specialty: Term used to gather in a single family the set of surgical procedures performed on a specific organ / disease. (Guido and Conforti 2017).

9. Annexes

No. Annexed	*Name*	*Development*	*Type of file*	*Relevance to the project (1-5)*
1	Recovery time in cubicles	Own	Excel (.xlsx)	3
2	Relation between surgery and recovery times	Own	Excel (.xlsx)	1
3	Surgeries demand forecast: 5 years	Own	Excel (.xlsx)	5
4	Recovery cubicles occupation per hour	Own	Excel (.xlsx)	4
5	Confidentialy letter	Hospital	PDF	5
6	Hospital Resourse Planning Aplication	Own	Excel (.xlsx)	5
7	Lineal programming model	Moreno, Rivera, Zuleta	PDF	1
8	HRP proposal letter	Own	PDF	5
9	Literature review summary chart	Own	PDF	4
10	Algorithms flowcharts	Own	PDF	4

References

Alejandro Rivera, Camilo Zuleta, and Angela Moreno. 2018. “Diseño de Un Aplicativo Para La Programación de Salas de Cirugía Teniendo En Cuenta El Impacto de La Reprogramación.” Trabajo de grado en modalidad de aplicación, Pontificia Universidad Javeriana.

Belciug, Smaranda, and Florin Gorunescu. 2015. “Improving Hospital Bed Occupancy and Resource Utilization through Queuing Modeling and Evolutionary Computation.” *Journal of Biomedical Informatics* 53 (February): 261–69. https://doi.org/10.1016/j.jbi.2014.11.010.

Belien, Jeroen, Erik Demeulemeester, and Brecht Cardoen. 2006. “Visualizing the Demand for Various Resources as a Function of the Master Surgery Schedule: A Case Study,” 20.

Blake, John T., Franklin Dexter, and Joan Donald. 2002. “Operating Room Managers’ Use of Integer Programming for Assigning Block Time to Surgical Groups: A Case Study:” *Anesthesia & Analgesia* 94 (1): 143–48. https://doi.org/10.1097/00000539-200201000-00027.

Burdett, Robert, and Erhan Kozan. 2016. “A Multi-Criteria Approach for Hospital Capacity Analysis.” *European Journal of Operational Research* 255 (2): 505–21. https://doi.org/10.1016/j.ejor.2016.05.041.

Cancer Council Australia. 2016. “Understanding Surgery.”

Cardoen, Brecht, Erik Demeulemeester, and Jeroen Beliën. 2010. “Operating Room Planning and Scheduling: A Classification Scheme.” *International Journal of Health Management and Information* 1 (1): 71–83.

Choi, Sangdo, and Wilbert E. Wilhelm. 2014. “On Capacity Allocation for Operating Rooms.” *Computers & Operations Research* 44 (April): 174–84. https://doi.org/10.1016/j.cor.2013.11.007.

Dubois, Salvador Martínez. 2001. *Cirugía: bases del conocimiento quirúrgico y apoyo en trauma*.

McGraw-Hill Interamericana.

Fanti, M. P., A. M. Mangini, M. Dotoli, and W. Ukovich. 2013. “A Three-Level Strategy for the Design and Performance Evaluation of Hospital Departments.” *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 43 (4): 742–56. https://doi.org/10.1109/TSMCA.2012.2217319.

Gara Miranda Valladares, Jésica De Armas Adrián, and Coromoto León Hernández. 2012. “Problemas de corte: métodos exactos y aproximados para formulaciones mono y multi-objetivo,” 261

Guerriero, Francesca, and Rosita Guido. 2011. “Operational Research in the Management of the Operating Theatre: A Survey.” *Health Care Management Science* 14 (1): 89–114. https://doi.org/10.1007/s10729-010-9143-6.

Guido, Rosita, and Domenico Conforti. 2017. “A Hybrid Genetic Approach for Solving an Integrated Multi-Objective Operating Room Planning and Scheduling Problem.” *Computers & Operations Research* 87 (November): 270–82. https://doi.org/10.1016/j.cor.2016.11.009.

Hernández, Germán Enrique Campos, Diego Ramón Espinosa Casallas, Pedro Antonio Gutiérrez Leguízamo, and Francisco Javier Martínez Cadavid. n.d. “Televisión Digital en Colombia: Posibilidad para diseñar aplicativos interactivos” 10 (2): 7.

Holm, Lene Berge, Hilde Lurås, and Fredrik A. Dahl. 2013. “Improving Hospital Bed Utilisation through Simulation and Optimisation.” *International Journal of Medical Informatics* 82 (2): 80–89. https://doi.org/10.1016/j.ijmedinf.2012.05.006.

“ISO 13053-1, Quantitative Methods in Process Improvement — Six Sigma — Part 1: DMAIC Methodology.” 2011. 2011. https://www.iso.org/obp/ui/#iso:std:iso:13053:-1:ed-1:v1:en.

Li, Xiangyong, N. Rafaliya, M. Fazle Baki, and Ben A. Chaouch. 2017. “Scheduling Elective Surgeries: The Tradeoff among Bed Capacity, Waiting Patients and Operating Room Utilization Using Goal Programming.” *Health Care Management Science* 20 (1): 33–54. https://doi.org/10.1007/s10729-015-9334-2.

Marynissen, Joren, and Erik Demeulemeester. 2016. “Literature Review on Integrated Hospital Scheduling Problems.”

Neyshabouri, Saba. 2016. “Two-Stage Robust Optimization with Applications in Health Care and Combinatorial Optimization.” PhD Thesis, George Mason University.

Oostrum, Jeroen M. van, Eelco Bredenhoff, and Erwin W. Hans. 2010. “Suitability and Managerial Implications of a Master Surgical Scheduling Approach.” *Annals of Operations Research* 178 (1): 91–104. https://doi.org/10.1007/s10479-009-0619-z.

Penn, M. L., C. N. Potts, and P. R. Harper. 2017. “Multiple Criteria Mixed-Integer Programming for Incorporating Multiple Factors into the Development of Master Operating Theatre Timetables.” *European Journal of Operational Research* 262 (1): 194–206. https://doi.org/10.1016/j.ejor.2017.03.065.

Schmidt, Robert, Sandra Geisler, and Cord Spreckelsen. 2013. “Decision Support for Hospital Bed Management Using Adaptable Individual Length of Stay Estimations and Shared Resources.” *BMC Medical Informatics and Decision Making* 13 (1): 3.

Siciliani, Luigi, and Jeremy Hurst. 2005. “Tackling Excessive Waiting Times for Elective Surgery: A Comparative Analysis of Policies in 12 OECD Countries.” *Health Policy* 72 (2): 201–215.

Sivanandam, S. N., and S. N. Deepa. 2007. *Introduction to Genetic Algorithms*. Berlin ; New York: Springer.

Spratt, Belinda, and Erhan Kozan. 2016. “Waiting List Management through Master Surgical Schedules: A Case Study.” *Operations Research for Health Care* 10 (September): 49–64. https://doi.org/10.1016/j.orhc.2016.07.002.

Suryani, Erma, Shuo-Yan Chou, Rudi Hartono, and Chih-Hsien Chen. 2010. “Demand Scenario Analysis and Planned Capacity Expansion: A System Dynamics Framework.” *Simulation Modelling Practice and Theory* 18 (6): 732–51. https://doi.org/10.1016/j.simpat.2010.01.013.

Vardhaman Mahaveer Open University. 2014. “Quantitative Techniques.”

Wetzstein, Branimir, Zhilei Ma, and Frank Leymann. 2008. “Towards Measuring Key Performance Indicators of Semantic Business Processes.” In *Business Information Systems*, edited by Witold Abramowicz and Dieter Fensel, 7:227–38. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-79396-0_20.