Applicability of Advanced Planning and Scheduling on Surgical Blocks

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ABSTRACT

An assessment of the suitability of Advanced Planning and Scheduling software on operating rooms and materials centre is carried out. From data gathering and process mapping a scheduling system is implemented and compared to a private hospital's approach and information system. A method for compromising schedule assertiveness and productivity is proposed and tested on a simulation setting. Final remarks contend that Advanced Planning and Scheduling is a viable tool for surgical block scheduling on the studied hospital and may improve synchronicity with materials centre, sophisticate rescheduling and enable scenario comparison through scheduling simulation.

Key words: *Surgery scheduling. Advanced Planning and Scheduling. Surgery Length-of-Stay. Lognormal curve. Surgery service levels.*

1 INTRODUCTION

As operational costs grow faster than budget, it is increasingly harder for clinics to manage capacity by means of acquiring new equipment, expanding infrastructure and hiring personnel. In that scenario, improving operational efficiency is a compelling alternative to further harness the potential of existing facilities.

Operating Room (OR) is a service critical to many hospitals. A survey (JACKSON, 2002) was carried out among over 200 healthcare executives. The result showed that over 60% of the respondents believed that OR only accounts for 20 to 40% of total revenue. Whereas the actual percentage that OR contributes is 68% (Jackson, 2002). Decision regarding the best use of scarce resources can become increasingly complex as situation worsens: greater disease incidence, poorer healthcare system infrastructure and other societal factors impose severe constraints on decision-makers, who must compromise conflicting objectives such as reducing overtime meanwhile increasing service levels (GRIFFIN, KESKINOCAK and SWANN, 2013). Such context draws attention to analytical tools which enable to frame the complex nature of healthcare operations. The present article focuses on the use of Advanced Planning and Scheduling (APS) systems to tackle this problem. APICS (2008) describes APS as a software that employs advanced mathematical algorithms to perform optimization a simulation on finite capacity scheduling, sourcing, capital planning, forecasting and demand management. These techniques simultaneously take a range of constraints and business rules into account to provide real-time planning and scheduling decision support, available-to-promise capabilities.

Hans et al (2011) proposes a healthcare planning and control hierarchical framework which split decision-making into four levels: strategic level, tactical level, operational level, as well as offline and online operational level. The strategic level addresses dimensioning issues such scale of ORs, instruments and personnel, as well as which surgeries to offer and to which extent demand should be served. The Tactical level aggregates several weeks of demand, in which the usual outcome is the OR capacity (in number of days) each specialty gets throughout the planning horizon. The operational level is split in two: the Offline operational level, which encompasses sequencing, rostering of personnel and reservation of resources for add-on surgeries so as to avoid critical resource conflicts (instrument sets, surgeons etc), and the Online operational level, which involves monitoring and immediate decision-making. APS systems applied to OR may encompass all offline operational level decision-making, aiming to ease the burden of the online operational level.

The output of APS is a list of information as to surgeries, like which surgeries to be performed; where; and when. That enables schedules to stay within constrains whilst pursing particular goals. Demeulemeester et al. (2013) argue the most frequent objectives in literature are related to utilization, waiting time, preference (e.g. allocating specific surgeons to their patients), finance (e.g. cash flow improvements related to better material control), make-span, and no-show rates.

Due to improper scheduling, OR professionals may be subject to stay idle and precious resources such as working hours of nurses, anaesthetists and instrumentalists may be wasted (STEPANIAK et al., 2009). An effective scheduling is capable of reducing wastes, patient waiting times and improve the overall quality of care provided (HALL, 2012). Research shows that surgical delays represent an important determinant in customer satisfaction throughout the continuum that precedes and succeeds care provisioning (TARAZI et al, 1998). There is strong evidence that delays in elective surgery may affect patient satisfaction more than issues relating to the anaesthetics phase itself (BROWN et al, 1997). Beyond satisfaction, surgery delays connected to no-shows, timetable collision and poor scheduling can impact on the final result of elective surgeries (REASON et al., 1995). Based on the time it takes to finish a schedule and on its quality, actual adherence is usually low (BEAULIEU et al. 2000). Suggested start times and resource allocation are often unrealistic, demanding several adjustments on the operational level. Hence, the main goal in operations management is to identify and fight sources of variation (TENNANT, 2002).

This article is structured as follows. Section 2 contains the References, where fundamental concepts in Advanced Planning and Scheduling (APS) are presented, followed by the main contributions in OR Scheduling literature. Section 3 presents the Methodological Procedures, where the organization targeted by the study, relevant taxonomy, the main inputs and outputs (data, processes) expected and APS tools are described. Section 4 holds Results and Discussion, in which the modelling process is described in detail, followed by critical analysis of key performance indicators. The remaining sections include a summary to the results obtained and conclusion.

2 LITERATURE REVIEW

Delays on operatory and pre-operatory surgical procedures are shown to affect customer satisfaction to a greater extent than intra-anaesthetic issues (STEPANIAK et al., 2009). Surgery delays due to cancelling, timetable collision and poor scheduling may even impact the final outcome of elective surgeries (REASON et al., 1995).

Based on the time it takes to assemble schedules and on their low quality, once ready, evidence indicates that suitability of surgical schedules is low (the order of activities and dates determined on scheduling may show themselves unrealistic and many compromises are carried out on the operational level) (CARTER et al., 2001). Bearing that in mind Deming argues that the true enemy of quality is process variability. Hence, a scheduling process capable of reducing variability may improve patient flow and result in a more evened and predictable workload.

2.2 OR scheduling decision making taxonomy

Classic decision making taxonomy (ANTHONY, 1965) segments the decision process in strategic, tactical and operational. Such approach may as well be applied to healthcare. On the strategic level, structural and organizational identity (mission, vision and values) decisions are identified. They tackle the dimensioning and development of a healthcare system.

The operational level, such as in manufacturing, is better framed if one distinguishes between scheduling and activity. The offline operational level encompasses short-term decision-making, such as specialty selection, surgery sequencing, nursery team dimensioning and inventory replenishment. The online operational level, on its turn, is a reactive decision-making frame, where all uncertainties materialize. Activity on this level typically includes triage, emergency case scheduling, emergent equipment sterilization and dealing with paperwork complications.

2.3 OR scheduling literature overview

Demeulemeester et al. (2013) present a literature review encompassing ten years of research. They highlight the distinction between advanced scheduling, allocation scheduling and external resource scheduling. Advanced scheduling stands for the process of fixing a surgery date for a patient. Allocation scheduling consists on the OR and the starting time of the procedure on the specific day of surgery. External resource scheduling is defined as the process of identifying and reserving all resources external to the surgical suite necessary to ensure appropriate care for a patient before and after surgery. The present article is concerned about both advanced and allocation scheduling alongside internal resource pegging, meaning the sufficient assignment of resources directly related to the surgical procedure.

Two major patient classes are mentioned in literature (DEMEULEMEESTER et al., 2013). Elective patients relate to patients for whom the surgery can be planned in advance. Nonelective patients include emergencies, when the surgery has to be carried out immediately, and an urgency if it may be postponed. Hans and Vanberkel (2012) address the strategic decision of whether it makes sense to keep exclusive emergency operating theatres. Based on two policies (Figure 1), the authors conduct a discrete-event simulation study based on the setting of the Dutch hospital Erasmus DC. At the time, the location presented 12 operating rooms, all able to take elective cases. Emergency surgeries however required special equipment, hence adding an economic dimension to the problem. Besides, due to the stochastic nature of emergency surgery demand, the authors argue that capacity allocation is not trivial. Initially, two policies are compared. The first assigns one OR specifically for emergency cases and the second assigns a minor percentage of each room's time to emergency. The results show that the latter outperforms the former in all the metrics observed.

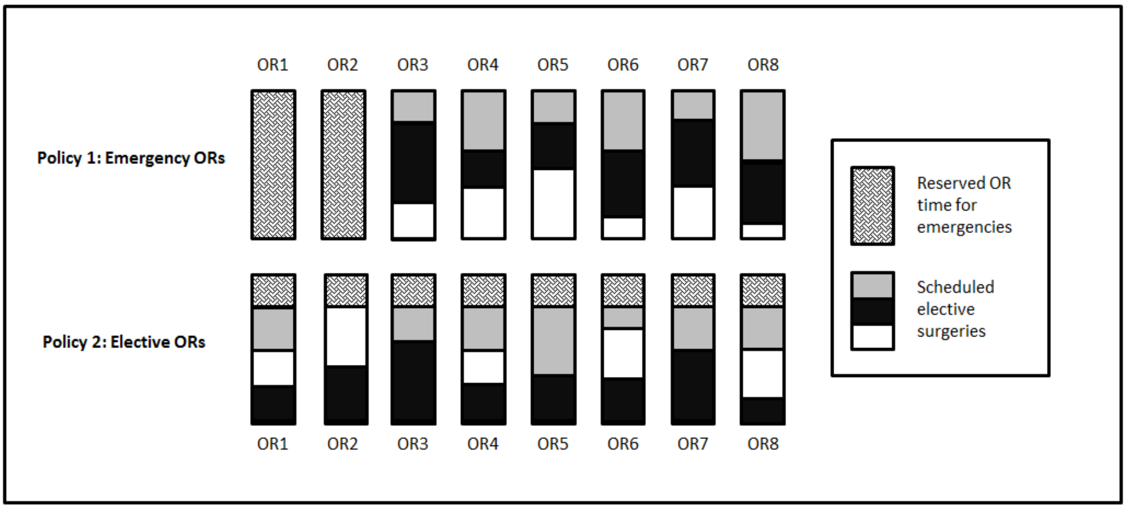

Figure 1 – Comparison of two surgery scheduling policies. Source: Hans and Vanberkel (2012).

Performance metrics analysed in literature are increasingly multi-criterial (DEMEULEMEESTER et al., 2013). Such phenomenon may be linked to the conflicting nature of management, healthcare professionals and customer objectives. A common metric is patient throughput time, since long queues up to surgery start and delay on the very surgery are chronic issues in healthcare.

2.4 Length-of-stay modelling

Story (2011) questions the way in which variability has been considered in healthcare planning. Adoption of simple averages instead of more sophisticated data set representation tools, for instance, candlestick charts and histograms, leads to distortions in scenario analysis. The author proposes the use of a Length of Stay (LOS) histogram (Figure 2). A long tail is perceptible in the distribution, agreeing with the premise that the number of patients with high LOS decreases as LOS grows. That may be explained, according to the author, by mentally challenged patients, intoxicated patients, patients with abdominal pain, patients waiting for a bed and other situations of delay. Ideally, we would like to eliminate such long tail so as to approach a normal curve, with low variance, a pattern characteristic to high precision industrial settings. Many authors defend the idea that histograms showing long tails on the right hand side and skewed normal distribution to the left resemble lognormal distributions. Strum, May and Vargas (2000) suggest that, in the case of surgery practices, it is often found that the lognormal distribution provides a good fit for surgery durations. Law (2007) states that the lognormal distribution may be employed to model duration. They use it to denote "Time to perform some task; quantities that are the product of a large number of other quantities (by virtue of central limit theorem); used as a rough model in the absence of data."

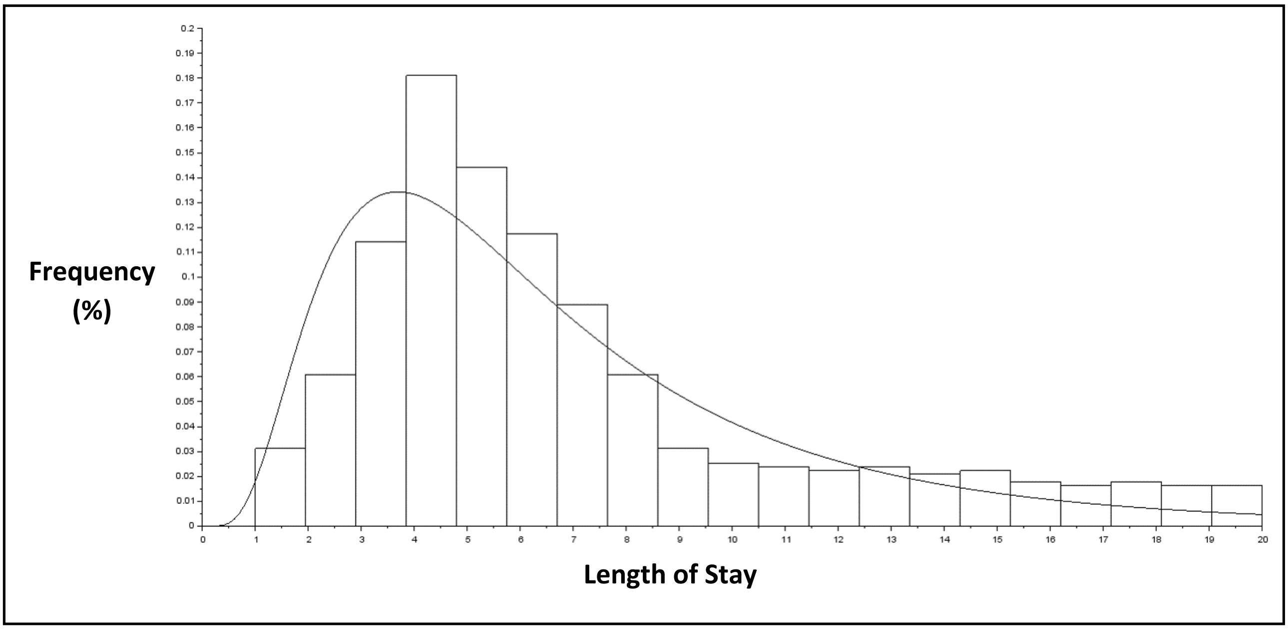

Figure 2 – Histogram and lognormal model of an example Length of Stay (LOS) distribution. Source: Story (2011).

Once a suitable probability distribution considered fit for the phenomenon being modelled, a number of statistical tools become available. For example, the cumulative distribution function (CDF) may be used to calculate what percentage of surgeries are expected to terminate in a given time. That percentage is defined as the service level and may also be employed the other way around, for instance, so as to reach specific service levels it is possible to determine what length of time should be fixed.

2.5 OR scheduling techniques

From the perspective of modelling, operating room scheduling presents original contribution. Pinedo (2008) points that the first works to emerge on the fields of operations research and industrial engineering showed up on the 50's and held results by W.E. Smith and S.M. Johnson. On the upcoming decades, the most prominent contributions were related to taxonomy in the context of the theory of complexity, introduction of stochastic scheduling models and lastly the spread of computational resources on manufacturing sites that brought scheduling to the realm of everyday activities. However, from the context of healthcare a whole new scheduling came into being. Hans and Vanberkel (2012) consider a scenario in which emergency surgeries are scheduled on the same room as elective surgeries. On this scenario, emergency patients are served once an elective surgery ends. These elective surgery completion times are denoted as "break-in-moments" (BIMs). When those BIMs are evenly distributed, surgery waiting time is reduced. That may be reached by scheduling of OR in such a way that the greatest interval between two consecutive BIMs be reduced. The authors prove that the scheduling problem is NP-hard and suggest a series of methods to address it, both exact and based on heuristics. A graphical representation of the problem is presented on Figure 3.

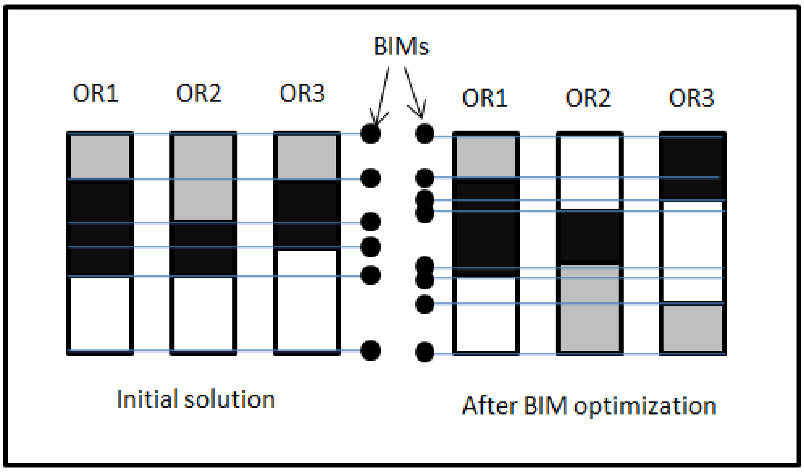

Figure 3 – Example BIM optimization. Source: Hans and Vanberkel (2012).

Denton, Viapiano and Vogl (2007) show that sequencing decisions produce a high impact in the final schedule performance, especially when overtime and patient waiting costs are similar. In addition, the authors demonstrate that simple sequencing heuristics, such as surgery of lesser variance preceding the ones with higher variance, may result in practical gain. Scheduling patients with great variability of their procedure or inclined to no-showing later on in the day may lead to lower expected costs. On the context of multiple procedure scheduling bases on duration, the Shortest Processing Time (SPT) heuristic has been show prominent in comparison to other heuristics such as LPT (Longest Processing Time), procedure variation and procedures' coefficient of variation.

Rosseti, Buyurgan and Pohl (2012) describe the healthcare supply logistics from the technological and managerial point of view. They contextualize the problem via a blood supply chain case study. Blood logistics presents formidable technical challenges. Aside from type compatibility issues, blood also poses the challenge of consisting of several different Stock Keeping Units (SKUs) which compete for the same resource. A blood bag may either be employed *in natura* or be broken down to components such as plasma, platelets and red blood cells. Additionally, as the study suggests, short shelf lives (35 days for adult red blood cells, 14 days for irradiated red blood cells and 5 days for platelets) impose extra burden of complexity. Lastly, the authors carry out a simulation study and arrive to the conclusion that small changes may increase system performance, for instance, inventory reduction, better material handling, enabling two deliveries per week instead of one and adoption of FIFO rules.

Griffin, Keskinocak and Swann (2013) note that decisions related to better use of scarce results may become very complex. As a result, trade-offs associated to resource allocation in developing countries promotes the opportunity of employing analytical techniques. The authors propose an optimization model and decision support tool on a malaria prevention campaign. Authors demonstrate through numerical experiments that the impact of both good and bad allocation decisions is high.

2.6 APS functions and former applications

APICS (2008) conceptualizes APS as a modular set of applications, a manager's toolset for extended supply chain management (SCM). APS creates a schedule for the supply chain as a whole and each of its subsets such as factories. The schedule contains all orders and operations in an optimized sequence that can be realistically scheduled at each work center. The start and finish times for all orders are listed in their proper sequence. APS is a smart scheduler and responds to situations where required materials, labor and/or plant capacity are insufficient for demand such as by setting priorities by importance of the customer or order profitability.

As depicted in Figure 4, APS functions branch in three different aspects. In this study, a narrower definition of APS is, mainly focused on the Production function. Material flow and purchasing practices were in light of scheduling, mainly concerning the impacts of material shortages to surgical delays.

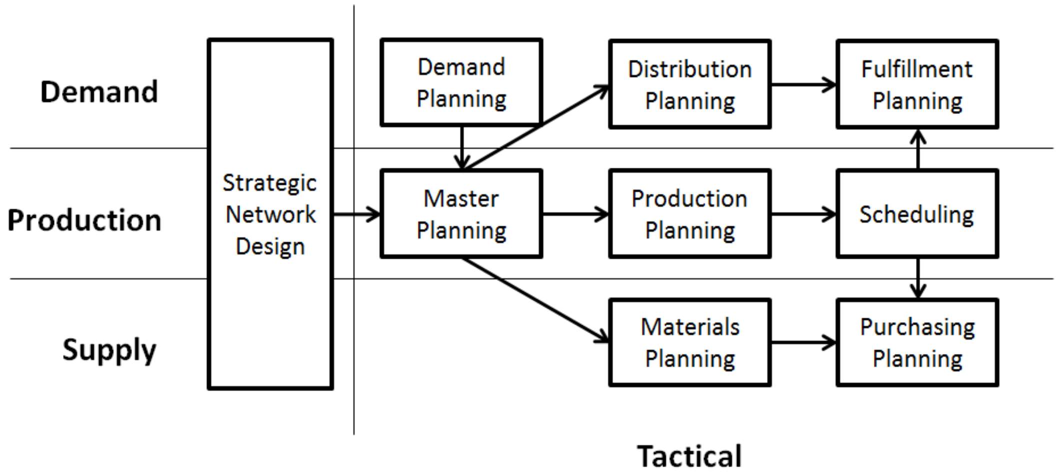

Figure 4 – APS functions. Source: APICS (2008).

Voudouris et al. (2006) briefly contrast the history of IT tools adoption on manufacturing and services, arguing productivity-driven IT innovations traditionally target manufacturing. The authors propose an APS framework specifically for services, entitled Field Optimisation Service (FOS) and attempt to provide evidence for the adequacy of the framework for “field services” such as construction sites and claim applicability to office-like environments like call centres. The framework follows APICS’ definition of APS (2008) and addresses demand planning, supply network planning and global capable-to-promise proprietary systems.

3 METHOD

3.1 Research method

The proposed research was of applied nature, namely an explanatory case study seeking to assess the adequacy of APS systems to healthcare settings and to provide managers with a quantitative framework for decision making. Based on the collected data, a scheduling simulation model was deployed to assess room for improvement in current scheduling practices. The model findings was contrasted with current scheduling policies and performance metrics.

3.2 Study setting

The company presented in this article is a private hospital situated in southern Brazil. The organization is composed of two units located in an urban context. The main unit supports all sorts of medical services, hospitalization, ambulatory and emergency. The complementary unit offers appointments, medical examinations and support services.

Currently, the company presents over 3000 workers and has a year net worth of R$ 400 million. Classified as a medical service organization, their structure encompasses, among other facilities, emergency, surgical block and obstetrics. According to top management, surgical activities stand for the main source of revenue, an aspect that led to a major upgrade through the establishment of a dedicated plastic surgery area. From the viewpoint of surgery execution, capacity is constrained by availability of qualified personnel (surgeons, anaesthetists, technicians), tools (laparoscopy tower, lasers, x-ray), materials (medications, anaesthetics) and both recovery and operating rooms.

The choice for the subject hospital was due to the interest shown on early conversations on refining of the scheduling process. Another proponent hospital, already undergoing a consultancy process on scheduling, declined the offer arguing sharing data for the study was not appropriate at the time.

3.3 Relevance

The main contribution intended with this study was to assess new ways of bringing together higher-end, scheduling staff to operational technicians responsible for the ongoing challenge of surgical block management. Collaboration and shared decision making in OR scheduling is non-trivial: scheduling staff may have to decide for whether to assign certain surgery to specific room on a particular time regardless of their understanding of constraints such as availability of specialized equipment, material flow (availability of reusable devices and medications), sequence-dependent changeover (how the transition from one kind of surgery to another impacts setup and clean-up) and detailed on-site patient experience (complaints such as meals releasing smell among fasting, recovery patients are hardly ever regarded as a scheduling matter). Figure 5 depicts how an effective scheduling system are reliant on functions other than the information system and collaboration across areas is vital.

The main question addressed by the present study was whether APS systems perform well in healthcare settings. Successful adequacy to industrial settings may not immediately extrapolate to healthcare operations. An aspect critical to the scheduling frameworks is sufficient tracking of the sources of variability, especially with regard to processing times. This study modelled and assessed the validity of length-of-stay processes by means of lognormal distribution estimation.

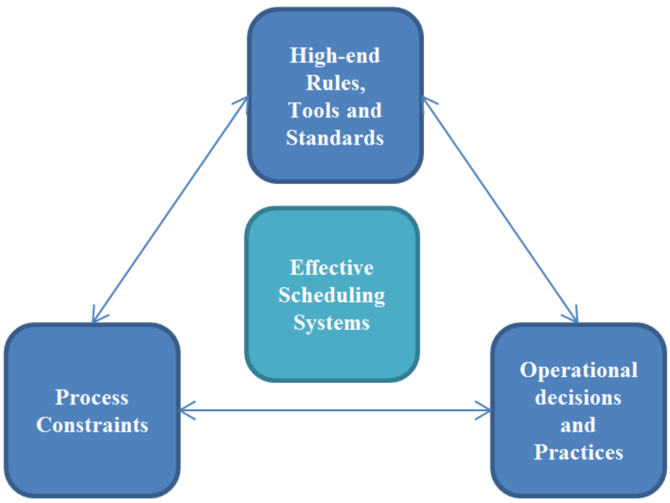

Figure 5 – Main influences on scheduling system performance. APS systems seek to bridge the gap between high-end scheduling and operational reality through the realization of process constraints. Source: conceived by the author.

3.4 Scope

The current work involved the development of a feasible scheduling model, in tune to the hospital’s reality. An actual APS project would require the software to be fully integrated to the transactional database, extended employee training and compilation of data and information currently unavailable. For simulation purposes, assumptions were made regarding availability of resources that would otherwise require counting, such as material stock levels, and measurement, such as operational processing times. The scheduling model prioritized the new proposed models whilst attempting to respect current business rules.

Despite interaction among areas, since patients move from the surgical block to admission and vice-versa, both are independently managed. Each area answers for their exclusive database, organogram and goals. Due to time and resources constraints, this study was limited to the surgical block. Throughout interviews and data gathering, business rules applied on the surgical block were properly noted and applied to the model.

Emergency surgeries are not directly subject to the scheduling process of a surgical block, since demand emerges on the execution phase and resources are promptly allocated. In spite of that, emergency surgeries are critical to maintain healthy levels of utilization and must be taken into consideration. Emergency demand peaks may compromise material allocation, human and technological resources, as well as rendering schedules unattainable. Demand for elective and emergency surgeries on the hospital analysed in this study are conflicting and slacks must be set in order to ensure service levels. This study intended to determine current slacks pertaining scheduling business rules and to analyse them on the context of the new scheduling method, suggesting improvements made available by the new methodology.

3.5 Limitations

Commercial APS systems often employ algorithms based on heuristics due to the computational complexity posed by scheduling problems. Such procedures do not guarantee strictly optimal resource allocation. Instead of focusing on the goal of a perfect schedule, business rather prefer a practical, feasible scheduling system that may be quickly deployed. Besides the inability to reach for the global optima, some algorithms resort to randomization and results may not be reproducible.

Operational scheduling is heavily reliant on process stability and control. A successful implementation of finite scheduling systems presupposes the following aspects.

i) Workforce and resources have to consume precise amounts of input materials defined on the bill of materials. The greater the gap between scheduling and execution, the greater the stock counting costs.

ii) Processes have to be under control to the point where one can ensure the sequence (neither anticipate nor postpone activities disregard the schedule) and the start times for activities be met. If such assumptions do no not hold, finite scheduling semi-optimization is not met. Staff then may abandon the schedule altogether and carry out production at will.

iii) Cycle times, storage capacity, workforce availability, material constraints, routings and additional database inputs have to be diligently updated and be sufficiently sound to the execution setting. APS demands deep knowledge and parameterization, however many companies fall short of data on the beginning of software deployment.

iv) Process execution inputs, a traditionally time-consuming task, is critical to keep APS up-to-date. Tasks of this sort are of a repetitive nature and will possibly be overlooked without proper motivation for the workforce. Conceptually, APS bound to work “in the past”, as there is no real-time integration for most solutions.

In addition to the aforementioned assumptions, the commercial APS software adopted in this study also face the following challenges:

There is no native support for material flow in midst of a task. The subject hospital has recently began to try the practice of collecting material for sterilization in the middle of the surgery to improve material flow. Moreover, the process is of difficult standardization, since it is not known beforehand what items, in which quantities and how early such intermediate transfers will take place, therefore not easily schedulable.

Random probability variables such as lognormal durations are not directly supported. Every scheduled task requires a single, deterministic value for its duration. Stochastic scheduling may result in increased computational expense due to the increase of possible outcomes and no widespread commercial scheduling solution supports the required heuristics. On this study, a small scenario generation was employed on the fashion of scenario-based stochastic scheduling algorithms, however with as few as one hundred (100) instances.

3.6 Data collection and modelling

APS systems follow a paradigm of translating operational reality to model configurations. Figure 6 highlights elements in this process. As a first step, information gathering is required to understand the surgical block and its scheduling needs. From that a knowledge representation phase starts, where data and information obtained are framed in descriptive tools. Effective development comes third, in which APS features were deployed both for scheduling and performance reports. In the end a fine tuning of the model is required, when the hospital team expertise assessed the model and made sure the model was sound.

A series of ten directed meetings was carried out with representatives of hospital coordination, process division, surgical block and information technology. Major technical challenges such as large database extraction, scheduling rules formulation and the problem of deterministic process duration were promptly addressed. Process mapping were performed through narrative and process schematics.

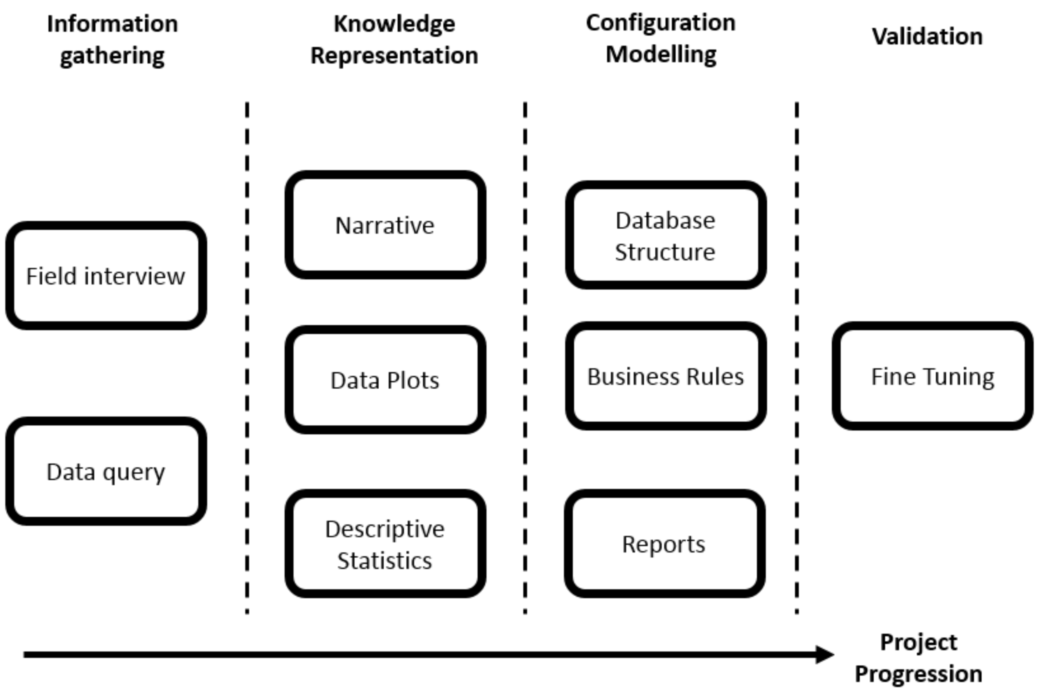

Figure 6 – Configuration process. Source: conceived by the author

Information gathering was segmented in two steps. The first was a field interview, where visits to the operational level *in loco* aim to clarify the nature of procedures and resources key to the surgery block routine. Such procedure was carried out alongside a technician directly involved in operating room activities instead of higher-end planning and strategy staff. Following preliminary meetings, a session of question and answers took place alongside the scheduling staff in order to identify elements crucial to the modelling and understanding of the process. The second step was database extraction. Reliance on extensive historical data allowed for objective analysis and better use of information resources often not explored in depth by organizations. The procedure consisted of a single query to the hospital's database, omitting private information that might otherwise identify patients and staff. Table 1 compiles the content covered in database extraction and meetings. Such activities occurred in parallel to the establishment of theoretical background, aiming towards extra room for innovation and problem solving at the latter stage of this study.

Table 1 – Modelling and configuration database and operational input. Source: conceived by the author.

Table	Description	Fields
Resource Groups	Types of rooms and beds	Code, Description, Resource
Resources	Individual rooms and beds belonging to Resource Groups	Code, Description
Bill of Materials	List of expendable kits and items	BoM Level, Code, Description, Quantity
Surgeries	List of surgeries and their activities	Code, Description, Triage Time, Surgery Time, Setup Time
Schedules	Records of activities	Begin of Triage/Surgery/Recovery, End of Triage/Surgery/Recovery, Surgery,
Constraint Groups	Types of personnel and tools required for a specific activity	Group, Constraint
Constraints	Unique personnel and tools belonging to Constraint Groups	Constraint, Begin of Shift, End of Shift, Quantity on Shift

From the development of the model and the historical data, the schedule effectively followed by the surgical block was represented. Sources of variability, database inconsistencies and further issues detrimental to model realism were discussed alongside the personnel responsible for planning and execution on the surgical block. Incoherent time measurements, unfeasible schedules and any issues which could not be resolved by arbitration and consensus were removed. Discussion meetings carried out along the project provided an atmosphere for the errors to be properly pointed out.

3.7 Analysis and outcomes

Once model configuration was deployed, process analysis started, as presented in Figure 7. Scenario generation provided simulations of scheduling settings. In this step, many situations may be tested: from the current average workload, to a situation of high system distress (e.g. a week of unexpected high demand of traumatic emergency surgeries), to quantifiable process improvements and changes the hospital were willing to analyse.

Analysis were carried out by means of Key Process Indicators (KPIs) such as process ruptures and makespan. Conclusions were then be drawn through observation and pattern-seeking paradigms such as emergent phenomena, from complexity systems theory. The final outcome is the "Project Overview Report and Results" deliverable to be shared with hospital staff and related researchers.

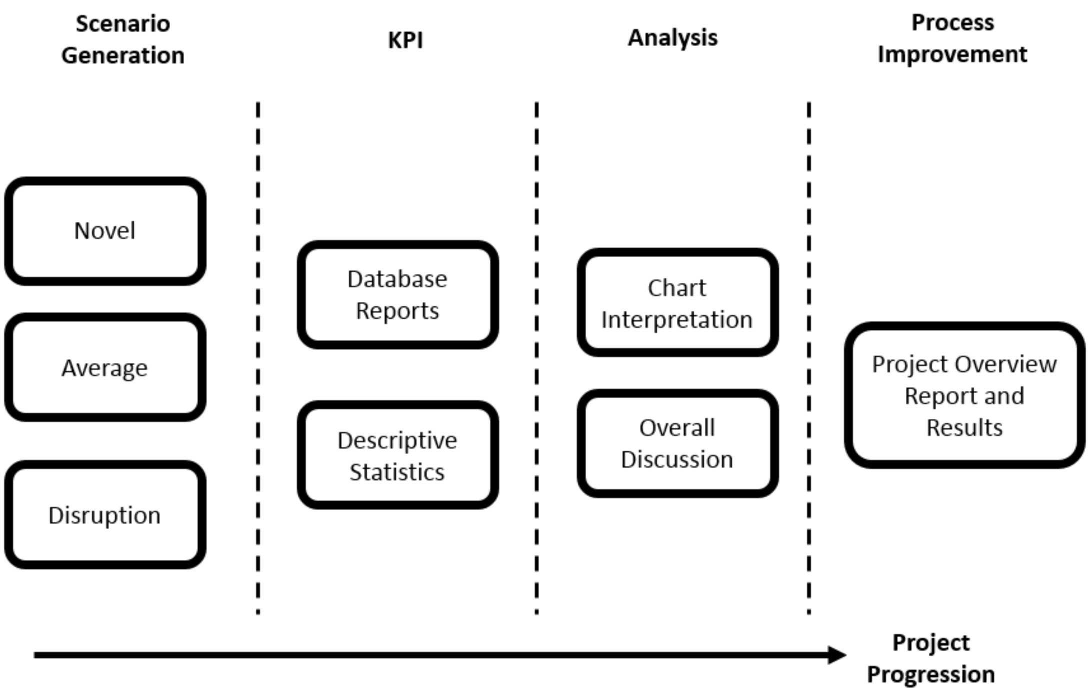

Figure 7 – Project Progression. Source: conceived by the author.

4 RESULTS

4.1 Overall Setting

The surgical block is comprised of three triage resources, twelve heterogeneous operating rooms and a varying pool of recovery beds that average up to twenty beds. Currently, over five thousand different types of surgeries are supported. Surgery allocation may be constrained by availability of specialized tooling (not all equipment are present in every room). An average of thirty technicians and directly involved employees alternate between three working shifts.

Figure 9 presents an overview of the surgical block and the standard route of elective patients along the process; also, a specific area for material handling is depicted. On step one, incoming patients go through triage on either of two simple triage room or a "pre-anaesthetic" fully equipped room, depending on his or her health state. Next, all patients must be transferred to a waiting room where final paperwork is reviewed and the patient waits until the surgery team is ready. Then surgery is carried out in either of the twelve rooms and, finally, the patient is moved to the recovery area.

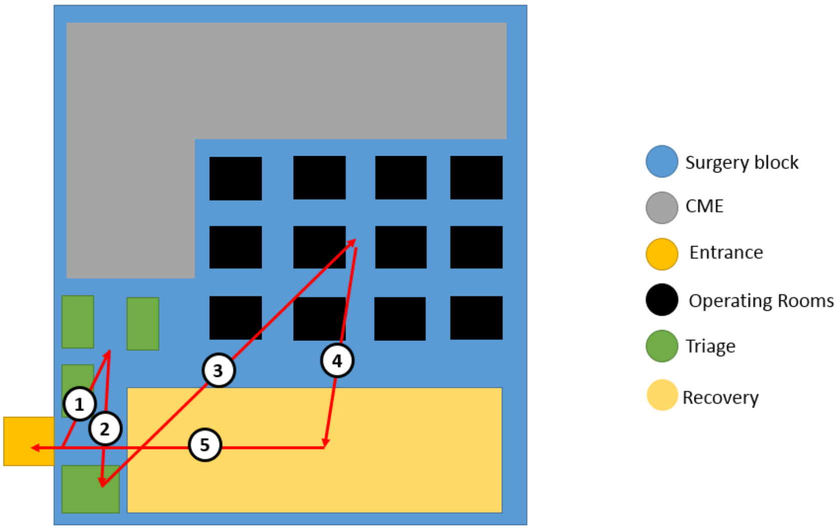

Figure 9 – Patient flow. Source: conceived by the author.

The recovery area is segmented in rooms specific to patient groups. Figure 10 depicts a main hall for both adult men and women, an exclusive child recovery room (which is converted to serve all ages depending on the time of day). The yellow areas represent four special rooms for patients that require extra attention. Lastly, the brown figure represents a separate elevator that gives access to Intensive Care Units and the orange figure is an area managed by an external organization.

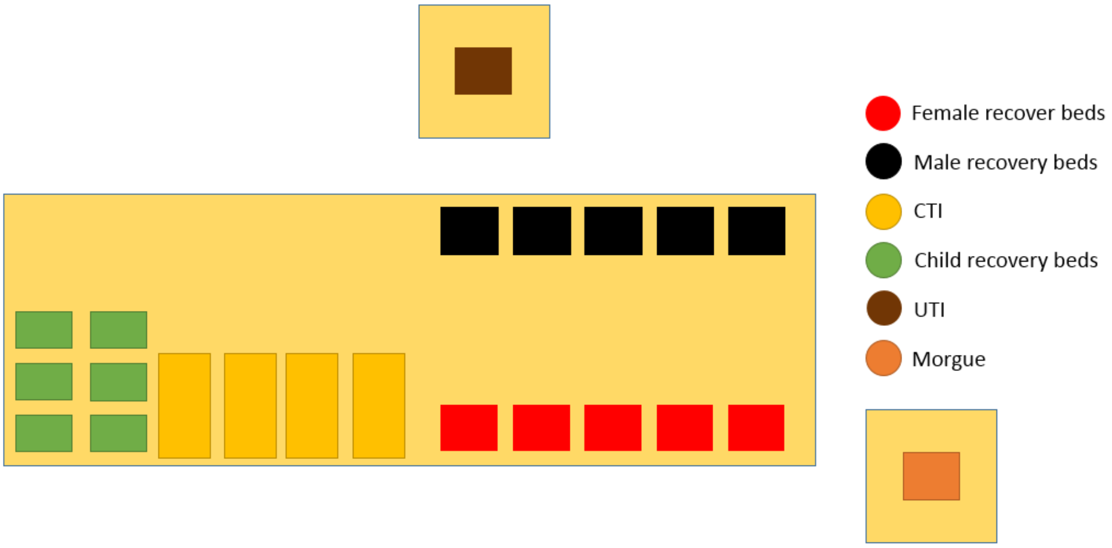

Figure 10 – Patient recovery. Source: conceived by the author.

In addition to patient flow, material flow is critical to surgical block performance. Figure 11 presents the different flows inside the Materials Centre (CME). Steps one through four resemble an assembly line dedicated to cleaning parts. In these steps, different sorts of tools may undergo custom cleaning process, depending on how stiff a decontamination is required. As the materials come dry and are assorted, they are either packed for individual physicians or as global “material kits” which are commonplace to most surgeries. The final step brings together proper tooling and consumables from the pharmacy (medications, bandages etc) on dedicated carts. Also, highly valuable props (special goods) are also brought to their carts, which once ready wait for a call by a technician when a surgery room may already receive the goods for the next surgery.

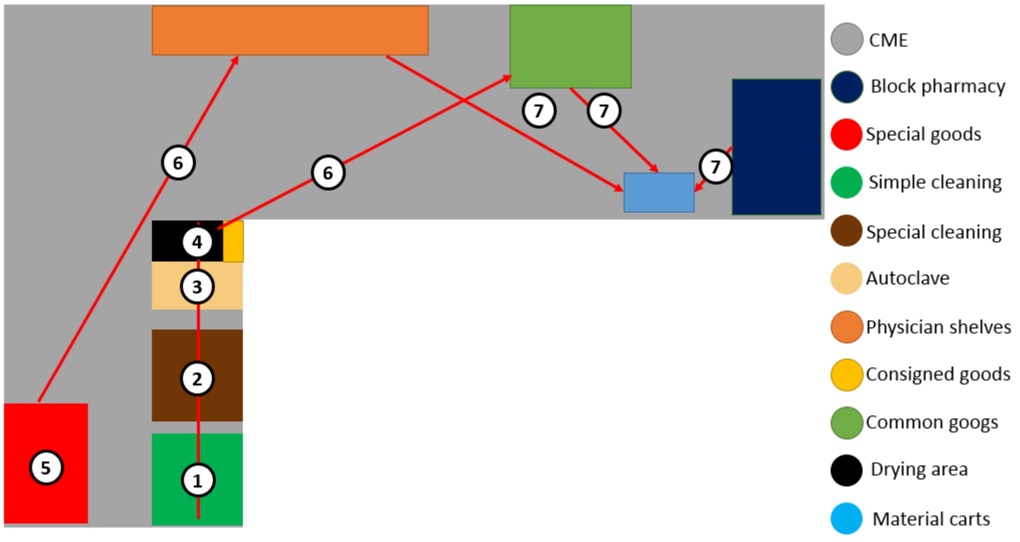

Figure 11 – Material flow. Source: conceived by the author.

4.2 Scheduling process

On the subject hospital, surgical block scheduling begins through a process analogue to a call centre. Circa ninety percent (90%) of surgeries are scheduled by phone and the remainder is personally, by the surgeons. In contrast to a university hospital, surgeons possess greater autonomy to decide for the time of the day at which the surgery takes place. Between sixty (60%) to seventy percent (70%) of surgeries take place in recurrent time slots allotted to specific surgeons. Upcoming surgeries ought to be communicated ten days in advance. Otherwise, the pinned time slot may be reassigned to any other job. The remainder of surgeries are sporadic demands from doctors short of dedicated time slots, urgent surgeries (known 24 to 48 hours in advance) and emergency surgeries (known 12 to 24 hours in advance).

The current information system enables many automated validations on the act of scheduling. Every surgery is allocated manually, however scheduling may be limited according to availability of equipment and boxes, blood, consigned products, imagery, laboratory results and surgeon timetable. A bill of materials provides the initial input to the materials required by the surgery, but it is possible to customize accordingly.

Scheduling rules do not follow specific optimization heuristics. As a general rule, surgeries are scheduled based on a first in, first out (FIFO) discipline subject to availability of resources. The only distinguished high-level preference is for allocation of longer surgeries in the morning. Predetermined timetables and medic-oriented scheduling allows little room for optimization via sophisticated sequencing rules.

Currently, the goals set for the surgical block push the system in opposing directions. One of the goals is to reach twenty two hundred (2200) surgeries per month productivity rate. On its all-time peak productivity, the block was able to process 2170 surgeries in a month. In order to reach for that goal, an average of 90 surgeries per day to be processed is required. The other major goal is to specialize in high complexity surgeries, which are traditionally longer and require greater backstage workload and resource allocation. The block staff agrees that, aside from increasing rough capacity, prominent process improvements is required in order to meet upcoming standards.

4.3 Data overview

The theoretical shape of duration histograms is marked by the presence of Gaussian-like curves skewed to the left and a long tail of extreme data to the right. The histograms in Figure 12 were drawn based on historical data and provide visual evidence supporting Story's theory.

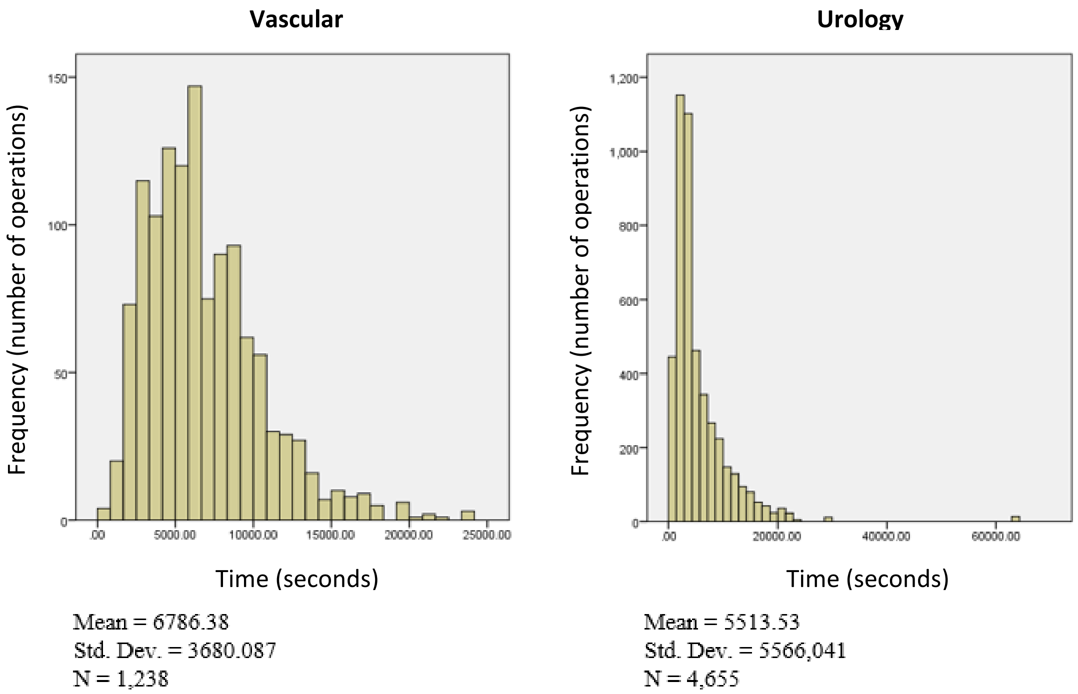

Figure 12 – Duration histogram for Vascular and Urology surgeries.

Choosing values of expected duration for scheduling is a decision critical to synchronicity in surgical block management. Adopting smaller values increases the risk of system disruption and subsequent activities enjoy smaller slack for absorbing variability and may face delay. Higher values mean a greater number of surgeries are completed in the allotted time. However, the resulting planned productivity (measured as the global lead-time) is reduced. Currently, the scheduling staff decides for the time by empirically weighting the mean arithmetic historical duration for a specific surgery and the past performance of individual doctors, when available. Further descriptive statistics such as dispersion and shape metrics are not used. Figure 13 presents the modelling of the processes in Figure 12.

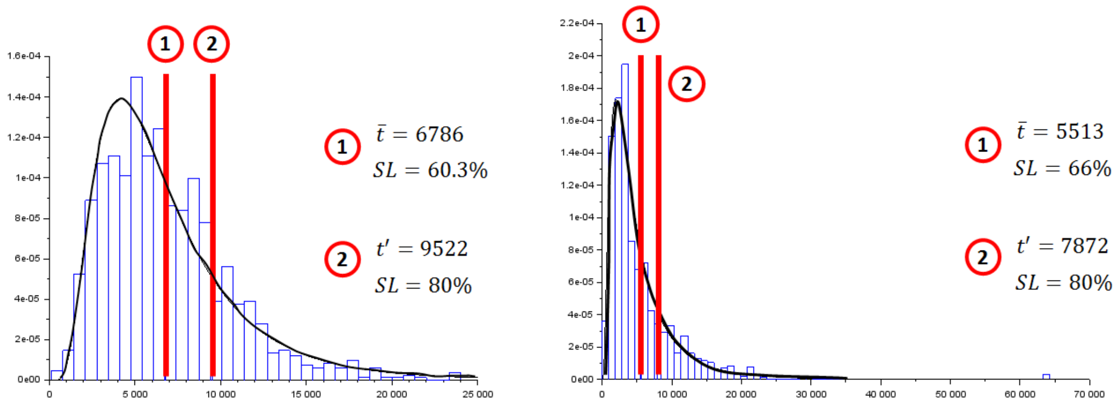

Figure 13 – Lognormal curves for Vascular and Urology surgeries.

4.4 Surgical block model

Scheduling is prepared through a transactional information system and released each morning via printed copies passed down to nurses and technicians. The schedule is comprised of a list of rooms, start times and special equipment assigned for each surgery. Such control sheets are attached to the surgical block main corridor’s wall and are gradually redacted, rearranged or confirmed as events unfold. Changes and controls are handwritten and receive little to no feedback from the information system. Technicians account for information flow throughout pertaining areas such as CME, IT, ambulatory and intensive care.

For simulation purposes, a sample was extracted for scheduling as mentioned in section 4.6. Each instance consisted of three jobs: the surgery itself, room cleaning and patient recovery. The last two were allowed to be processed in parallel, since when a patient leaves for recovery, the room is immediately available for cleansing.

Process durations are routinely registered in the block. On the main database, surgical time is segmented in anaesthetics and surgery. Anaesthetics begins with patient admission on the operating room and terminates in intubation, when surgery begins up to the moment when the patient leaves the room. For scheduling purposes, both durations are aggregated to a single job time. Recovery times are measured as the difference between arrival to a recovery bed and patient transference or dismissal. Cleansing begins when technicians enter the operating room and end when they leave. It is important to highlight that though the room is technically ready after ten to twenty minutes of decontamination and setup, actual slack times between surgeries is around fifty minutes, According to a recent analysis carried out by the block staff, the three main sources for such idleness are delays in medical teams, patient-wise issues and lack of synchronism with CME.

Equipment availability, though varying through time, had its typical value, as communicated by the block staff, assumed for the APS model. In addition, a cleansing staff constraint was set, limited to two teams on working hours and a single team when off-shift. Such personnel constraints are important for the block (if only two teams are available, scheduling the end of 12 surgeries for the same time would result in waiting times), but are not directly managed on the information system.

4.5 CME model

A guided visit to CME was undertook so as to understand the operational constraints and impacts the Scheduling department has on CME activity. The assessment revealed that surgical scheduling is currently carried out with little knowledge of CMEs need for synchronicity and resource scarcity. Whereas some hospitals may face lack of sheer sterilization capacity, on the present hospital it is reported that few spare items account more for replenishment challenges. When asked about how well the APS methodology would fit for the CME section, the person interviewed showed optimism. In contrast to Surgical Block scheduling, CME’s processes are considerably less susceptible to variability. Cycle times consist on machine settings and have to be precise so as to match regulatory standards, whereas surgical durations are a influenced by many human factors.

It was stated on the interview that the hardest challenge in meeting the surgical block's demands is in it being "a mathematical process", i.e. relying on a deterministic methodology on a highly stochastic setting. Surgeries are scheduled base on their average duration and the slack planned for intraday sterilization are nominal cycles, which means they do not give proper account for conditional resource load and system variability. The result is that CME and Surgical Scheduling areas cooperation is often lost and supply-demand relationship quickly erodes to a reactive approach. APS tackles this problem by scheduling both areas as one, ensuring a more refined, viable schedule to be released on the first place. Furthermore, since intraday rescheduling is performed manually, reassigning materials do new sterilization batches may be subject to human error and not account for all due operational constraints, slack times and batch synchronicity requirements. Automation of computational resource constraint validation via APS may speed up the generation of new priorities and schedules.

Figure 14 presents the main work area on the APS application. On the upper part, a Gantt chart of seven surgical rooms are displayed. Job bars representing operation, cleansing and recovery are coloured to differentiate surgeries according to their specialties, from the thirty-six (36) adopted by the hospital. Length of each bar, obtained from the hospital's database, are identical to actual surgeries performed on the block for the given example. The lower part of the figure presents utilization plots for secondary constraints. The green graph depicts allocation of cleansing personnel over time, where for day shifts two teams were allotted, and a single team for night shifts. The blue graph shows the utilization of laparoscopy video towers, a constraint managed by the existing information system.

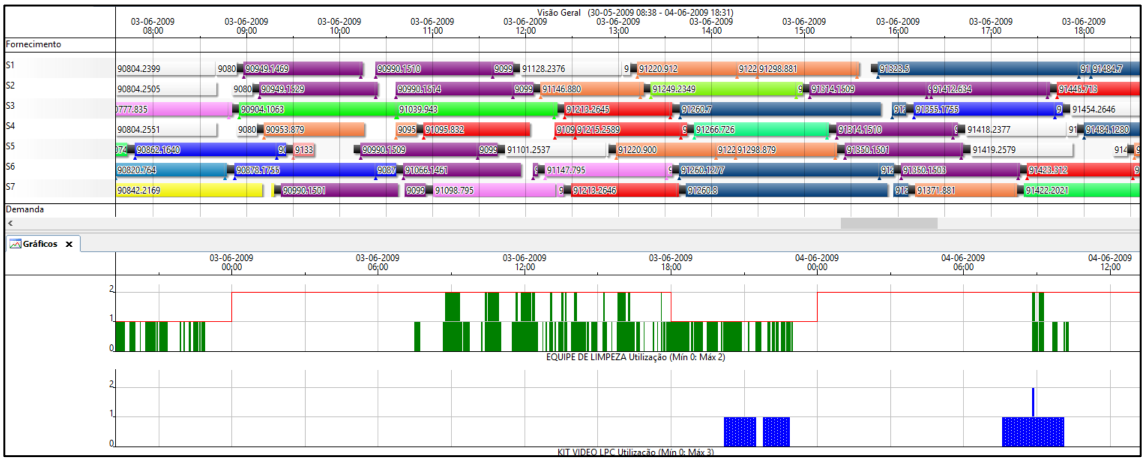

Figure 14 – Gantt chart and constraint plots. Source: conceived by the author.

4.6 A method for compromising slack and productivity

The simulation study conducted on the APS model configured akin to the resources, operational constraints and materials of the surgical block enabled the collection of data presented in Figure 14. A scenario comprised of 445 recorded surgeries out of 50000 provided in the dataset was used in the study. The goal was to assess the impact of different service levels on scheduling disruption and productivity. On the simulation runs service levels between 1% and 81% were tested, a scheduling scenario for each and performance metrics were contrasted with sample data. After 81% service level threshold, surgeries began to exceed the allotted working hours, meaning they would not possibly be scheduled.

The number of ruptures (NoR) stands for the instances where surgeries exceed their allotted time, defined as

$$NoR = \sum_{j=1}^{n} \begin{cases} 1 \; if \; p_j > t_j \\ 0 \; otherwise \end{cases} \qquad (1)$$

where n is the sample size, j are the individual surgeries, p_j are their actual processing times and t_j their allotted time.

Productivity is measured as the sample's *Makespan* for the resulting schedule, defined as

$$Makespan = C_n - S_1 \qquad (2)$$

where n is the sample size, C_n the last job's completion time and $S_1$the first job's start time.

Figure 14 frames the compromise between productivity and assertiveness as a bi-objective optimization problem. Points outside the Pareto front are inappropriate with regard to the analysed criteria. It is noteworthy that the service level corresponding to the t_j employed by the hospital does not belong to the frontier, suggesting that better service levels may be selected based on the productivity goals and acceptable NoR for the surgical block.

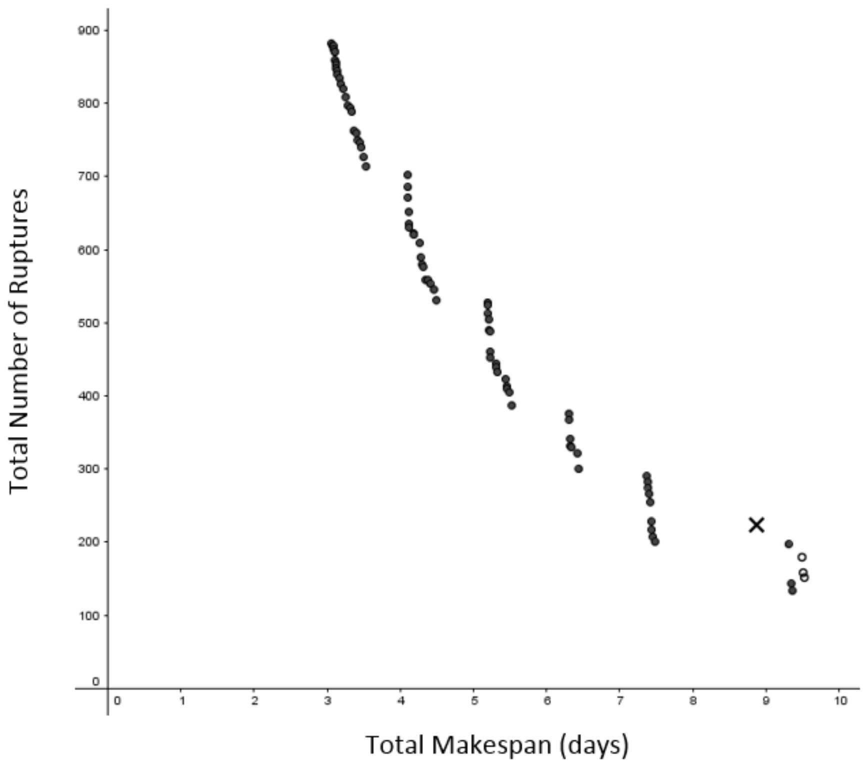

Figure 15 – Pareto front of utilization levels. The grey dots imply service levels in the optimal frontier. Blank dots are suboptimal solutions outside the frontier. Point "X" is the performance of the current method adopted by the hospital. Source: conceived by the author.

4.7 Discussion and results

Table 2 is comprised of aspects in which an APS system would be helpful in comparison to the current system adopted by the hospital. It is important to point out that the highlighted aspects pertain the reality of the studied hospital. Nonetheless, the same principles may apply to similar-sized units with akin business models. Historically, healthcare industry has been lagging behind on adoption of complex information systems to aid operations management. To certain extent, constraint management is still fairly handcrafted, reliant on extensive spreadsheets and physical documentation, prone to human error and time-consuming.

Table 2 – Comparison of current and proposed scheduling processes. Source: conceived by the author.

Aspect	Current	Proposed
Rescheduling	Manual/operational, with little or no information system feedback. Consequences over operational constraints and synchronicity are empirically assessed.	Semi-automated (requires scheduler's input and analysis). Automatic verification and validation of impacts of the new schedule on the availability of equipment, materials and personnel.
Simulation	High-level analysis dependent on simplifying assumptions. Little regard to finer details and operational constraints.	Detailed model of operational constraints and rapid generation of scenarios such as high demand for emergency surgeries or high volume of surgeries that require scarce resources, measuring the impact of acquisition of new equipment and new operational rules, such as de-constraining dedicated rooms and new scheduling criteria.
CME interaction	Surgical scheduling with little support to material flow capacity is passed down to CME, which establishes its own list of priorities according to urgency of upcoming surgeries. The scheduling system accounts for nominal lead-times only, disregarding most of complexity.	Finite capacity scheduling of CME, accounting for operational constraints and detailed cycle times for individual machines and technicians. Customized material allocation rules enable for minimalistic prioritization of batches. Simultaneously scheduling CME and the surgical block enables for greater synchronism and assertiveness when programming both areas.

5 CONCLUSION

The present study sought to explore the applicability of APS methodology on the context of surgical block scheduling. From the literature review on the relevance of scheduling, field contributions on mathematical and statistical tools and applied research on a private hospital, this study sought to validate some probability properties proposed in theory, to frame the surgical scheduling problem on the grounds of APS and to highlight possible benefits with respect to the current method and system adopted by the hospital.

The research revealed that the lognormal distribution is appropriate for modelling the surgical durations and that the statistical analysis combined to an APS methodology may enable a more comprehensive and assertive management of the variability and its effects associated to operational complexity. It was observed that several functionalities, such as constraint validation and material availability, assigned to APS systems, may already be found implemented on other commercial information systems. On the analysed hospital, adoption of an APS system represents prospect of improvement in synchronism and communication between the surgical block and the materials centre. Further benefits include increase in agility and precision on rescheduling, as well as ease to simulate multiple settings of demand and equipment malfunction, absenteeism etc.

Limitations of this study include the lack of a real deployment of an APS solution. Sources of information such as database extraction and staff knowledge help in contrasting the required processes and flows the surgical block orchestrates to the assumptions made by APS systems. Cultural barriers, performance measurements instead of estimates and unexpected modelling issues may only be tested through an actual implementation. Database integrity, process control and cultural change are also key success factors that require further research.

Further research may include a pilot run of APS so as to assess whether improvements raised by the present study hold true. A case study about the Return Over Investment (ROI) of APS systems is also of great interest to healthcare suppliers. Lastly, an analysis of how lean principles and process improvement may enhance scheduling performance is also desirable.

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