CIRRELT-2020-09

On Integrating Patients Appointment Grids and Technologist Schedules in a Radiology Center

Dina Bentayeb
Nadia Lahrichi
Louis-Martin Rousseau

April 2020

Bureau de Montréal
Université de Montréal
C.P. 6128, succ. Centre-Ville
Montréal (Québec) H3C 3J7
Tél. : 1-514-343-7575
Télécopie : 1-514-343-7121

Bureau de Québec
Université Laval,
2325, rue de la Terrasse
Pavillon Palasis-Prince, local 2415
Québec (Québec) G1V 0A6
Tél. : 1-418-656-2073
Télécopie : 1-418-656-2624

On Integrating Patients Appointment Grids and Technologist Schedules in a Radiology Center

Dina Bentayeb, Nadia Lahrichi[*], Louis-Martin Rousseau

Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)
and Department of Mathematics and Industrial Engineering, Polytechnique Montréal

Abstract. Optimal patient appointment scheduling improves medical center performance and reduces pressure from excess demand. Appointment scheduling efficiency depends on resource management, and staff are a key resource. Personnel scheduling takes into account union rules, skills, contract types, training, leave, illness, etc. When combined with appointment scheduling constraints, the complexity of the problem increases. In this paper, we study the combination of the patient appointment grid and technologist scheduling. We present a well-detailed framework outlining our approach. We develop two versions of a mixed-integer programming model: integrated and sequential. In the first version, we elaborate the appointment grid and the technologist schedules simultaneously, while in the second version we generate them sequentially. We evaluate the proposed approach using real data from the MRI department of the Centre hospitalier de l'Université de Montréal (CHUM) radiology center. We study different scenarios by testing several technologist rules and planning construction methods. Obtained solutions are compared to the current CHUM scheduling approach.

Keywords: Scheduling, patient appointment grid, radiology, policies.

Acknowledgements. Partial funding for this project has been provided by NSERC and Hanalog, the Canada research chair in healthcare analytics and logistics. We gratefully acknowledge the support of the Fonds de recherche du Québec through their Infrastructure Grant.

---

[*] Corresponding author: nadia.lahrichi@polymtl.ca

Dépôt légal – Bibliothèque et Archives nationales du Québec
Bibliothèque et Archives Canada, 2020

1 Introduction

In recent years, increasing access requests and limited medical budgets have put pressure on hospitals to minimize costs while maintaining a high standard of care. Many healthcare facilities have costly equipment which is in high demand, especially in radiotherapy and imaging centers. A shortage of medical personnel results in machine underutilization, unmet demand for services and long patient waitlists. Between 1993-2003, the number of MRI exams and the number of computed tomography (CT) scans performed in Ontario, Canada increased threefold (Van Nynatten and Gershon, 2017). Currently, Canadians must wait an average of 4.8 weeks for a CT scan, and 9.3 weeks for an MRI scan (Bacchus and Mackenzie, 2019). Healthcare administrators are forced to manage their resources efficiently by reducing operational costs while ensuring patient satisfaction. The workforce represents an important source of direct costs; however, good management maximizes the number of patients seen per day, and reduces new investments.

Schedulers in medical centers tend to adopt the simplest scheduling version that they can implement manually and easily. Appointments scheduling and staff scheduling are usually performed separately. Appointment grids are standardized and their elaboration is not contingent upon the human resource or material resource planning. As a consequence, machine schedules are static and the associated personnel planning is predetermined. Moreover, the number of personnel allocated to treat a given patient is usually fixed and depends on the shift type rather than patient status, especially in the case of technologists in the imaging and the radiotherapy centers.

In any healthcare center, the medical personnel have varying levels of training and skill, and their patients have different treatment characteristics. Some patient categories require the availability of appropriate personnel; for others, the presence of more than one caregiver or technician is needed to ensure a more efficient treatment. So while, the elaboration of the appointment and staff schedules in a standardized manner is convenient, adding flexibility allows us to capture the complexity of the problem in real life, including the heterogeneity of patients and medical personnel.

Since one of the big challenges of healthcare research projects is their real-world application, we collaborated with the MRI department of the Centre hospitalier de l'Université de Montréal (CHUM) radiology center from the outset of our study, to determine the feasibility of our solutions. To ensure the inclusion a wide range of real-world constraints, we consulted a multidisciplinary team of administrators, including: the head of the imaging department, a radiologist, an administrative coordinators, as well as planners and assistants.

As with most of medical centers, the design of the appointment grid and technologist schedules at the CHUM is performed manually and separately (Figure 1) by two different agents. The master appointment grid is pre-defined, while the technologist schedules are prepared for each period based on technologists' availability and skills. The technologist schedules are made first, then the functional grid is generated according to the modifications produced. Modifications related to the grid, such as machine shut down, lead to adjustment of the technologist schedules. Any change or adjustment in data requires communication between the schedulers. They then try to apply the fewest possible modifications, in an attempt to approximate the basic schedule.

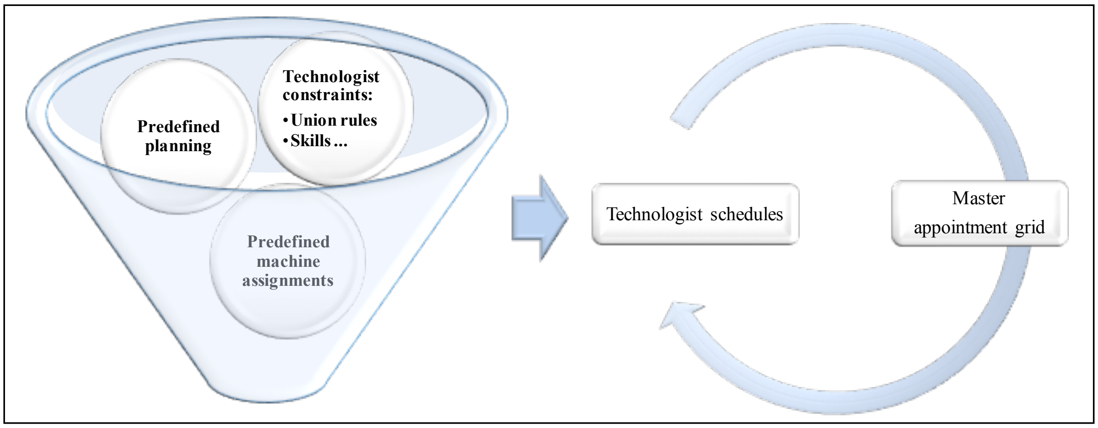

Figure 1: The CHUM scheduling approach

In this paper, we propose a monthly (tactical-level) appointment grid and technologist scheduling approach, which takes demand into consideration. We provide an optimal allocation of personnel resources to maximize machine utilization and the number of patients seen per day. Our contribution is a managerial tool for healthcare administrators which guides their decision-making on staff structure, recruitment, working rules, and planning construction methods. Our research also helps managers compare their current process to more optimal processes, based on analysis of real data. This new information can subsequently be used to improve scheduling system efficiency. We define a well-detailed and structured framework composed of seven steps:

1. Problem definition and objective: The elaboration of the appointment grid and technologist schedules is performed separately in most medical centers. Schedulers adopt standard and predetermined scheduling patterns. This makes manual resolution easier, but the approach lacks efficiency. We propose an approach that considers the construction of the appointment grid and the technologist schedules simultaneously.

2. Problem formulation and resolution: We present two versions of our optimization model: integrated and sequential. The integrated model consists of simultaneous appointment grid and technologist scheduling. In the sequential model, we elaborate technologist schedules first, then, design the appointment grid. For both models, we determine the following for each technologist: their days off, the daily machine assignment, and the start and break times during the workday. For each machine we determine the following: the type, the number and the sequence of the exams. We formulate the problem as a mixed-integer program (MIP), and solve it with CPLEX.

3. Data collection: The proposed approach is applied to real datasets from the MRI department in the CHUM radiology center. We use historical data spanning a period of three months. Collected data includes: exam category distribution, technologist contract types, union rules, machine capabilities, technologist skills, etc.

4. Data investigation: One of the objectives of this study is to process the collected data and extract useful information to help us master the scheduling system. We lead a data-driven study of the impact of allocating a variable number of technologists to execute an exam category on the total number of patients seen per scheduling period.

5. Experimental setting: We present the experimental setting based on our study objectives. We lead a discussion with the CHUM managers to define the experiment's limits and challenges and to determine what elements that they aim to analyze via this study. Based on input from the CHUM managers, we evaluate the two versions of the mathematical model while changing two CHUM standard scheduling elements: technologist working rules, and technologist planning construction methods. The obtained solutions are compared not only to the CHUM real case, but also to the CHUM planned solution. To evaluate scheduling performance, we consider technologist satisfaction and the CHUM center gain. On the one hand, schedule stability is a key component of any good solution. In fact, technologists prefer to minimize changes to planning and machine assignment throughout the week. Moreover, the minimization of exam category changes in the grid appointment increases technologists' efficiency. On the other hand, the maximization of machine utilization and the number of treated patients increases the CHUM managers' satisfaction and patient access to the center.

6. Results evaluation: We evaluate the solution quality of each scenario, and we run a comparison to the CHUM scheduling approach. We discuss the impact of changing technologist scheduling

rules and allowing more flexibility in planning construction methods.

7. Solution selection: We present a summary of the obtained results to the CHUM administrators, and discuss general managerial insights from the tool we developed. We advise them about which solutions could be implemented to improve efficiency, and clarify the impact versus the challenges of applying each scenario in real life.

The rest of the paper is organized as follows: Section 2 gives an overview of the relevant literature related to our work. Section 3 defines the problem statement and presents the proposed scheduling approach. Section 4 introduces the case study. In Section 5 we discuss the obtained results. Section 6 concerns the solution selection plan. Finally, we conclude with a summary of the present study.

2 Literature review

We address two sides of the scheduling problem in this paper: appointment grid scheduling and technologist scheduling, which is a particular type of personnel scheduling.

The challenges associated with personnel scheduling depend on the level at which decisions are made. At the strategic level, we determine: the size of the manpower, the skills, the contract, the number of trainees, etc. Tactical decisions include personnel schedules over some days or weeks, trainee planning and rotation, etc. However, at the operational level we present more detailed personnel schedules by attributing, for example, the tasks to perform and their sequence.

The personnel rostering or scheduling problem considers the tactical and operational levels of the planning horizon. This problem is divided into three different types: shift scheduling, days-off scheduling and tour scheduling, which integrates the first two classes. Ernst et al. (2004) define personnel scheduling as a well-defined process composed of a number of modules: demand modeling, days-off scheduling, shift scheduling, line of work construction, task assignment, and staff assignment. In the literature, authors apply different methods to model and solve the problem, such as mathematical programming approaches, constraint programming, decomposition, metaheuristics, simulation, etc. (Van den Bergh et al., 2013; Ernst et al., 2004; Alfares, 2004).

There are many challenges in the construction of personnel schedules, relating to the unique characteristics of the problem. An employer recruits its workforce with different types of contracts: full-time, part-time and casual. In some cases, the employees are from heterogenous sets and they do not have the same skills (Van den Bergh et al., 2013), so specific tasks are assigned to the appropriate person. Moreover, there are several constraints to consider in modeling the problem, such as government regulations and employer rules.

In healthcare systems, the scheduling problem is most often studied in relation to nurse scheduling and physician scheduling; we refer the reader to Burke et al. (2004) and Erhard et al. (2018). The authors of these papers aim to effectively consider the complexity of the problem, taking into account fairness, preferences, and shift types. In fact, there are two main shift types: predefined and flexible. The first type has been studied widely in the literature with some authors studying overlapping shifts (Erhard et al., 2018). With flexible shift types, it is possible to assign shifts with different start times and lengths. Brunner et al. (2009) introduce a physician scheduling model that combines shift scheduling, days-off scheduling and line of work construction, while permitting flexible shifts, breaks and overtime. In a subsequent paper they solve the size of realistic instances by developing a branch-and-price algorithm (Brunner et al., 2010). Stolletz and Brunner (2012) present a physician scheduling model with flexible shifts and fairness aspects. They reduce the set covering approach by generating all possible shifts in a preprocessing step using an algorithm. In the literature, the technologist scheduling problem has not attracted much attention, only a few published papers deal with this problem. Chen et al. (2016) propose a two-stage method for the allocation and scheduling of radiologic technologists. The first step determines the minimum required number of technologists; the second step establishes their schedules. Yuura et al. (2017) present a model for radiographer scheduling by integrating their skills and the trainee training. Vieira et al. (2018) optimize the allocation of radiotherapy technologists to multiple operations by considering stochastic patient arrivals.

Some studies combine the scheduling of resources with the scheduling of another component of the process, such as patients. Ogulata et al. (2008) study physiotherapist and patient scheduling over the workday. They maximize the number of treated patients while taking into account fairness among physiotherapists by balancing the workload between them. There are two studies concerning patient and resource scheduling in nuclear medicine. The procedures or tests in this speciality area of radiology are multi-stepped and require multiple human resources: technologists, nurses, physicians and managers. The first study (Pérez et al., 2011) proposes an algorithm with a fixed procedure-resource assignment, and another algorithm that performs this assignment using an integer programming model for days with high demand. Pérez et al. (2013) extend the two algorithms to the stochastic online optimization, starting with the offline version.

For patient scheduling based on appointment systems, a redesign of the appointment grid according to patient categories, or service time types, leads to a more efficient scheduling system. Huang and Verduzco (2015) reclassify the patient scheduling groups and determine their time slot lengths. Van Sambeek et al. (2011) propose a new scheduling strategy to improve patient access time. They change the master appointment schedule by minimizing the number of block types, keeping only the important patient categories. Bentayeb et al. (2018) present a new appointment schedule based on a service time prediction model, which is elaborated using a data mining method.

In the existing literature, authors address only the patient appointment grid design, or they deal with patient scheduling with resource assignment at the operational level. They do not incorporate the tactical staff scheduling problem, taking into account the real constraints and personnel satisfaction. In this paper, we aim to study the impact of the combination of patient appointment and technologist scheduling on the number of treated patients. We evaluate different scenarios based on real data, by changing the technologist planning construction and the working rules.

3 Problem statement and modeling

In this section, we describe the characteristics of the appointment grid and technologist scheduling problem. We then present the mathematical formulation.

3.1 Problem statement

Technologist scheduling is complicated in real life. We are dealing with people, so we must consider their working conditions, contract types, leaves, illnesses, etc.

Technologist scheduling interacts with patient appointment management. The integrated planning of these two elements represents the fundamental problem; however, the consideration of all of the real appointment and technologist constraints amplifies the problem's complexity.

In the radiology centers, specifically in the MRI department, there are different technologist groups classified by their work contracts. In a shift work system, the technologist can work in the morning, in the afternoon, or in the evening. Moreover, he can be on a full-time or a part-time contract that also determines the number of compulsory hours that he has to work every fortnight. This is variable in the case of part-time jobs; the number of hours may differ depending upon whether the technologist works six, seven or eight days per fortnight.

Technologists also differ according to their skills. The training process in the MRI department is long. The need to use more machines and the high volume of patients prevent technologists from being trained to do all exam categories.

Moreover, the MRI machines are not identical in terms of transmitted magnetic field, design, manufacturer, license, etc. Each machine is dedicated to performing specific sets of exam categories.

Assigning exam categories depends not only on technologist skills and machine types, but also on time periods. In fact, some exam categories require the availability of other medical personnel, so they must be executed on pre-determined days and during specific slots.

Furthermore, the number of allocated technologists influences the performance of the exam execution process. For some categories, assigning more than one technologist increases the number of patients treated per time period. For other categories, the assignment of multiple technologists is a requirement.

Most centers allocate technologists based on their total number per shift. The number of technologists allocated to a machine is uniform per shift. Assigning exam categories to machines is done independently by taking into account the opening and closing hours of rooms.

Considering all these constraints in an integrated way leads to many challenges. In fact, most medical centers including the CHUM radiology center perform scheduling manually, and schedulers prefer to keep a standard and predetermined scheduling format to minimize changes.

In this article, we propose a mathematical model which includes simultaneous appointment and technologist scheduling. We evaluate the proposed model using real data from the MRI department of the CHUM radiology center.

3.2 Model

We present a mixed-integer programming model to optimize the design of the appointment grid and the elaboration of the technologist schedules. We suggest two versions of the mathematical model: integrated and sequential. We first present the integrated model, followed by the sequential version.

We develop a model to schedule exam categories and technologists monthly. The planning horizon is 28 days ($j \in J$) over four weeks. Each week $i \in$ I consists of weekdays from Monday to Thursday $j \in W_i$, and weekend days $j \in J_W$. J_W=$J_{st} \cup J_{sn}$, where J_{st} is the set of Saturdays, and J_{sn} is the set of Sundays. The set of days J is divided into two subsets of 14 days: the first 14 days in the planning is J1, and the second 14 is J2.

Our model takes into consideration technologist working conditions according to union rules and contracts. Technologists have a determined number of consecutive days q that they can work.

Technologist $t \in T_k$ cannot work more than k days over 14 days. In addition, there is a set of technologists $t \in T_W$ who cannot work on the weekend.

In our model, we use the terms "shift" and "planning". To avoid any confusion, we give their definitions: a shift is a period of time during the day or night when an employee or a group of employees is scheduled to work; however, planning is the daily schedule that determines the start and end times of the shift, the slots for work and the break times.

We note F and P sets of shifts and planning respectively. For each shift $f \in F$, there is a set of associated planning $p \in P_f$. The present model formulation splits the day into slot $s \in S_d$ of length $d \in D$ in hours. To determine if a given planning p covers a slot s, we use a binary parameter l_{ps}.

The technologist assignment depends on his competence. Binary parameters b_{tc} and a_{tpm} define the possibility of assigning a technologist t to a category c, or a technologist t to planning p and a machine m respectively.

The exam category c determines the possibility to assign it to a machine using a binary parameter e_{cm}, and to a slot on a given day by a binary parameter g_{csj}.

The execution of each exam category needs m_c technologists. The number of technologists $h \in H$ that perform a category c sets the average number of executed exams of category c per hour n_{hc}.

In the radiology center, the demand is variable. Therefore, the model respects the required number of one-hour slots for each category (parameter r_c). Moreover, we consider the minimal coverage of active machines during a shift using a parameter o_f.

Our model decides:

- if category c is performed on machine m, slot s and day j, using binary variables x_{cs}^{mj};
- if planning p is assigned to technologist t and machine m on day j, using binary variables y_{pt}^{mj};
- day-off j of a technologist t, using binary variables γ_{tj};
- the number of technologists h who perform each category c, on machine m, slot s and day j, using binary variables β_{hcs}^{mj}; and
- the number of treated patients on each slot s during day j on machine m, using binary variables z_{s}^{mj}.

The model considers the stability of:

- grid appointment, using binary variables δ_s^{mj}, equal to 1 if a change of category is made on slot s, day j, machine m;
- technologist schedule by machine, using binary variables α_{tj}^m, equal to 1 if technologist t changes a machine m on a day j; and
- technologist schedule by planning, using binary variables $\alpha_{tj}^{'p}$, equal to 1 if technologist t changes planning p on a day j.

3.2.1 Integrated model

Our objective function contains four sub-objectives. The first two maximize machine utilization and the number of patients seen over the scheduling period. Our model also prioritizes assigning weekends as days off for technologists. The latter subobjectives ensure the stability of the appointment grid and the technologist schedules. The third term in the objective function penalizes the change of category on the same machine during a day. The last term penalizes the change of machine and planning for a technologist during a weekday.

We maximize

$$\sum_{s\in S}\sum_{m\in M}\sum_{j\in J}(\sum_{c\in C} x_{cs}^{mj} + z_s^{mj}) + \sum_{t\in T}\sum_{j\in J_W}\gamma_{tj} - \sum_{s\in S}\sum_{m\in M}\sum_{j\in J}\delta_s^{mj} - \sum_{t\in T}\sum_{j\in J}(\sum_{m\in M}\alpha_{tj}^m + \sum_{p\in P}\alpha_{tj}^{'p}) \tag{1}$$

Constraints (2) and (3) represent the unicity constraints. Constraints (2) ensure that we can assign at most one exam category to a slot on a given machine during a day. Constraints (3) ensure that a technologist cannot work on more than one machine according to more than one planning per day.

$$\sum_{c\in C} x_{cs}^{mj} \leq 1, \quad \forall\, s\in S,\, m\in M,\, j\in J \tag{2}$$

$$\sum_{p\in P}\sum_{m\in M} y_{pt}^{mj} \leq 1, \quad \forall t\in T,\, j\in J \tag{3}$$

In order to respond to the realistic demand, there is a minimum coverage to consider. Constraints (4) define the minimal number of each category over the scheduling period. Moreover, the imaging center determines the minimum number of active resources in each department on weekends, to cover planned appointments as well as emergencies. This is enforced by constraints

(5).

$$\sum_{d\in D}\sum_{s\in S_d}\sum_{m\in M}\sum_{j\in J} d x_{cs}^{mj} \geq r_c, \quad \forall\, c\in C \tag{4}$$

$$\sum_{p\in P_f}\sum_{t\in T}\sum_{m\in M} y_{pt}^{mj} \geq o_f, \quad \forall\, j\in J_W,\, f\in F \tag{5}$$

In the MRI department, there are different exam categories that may require specific material and personnel resources. Before assigning an exam category to a slot on a machine, we have to secure the availability of the minimal number of appropriate technologists. This is ensured by constraints (6). Furthermore, we may execute an exam category only on the proper machines and during the suitable slots and days. These two restrictions are enforced by constraints (7) and (8), respectively.

$$\sum_{p\in P}\sum_{t\in T} b_{tc} l_{ps} y_{pt}^{mj} \geq m_c x_{cs}^{mj}, \quad \forall\, c\in C,\, s\in S,\, m\in M,\, j\in J \tag{6}$$

$$x_{cs}^{mj}(1-e_{cm}) = 0, \quad \forall\, c\in C,\, s\in S,\, m\in M,\, j\in J \tag{7}$$

$$x_{cs}^{mj}(1-g_{csj}) = 0, \quad \forall\, c\in C,\, s\in S,\, m\in M,\, j\in J \tag{8}$$

Technologists are not all trained to work on every machine, nor do they all have the same work contract. Some technologists can work only the morning planning; contrariwise, others work only the evening planning. Constraints (9) attribute the appropriate planning and machine to each technologist.

$$y_{pt}^{mj}(1-a_{tpm}) = 0, \quad \forall\, p\in P,\, t\in T,\, m\in M,\, j\in J \tag{9}$$

Our model takes into account hospital and government regulations pertaining to technologists' work. Technologists cannot work more than five consecutive days ($q = 5$), nor can they more than one weekend every two weeks. This is guaranteed by constraints (10) and (11), respectively. Constraints (12) ensure that the technologist on duty has to work both weekend days with the same assignment of machine and planning. Constraints (13) and (14) define the number of days that a technologist has to work over the scheduling period, according to his contract.

$$\sum_{p\in P}\sum_{m\in M}\sum_{j'=j}^{j+q} y_{pt}^{mj'} \leq q, \quad \forall\, t\in T,\, j\in \{1,..,max(J)-q\} \tag{10}$$

$$\sum_{p\in P}\sum_{m\in M} y_{pt}^{mj} + \sum_{p\in P}\sum_{m\in M} y_{pt}^{m(j+6)} \leq 1, \quad \forall\, t\in T,\, j\in J_{Sn} \tag{11}$$

$$y_{pt}^{mj} = y_{pt}^{m(j+1)}, \quad \forall\, p \in P,\, t \in T,\, m \in M,\, j \in J_{St} \tag{12}$$

$$\sum_{p \in P} \sum_{m \in M} \sum_{j \in J_1} y_{pt}^{mj} = k, \quad \forall\, t \in T_k \tag{13}$$

$$\sum_{p \in P} \sum_{m \in M} \sum_{j \in J_2} y_{pt}^{mj} = k, \quad \forall\, t \in T_k \tag{14}$$

Constraints (15) define binary variables γ_{tj}. In some cases, technologists cannot work on weekends, either because they are not yet trained on all machines, or because they are pregnant. Constraints (16) avoid assigning this group of technologists to the weekends.

$$1 - \sum_{p \in P} \sum_{m \in M} y_{pt}^{mj} = \gamma_{tj}, \quad \forall\, t \in T,\, j \in J \tag{15}$$

$$\gamma_{tj} = 1, \quad \forall\, t \in T_W,\, j \in J_W \tag{16}$$

One of the main objectives of this paper is to study the impact of the number of technologists allocated to perform an exam category on the number of patients seen. Constraints (17)-(19) are imposed to determine the number of patients treated in a given slot based on the number of assigned technologists.

$$\sum_{p \in P} \sum_{t \in T} l_{ps} y_{pt}^{mj} = \sum_{c \in C} \sum_{h \in H} h \beta_{hcs}^{mj}, \quad \forall\, h \in H,\, s \in S,\, m \in M,\, j \in J \tag{17}$$

$$\sum_{h \in H} \beta_{hcs}^{mj} = x_{cs}^{mj}, \quad \forall\, c \in C,\, s \in S,\, m \in M,\, j \in J \tag{18}$$

$$z_s^{mj} \le \sum_{h \in H} \sum_{c \in C} d n_{hc} \beta_{hcs}^{mj}, \quad \forall\, c \in C,\, s \in S_d,\, m \in M,\, j \in J,\, d \in D \tag{19}$$

To enhance the quality of the proposed solution, we have to consider the stability of schedules. To track machine or planning changes for technologists during weekdays, we use variables α_{tj}^{m} and $\alpha_{tj}^{'p}$ in constraints (20) and (21), that are penalized in the objective function. On the other hand, the variables δ_s^{mj} in constraints (22) calculate the change of category from one slot to the next one on the same machine during a day, which is minimized in the objective function.

$$\sum_{p \in P} y_{pt}^{mj} \le \sum_{p \in P} y_{pt}^{m(j+1)} + \gamma_{t(j+1)} + \alpha_{t(j+1)}^{m}, \quad \forall\, t \in T,\, m \in M,\, j \in W_i,\, i \in \{1,2,3,4\} \tag{20}$$

$$\sum_{m \in M} y_{pt}^{mj} \le \sum_{m \in M} y_{pt}^{m(j+1)} + \gamma_{t(j+1)} + \alpha_{t(j+1)}^{'p}, \quad \forall\, t \in T,\, p \in P,\, j \in W_i,\, i \in \{1,2,3,4\} \tag{21}$$

$$x_{cs}^{mj} + x_{c'(s+1)}^{mj} \ge \delta_{s+1}^{mj} + 1, \quad \forall\, c \in C,\, c' \in C,\, c \ne c',\, s \in S,\, m \in M,\, j \in J \tag{22}$$

Constraints (23)-(29) serve to define the value ranges of our variables.

$$x_{cs}^{mj} \in \{0,1\}, \quad \forall\, c \in C,\, s \in S,\, m \in M,\, j \in J \tag{23}$$

$$z_{s}^{mj} \in \mathbb{N},\, \delta_{s}^{mj} \in \{0,1\}, \quad \forall\, s \in S,\, m \in M,\, j \in J \tag{24}$$

$$\beta_{hcs}^{mj} \in \{0,1\}, \quad \forall\, h \in H,\, c \in C,\, s \in S,\, m \in M,\, j \in J \tag{25}$$

$$y_{pt}^{mj} \in \{0,1\}, \quad \forall\, p \in P,\, t \in T,\, m \in M,\, j \in J \tag{26}$$

$$\alpha_{tj}^{m} \in \{0,1\}, \quad \forall\, t \in T,\, j \in J,\, m \in M \tag{27}$$

$$\alpha_{tj}^{'p} \in \{0,1\}, \quad \forall\, t \in T,\, j \in J,\, p \in P \tag{28}$$

$$\gamma_{tj} \in \{0,1\}, \quad \forall\, t \in T,\, j \in J, \tag{29}$$

3.2.2 Sequential model

The basic formulation of the sequential model is very similar to that of the integrated model, but we separate it into two models. The first one (the technologist scheduling model) considers the technologist schedule constraints. The second one (the appointment scheduling model) takes into account the exam category assignation constraints. In order to link the two models, and to propose a feasible and a realistic solution, we add some notations and constraints, and we change the objective function. The complementary mathematical formulation is as follows:

$Parameters:$

$r_h^{'}$	the minimal number of slots where it is possible to treat categories that require at least h technologists
Y_{pt}^{mj}	binary parameter represents the obtained value of y_{pt}^{mj} as output of the technologist scheduling model

$Variables:$

u_s^{mj}	binary variable, equal to 1 if at least one technologist is active on machine m, slot s, day j
v_{sh}^{mj}	binary variable, equal to 1 if at least h technologists are active on machine m, slot s, day j

We divide the objective function of the integrated model into two separate objective functions for technologist (1a) and appointment (1b) scheduling. We add a new term in the objective function (1a), that maximizes machine utilization by increasing the number of active slots.

- Technologist scheduling model

  We maximize

$$\sum_{s\in S}\sum_{m\in M}\sum_{j\in J} u_s^{mj} + \sum_{t\in T}\sum_{j\in J_W}\gamma_{tj} - \sum_{t\in T}\sum_{j\in J}\Big(\sum_{m\in M}\alpha_{tj}^{m} + \sum_{p\in P}\alpha_{tj}^{\prime p}\Big) \tag{1a}$$

  We consider the technologist scheduling constraints of the integrated model ((3), (5), (9)-(16), (20), (21), (26)-(29)), plus the following constraints:

$$\sum_{p\in P}\sum_{t\in T} l_{ps} y_{pt}^{mj} \geq u_s^{mj}, \quad \forall\, s\in S,\, m\in M,\, j\in J \tag{2a}$$

$$\sum_{p\in P}\sum_{t\in T} l_{ps} y_{pt}^{mj} \leq max(H), \quad \forall\, s\in S,\, m\in M,\, j\in J \tag{3a}$$

$$\sum_{p\in P}\sum_{t\in T} l_{ps} y_{pt}^{mj} \geq h v_{sh}^{mj}, \quad \forall\, h\geq 2,\;\; s\in S,\, m\in M,\, j\in J \tag{4a}$$

$$\sum_{d\in D}\sum_{s\in S}\sum_{m\in M}\sum_{j\in J} d v_{sh}^{mj} \geq r_h^{'}, \quad \forall\, h\geq 2 \tag{5a}$$

  Constraints (2a) ensure that a slot on a given machine is active if at least one technologist is assigned to this time period. Constraints (3a) avoid assigning more technologists than allowed. Constraints (4a) and (5a) reserve capacity on appropriate resources to perform categories that require more than one technologist.

- Appointment scheduling model

  We maximize

$$\sum_{s\in S}\sum_{m\in M}\sum_{j\in J}\Big(\sum_{c\in C} x_{cs}^{mj} + z_s^{mj}\Big) - \sum_{s\in S}\sum_{m\in M}\sum_{j\in J}\delta_s^{mj} \tag{1b}$$

  We consider the appointment scheduling constraints of the integrated model ((2), (4), (6)-(8), (17)-(19), (22)-(25)) including two modified constraints. The technologist assignations, which are the output of the technologist scheduling model, represent an input for the appointment scheduling model. We replace the variables y_{pt}^{mj} with the parameters Y_{pt}^{mj} in constraints (17) and (6), resulting in constraints (2b) and (3b).

$$\sum_{p\in P}\sum_{t\in T} b_{tc} l_{ps} Y_{pt}^{mj} \geq m_c x_{cs}^{mj}, \quad \forall\, c \in C,\, s \in S,\, m \in M,\, j \in J \tag{2b}$$

$$\sum_{p\in P}\sum_{t\in T} l_{ps} Y_{pt}^{mj} = \sum_{c\in C}\sum_{h\in H} h\beta_{hcs}^{mj}, \quad \forall\, h \in H,\, s \in S,\, m \in M,\, j \in J \tag{3b}$$

We have presented two versions of our appointment grid and technologist scheduling approach, in order to compare the proposed integrated version regarding the sequential method. The two versions are evaluated through different scenarios based on a case study.

4 Case study

The proposed scheduling models are applied using real data from the MRI department of the CHUM hospital, and they are compared to the real schedules. Our data is from January, February and March of 2019.

4.1 Data collection

In order to provide input data for our scheduling model, we collect data related to exam category distribution, machine capability, exam assignment, technologist shift structure, number of available technologists, technologist skills, technologist posts, minimal coverage, etc.

In the hospital, two schedulers elaborate the appointment grid and the technologist schedules separately. The design of the grid is basically fixed. The number of each exam type is based on the category distribution according to the patient waiting list. The assignment and sequence of the exams are related to different constraints, including the exam categories and the machine capability. Since the technologist scheduling deals with humans, who can be unpredicable, it undergoes more changes and instability. From month to month, and sometimes from week to week, the number of technologists varies as a function of leave, training, recruitment, etc.

Figure 2 shows the MRI category distribution for the year 2018. There are seven main categories : neuroradiology, abdominal, musculoskeletal, breast, cardiac, breast biopsy and vascular. 20% of the department's capacity is reserved for research and emergency exams, which can fall under any MRI category. The neuroradiology and the abdominal exams account more than 50% of the demand. The musculoskeletal and breast represent 13% and 7% of the performed exams, respectively. Cardiac, breast biopsy and vascular are the minority exams, constituting less than

5% of MRI requests.

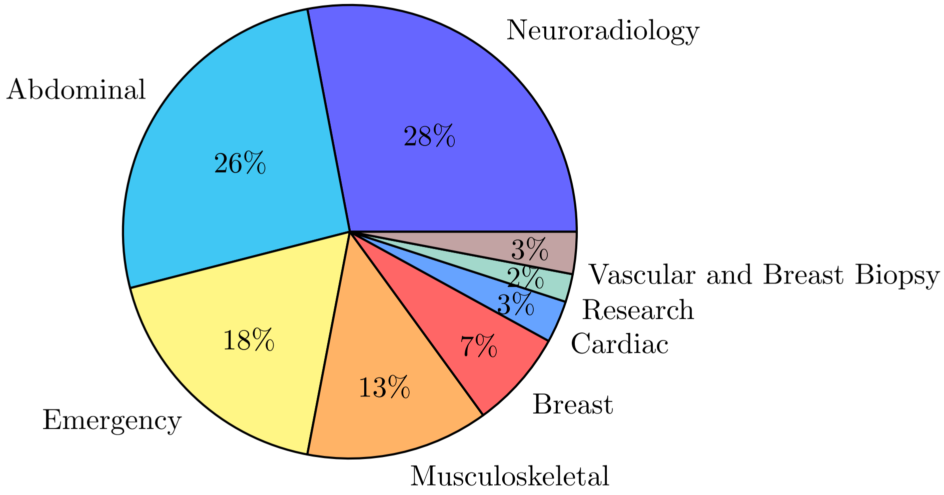

Figure 2: MRI Category distribution in the CHUM radiology center during 2018

The CHUM center contains six MRI machines from three different manufacturers. Three machines produce a magnetic field of 3 Tesla, while the magnetic field generated by the other three is 1.5 Tesla. Assigning an MRI exam to a machine depends on its category. Table 1 shows that neuroradiology and musculoskeletal exams may be performed on five out of six machines . Breast, cardiac and breast biopsy exams can only be executed on one machine. Abdominal MRI is performed on three machines, while vascular is performed on two machines.

Table 1: Exam-machine assignment possibilities

MRI category	Number of allowed machines
Neuroradiology	5
Abdominal	3
Musculoskeletal	5
Breast	1
Cardiac	1
Vascular	2
Breast biopsy	1

There are some exams that can be done only on specific days or during specific time slots. Breast biopsy and cardiac exams require the availability of appropriate physicians. The breast biopsy MRI can only be performed on Tuesday and Thursday from 12:30pm to 2:30pm. The cardiac MRI can be performed on weekdays from 8am to 4pm. The breast exam demands an injection that may cause an allergic reaction in some patients. Exams requiring an injection cannot be performed after 10pm, to ensure that the center is still open and a technologist is present to take care of the patient in case of emergency.

Technologists in the MRI department work under rotating shifts. Shifts are successive, covering 16.5 hours per day, from 7am to 11:30pm. The morning shift starts between 7am and 9:30am, plus another shift that starts at 12pm. The start time for the evening shift is between 3pm and 4:30pm. The number of technologists for the morning shift is greater than the number of technologists for the evening shift. The scheduler generally assigns two technologists per machine during the morning shifts, and one technologist per machine during the evening. This can lead to underutilization of MRI machines in the evening.

Each technologist has three breaks per day: one break of one hour, and two breaks of 15 min. Technologists prefer to merge the two breaks of 15 min into one break of 30 min, and they take it at the end of their work day. Technologists who work the morning shift starting between 7am and 9:30am have one hour for their lunch break, and they leave 30 min before the end of their shift. However, the meal break in the remaining shifts is only 30 min, and the technologists' working day ends one hour in advance.

The opening and the closing hours are basically fixed for each machine. They are based on the predetermined technologist planning assigned to machines. For example, machines A and D are usually active only during the morning shifts. However, other machines are active in the morning and the evening shifts.

During the period of the study, the center had nineteen full-time technologist posts, and six part-time posts for technologists that work only six, seven or eight days per two weeks. Technologists take their annual leave at different times during the year. Moreover, maternity and deferred salary leave leads to a technologist shortage during some periods. To cover the resource gap, some technologists accept shift changes or changes to their post type for a duration.

According to labor regulations, technologists can work one weekend over a two-week period. However, the center allows just one active machine for each weekend shift. In order to enhance patient access during the weekend, the availability of at least two active machines and two technologists in the morning shift has been required since February 2019. Moreover, the center tries to promote ongoing technologist training. Currently, all technologists can work on machines A, B and E, and they will be trained in the future to work on other machines and to perform complicated exams, such as cardiac exams.

4.2 Data investigation

Our objective is to evaluate the impact of the number of technologists that perform MRI exams on service time. Figure 3 describes the patient exam execution process in the MRI department of the CHUM radiology center. Upon arrival to the center, the patient is registered. This appears directly in the CHUM appointment system, informing technologists that the patient is present. The patient changes his clothes and sits in the waiting room. During this period, the patient fills out questionnaires.

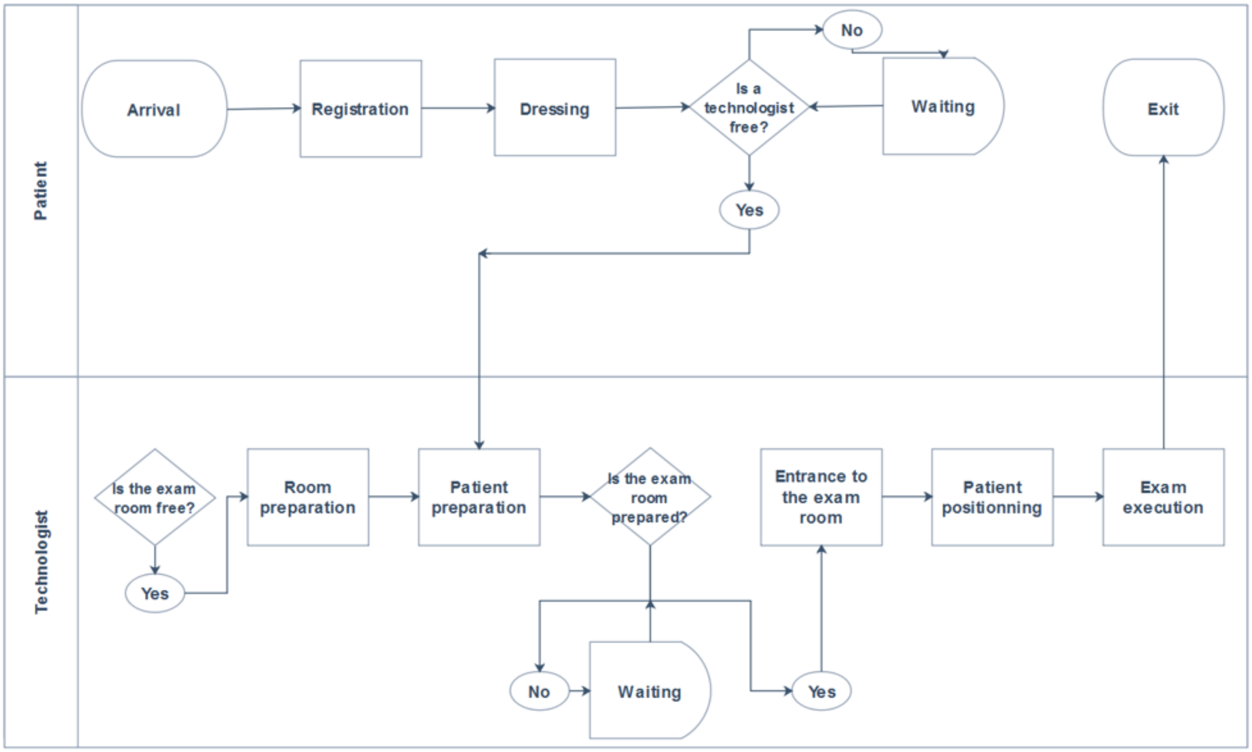

Figure 3: Patient exam execution process

If the MRI machine is free, a technologist has to clean and prepare the room for the planned exam. The technologist locates the patient in the waiting room, and they head toward the preparation room. The technologist checks and fills in missing information in the patient questionnaires. He describes MRI exam procedure and its duration. Some MRI exams require a specific injection. In particular exam categories, most patients are injected. In such cases the technologist has to prepare the patient for the injection by placing the catheter.

Once the patient is ready, the technologist guides him to the exam room. He positions the patient on the MRI machine. Then, the exam is performed. Once the exam is completed, the patient leaves the room.

In the MRI department, all exam categories can be executed by one technologist, except the breast biopsy exam, which requires at least two technologists. The availability of more than one technologist for some processes promotes system efficiency. For example, the preparation of the patient takes between 5 and 15 minutes. Sometimes the technologist has to fill out the questionnaire with the patient because he is unable to do it by himself or he doesn't have enough time. This increases the patient preparation duration. If two technologists were available for each exam, one could prepare and assist the patient with paperwork while the other one is monitoring the current patient in the exam room. Other tasks such as room preparation and patient positioning are likewise faster in the presence of two technologists.

Due to the limited number of technologists in the CHUM radiology center, it is not possible to assign two technologists to every MRI exam. In this study, we select the exam categories for which the allocation of more than one technologist has the greatest impact on increasing the patient access.

In the MRI database, we find all the information related to each performed exam. However, only the technologist who executes the exam is registered. Patient appointments and technologist schedules are elaborated in two separate files by two different planners, making it is difficult to identify every technologist who attended a given exam. We run a statistical analysis on real data from January, February and March of 2019. Based on planning of assigned technologists to each machine, we determine the number of technologists for each exam, assuming that the break times corresponding to planning are respected.

Table 2 shows the average number of treated patients per hour for each category as a function of the number of allocated technologists. The difference is significant for some MRI categories, including neuroradiology, abdominal and breast exams; however, it is not the case for the remaining categories. This analysis helps us construct a more efficient appointment grid by assigning each exam to the convenient time period.

We use collected and prepared data to evaluate the current CHUM approach versus the performed scenarios.

4.3 Current approach

In the CHUM MRI department, planners elaborate technologist schedules based on predefined planning and machine assignments. Then, they check the feasibility of the appointment grid (Figure 1).

Table 2: The average number of treated patient per hour

MRI category	One technologist	two technologists
Neuroradiology	1.54	1.8
Abdominal	1.16	1.4
Musculoskeletal	1.46	1.48
Breast	1.48	1.9
Cardiac	0.73	0.87
Vascular	1.6	1.67
Breast biopsy	-	0.8

We generate technologist schedules using our sequential model with the current rules (CHUM-plan), allowing for each machine specific planning. Following the current approach, we rectify the master grid according to the technologist schedules. For example, if we don't have an available technologist in a given slot or day, we cannot attribute an exam category during this period.

The elaboration of the grid and technologist schedules is included in the tactical level of planning. However, in the operational level, unforeseen and unexpected decisions are managed. In the CHUM center, the difference in planning between the two levels stems from patient no-shows and the non-optimal method adopted by the patient scheduling agent, leading to empty slots in the appointment grid. Scheduling agents call patients one by one and plan them immediately. It is challenging to find the best combination of available patients to fit perfectly in the defined slots. Moreover, the long waiting time to get an appointment, drives patients to schedule the exam in another center. So, gaps in the appointment grid may be attributed to the difficulty of finding the right patient at the right moment.

Due to the gap between real and planned schedules, we evaluate our solutions with the planned schedules, and we also present the real case (CHUMreal).

4.4 Experimental design

This section concerns the experimental design. Our objective is to provide a managerial tool that evaluates the impact of administrator decisions on system performance. In order to determine which elements of the scheduling system to focus on in our study, we have analyzed the working conditions and rules at the CHUM, and spoke with managers about the challenges they face, the flexibility they have, and the framework limits. This discussion leads to three main areas where we saw potential for improvement in system performance: technologist weekend assignment frequency, technologist training, the planning construction method. The limits are detailed as follows:

Technologist weekend assignment frequency According to union rules, technologists can work one weekend every two weeks. However, in practice, during the weekend, the CHUM opens only one or two machines during the morning shift, and one machine during the evening shift. Therefore, technologists work at most one weekend morning shift every seven or eight weeks, and one weekend evening shift every four weeks.

Technologist training In 2017, a new CHUM megahospital complex was opened, and personnel and equipment from three different hospitals (Hôtel-Dieu, Notre-Dame, and Saint-Luc) began to be reorganized and redistributed. Technologists were not trained to work on all machines. Although the center tries to train all technologists, the training process is long and the high demand does not allow launching several training sessions at the same time.

The planning construction method The CHUM assigns specific planning for each machine. This facilitates manual schedule elaboration, and minimizes changes to the standard appointments grid. The master grid contains exam category blocs of 30 min. The two most important aspects of the planning construction method are the start and the break times.

In this study, we modify these three separate elements of the scheduling process, and we measure the impact on system performance.

We compare three technologist weekend assignment frequencies: the weekend assignment applied by the CHUM (CHUM_W), one weekend over two weeks (1/2), and one weekend over four weeks (1/4). We consider two cases of technologist training: technologists have current skills (TRAIN_{CHUM}), and all technologists are trained (TRAIN_{all}). We define a rule as a combination between the technologist weekend assignment frequency and the technologist training case; it represents the technologist working conditions in the center. Table 3 summarizes the five rules that we consider.

Table 3: Rules

	Technologist weekend assignment frequency			Technologist training	
	CHUM_W	1/2	1/4	TRAIN_{CHUM}	TRAIN_{all}
R0	✓			✓	
R1		✓		✓	
R2			✓	✓	
R3	✓				✓
R4		✓			✓

Regarding the planning construction method, we introduce slots of 1h and slots of 30 min. We consider four planning construction methods. The idea is to allow more choices in the planning construction. We act on two factors: technologist start time and the corresponding meal time, while respecting the time interval constraints. We present two start time alternatives based on the offset between the possible planning of each shift: 1 hour, or 30 minutes. The technologist takes his meal break according to his shift start time. Let D_{meal} be the duration between the two actions. We consider two cases depending on the variation of D_{meal}. In the first case (D_{meal} fixed), D_{meal} is equal to four hours in the morning shift, and two hours in the evening shift. In the second case (D_{meal} variable), the values of D_{meal} in the morning shift vary between two hours and six hours; in the evening shift they vary between two hours and three and a half hours.

In Table 4, we show the four possible planning construction methods based on the changes to technologist start and meal times.

Table 4: Planning construction methods

	Start time		Meal time	
	1h offset	30 min offset	D_{meal} fixed	D_{meal} variable
P1	✓		✓	
P2		✓	✓	
P3	✓			✓
P4		✓		✓

In this paper, we will compare the performance of the sequential and the integrated models for each scenario. A scenario is defined as a combination of a rule and a planning construction method (R_iP_j).

4.5 Performance indicators

The quality of the proposed solution is measured based on the number of patients, schedule stability, and machine utilization.

Number of patients The number of patients treated over the planning horizon. In the application of our model, we estimate this number based on the number of technologists allocated to each time slot, using Table 2.

Schedule stability Schedule stability is a factor of schedule quality. Maximizing the schedule stability involves minimizing changes to the schedule. For technologist scheduling, stability is determined by the number of changes made to planning or to machine assignment for a technologist from day to day, during weekdays. In appointment scheduling, stability is determined by the total number of category changes from one slot to the next one, on the same machine, during a day.

Machine utilization The ratio between the time period when the machine is active and the machine capacity, during opening hours.

5 Results and discussion

In this section, we use a series of scenarios to evaluate the performance of the two versions of the proposed model, by combining possible planning and rules as described in Section 4.4. Each scenario is applied to three data sets from real data collected in the CHUM radiology center. The data are from January, February and March of 2019.

5.1 Results

The aim of this study is to compare the quality of the results obtained from the integrated and the sequential models, regarding the planning structure and the rules. We carry out 120 computational experiments. The models are coded with JuMP (Dunning et al., 2017) for mathematical optimization in Julia. They are solved by CPLEX Solver, using a PC with an Intel Core i7 2.80 GHZ and 16 GB RAM processor. The maximum allowed computational time is eight hours. The average computational time varies between about one and a half hours and four and a half hours, depending on planning construction method. The increase in the number of choices when elaborating planning increases the computational time.

Figures 4, 5 and 6 represent the computational results by planning and by rules. We evaluate the performed scenarios based on the performance indicators described in Section 4.5.

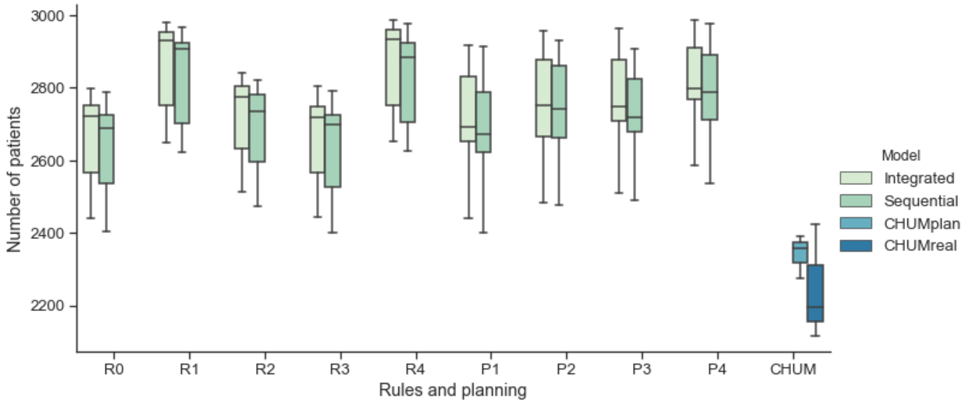

Figure 4: Number of patients

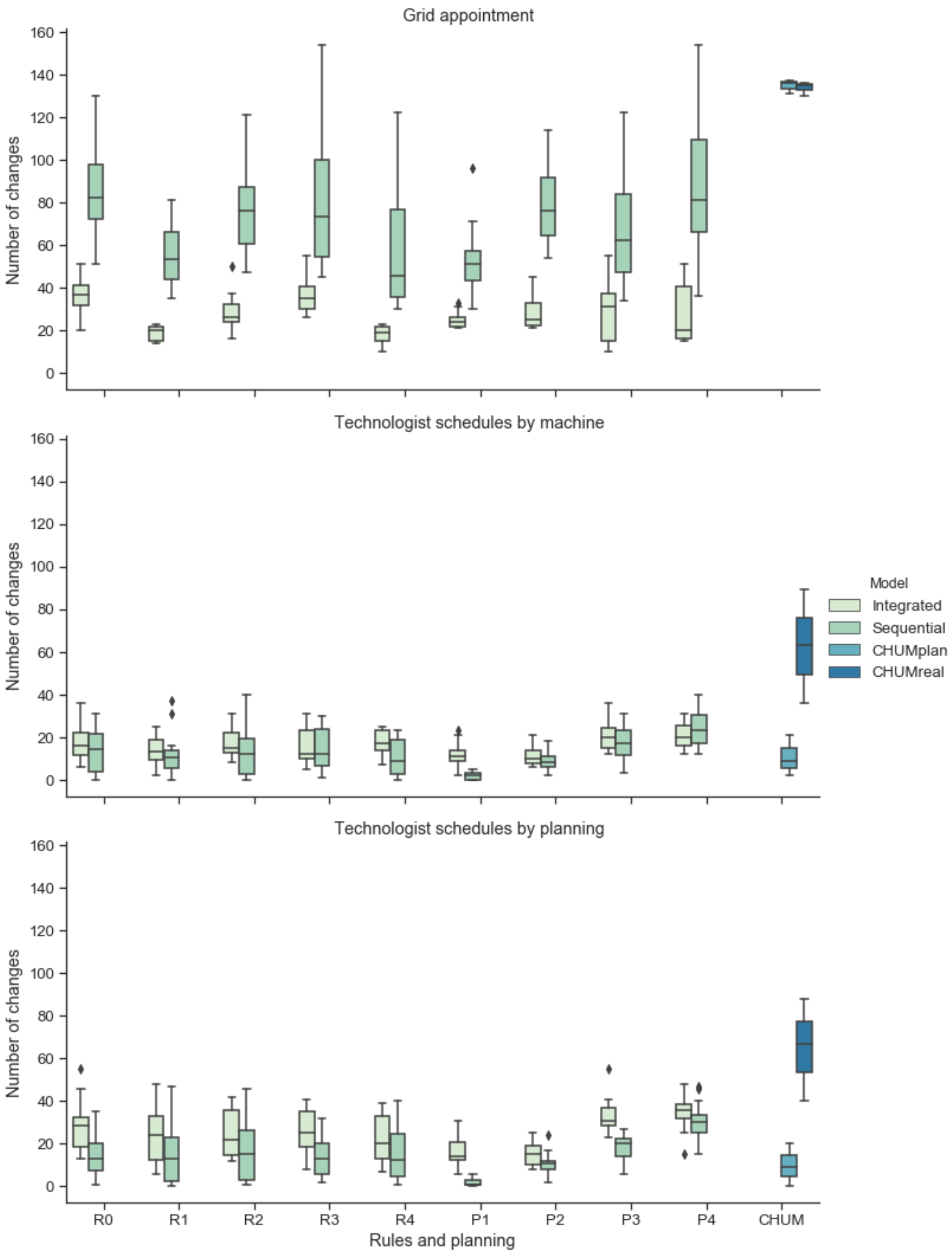

Figure 5: Schedule stability

Number of patients Both versions of the model give good results in terms of the number of treated patients. There is a significant increase by applying rules R1 and R4, with a minimum value of 10%. P4 promotes patient access more than other planning construction method. There isn't a big difference between methods P2 and P3.

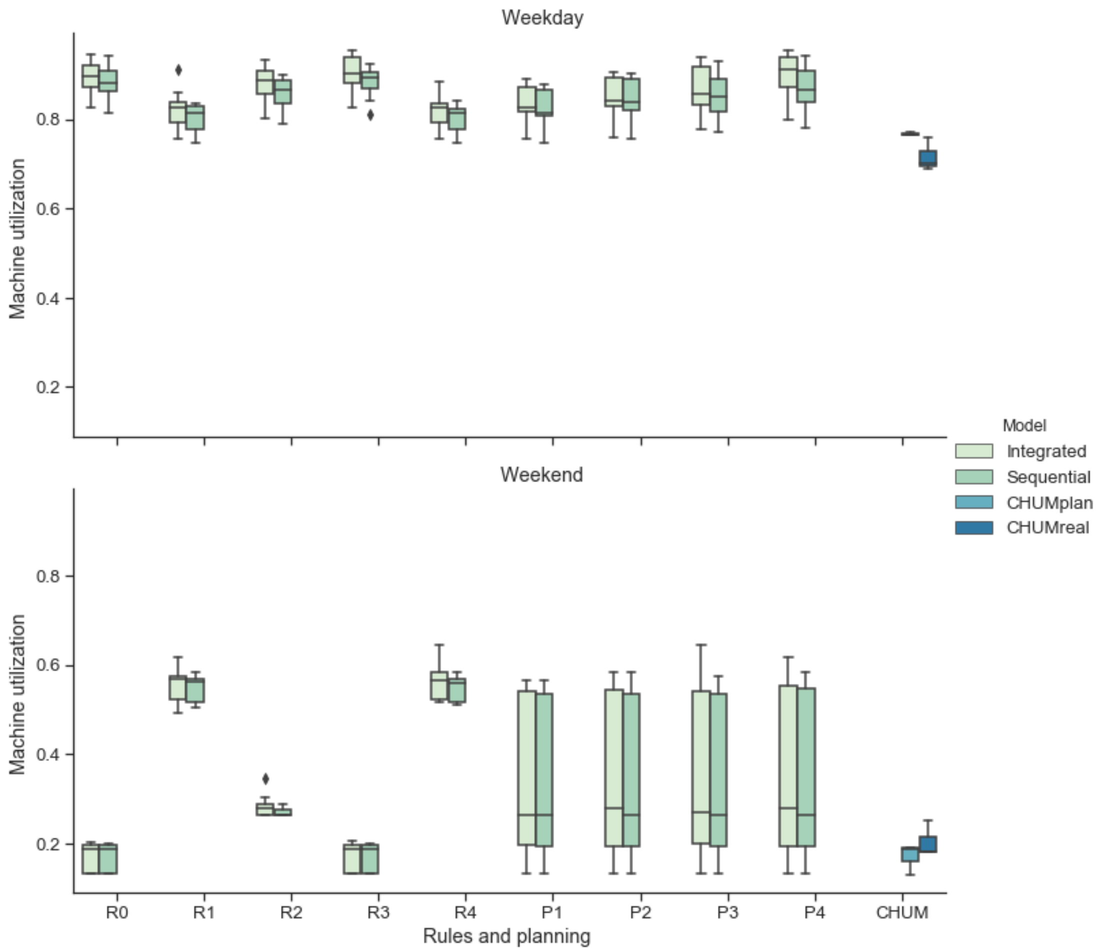

Figure 6: Machine utilization

Schedule stability The quality of the obtained solution in terms of stability varies by model as well as by indicator. Category changes increase when the sequential model is applied, reaching a maximum value of 154. The more choices we add to planning construction, the more category changes we see in the grid. The difference between the average value of P1 and P4 is 34 for the sequential model. Technologist training reduces category changes by an average of 33% . There is only a slight difference between the sequential and integrated models concerning the machine stability. However, the gap is large for planning stability, with an average value equal to 10. In all scenarios, the sequential model gives us the best results. In the sequential model, we start with the construction of the technologist schedule, with the objective of maximizing stability. Afterwards, we elaborate the appointment grid. We find that technologist schedule stability is much more important than the grid stability in terms of overall system performance.

Machine utilization Machine utilization depends on the planning construction method. The method that considers more choices in the planning of start and meal times increases machine utilization. It helps to find the best mix of planning that maximizes utilization. Rules that allocate more technologists during weekends (R1, R2, R4) decrease the machine utilization on weekdays by about 6%. However, they increase utilization on weekends by 28%. Due to the limited personnel resources, there must be a balance between machine utilization on weekends versus weekdays. Rules R1 and R4 produce the maximum values for machine utilization during weekends, but reduce utilization during the weekdays.

All tested scenarios outperform the current CHUM procedures. The ability to modify the grid design, and to assign different planning and a variable number of technologists to each room, leads to improved performance of the technologist schedules and the grid appointment.

Comparing the CHUM planned scenario and the CHUM real case, we find that the CHUMplan gives good results specially for the stability of technologist schedules, as well as the number of treated patients. On the one hand, technologist schedules in the CHUMplan are elaborated using an optimization model that minimizes the number of machine and planning changes. In addition, unexpected events such as absence are not considered in the planned scenario. This explains the gap between the CHUMplan and the CHUMreal in terms of schedule stability. On the other hand, in the planned scenarios, we don't take into account patient no-shows and the non-optimality of the patient assignment method. This justifies the difference in the number of treated patients between the two cases. Moreover, machine utilization in the real case may be influenced by overtime work that is difficult to consider in the planned scenarios, because it is usually undocumented.

To present a fair and accurate evaluation of our approach, we measure the projected gain from implementing our proposed models, compared to the CHUMplan model. We calculate the potential gain according to the best attained value and the average real value.

For the CHUMplan model, an increase of 21% in terms of the number of treated patients, 92% for category changes, 20% for machine utilization during the weekday, and 73% during the weekend. Concerning technologist schedule stability, we can produce schedules with zero machine or planning changes, especially in the sequential model.

5.2 Discussion

The experiment confirms that both the sequential and integrated models largely outperform the scheduling outcomes obtained by the CHUM approach.

As mentioned earlier, the CHUM approach fixes the planning assignment to each machine, and the number of allocated technologists to each shift. It also limits modifications according to the master grid. In contrast, our proposed model allows the ability to assign any planning to any room, and to generate the appropriate appointment grid depending on the technologist schedules.

We show that adding more flexibility to technologist planning construction improves the performance of the generated schedules. The gap in the number of treated patients between the planning with the least flexibility (P1) and the planning with the greatest flexibility (P4) is approximately 4% on average. Moreover, rules influence the scheduling efficiency. Rules R1 and R4 represent the perfect case of the CHUM working conditions: Technologists can work one weekend over two weeks. The application of these rules increases the number of treated patients by 7% compared to R0, which represents the current CHUM rule.

In general, both the sequential and integrated models work well and produce good results. The sequential model has superior performance for some indicators such as technologist stability, while other indicators, such as grid stability, do not perform as well. The sequential model by its nature does not simultaneously consider all of the performance indicators. Once the technologist schedules are generated, maximizing the machine utilization and schedule stability, they remain unchanged. The number of treated patients is considered in the second step of the model, which is the generation of the grid. In order to maximize gain while respecting all exam category constraints, the sequential model is forced to make more category changes in the grid. However, the integrated model simultaneously combines the elaboration of technologist schedules and the appointment grid. Although this version of the model is harder to solve, it takes into consideration all performance indicators. The simultaneous model is designed to find a balanced trade-off between all of the sub-objectives, thereby increasing the quality of the obtained solution, as shown by performance indicators.

6 Solution selection

CHUM managers were interested and motivated to apply the present study to their work. We presented an evaluation of our integrated and sequential models through different scenarios that consider the proposed planning (P1, P2, P3, P4) and rules (R0, R1, R2, R3, R4) applied to real data from the CHUM MRI department.

The results show that the integrated model leads to good overall performance in the elaboration of technologist schedules and the appointment grid. Our evaluation of this model demonstrated favorable results across all performance indicators. The CHUM managers decide to select the integrated model, and to choose the planning structure and the rule based on the number of treated patients.

To assist the CHUM managers with implementing the model, we classified obtained solutions based on the effort required to implement them, and their impact on the center performance. We created an impact-effort matrix, which is a decision-making tool that utilizes graphic representation of a problem. The objective is to prioritize solutions with high impact and quick gain, to determine the most efficient applications.

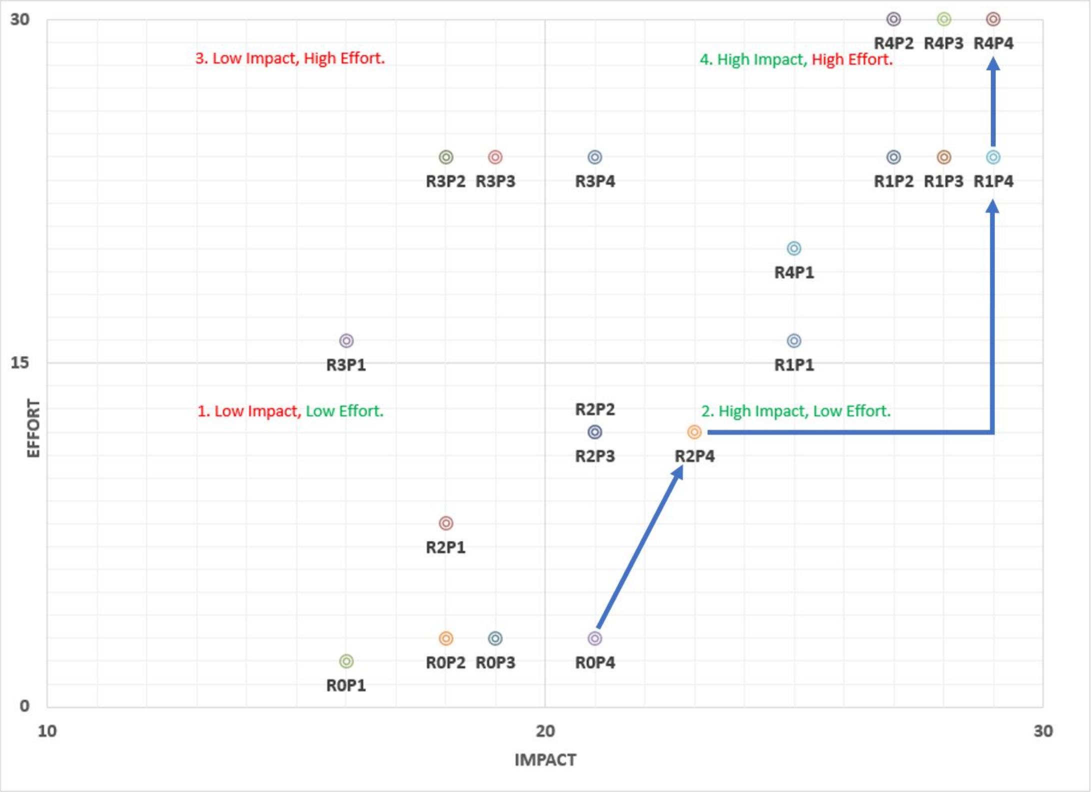

Figure 7: Impact-effort matrix

The impact axis in Figure 7 represents the percentage gain in the number of treated patients compared to the CHUMplan model. The effort axis represents the difficulty of implementing the solution in the CHUM center. The effort values were attributed during a meeting with the CHUM managers.

Figure 7 shows that solutions founded by applying R0 with P1, P2 and P3, produce a low impact with low effort. This is logical, because R0 represent the CHUM current rules. Rule R3 combined with P1, P2 and P3 is a waste of time when considering the low impact of that solution. The application of R1 and R4 is integrated among major projects that need complex activities. The establishment of R2 with P2, P3 and P4 is considered a quick win project, with high impact from low effort.

The arrows on the grid indicate the hierarchical direction of solution recommendations. Firstly, we are interested in actions that ensure high impact and require low effort. We propose starting with the current CHUM rules and to only change the planning construction (R0P4). Next, we move to R2P4 by increasing the technologist weekend assignment frequency to one weekend over four weeks. The second step represents the application of projects that need more effort and have bigger implications for staff. We suggest increasing the technologist weekend assignment frequency (R1P4). Integration of technologist training will lead to the maximization of gain. The proposed solution implementation plan allows for CHUM managers to improve their scheduling system efficiency and to enhance patient access to the center, while avoiding an abrupt transition for their staff.

7 Conclusion

In this paper, we introduce a structured framework to improve the scheduling system in a healthcare center. The proposed approach is defined step-by-step, starting with the problem definition and resolution, to the experimentation and the solution selection. We present the problem of technologist scheduling and appointment grid design. In most healthcare centers, these two elements are considered separately. However, in this paper, we study the simultaneous scheduling of technologists and the patient appointment grid. We take into account the real-life constraints of the problem. We develop a mixed-integer programming model with two versions: integrated and sequential. The integrated version combines the construction of the appointment grid and technologist schedules. In the sequential version, we start by scheduling the technologists, and subsequently elaborate the appointment grid. We examine the impact of the number of technologists allocated to execute the exam on the total number of treated patients. The aim of this study is to evaluate the two versions of the model, using real data from the MRI department of the CHUM radiology center. The evaluation is performed based on the current scheduling approach of the center, by testing several technologist working rules and planning construction methods. The solution performance is measured by the number of treated patients, schedule stability and machine utilization.

The two versions of the model give good results compared to the CHUM scheduling approach.

However, the sequential model gives satisfying results according to some indicators, such as the technologist schedules stability, to the detriment of other indicators, such as the grid appointment stability. This is due to the non-integration of all objectives simultaneously. Added flexibility in the technologist planning construction, and an increase in the frequency of technologist weekend assignments improve the scheduling system performance.

References

Alfares, H. K. (2004). Survey, categorization, and comparison of recent tour scheduling literature. Annals of Operations Research, 127(1-4):145–175.

Bacchus, B. and Mackenzie, M. (2019). Waiting your turn: Wait times for health care in canada, 2019 report. Fraser Institute, https://www.fraserinstitute.org/sites/default/files/waiting-your-turn-2019-execsum.pdf.

Bentayeb, D., Lahrichi, N., and Rousseau, L.-M. (2018). Patient scheduling based on a service-time prediction model: a data-driven study for a radiotherapy center. Health care management science, pages 1–15.

Brunner, J. O., Bard, J. F., and Kolisch, R. (2009). Flexible shift scheduling of physicians. Health care management science, 12(3):285–305.

Brunner, J. O., Bard, J. F., and Kolisch, R. (2010). Midterm scheduling of physicians with flexible shifts using branch and price. IIE Transactions, 43(2):84–109.

Burke, E. K., De Causmaecker, P., Berghe, G. V., and Van Landeghem, H. (2004). The state of the art of nurse rostering. Journal of scheduling, 7(6):441–499.

Chen, P.-S., Lin, Y.-J., and Peng, N.-C. (2016). A two-stage method to determine the allocation and scheduling of medical staff in uncertain environments. Computers & Industrial Engineering, 99:174–188.

Dunning, I., Huchette, J., and Lubin, M. (2017). Jump: A modeling language for mathematical optimization. SIAM Review, 59(2):295–320.

Erhard, M., Schoenfelder, J., Fügener, A., and Brunner, J. O. (2018). State of the art in physician scheduling. European Journal of Operational Research, 265(1):1–18.

Ernst, A. T., Jiang, H., Krishnamoorthy, M., and Sier, D. (2004). Staff scheduling and rostering: A review of applications, methods and models. European journal of operational research, 153(1):3–27.

Huang, Y. and Verduzco, S. (2015). Appointment template redesign in a women's health clinic using clinical constraints to improve service quality and efficiency. Applied clinical informatics, 6(02):271–287.

Ogulata, S. N., Koyuncu, M., and Karakas, E. (2008). Personnel and patient scheduling in the high demanded hospital services: a case study in the physiotherapy service. Journal of medical systems, 32(3):221–228.

Pérez, E., Ntaimo, L., Malavé, C. O., Bailey, C., and McCormack, P. (2013). Stochastic online appointment scheduling of multi-step sequential procedures in nuclear medicine. Health care management science, 16(4):281–299.

Pérez, E., Ntaimo, L., Wilhelm, W. E., Bailey, C., and McCormack, P. (2011). Patient and resource scheduling of multi-step medical procedures in nuclear medicine. IIE Transactions on Healthcare Systems Engineering, 1(3):168–184.

Stolletz, R. and Brunner, J. O. (2012). Fair optimization of fortnightly physician schedules with flexible shifts. European Journal of Operational Research, 219(3):622–629.

Van den Bergh, J., Beliën, J., De Bruecker, P., Demeulemeester, E., and De Boeck, L. (2013). Personnel scheduling: A literature review. European journal of operational research, 226(3):367–385.

Van Nynatten, L. and Gershon, A. (2017). Radiology wait times. University of Western Ontario Medical Journal, 86(2):65–66.

Van Sambeek, J. R., Joustra, P. E., Das, S. F., Bakker, P. J., and Maas, M. (2011). Reducing mri access times by tackling the appointment-scheduling strategy. BMJ Qual Saf, 20(12):1075–1080.

Vieira, B., Demirtas, D., van de Kamer, J. B., Hans, E. W., and van Harten, W. (2018). A mathematical programming model for optimizing the staff allocation in radiotherapy under uncertain demand. European journal of operational research, 270(2):709–722.

Yuura, H., Miyamoto, T., and Hidaka, K. (2017). An integer programming model for radiographer scheduling considering skills and training. In 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), pages 889–893. IEEE.