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Design and analysis of an outpatient orthopaedic clinic performance with discrete event simulation and design of experiments

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ABSTRACT

Considering that demand for healthcare services is constantly increasing, outpatient services must improve their performance. Being able to satisfy the demand with a limited outpatient service capacity is an important operational challenge. The objective of our research consists in studying the relationships and interactions between patient flows, resource capacity (number of consulting rooms and number of nurses) and appointment scheduling rules in order to improve an outpatient orthopaedic clinic performance. Discrete event simulation is used to model outpatient flows. An experimental design was developed to test how to assign consulting rooms and nurses to each orthopedist considering four appointment scheduling rules and three patient flow types of varied complexity. Analysis of variance and the Tukey test are used to evaluate the simulation results. Our conclusion is that in order to improve the outpatient orthopaedic clinic performance, resources (consulting rooms, nurses) and appointment scheduling rules must be adapted to the different patient flows.

1. Introduction

Considering a growing demand for healthcare services, it becomes essential for outpatient services to review how they do things in order to improve and increase their performance. Outpatient services such as consulting, treatments and follow-up of patients, coming through emergency or with a scheduled appointment, are often grouped together in a unique location. Being able to satisfy the demand with a limited outpatient service capacity is an important operational challenge.

In this paper we study an outpatient orthopaedic clinic located in a public medical and social healthcare center in the province of Québec (CSSS) and that uses its radiology services. Approximately 22,000 patients come to the clinic every year. This represents between 400 and 450 patients per week depending on the number of orthopedists present. The decision makers of the outpatient orthopaedic clinic are concerned by the importance of reducing patient waiting times while keeping a high proportion of occupied time for medical staff. Indeed, they are receiving many complaints about long patient waiting times.

The clinic is opened from 8h00 AM to 5h00 PM, Monday to Friday and includes six examination rooms. A total of eight orthopedists and four nurses work in the outpatient orthopaedic clinic. On Mondays, Tuesdays and Wednesdays consulting periods are reserved to specific orthopedists, two on each day. Table 1 presents the outpatient orthopaedic clinic schedule over a week. This schedule is constructed according to each orthopedist's surgery schedule.

Each consulting period is managed by an orthopedist using three examination rooms and working with two nurses. On Thursdays and Fridays only half a day is reserved to a specific orthopedist leaving the other periods free for any orthopedist wishing to use them. The weekly number of consulting rooms and nurses required by an orthopedist depend on his or her patient caseload. For instance, some orthopedists may need to be at the clinic two days a week while others may need only one day. Orthopedists' caseload is variable. For instance, an orthopedist may have to see 80 patients weekly and another one only 50. According to the orthopaedists availability, the number of patients seen each day may vary between 40 and 50 per orthopaedist. Consulting rooms and periods must thus be assigned to each orthopaedist together with nurses to assist them weekly. Since the clinic intends to hire new orthopedists soon the assignment of consulting rooms and nurses to orthopedists and the appointment schedules (rules and number of patients) need to be reviewed.

The number and the type of patients scheduled daily vary according to the number of consulting rooms and the number of nurses available. Generally each patient has an appointment with

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Table 1
Weekly orthopedists' schedules of the outpatient orthopaedic clinic.

Day	Room 1 Nurses 1 et 2	Room 2	Room 3	Room 4 Nurses 3 et 4	Room 5	Room 6
Monday	Orthopedist 1			Orthopedist 2		
Tuesday	Orthopedist 3			Orthopedist 4		
Wednesday	Orthopedist 5			Orthopedist 6		
Thursday	Free	Free	Free	Orthopedist 7		
Friday	Orthopedist 8			Free	Free	Free

a specific orthopedist and the consulting periods assigned to each orthopedist are known in advance. Appointment schedules for each orthopedist cover a three month period.

The appointment scheduling rule currently used by the outpatient clinic consists in scheduling 2–3 patients per orthopedist every 10 min with a lunch break between 11h30 AM and 12h30 PM. With this rule it is possible to schedule 57 patients per day for each orthopedist, most of them are scheduled before 11h30 AM and only a few after 2h30 PM. This schedule usually generates bottlenecks and very long patient waiting times during mornings. This is one of the reasons why more efficient appointment scheduling rules needed to be defined and tested.

Patients may follow up to three trajectories (Fig. 1). Rectangles are for process steps, arrows for patients traveling through the clinic and triangles for patients waiting:

- Trajectory 1: The patient must go to radiology before meeting with the orthopaedist. This trajectory has two steps.
- Trajectory 2: The patient only meets the orthopaedist. This trajectory has only one step.
- Trajectory 3: The patient must have his plaster removed by the nurse, go to radiology and meet the orthopaedist. This trajectory has three steps.

Data provided by the clinic show that:

- 35% of patients follow trajectory 1.
- 50% of patients follow trajectory 2.
- 15% of patients follow trajectory 3.

This is a mix flow type which is the one usually observed in most orthopaedic clinics. However percentages may differ.

The decision makers wish to reduce the mean patient lead time to less than 60 min and to determine rules for the assignment of consulting rooms and periods to host the new orthopedists. Some of the current orthopedists are afraid that improving patient lead times might reduce the daily number of patients they can see at the clinic and increase their idle time. They think that each orthopedist should be able to see at least 50 patients daily, if they wish, and that their proportion of occupied time should be at least 85%.

The objective of our study consists in studying the relationships and interactions between patient flow types, resource capacity (number of consulting rooms and number of nurses) and appointment scheduling rules in order to find a way to improve an outpatient orthopaedic clinic performance. Our research intends to verify, for orthopaedists needing more than one day weekly to see patients, if patients should be scheduled according to their trajectory. This research contributes to the literature in three ways. First, it considers and evaluates different patient flows for one process (one, two or three-step trajectories). Few papers exist on patient trajectories and on their relationship with appointment scheduling rules in the literature (Santibanez, Chow, French, Putterman, & Tyldesley, 2009; White, Froehle, & Klassen, 2011). Second, this research also takes into account resource assignment (consulting rooms, nurses), appointment scheduling rules and how they impact on the patient flows. The study of the relationship between resource assignment, appointment scheduling rules and patient flows will allow a better understanding of how to plan resources in complex systems. Finally, our model is about a real case study of an outpatient clinic which is not the case of many papers that are more theoretical (Cayirli, Veral, & Rosen, 2006; Liu & Liu, 1998; Rohleder & Klassen, 2000; Swisher, Jacobson, et al., 2001; Yang, Lu, & Quek, 1998). Our model was built with empirical data representing real service times. It takes into account orthopedists lateness and absence and walk-in patients.

2. Literature review

2.1. Appointments scheduling

Appointment scheduling in an outpatient clinic consists in determining the sequence of patients to optimize some performance measures. Many papers can be found in the literature on appointments scheduling. They can be divided into two categories: static and dynamic problems. When appointments are scheduled without the possibility to modify the schedule, it is considered as a static problem. This is how appointments are scheduled in most healthcare services. Therefore many papers are devoted to these scheduling appointment problems. When the appointment schedule can be constantly reconsidered during a given day

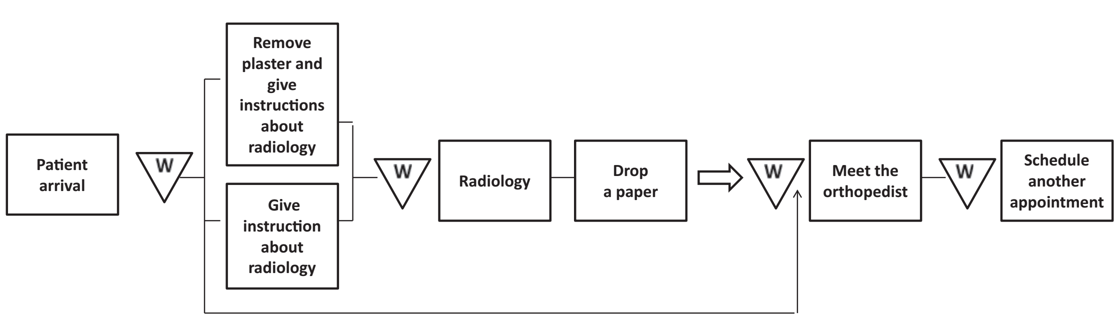

Fig. 1. Mapping patient trajectories.

depending on the current state of the clinic (or any other healthcare system), it is considered as a dynamic problem (Fries & Marathe, 1981; Liao, Pegden, & Rosenshine, 1993; Patrick, 2012).

Most appointment schedules are constructed based on specific decision rules to minimize negative effects related to patients arriving late, no-shows or walk-ins. Cayirli and Veral (2003) present a literature review on decision rules to schedule appointments. The most studied rules are: (1) variable blocks/fixed intervals rule consisting in planning appointment periods of varied size (one, two or more patients) while keeping fixed intervals (Cayirli & Yang, 2012; Denton & Gupta, 2001), (2) individual blocks/variable intervals rule consisting in planning appointment blocks of size one with intervals of varied size (Ho & Lau, 1992; Vanden Bosch, Dietz, & Simeoni, 2000; White et al., 2011) and (3) DOME rule consisting in planning m appointment blocks during fixed short periods of time (intervals) at the beginning and at the end of the day, and the remaining ones during fixed long periods of time in the middle of the day (Robinson & Chen, 2003; White et al., 2011). In our research the variable block/fixed intervals rule is used to schedule patients in two ways: one patient every 10 min or two patients every 20 min. Another rule, variable block/variable intervals, has been defined and tested. A time study performed at the clinic allowed us to determine the variable blocks and intervals. This rule is detailed in Section 3.2.

Few authors worked on multiple steps healthcare systems (Saremi, Jula, ElMekkawy, & Wang, 2013; Swisher et al., 2001). For one-step healthcare systems, researchers worked mainly on the patient arrival process. They studied the consequence on outpatient services performance of late patients (Cayirli & Yang, 2012; Robinson & Chen, 2003; Tai & Williams, 2012), of no-shows (Chakraborty, Muthuraman, et al., 2010; Klassen & Rohleder, 1996, 2004) and of walk-ins (Salzarulo, Bretthauer, Côté, & Schultz, 2011). The main strategies used to make up for late patients, no-shows and emergencies (unplanned patients) are overbooking (LaGanga, 2011; LaGanga & Lawrence, 2007) and leaving free appointment blocks (Klassen & Rohleder, 2004). Some authors studied how varied consulting times with the orthopedist impacted on service performance (Salzarulo et al., 2011; White et al., 2011) while others measured the impact on service performance of late patients and of the orthopedists' service breaks (Hart, 1995; Liu & Liu, 1998; Santibanez et al., 2009).

In the literature, most performance measures used to evaluate appointment schedules are average patient waiting time, average personnel idle time and average personnel overtime. It may be difficult to obtain the best values for those three measures at the same time. A multi-objective function is usually defined with weights allocated to each measure (Babes & Sarma, 1991; Denton et al., 2001; Jared, Zhen, et al., 2010; Mital, 2010).

Finally, all these appointment scheduling problems are either solved with analytic methods (Denton et al., 2001; Robinson & Chen, 2001; Guangfu & Williams, 2011) or with simulation techniques (Klassen & Yoogalingam, 2009; Rohleder, Lewkonia, Bischak, Duffy, & Hendijani, 2011; Wijewickrama & Takakuwa, 2012). Considering that our study includes many factors interacting between each other, we used discrete event simulation to test scheduling rules.

2.2. Capacity management

Capacity management of outpatient services consists in determining the resources required (consulting rooms, doctors, and nurses) to improve performance. Côté (1999) determined the number of consulting rooms required to serve all patients. He found that having too many consulting rooms results in a transfer of the waiting time from the waiting room (patients) to the consulting room (doctors and nurses). Santibanez et al. (2009) showed that there are more advantages for doctors to share the use of the same examination rooms. Berg et al. (2009) showed that there is a positive linear relationship between the number of patients examined and the number of examination rooms. They tested ratios of one examination room per doctor (1:1) and of two examination rooms per doctor (2:1). With a higher ratio, more auxiliary personnel (nurse, secretaries) are needed to improve performance. They also came to the conclusion that a better appointment schedule could increase the number of patients seen without adding resources. Hulshof et al. (2012) used two types of rules to assign consulting rooms to doctors. The first one called "patients to doctor" assigns one consulting room to each doctor and the second one called "doctor to patients" assigns many consulting rooms to all doctors, doctors traveling from one room to the other to meet their patients. The "doctors to patients" rule is more efficient when the traveling time between two rooms is less than the time required to prepare the patient. They also developed a method to compute the maximum number of consulting rooms to assign to each doctor. In our research we vary the number of consulting rooms and the number of nurses.

2.3. Patient trajectory

Patient trajectories in healthcare systems were mostly analyzed using simulation models through continuous improvement processes. Jun, Jacobson, et al. (1999) surveyed more than 100 papers on simulation modeling of healthcare systems. Young (2005) explained how simulation can help healthcare decision makers determine alternative patient trajectories with a Lean methodology. Cooper, Brailsford, and Davies (2007) mentioned that simulation is especially useful when there are queues for limited resources, budgetary constraints or interactions between individuals (nurses, doctors, patients) which is the case for many hospitals including outpatient services. Rohleder et al. (2011) used discrete event simulation to reduce patient waiting time in an outpatient orthopaedic clinic. Through the simulation model, different solutions were tested to determine appointment schedules that can improve performance, make better use of human resources and assure that the clinic could open on time. However they did not test combinations of trajectories.

Not so many studies present the interactions between appointment scheduling rules, resource capacity and patient trajectories. Santibanez et al. (2009) used simulation modeling to evaluate the impact of a clinic opening time, the number of medical students, appointment planning (rules, consultation duration, adding new appointments) and resource assignment (fixed or flexible) on patients waiting time, personnel overtime and proportion of occupied time. He modeled three oncology services (radiology, surgery and medical oncology) opened simultaneously and sharing 25 examination rooms. The model takes into account the presence of residents and medical students during the patient's examination. After analyzing the scenarios, Santibanez observed that the best results were obtained when simultaneous modifications were applied to the system. These led to a 70% reduction of patients' waiting time and a 25% reduction of the space required for the consulting rooms without any decrease in the number of patients seen. He concluded that for a better performance, clinics must open on time, appointments must be planned carefully and consulting rooms must be assigned dynamically to the different oncology services according to their specific needs. Only one patient trajectory was studied contrary to our research.

White et al. (2011) developed a discrete event simulation model to study six scheduling rules, varied consulting times, up to 5 consulting rooms and different percentages of patients flowing through radiology and how it had a joint impact on the proportion of occupied time for medical personnel and patients' waiting time.

Results suggest that planning appointments of small duration and variance at the beginning of the day (and conversely, appointments of long duration and variance at the end of the day) reduces patients waiting time without reducing the proportion of occupied time for doctors or expanding clinic business hours. Moreover they showed, as expected, that increasing the number of consulting rooms beyond a certain threshold has no effect on the proportion of occupied time for orthopedists. However, having too few consulting rooms will result in a negative effect on patient flows. Their simulation model considers two patient trajectories (with and without a radiology step). Each doctor receives 32 patients during a 4 h period with 5 secretaries, 3 nurses and 2 radiologists. During that period radiologists' work is dedicated to the clinic. Our research differs from White et al. (2011)'s as we consider a combination of trajectories resulting in different flow types. We also consider a mix flow with 3 steps instead of 2. Moreover we studied two additional flow types to determine appointment schedules and resource assignment when an orthopaedist's caseload requires more than one day.

In our research, interactions between appointment scheduling rules, the number of consulting rooms and the number of nurses assigned to orthopedists were studied considering three patient flow types. To our knowledge, our research is among the few ones (White et al., 2011) taking into account a system with many patient flow types characterized by multiple steps, different patient loads and the fact that many doctors must share limited resources (six consulting rooms and four nurses). Our results will provide ways to assign patients to each orthopaedist's working days for a better use of resources when more than one day is necessary to see them, to schedule appointments daily and to assign consulting rooms and nurses to orthopedists weekly.

3. Research methodology

3.1. Discrete event simulation

Discrete event simulation has been used to model patient trajectories at the outpatient orthopaedic clinic. Relevant data was collected at the clinic to be able to build an appropriate simulation model with the ARENA software. The model's entities are patients. It begins when a new patient arrives at the clinic. The patient then waits to be called by the. The nurse will either:

(1) Give instructions about radiology to the patient (trajectory 1).
(2) Invite him to meet directly the orthopedist (trajectory 2).
(3) Remove his plaster and give instruction about radiology (trajectory 3).

Once the patient has finished with radiology he comes back to the clinic and drops a sheet in the required pigeonhole to inform the nurse that he is now ready to meet the orthopedist. The nurse will first verify if the patient file is complete. Before the consult with the orthopaedist the nurse helps the patient to get settled in the consultation room. When an orthopaedist has a consult with a patient, a nurse may assist him or not (prepare injections, bandages, etc.). The time spent by the nurse when meeting with the patient and to get the patient settled has been measured and is given in Table 2. After his consult with the orthopedist the patient can schedule another appointment, if needed, and leave the clinic. The orthopaedist completes files after meeting with the patient. The time to complete the files has also been measured (Table 2). The times provided in Table 2 also include patient traveling times in the clinic.

Interarrival patient rates at the clinic were determined from real patient arrival times (or according to appointment schedules). To reflect reality adequately our model considered orthopedists lateness and absence and walk-in patients as fixed parameters (they correspond to the worst values observed). According to the data collected there are on average 5 walk-ins every day. Interarrival walk-ins rates at the clinic were determined from real walk-ins arrival times.

Orthopaedists are absent on average 177 min of their 8 h shift (37%) because they arrive late or must perform other tasks in the hospital. We focused on orthopaedist's absence because nurses' absence time is very small and has no real impact on patient lead times. We are aware that using fixed parameters for walk-ins and lateness does not reflect completely the reality. We intend to tests varied values in future research.

Two basic models were developed. The first model is based on real values obtained from data collection, such as patient arrival times, and is named the REAL model. The second model is based on patient appointment schedules and is named the THEORETICAL model. Both basic REAL and THEORETICAL models were built with statistical distributions of the service times at each step of the patient's trajectory (Table 2).

The REAL model reproduces the current process at the clinic and was tested to make sure that it represented the real data collected. It takes into account patients arriving on time or late. The REAL model was validated by comparing the average observed and simulated lead times (difference between the patient leaving time and arrival time) over the four days and with different patient arrival rates daily (number of patients per period). Lead time is a good indicator in such a process since it includes all independent variables (service time for each step, arrival rates, etc.) and their variance (Kelton, Sadowski, & Sturrock, 2007).

The simulation model was run 150 times. Table 3 provides comparison between observed patient lead times and simulated patient lead times.

The difference between the average observed patient lead time and the average simulated patient lead time according to real patient arrival rates is less than 5% for each simulated day. Moreover our simulation model is validated by the fact that the same model was used to simulate the clinic process for the four days (Monday to Thursday) and different data. Since the clinic activities are over a finite horizon, there is no need to consider a warm-up

Table 2
Statistics used in the simulation model.

Steps	Mean observed service times (min)	Standard deviation (min)	Statistical distribution (min)	Chi-square (*p*-value)
Remove plaster	4.58	2.51	2 + Expo (3.42)	<0.005
Nurses give instruction for radiology	2.19	1.41	Gamm (0.621, 3.53)	0.308
Radiology	21	8.48	Norm (21, 8.41)	>0.75
Nurse service time to get the patient settled (before the consult)	1.75	2.19	Expo (1.75)	<0.005
Meet the orthopaedist	4.63	2.84	Gamm (2.14, 2.16)	0.232
Nurse service time with the orthopaedist (during the consult)	2.01	2.99	Logn (1.99, 3.04)	0.245
Time to complete files by the orthopaedist (after the consult)	1.22	1.08	3∗Beta (0.531, 0.592)	>0.15
Schedule another appointment	2.20	1.51	Logn (2.21, 1.55)	0.121

Table 3
Average observed and simulated patient lead times.

Day	Rooms 1 to 3			Rooms 4 to 6		
	Average observed lead time (min)	Average simulated lead time (min)	Difference (%)	Average observed lead time (min)	Average simulated lead time (min)	Difference (%)
Monday	142.48	141.18	0.91	139.83	140.87	0.74
Tuesday	Canceled			111.27	116.40	4.41
Wednesday	88.03	91.86	4.17	121.30	118.20	2.62
Thursday	Canceled			146.98	147.73	0.51

period. However our simulation model makes sure that the clinic is empty at the end of each run.

The THEORETICAL model is similar to the REAL one. Patient arrivals in the THEORETICAL model are determined according to the scheduled appointments. We assume that patients arrive on time. Therefore it does not take into account patients lateness or patients arriving before their appointment time. The latter represents 76% of all patients. Many patients choose to arrive early. This voluntary waiting time is thus not taken into account in our model. We decided to exclude patient lateness from this model to make sure that we could measure only the impact of the appointment scheduling rules on patient lead times, the number of patients seen by an orthopedist and the proportion of occupied time for orthopedists. Patients arrival was considered as a fixed parameter (on time arrival) and appointment scheduling rules as multilevel decision factors (Section 3.2).

Patients lateness will be tested in future research. However we kept in our theoretical model orthopaedists lateness and walk-ins for more realistic results. The THEORETICAL model was used to simulate the experiments described in the next section.

3.2. Design of experiments, decision factors and performance measures

Considering that the appointments at the clinic were canceled on Tuesday and Thursday, it left us two typical days for our experiments. Monday was used in our design of experiments because it represented the worst case (the greatest number of patients scheduled) as its average patient lead time was the highest.

Our experimental design considers four decision factors: (1) patient flow types, (2) appointment scheduling rules based on orthopedist service times, (3) number of nurses and (4) number of consulting rooms.

3.2.1. Patient flow types

The proportion of patients going through the different trajectories was measured and different patient flow types were defined. The following mix flow is the closest to the real outpatient clinic process: 50% of patients go through trajectory 2, 35% through trajectory 1 and 15% through trajectory 3. This flow type presently requires two nurses (to remove the plaster, prepare patients, etc.) and at least three consulting rooms to minimize orthopaedists 'idle time. We tested if this mix flow type could be improved with less consulting rooms, less nurses and new appointment scheduling rules. We also verified if different trajectory combinations might reduce patients waiting time, orthopaedist's idle time and required resources.

Let us explain through an example how patients can be scheduled if the weekly orthopaedist's caseload corresponds to 80 patients. The 80 patients would be divided as follows: 48 follow trajectory 2, 24 trajectory 1 and 8, trajectory 3. These proportions correspond approximately to the mix flow. Considering that orthopaedist can only see 50 patients daily, resources must be assigned to that orthopaedist over 1.5 days. Table 4 provides three solutions to distribute the 80 patients over 1.5 days depending on their flow type.

With solution 1, 15 trajectory 1 patients, 30 trajectory 2 patients and 5 trajectory 3 patients could be seen the first day (three consulting rooms and two nurses are required). On day 2, 9 trajectory 1 patients, 18 trajectory 2 patients, and 3 trajectory 3 patients could be seen (three consulting rooms and two nurses are required). This flow type is the mix flow type.

With solution 2, 24 trajectory 1 patients, 18 trajectory 2 patients, and 8 trajectory 3 patients could be seen the first day (three consulting rooms and two nurses are required for this mix flow type). On day 2, the orthopaedist would see 30 trajectory 2 patients and no patient following other trajectories. This flow type is the orthopaedist flow type.

With solution 3, the first day is devoted to trajectory 2 patients only (48). On day 2, 24 trajectory 1 patients and 8 trajectory 3 patients could be seen. This flow type is the radiology flow type.

In the first solution, 4 nurses and 6 consulting rooms are required weekly by the orthopaedist. For solutions 2 and 3, the number of consulting rooms and nurses required still need to be determined since these solutions are not currently used by the clinic. We assume that it could be possible to see the same number of patients with less resource.

The following three flow types were tested:

- Flow type 1 (mix): 35% through trajectory 1, 50% of patients go through trajectory 2 and 15% through trajectory 3.
- Flow type 2 (orthopedist): all patients go through trajectory 2.
- Flow type 3 (radiology): 50% of patients go through trajectory 1 and 50% through trajectory 3.

Table 4
Patient distribution among different flow types.

Patient distribution	Number of patients					
	Solution 1		Solution 2		Solution 3	
	Day 1 (8 h)	Day 2 (4 h)	Day 1 (8 h)	Day 2 (4 h)	Day 1 (8 h)	Day 2 (4 h)
Flow type	Mix	Mix	Mix	Ortho	Ortho	Radiology
Trajectory 1	15	9	24	0	0	24
Trajectory 2	30	18	18	30	48	0
Trajectory 3	5	3	8	0	0	8
Daily total number of patients	50	30	50	30	48	32
Number of consulting rooms	3	3	3	To be tested	To be tested	To be tested
Number of nurses	2	2	2	To be tested	To be tested	To be tested

Those three flow types were modeled in the simulation model. Our objective is to determine if the same scheduling and resource assignment rules should be used for all flow types.

3.2.2. Appointment scheduling

The appointment scheduling rules impose a patient arrival pattern to the clinic. The choice of the rules to test was based on the following: (1) low variability of orthopedists service times (orthopedists service times vary from 5 to 8 min per patient), (2) most orthopedists wish to see between 40 and 55 patients during an eight-hour shift, and (3) the last patient's appointment should be no later than 4h00 PM (the orthopedist has then enough time to complete his files). Since all orthopedist service times are less than 10 min and to ease secretaries' work, appointments were scheduled every 10 min. We are aware that if the time between two appointments is close to the real orthopedist service time this will reduce the orthopedist waiting time.

The appointment scheduling rule currently used by the outpatient clinic (rule 0, Section 1) consists in scheduling 2 or 3 patients per orthopedist every 10 min between 8h00 AM to 2h30 PM with a lunch break between 11h30 AM and 12h30 PM. The three appointment scheduling rules described below schedule patients between 8h00 AM and 3h50 PM. The total scheduling period is longer since it ends at 3h50 PM instead of 2h30 PM for rule 0. It allows to smooth appointments over the whole day. No patients are scheduled between 12h00 and 12h30 PM during the lunch break which is reduced compared to rule 0.

Since the time spent by the orthopedist with a patient does not vary a lot and does not exceed 10 min, it makes sense scheduling a patient every 10 min per orthopedist. This is rule 1. Orthopedists do not really appreciate this rule because they think it can only be efficient (meaning orthopedists will not wait) if patients arrive on time. This rule performs very well when consulting times are short as shown in Klassen & Rohleder, 1996; Rohleder & Klassen, 2000. They obtained reduced patient waiting time for a one step process. We expect rule 1 to be adequate for flow type 2.

Appointment scheduling rule 2 consists in scheduling two patients every 20 min per orthopedist. With this rule, considering that it is more likely to have at least one of the two patients on time, orthopedists should wait less. This rule is efficient when consulting times are short. Indeed it reduces the risk for the orthopaedist to wait since one patient should be present if either one of them is late. In case the patient is late his waiting time might be longer. We expect rule 2 to be adequate for flow type 2.

Appointment scheduling rules 1 and 2 are among the most known and used in the healthcare sector especially for one-step patient trajectories (patient–doctor). However as mentioned before, it is impossible to schedule 50 patients between 8h00 AM and 4h00 PM (the minimum daily number of patients desired by the orthopedists) with appointment scheduling rules 1 and 2 (45 and 46 patients respectively). To schedule 50 patients for each orthopedist every day, the outpatient orthopaedic clinic would have to be opened until 7h00 PM. Rules 1 and 2 do not consider services required by patients (plaster, radiology, etc.).

Rule 3 considers that the patient is always available when the orthopaedist is ready to see him (every 10 min) regardless of the trajectory type. For instance if the patient must go through radiology before meeting with the orthopaedist, his appointment must be scheduled accordingly to avoid bottlenecks.

Appointment scheduling rule 3 consists in scheduling seven patients per 60 min periods for each orthopedist according to the type of service required by patients. Consider, for instance, the scheduling pattern of the first period of the day starting at 8 h AM. Two patients needing radiology services (trajectory 1) are scheduled at 8 h AM to be seen later by an orthopedist. At 8h10 AM one patient going through trajectory 3 (orthopedist only) is scheduled followed by another one at 8h20 AM. The orthopaedist working day begins at 8h10 AM. At 8h30 AM one patient needing to go through trajectory 3 (with plaster) and one through trajectory 1 (radiology) are planned. Let us note that at that time the orthopedist will be available to see the first patients coming back from radiology. Finally a trajectory 2 patient is scheduled at 8h50 AM. Appointment scheduling rule 3 imposes different types of patients from period to period. With rule 3, it is possible to schedule 53 patients daily for each orthopedist which is more than rules 1 and 2. We expect rule 3 to be better for flow type 1 than rule 0.

The appointment scheduling rules can be summarized as follows:

- Rule 0: schedule 57 patients daily for each orthopedist, most of them before 11h30 AM.
- Rule 1: schedule one patient every 10 min per orthopedist. With this rule it is possible to schedule 45 patients daily for each orthopedist.
- Rule 2: schedule two patients every 20 min per orthopedist. With this rule it is possible to schedule 46 patients daily for each orthopedist.
- Rule 3: schedule seven patients per 60 min periods for each orthopedist according to the type of service required by patients. With rule 3, it is possible to schedule 53 patients daily for each orthopedist.

3.2.3. Capacity allocation

Management capacity of an outpatient services consists in determining the resources required (consulting rooms, doctors, and nurses) to improve performance. In our research we vary the number of consulting rooms (1–3) together with the number of nurses (1 and 2) assigned to each orthopaedist. Each nurse is assigned to a specific orthopaedist as in the clinic under study.

The decision factors and their respective levels can be found in Table 5.

3.2.4. Performance measures

The impact of the decision factors on performance measures was evaluated from the patients and the orthopedists point of view. The patient lead time in the outpatient clinic measures the impact on patients while the number of patients seen and the proportion of occupied time for orthopedists measure the impact on orthopedists.

A patient lead time is the time elapsed between his arrival and his departure from the clinic. It includes waiting and service time. For our model, the number of patients seen by an orthopedist is the number of patients who completed all steps of a trajectory during regular opening hours. If some patients are still in the waiting room after regular opening hours, orthopedists and nurses have to work overtime to see them. In the province of Québec, orthopedists are on fee for service. Therefore their salary depends on the number of patients seen which is thus an important performance measure for them. It is also an important performance measure to evaluate the clinic efficiency. Nurses' overtime is costly for the clinic. We are thus interested by the number of patients seen during regular hours and our model does not count patients after regular hours. The proportion of occupied time for orthopedists is the ratio of the time spent doing work related to patients (consulting, filling files, verifying X-rays, etc.) over the total time spent at the clinic (including idle time).

3.2.5. Design of experiments

72 experiments were performed (3 consulting rooms $\times$ 2 nurses $\times$ 4 appointment scheduling rules $\times$ 3 types of patient flow)

Table 5
Decision factors and their respective levels.

Decision factor	Number of levels	Level descriptions
Number of consulting rooms (S) assigned to orthopedists	3	1 room 2 rooms 3 rooms
Number of nurses assigned to orthopedists (I)	2	1 nurse 2 nurses
Patient flow type (F) according to trajectories: (1) Radiology–orthopedist (2 steps) (2) Orthopedist (1 step) (3) Plaster–radiology–orthopedist (3 steps)	3	Mix: 35% (trajectory 1), 50% (trajectory 2), et 15% (trajectory 3) Orthopedist: 100% (trajectory 2) Radiology: 50% (trajectory 1) et 50% (trajectory 3)
Appointment scheduling rule (R)	4	Current (no specific rule) (rule 0) Uniform: 1 patient every 10 min (rule 1) Uniform: 2 patients every 20 min (rule 2) Pattern of 7 patients every 60 min (rule 3)

with the simulation model and 5 replications per experiment were computed for a total of 360 simulations. Analysis of this experimental design was done with the Minitab 16 software with a significance level of 5%. When a decision factor or an interaction was significant, the Tukey test was used to make a pairwise comparison of the means for each level of the decision factor or interaction. The Tukey test allows to compare the 72 experiments and to group those with statistically equivalent patient lead times, number of patients seen by an orthopedist and proportion of occupied time for orthopedists. Let us recall that the results provided in Section 4 are for Monday.

4. Results

The different decision factors and their impact on the performance measures were examined to determine which ones minimize patient lead times, maximize the number of patients seen by an orthopedist and the proportion of occupied time for orthopedists.

4.1. Patient lead times

The 72 experiments are denoted A to Z, AA to AZ and BA to BT. Their respective results can be read from left to right and from top to bottom. This notation was used in Tables 7, 9 and 11–13.

The analysis of variance (ANOVA) performed with Minitab 16 shows (Table 6) that the four decision factors: patient flow type, appointment scheduling rule, number of consulting rooms assigned to orthopedists and number of nurses assigned to orthopedists, had a significant effect on patient lead times in the outpatient clinic. The effect is measured by the change induced on the performance measure by a change of level of the decision factor. A significant factor indicates that at least one of the means of one of the factor levels is statistically different from the others.

Decision factors having the most important effect (largest mean square) on patient lead times are appointment scheduling rules, the number of consulting rooms and nurses assigned to orthopedists. It confirms how important it is to schedule patients and to assign consulting rooms and nurses to orthopedists adequately. The effects of decision factors on patient lead times are shown in Fig. 2.

The patient flow type leading to the smallest average patient lead time, 99 min, is the orthopedist flow type (2) where all patients follow the same one-step trajectory. The patient flow type leading to the longest average patient lead time, 163 min, is the radiology flow type (3) with 50% of patients following the two-step trajectory 1 and 50% following the three-step trajectory 2. This suggests that a more complex trajectory (with more steps) produces longer patient lead times as expected. Also a higher percentage of patients following complex trajectories results in a longer patient lead time. We can observe a reduction of the average patient lead time by 37 min on average as the number of nurse increases from 1 to 2. When the number of consulting rooms increases to 2, the reduction is 54 min on average. Fig. 2 shows that with the current appointment scheduling rule 0, the average

Table 6
ANOVA for patient lead times.

Sources	DF	SS	MS	*p*-Value
Patient flow type (F)	**2**	**245,378**	**122,689**	**0.000***
Rules (R)	**3**	**646,179**	**215,393**	**0.000***
Patient flow * Rules	**6**	**7882**	**1314**	**0.041***
Rooms (S)	**2**	**278,325**	**139,162**	**0.000***
Patient flow * Rooms	**4**	**23,517**	**5879**	**0.000***
Rules * Rooms	6	2884	481	0.560
Patient flow * Rules * Rooms	12	11,694	975	0.078
Nurses (I)	**1**	**123,395**	**123,395**	**0.000***
Patient flow * Nurses	**2**	**26,696**	**13,348**	**0.000***
Rules * Nurses	3	2016	672	0.334
Patient flow * Rules * Nurses	6	671	112	0.980
Rooms * Nurses	**2**	**14,991**	**7496**	**0.000***
Patient flow * Rooms * Nurses	**4**	**9889**	**2472**	**0.003***
Rules * Rooms * Nurses	6	6949	1158	0.071
Patient flow * Rules * Rooms * Nurses	12	5783	482	0.634
Error	288	170,055	590	
Total	359	1,576,305		

The bold values are significant factors and interactions.
DF: degree of freedom; SS: sum of squares; MS: mean square.
* *p*-Value significant at 5%.

Table 7
Experiments minimizing patient lead time sorted according to patient flow types.

Experiments	Q	K	V	X	P	J	L	R	BR	BN	BF	BT	BH	BL
Patient flow	1	1	1	1	1	1	1	1	3	3	3	3	3	3
Rules	2	1	3	3	2	1	1	2	3	2	1	3	1	2
Rooms	3	3	2	3	2	2	3	3	2	3	2	3	3	2
Nurses	1	1	2	2	2	2	2	2	2	2	2	2	2	2
Average patient lead time (min)	95	94.6	77.4	72.6	64.4	60	56.8	55.8	85.4	76.2	73.2	71	68.6	68.6

	AK	AU	AS	AT	AF	AL	AM	AI	AO	AV	AG	AN	AJ	AH	AP
Patient flow	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Rules	2	3	3	3	1	2	2	1	2	3	1	2	1	1	2
Rooms	1	3	2	2	1	1	2	3	3	3	2	2	3	2	3
Nurses	1	1	1	2	2	2	1	1	1	2	1	2	2	2	2
Average patient lead time (min)	98.2	86.4	86	84.6	83.2	73.4	67.6	67.2	64.4	57	55.2	48.6	46.8	43.6	43.2

Table 8
ANOVA for the number of patients seen by an orthopedist.

Sources	DF	SS	MS	*p*-Value
Patient flow (F)	**2**	**9378.29**	**4689.14**	**0.000***
Rules (R)	3	100.67	33.56	0.073
Patient flow * Rules	6	153.47	25.58	0.101
Rooms (S)	**2**	**11876.94**	**5938.47**	**0.000***
Patient flow * Rooms	**4**	**586.58**	**146.64**	**0.000***
Rules * Rooms	**6**	**396.82**	**66.14**	**0.000***
Patient flow * Rules * Rooms	12	212.47	17.71	0.255
Nurses (I)	**1**	**16714.47**	**16714.47**	**0.000***
Patient flow * Nurses	**2**	**657.16**	**328.58**	**0.000***
Rules * Nurses	**3**	**425.50**	**141.83**	**0.000***
Patient flow * Rules * Nurses	**6**	**497.04**	**82.84**	**0.000***
Rooms * Nurses	**2**	**300.01**	**150.00**	**0.000***
Patient flow * Rooms * Nurses	**4**	**275.14**	**68.79**	**0.001***
Rules * Rooms * Nurses	**6**	**287.39**	**47.90**	**0.003***
Patient flow * Rules * Rooms * Nurses	12	209.19	17.43	0.268
Error	288	4112.40	14.28	
Total	**359**	**46183.53**		

The bold values are significant factors and interactions.
DF: degree of freedom; SS: sum of squares; MS: mean square.
* *p*-Value significant at 5%.

Table 9
Experiments maximizing the number of patients seen by an orthopedist sorted according to patient flow types.

Experiments	F	V	X	D	L	R	AD	AV	AB	AP	AJ	AH	AT	AN	BB	BR
Patient flow	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3
Rules	0	3	3	0	1	2	0	3	0	2	1	1	3	2	0	3
Rooms	3	2	3	2	3	3	3	3	2	3	3	2	2	2	3	2
Nurses	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Average number of patients seen by an orthopedist	53.6	51.2	50	49.4	47.8	47.2	56.4	53.8	52.4	50.2	49.2	48.6	47.8	47	55	47.2

patient lead time is far too high (202.3 min) if compared with rule 1 (98.3 min), rule 2 (101.2 min) and rule 3 (119.3 min).

ANOVA also demonstrates that there are many significant interactions, meaning that a careful analysis of the impact of the decision factors must be done. There is a significant interaction when a change in one factor produces a different change in the performance measure at two levels of another factor. Since we observed significant double and triple interactions and in order to simplify the analysis, it is reasonable to analyze interactions involving the four decision factors. The Tukey test was used to analyze Patient flow * Rules * Rooms * Nurses interaction. Only the 29 experiments minimizing patient lead times are presented in Table 7 sorted according to patient flow types.

The patient flow type is related to the demand and since the demand can vary from one day to the other, it would be logical to adjust the clinic capacity (appointment scheduling rules, number of consulting rooms, and number of nurses) according to the patient flow type. Results in Table 7 indicate that the average patient lead times vary from 43.2 to 98.2 min which can be considered as an important gap.

The most astounding finding from the Table 7 results is that the current appointment scheduling rule (0) of the outpatient clinic never minimizes patient lead times. Therefore it looks like that if the current appointment scheduling rule (0) was rather chosen to please the orthopedists than to reduce patients' waiting time.

With mix flow type 1 (experiments Q, K, V, X, P, J, L and R in Table 7), patient lead times vary from 55.8 to 95 min depending on the combination of the appointment scheduling rules, the number of consulting rooms and the number of nurses. Three experiments (J, L and R) succeed in reducing the average patient lead time to less or equal to 60 min as wished by the orthopaedic clinic decision makers. We can observe that the average patient lead time increases to 95 min (experiments Q and K) if there is only one nurse. The average patient lead time also increases to 75 min (mean patient lead time for experiments V and X) when appointment scheduling rule 3 is used. With 2 nurses, 3 rooms and

Table 10
ANOVA – proportion of occupied time for orthopedists.

Sources	DF	SS	MS	p-Value
Patient flow (F)	**2**	**24182.1**	**12091.1**	**0.000**[*]
Rules (R)	**3**	**421.2**	**140.4**	**0.013**[*]
Patient flow * Rules	**6**	**638.6**	**106.4**	**0.012**[*]
Rooms (S)	**2**	**30117.3**	**15058.7**	**0.000**[*]
Patient flow * Rooms	**4**	**884.7**	**221.2**	**0.000**[*]
Rules * Rooms	**6**	**762.6**	**127.1**	**0.004**[*]
Patient flow * Rules * Rooms	12	220.3	18.4	0.926
Nurses (I)	**1**	**48071.1**	**48071.1**	**0.000**[*]
Patient flow * Nurses	**2**	**1031.9**	**515.9**	**0.000**[*]
Rules * Nurses	**3**	**2020.3**	**673.4**	**0.000**[*]
Patient flow * Rules * Nurses	**6**	**641.6**	**106.9**	**0.012**[*]
Rooms * Nurses	**2**	**971.0**	**485.5**	**0.000**[*]
Patient flow * Rooms * Nurses	**4**	**567.3**	**141.8**	**0.006**[*]
Rules * Rooms * Nurses	**6**	**580.8**	**96.8**	**0.021**[*]
Patient flow * Rules * Rooms * Nurses	12	317.4	26.5	0.759
Error	288	11014.8	38.2	
Total	**359**	**122443.1**		

The bold values are significant factors and interactions.
SS: sum of squares; MS: mean square.
[*] p-Value significant at 5%; DF: degree of freedom.

Table 11
Experiments maximizing the proportion of occupied time for orthopedists sorted according to patient flow types.

Experiments	F	D	X	V	L	R	AD	AB	AV	AJ	AT	AH	AP	AN	BB	AZ
Patient flow	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3
Rules	0	0	3	3	1	2	0	0	3	1	3	1	2	2	0	0
Rooms	3	2	3	2	3	3	3	2	3	3	2	2	3	2	3	2
Nurses	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Average proportion of occupied time for orthopedists	94.8	92	88.4	87.6	80.8	79.8	96	94.8	92.6	87.6	87.2	84.4	84.2	82.6	91.4	80.4

Table 12
Best solutions versus patient flow types.

Patient flow type	Experiments	Appointment scheduling rule	Number of rooms	Number of nurses	Patient lead time (min)	Number of patients seen	Proportion of occupied time (%)
Mix(1)	V	3	2	2	77.4	51.2	88.4
	X	3	3	2	72.6	50	87.6
	L	1	3	2	56.8	47.8	80.8
	R	2	3	2	55.8	47.2	79.8
Orthopedist (2)	AT	3	2	2	84.6	47.8	87.2
	AV	3	3	2	57	53.8	92.6
	AN	2	2	2	48.6	47	82.6
	AJ	1	3	2	46.8	49.2	87.6
	AH	1	2	2	43.6	48.6	84.4
Radiology (3)	BR	3	2	2	85.4	47.2	73.4
	BB	0	3	2	140.6	55	91.4

Table 13
Multicriteria analysis versus patient flow types.

Patient flow type	Experiments	Appointment scheduling rule	Number of rooms	Number of nurses	Number of rooms $\leqslant 2$ (50%)	Patient lead time $\leqslant 60$ min (30%)	Number of patients seen $\geqslant 50$ (20%)	Total score
Mix (1)	**V**	**3**	**2**	**2**	**1**	**0**	**1**	**0.7**
	X	3	3	2	0	0	1	0.2
	L	1	3	2	0	1	0	0.3
	R	2	3	2	0	1	0	0.3
Orthopedist (2)	AT	3	2	2	1	0	0	0.5
	AV	3	3	2	0	1	1	0.5
	AN	**2**	**2**	**2**	**1**	**1**	**0**	**0.8**
	AJ	1	3	2	0	1	0	0.3
	AH	**1**	**2**	**2**	**1**	**1**	**0**	**0.8**
Radiology (3)	**BR**	**3**	**2**	**2**	**1**	**0**	**0**	**0.5**
	BB	0	3	2	0	0	1	0.2

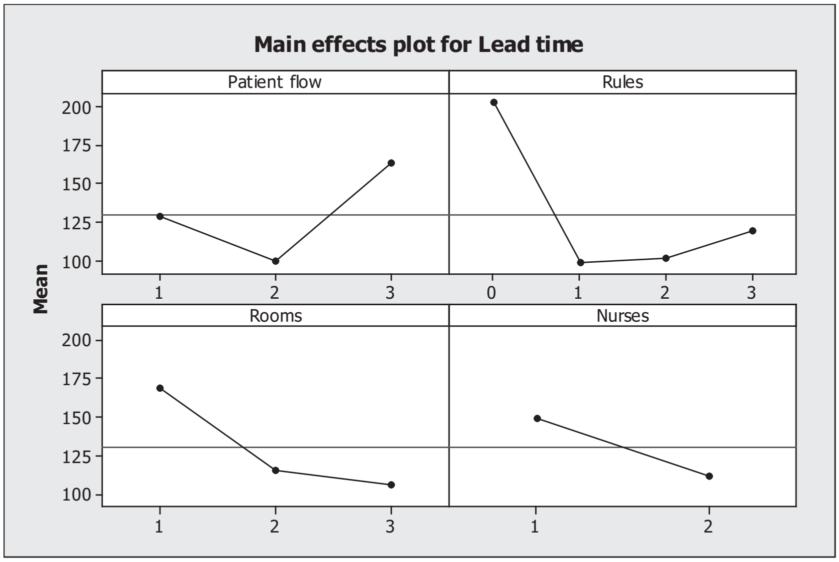

Fig. 2. Effect of decision factors on patient lead times.

appointment scheduling rules 1 or 2, we obtained the minimum average patient lead time of 56 min (mean value for experiments L and R). It is important to note that the average patient lead time is 60 min (experiment J) with 2 rooms instead of 3 which is a difference of only 4 min if compared with the smallest patient lead time of experiment R (55.8 min). This result is interesting since we get quite similar results with one room less. It thus seems possible to schedule patients with 3 orthopedists and 2 rooms each instead of 2 orthopedists and 3 rooms each without increasing patient lead times.

Patient flow times vary from 43.2 to 98.2 min for experiments AK, AU, AS, AT, AF, AL, AM, AI, AO, AV, AG, AN, AJ, AH and AP (Table 7) of orthopedist flow type 2. For six of them (AV, AG, AN, AJ, AH and AP) patient lead times are less than 60 min which correspond to the decision makers' goal. For experiments AG, AN and AH only two consulting rooms instead of three were used allowing one more orthopedist to be scheduled since one room becomes available. Let us also note that with experiment AG, it is possible to assign one nurse to two rooms (instead of two nurses) while satisfying the goal of a patient lead time less than 60 min. The patient lead time is longer when only one nurse is working, 65 min on average, and when only one consulting room is available, 78 min on average.

Experiments BR, BN, BF, BT, BH and BL of radiology flow type 3 result in patient lead times between 68.6 and 85.4 min. The decision makers' goal of a patient lead time being less than 60 min could not be reached with this patient flow type. This can be explained by the fact that this flow type is more complex including two and three-step trajectories. For experiments BH and BL we get the same patient lead time of 68.6 min but experiment BL uses two consulting rooms and appointment scheduling rule 2 and experiment BH, three consulting rooms and appointment scheduling rule 1. None of the experiments of radiology flow type 3 considers only one nurse.

4.2. Number of patients seen by an orthopedist

We also analyzed how the number of patients seen by an orthopedist varied depending on the decision factors. An ANOVA was performed to verify which decision factors have a significant effect on the number of patients seen by an orthopedist (Table 8). Results show that the patient flow type, the number of consulting rooms and the number of nurses have a significant effect on the number of patients seen by an orthopedist. Appointment scheduling rules have no effect on the number of patients seen by an orthopedist. Fig. 3 illustrates how decision factors impact on the number of patients seen by an orthopedist.

Flow type 2 allows an orthopedist to see the greatest number of patients (42 patients) while flow type 3 allows for the smallest number (30 patients). The number of patients seen by an orthopedist increases significantly, by 14 patients on average, when the number of nurses increases from one to two. It also increases, by 11 patients on average, when the number of consulting rooms is equal to two. However the appointment scheduling rule has no effect on the number of patients seen by an orthopedist.

ANOVA also shows that many double and triple interactions are significant, meaning that we must be careful when analyzing the impact of decision factors. The Tukey test was used to analyze interactions gathering all four decision factors. We present in Table 9 only the 16 experiments maximizing the number of patients seen by an orthopedist sorted according to the patient flow type.

We can observe that the average number of patients seen by an orthopedist varies from 47 to 56.4 patients. As shown by variance analysis, the patient flow type has a significant effect on the number of patients seen by an orthopedist and is involved in four of the significant interactions. It is thus important to consider the appointment scheduling rules, the number of consulting rooms and the number of nurses for each patient flow type.

For experiments F, V, X, D, L and R of mix flow type 1, the number of patients seen by an orthopedist varies from 47.2 to 53.6. Results of experiments F, V and X correspond to the orthopedists' goal to see at least 50 patients daily. These three experiments require two nurses with appointment scheduling rules 0 and 3. However with experiment V only two consulting rooms are required instead of three.

For experiments AD, AV, AB, AP, AJ, AH, AT and AN of flow type 2, the number of patients seen by an orthopedist varies from 47 to 56.4. Results of experiments AD, AV, AB and AP correspond to the orthopedists' goal to see at least 50 patients daily. These four experiments require two nurses with appointments scheduling rules 0, 2 and 3. However with experiment AB, only two consulting rooms are required instead of three.

For experiments BB and BR of flow type 3 the number of patients seen by an orthopedist varies from 47.2 to 55. Results of

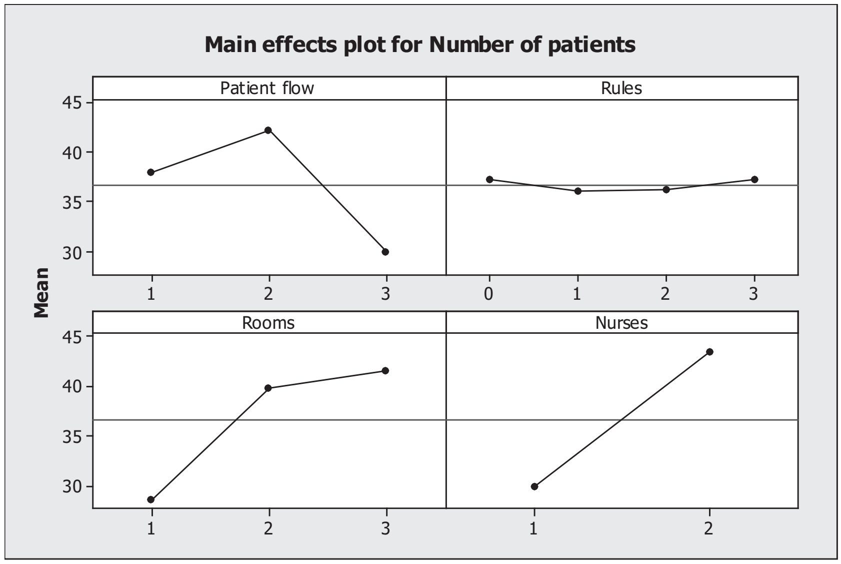

Fig. 3. Decision factors versus the number of patients seen by an orthopedist.

experiment BB correspond to the orthopedists' goal to see at least 50 patients daily. This experiment is the one currently used by the outpatient orthopaedic clinic. It requires two nurses (as for all experiments) and three rooms with appointment scheduling rule 0. The maximum number of patients that can be seen if there are two consulting rooms is 47.

4.3. Proportion of occupied time for orthopedists

Finally we also analyzed how the proportion of occupied time for orthopedists varied depending on the decision factors. Let us recall that orthopedists aim to be occupied at a proportion of at least 85%. Results of the ANOVA (Table 10) show that the number of nurses is the factor having the greatest effect on the proportion of occupied time for orthopedists. Fig. 4 illustrates how decision factors impact on the proportion of occupied time for orthopedists.

The proportion of occupied time for orthopedists increases significantly, by 18% on average, when the number of consulting rooms increases from 1 to 2. However when the number of consulting rooms goes from 2 to 3, the proportion of occupied time for orthopedists increases by 3% on average. The proportion of occupied time for orthopedists increases significantly, by 24% on average, when the number of nurses increases from 1 to 2 meaning that orthopedists need two nurses to improve their efficiency.

Since many interactions are significant, we must be careful when analyzing the impact of decision factors. The Tukey test was used to analyze interactions gathering all four decision factors. We present in Table 11 only the 16 experiments maximizing the proportion of occupied time for orthopedists sorted according to the patient flow type.

We can observe that the average proportion of occupied time for orthopedists varies from 79.8% to 96%. As shown by variance analysis, the patient flow type has a significant effect on the proportion of occupied time for orthopedists and is involved in five of the significant interactions.

For experiments F, D, X, V, L and R of flow type 1 the proportion of occupied time for orthopedists varies from 79.8% to 94.8%. For all experiments, two nurses are needed with appointment scheduling rules 0 and 3. The greatest proportions of occupied time for orthopedists were observed with experiments D and V requiring only two rooms.

For experiments AD, AB, AV, AJ, AT, AH, AP and AN of orthopedist flow type, the proportion of occupied time for orthopedists varies from 82.6% à 96%. Once again for all experiments, two nurses are needed. Appointment scheduling rules 0, 1 and 3 result in the greatest proportions of occupied time for orthopedists with experiments AB and AT requiring only two rooms (allowing for more available capacity).

Radiology flow type 3 includes only experiments BB and AZ. The proportion of occupied time for orthopedists varies from 80.4% to 91.4%. Both of them require two nurses but experiment AZ necessitates two rooms.

4.4. Analysis and validation

Each performance measure was analyzed independently in Sections 4.1–4.3. However, experiments minimizing patient lead times may not be the ones maximizing the number of patients seen by an orthopedist or the proportion of occupied time for orthopedists. Therefore factors needed to optimize the performance measures were determined according to the patient flow types and to combined results of Tables 7, 9 and 11. Those combined results can be found in Table 12.

Multicriteria analysis was used to evaluate the best solutions (Table 13) for each patient flow type. Multicriteria analysis is a decision support tool to help decision makers evaluate the impact of many criteria over a given performance measure. In our study, we considered the following criteria values and their respective weights: (1) no more than two rooms (50%), (2) less than 60 min patient lead times (30%) and (3) at least 50 patients seen by an orthopedist (20%). Weights were determined with the outpatient clinic decision makers. Each solution of Table 12 was evaluated as follows: 1 point if criteria value is satisfied and 0 otherwise. Total score is the sum of the criteria score times its weight. The highest total score is the most interesting solution. These solutions are in bold in Table 13.

For the mix flow type, results of experiments V, X, L and R were present in the three Tables 7, 9 and 11. For the orthopedist flow type, results of experiments AT, AV, AN, AJ and AH were also in the three tables. However results of the two experiments BR and BB from the radiology flow type were only found in two of the three Tables 7, 9 and 11.

For flow type 1, the solution with the highest score requires two rooms and two nurses with appointment scheduling rule 3. With this solution, 53 patients could be scheduled. Our simulation results indicate however that only 51 patients can be seen by an

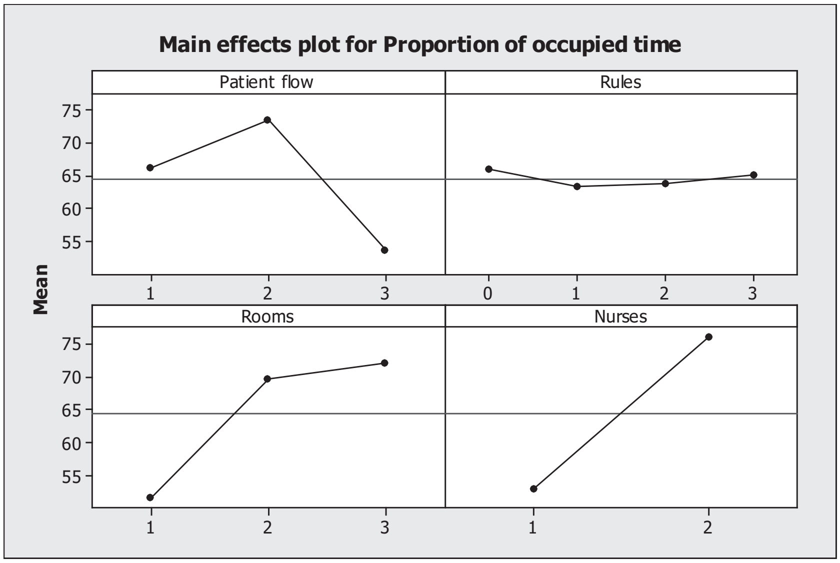

Fig. 4. Decision factors versus proportion of occupied time for orthopedists.

orthopedist without overtime. Considering that there are 5 walk-ins on average daily, the clinic should schedule 46 patients per orthopedist instead of 53. With around a patient lead time of 78 min and a proportion of occupied time for orthopedists of 88%, this solution is the best one found with this patient flow type.

For flow type 2, appointment scheduling rules 1 and 2 combined with two rooms and two nurses provide good solutions. The solution with appointment scheduling rule 1 gives a smaller patient lead time than with appointment scheduling rule 2. It is thus the chosen solution for the orthopedist flow type. Our results show that 48 patients can be seen by an orthopedist while 45 are scheduled. Therefore 3 of the average 5 walk-in patients could be seen by the orthopedist. Considering that there are on average 5 walk-ins daily for each orthopedist, the clinic should then schedule 43 patients instead of 45 for a total of 48 patients seen by each orthopedist. With an average patient lead time of 44 min and a proportion of occupied time for orthopedists of 84%, this solution is the best one found with this patient flow type.

For flow type 3, no solution satisfies all criteria values. With appointment scheduling rule 0, an orthopedist can see 55 patients on average daily and is occupied at a proportion of 91%. However the average patient lead time is 140 min which is very high and three rooms are needed. For the radiology flow type, appointment scheduling rule 3, combined with two rooms and two nurses, is the only one that may result in an excess capacity. However it would lead to a patient lead time of 86 min, 47 patients seen by an orthopedist and a 73% proportion of occupied time for orthopedists. In this case, none of the criteria is reached. With such results it would be interesting to consider other appointment scheduling rules for the radiology flow type.

The first series of tests included 5 replications of each experiment. The confidence interval is ±30 min for the patient lead time, ±5 patients for the number of patients seen by an orthopaedist and ±0.01 for the proportion of occupied time. To validate with more adequacies and over a longer period the best solutions of Table 13, 150 replications of each of them were performed. We took advantage of these new tests to verify if solutions involving 2 rooms were statistically equivalent to those involving 3 rooms. Table 14 compares the current observed solution with solutions of Table 13.

For the current solution (mix flow, appointment scheduling rule 0, 3 rooms and 2 nurses), patient lead time is equal to 141 min, the number of patients seen by an orthopedist to 55 and the proportion of occupied time for orthopedists is 94.8%.

Simulation tests showed that it is possible to reduce patient lead time. The reduction of patient lead time was obtained by

Table 14
Comparison of current solution and tested solutions versus patient flow types.

	Performance measures					
	Patient lead time (min)		Number of patients seen		Proportion of occupied time	
	Mean	Half-width	Mean	Half-width	Mean (%)	Half-width
Current observed solution						
Rule (0) Rooms (3) Nurses (2)	**141**	**<3.56**	**55**	**<0.75**	**94.8**	**0.01**
Solutions – mix flow						
Rule (3) Rooms (2) Nurses (2)	80	<3.00	49	<0.64	89	0.01
Rule (3) Rooms (3) Nurses (2)	77	<3.56	50	<0.75	92	0.01
Solutions – orthopedist flow						
Rule (1) Rooms (2) Nurses (2)	48	<1.92	48	<0.53	84	0.01
Rule (1) Rooms (3) Nurses (2)	47	<2.00	48	<0.49	87	0.01
Solutions – radiology flow						
Rule (3) Rooms (2) Nurses (2)	102	<3.81	43	<0.75	79	0.01
Rule (3) Rooms (3) Nurses (2)	87	<3.10	46	<0.71	83	0.01

The bold values are significant factors and interactions.

Table 15
Patients distribution according to flow types.

	Solution 1		Solution 2		Solution 3	
	Day 1 (8 h)	Day 2 (4 h)	Day 1 (8 h)	Day 2 (4 h)	Day 1 (8 h)	Day 2 (4 h)
Flow type	Mix	Mix	Mix	Orthopedist	Orthopedist	Radiology
Appointment scheduling rules	3	3	3	1	1	3
Number of rooms	2	2	2	2	2	2
Number of nurses	2	2	2	2	2	2
Patient lead time	80 min	80 min	80 min	48 min	48 min	102 min
Proportion of occupied time[a]	89%	89%	89%	84%	84%	79%
Number of patients seen[a]	49	31	49	31	48	32

[a] Depends on results of Table 14.

modifying the appointment scheduling rule. Indeed with the best solution of the mix flow type, patient lead time is equal to 80 min (43% reduction compared with current solution), 49 patients are seen by an orthopedist (11% difference with current solution) and the proportion of occupied time for orthopedists is equal to 89% (6% difference with current solution). It is worth noting that appointment scheduling rules have an important impact on patient lead times no matter which patient flow type is considered.

Results also demonstrate that reducing the number of rooms from three to two does not make a significant difference in patient lead times, the number of patients seen by an orthopedist or the proportion of occupied time for orthopedists, for the three patient flow types except radiology flow for which patient lead times vary more. The outpatient clinic could thus schedule the same number of patients with only two rooms and two nurses per orthopedist (total of 4 rooms and 4 nurses) while keeping good performance measures.

Finally, our study demonstrates how important it is to consider patient flow types when generating appointment schedules. Our results are very interesting since they allow scheduling appointments according to patient flow types when an orthopaedist's caseload requires more than one day. For the mix flow and the radiology patient flow types, the best appointment scheduling rule is rule 3, while rule 1 is better for the orthopedist flow type. It shows how important it is to adjust appointment scheduling rules to patients' trajectories. Table 15 presents how the three solutions to distribute 80 patients over two days can be evaluated with our three performance measures.

If the clinic schedules appointments according to the mix flow type for the two days (solution 1), patient total lead time is 160 min. It is 128 min with solution 2 and 150 min with solution 3. It shows that scheduling appointments based on the flow types has an impact on patient total lead time and consequently on their waiting time, without affecting the proportion of occupied time for orthopedists

5. Discussion and limitations

5.1. Discussion

Our results show that there are many ways to improve the clinic performance from the patient's and orthopaedist's point of view. For different flow types we identified the appointment scheduling rules, the number of consulting rooms and the number of nurses required to reduce patient lead time while maintaining the proportion of the orthopaedist's occupied time and the number of patients seen.

The clinic studied could operate with 2 consulting rooms instead of 3 for the three types of patient flows. Actually and as we showed in Table 1, two orthopedists use 3 rooms each every day for a total of 6 rooms used. If each of them uses 2 rooms instead of 3, it leaves an extra 2 rooms for another orthopedist. Knowing that the clinic intends to hire three new orthopaedist, this would leave them two rooms daily to receive patients. However this additional orthopedist needs two additional nurses to keep the same level of performance (patient lead time, number of patients seen and occupied time rate). Our results differ slightly from White et al. In the clinic setting studied by White et al., better results (occupied time rate, patient lead time) are obtained when at least three consulting rooms are assigned to each doctor instead of only two. However in their study they do not consider the possibility for orthopaedists to share the use of consulting rooms as it is for us. Moreover radiology services are dedicated to the clinic which is not the case in our study. However, this new assignment of rooms and nurses with additional orthopedists would allow the clinic to schedule more patients therefore reducing the size of the patients' waiting list. From a medical point of view this would be beneficial to patients' health condition.

Our study showed that modifying appointment scheduling rules allows for a significant reduction of patient lead time and consequently of their waiting time, without affecting the number of patients seen by an orthopedist or the proportion of occupied time for orthopedists. We showed that with the mix and radiology flow types, the best appointment scheduling rule is rule 3. This rule ensures that there is always a patient ready when the orthopaedist needs to see one. For the orthopaedist flow type (all patients follow only a one step trajectory), the best appointment scheduling rule is rule 1 (a patient is scheduled every 10 min). These results are consistent with Rohleder and Klassen (2000). It is obvious that reducing patient waiting times will increase patient satisfaction.

We also showed that when scheduling appointments according to flow types, it was possible to reduce total patient lead times over two days. A 20% decrease in total patient lead time (160 min for solution 1 and 128 min for 2 (Table 15)) contributes in improving patient satisfaction, reducing congestion in the waiting room and therefore facilitating movements in a clinic where many patients need technical aids. To our knowledge we are the first ones to consider different flow types to schedule appointments.

5.2. Limitations

In our study patient lead times take into account orthopaedists lateness and absences. If orthopaedists were present when the clinic opens patient lead times could decrease. It would be interesting verifying the impact on patient lead times of an increase of the orthopaedists presence.

The solutions (appointment scheduling rule, number of rooms and nurses) recommended according to each patient flow are good when patient are on time to their appointment. If patients arrive early our solutions still hold since it was patients' choice to arrive early. However patients' lateness may have an impact on the solutions to recommend. Future research could analyze how patient lateness contributes in modifying the clinic performance.

We intend to study how the clinic's performance can be improved if nurses are not assigned to a specific orthopedist or rooms but can rather work in any room and with any orthopedist depending on the needs. Also, to get better patient lead times, future works imply to review work organization (nurses and orthopedists) in order to reduce waste of time (traveling, waiting). It would be interesting to verify how work organization influence performance measures. We believe that it might be possible to schedule more patients with 4 nurses, 6 rooms and 3 orthopedists.

We studied three patient flow types: mix (trajectories 1, 2 and 3), orthopaedist (trajectory 3) and radiology (trajectory 2 and 3). Future research projects may imply testing more complex flow types with different trajectory combinations. Sensitivity analysis could be performed on each flow type by modifying the proportions of patients following each trajectory. Our research explored three scheduling rules. We are aware that many more rules could be tested according to the different flow types.

In the longer term, our research will consist in developing decision support systems to schedule appointments and determine resources required while taking into account orthopedists' caseload. Even if each clinic has its own specificities we think that our results can provide insights to help them plan appointments according to patient flow types when a doctor needs more than one day to see all his patients. Clinics could adapt our solutions to their own activities.

6. Conclusion

In this paper we studied relations and interactions between patient flow types, resource capacity (number of consulting rooms and number of nurses) and appointment scheduling rules to be able to propose new ways to improve an outpatient orthopaedic clinic performance. For better values of performance measures, one has to define appointment scheduling rules according to patient flow types. Until now, researchers spent more time on trying to schedule patients daily in outpatient clinics (operational level) by studying scheduling rules and resource capacity. However orthopedists' workload (number of patients and type of treatment required) can vary greatly from week to week. This research will contribute to develop new weekly appointment schedules for outpatient orthopaedic clinics (tactical level) considering orthopedists' patient load and their trajectories. An emphasis will be put on considering mix, orthopedist and radiology patient flows according to their specific demand in patients on a weekly basis. This research opens new opportunities for appointment scheduling according to patient flow types.

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