Algorithms for radiotherapy treatment booking

Sanja Petrovic*, William Leung*, Xueyan Song* and Santhanam Sundar #

* Automated Scheduling, Optimisation and Planning Research Group,
School of Computer Science and IT, University of Nottingham, Nottingham, UK.
Dept. of Oncology, City Hospital Campus, Nottingham University Hospitals NHS Trust, Nottingham, UK
* {sxp,wwl,xxs}@cs.nott.ac.uk, # santhanam.sundar@nuh.nhs.uk

Abstract

Two algorithms for booking courses of radiotherapy treatment sessions for the dynamic arrival of patients in a parallel machine environment are developed. Patients vary by due date, by which they should start their treatments, clinical category and treatment machine requirement. The first algorithm, mimicking current practice, books patients forward from the release date (i.e. the date when the patient can start radiotherapy treatment). The second algorithm books patients backwards from the due date. Feasible schedules of treatment sessions are generated for each patient with the aim to minimise the total number of patients who do not meet waiting time targets, the total length of waiting time breaches, and the total number of interruptions to treatment. The algorithms incorporate practical constraints that arise in real-life problems faced by the Nottingham University Hospitals NHS Trust, UK.

1 Introduction

Cancer is a group of diseases characterised by the uncontrolled growth and spread of abnormal cells. With a wide range of cancer types, there is a variety of approaches to treat cancer. The most common forms of treatment are surgery, chemotherapy, and radiotherapy. Typically, several forms of treatment are combined to increase the chance of success. For example, surgery is often followed by chemotherapy and/ or radiotherapy to ensure the elimination of cancerous cells. Radiotherapy often forms part of the treatment for the patient due to its minimally invasive nature. It has been estimated that about 50% of all cancer patients have radiotherapy as part of their treatment, Delaney *et al.* (2003).

A patient being prescribed radiotherapy treatment will generally have to first undergo several processes before the treatment: simulation (localisation of treatment fields) using a CT scanner or simulator, planning (clinicians deciding on the best way of delivering the amount of radiotherapy needed), and finally verification (of planning) using a simulator. Treatment fields are the precisely defined areas where the beams of radiation, varying by angle and intensity, will be targeted during treatment of the patient to destroy the cancerous cells. Only after these processes are completed can treatment sessions given on a daily basis, called fractions, begin. During treatment, ionising radiation is delivered by a linear accelerator (linac) to those precisely defined treatment fields on the patient to shrink the cancerous cells.

Each fraction lasts a set amount of time. The key performance metric is the time elapsed from decision to treat (the date of the consultation in which the patient and clinician agree the treatment plan for the first time) and first treatment session, see RCR (2006) for a detailed explanation. Any delay to the start of treatment or unscheduled interruption during treatment is likely to adversely affect the mortality rate, Dodwell and Crellin (2006), RCR (2002). Various compensatory strategies for missed treatments leads to increased toxicity, Hendry *et al.* (1996). Hence appropriate scheduling would improve radiation cure rates and minimise complications from radiation.

The first recorded study of scheduling within the related field of radiology encountered by the authors was by Lev and Caltagirone (1974). It describes a discrete event simulation model of patient flow in Temple University's Radiology Department (USA) written using GPSS simulation language with FORTRAN subroutines incorporated to handle complex decision processes and data manipulation. The first recorded study of scheduling of patients for radiotherapy treatments was by Larsson (1993). His scheduling system records waiting lists and patient details. However, it uses simple formulae rather than any scheduling heuristics. There is a scarcity of papers on scheduling in radiotherapy, though the major contribution that it can make has been recognised by the NHS (2006).

Since then, there has been a growing need to automate the management of the resources involved. Various information management systems have come into common use, such as Oncentra Clinic (www.nucletron.com). Such systems provide tools to handle the increasingly complex equipment and treatment techniques and attempt to provide some scheduling and management support. However, none of them exploits the full strength of state-of-the-art scheduling and optimisation methods.

One can draw an analogy between radiotherapy scheduling and a job shop scheduling problem where patients, treatment sessions, and linacs are the jobs, operations, and machines respectively. Patients follow a route partially dictated by the location and severity of the cancer. Linacs can be of high and low energy and they are treated as parallel machines. The best approximations to the measures of performance for radiotherapy treatments are: weighted number of tardy jobs and total weighted tardiness, which measure the number of patients that do not start their treatment on time, and the delay with the treatment, respectively.

Traditionally, departments operate by booking the patient as soon as the referral arrives. Therefore, of particular interest in this research are various dispatching rules developed for job shop problems. Vepsalainen and Morton (1987) discussed the effects of various dispatching rules in a job shop environment with the objective to minimise weighted tardiness. They investigated the performance of dispatching rules under different loads of the shop floor. Rajendran and Holthaus (1999) conducted a study of dispatching rules aiming to minimise percentage of tardy jobs and variance of tardiness. Ovacik and Uzsoy (1995) discuss the relative merits of local and global dispatching rules in a parallel machine environment.

This paper considers a real-world scheduling of treatment sessions that is faced by the Nottingham University Hospitals NHS Trust (UK). It introduces two different algorithms that can be used to schedule treatments for patients of different categories on a daily basis and details different criteria that can be used to assess the performance of those algorithms.

The paper is organised as follows. In Section 2, the radiotherapy problem is described. In Section 3, the two algorithms and criteria are presented. In Section 4, the results from our experiments are presented. The conclusion and a discussion of future work are given in Section 5.

2 Problem statement

The notation used in the problem statement and throughout the paper is as follows:

N - number of patients entering the treatment booking system on the current day
P_n - patients, $n = 1,\ldots,N$
C_n - category of patient P_n : A, B,C
r_n - release date of the patient P_n , i.e. the date when the patient can start his/ her treatments once all prior processes are completed
d_n - the due date by which the patient P_n has to start the treatment determined by the maximum acceptable waiting time for that category of patients
F_n - number of prescribed treatment sessions for patient P_n
I_n - number of interruptions to treatment
I_n^{max} - maximum allowed number of interruptions to treatment for patient P_n determined by the category C_n
m_n - energy of linacs on which patient P_n has to be treated on; high, low
M - set of linacs $M = \{mh_h \mid h = 1,\ldots,H\} \cup \{ml_l \mid l = 1,\ldots,L\}$
H - number of high energy linacs
L - number of low energy linacs
mh_h - $h = 1,\ldots,H$ high energy linacs
ml_l - $l = 1,\ldots,L$ low energy linacs
V_{Hd} - the capacity of high energy linacs on day d $(d = 1,\ldots,7)$ given as the maximum number of sessions
V_{Ld} - the capacity of low energy linacs on day d $(d = 1,\ldots,7)$ given as the maximum number of sessions
$[s_{n,f,m_n}]_{F_n}$ - a vector assigned for each patient P_n , $n = 1,\ldots,N$, which shows the days for F_n treatment sessions, $f = 1,\ldots,F_n$, for each treatment session of patient P_n on linacs of energy m_n

T_n - number of days between the release date and the due date of the treatment of patient P_n
U_n - determines whether patient P_n violates the due date of the start of his/ her treatment

We consider a daily scheduling problem in which N patients enters the treatment booking system which is partially booked with previously scheduled patients. Each patient has to be allocated F_n treatment sessions, on linacs, of high or low energy, that is denoted by m_n. If this m_n is high (low) the linacs to be considered for treatment are mh_h , $h = 1,\ldots,H$ (ml_l , $l = 1,\ldots,L$). A patient cannot have two treatment sessions on the same day.

Patients are of different categories: (A) emergency patients; (B) palliative treatments for pain alleviation; and (C) radical treatments for curative intent. For each category, the Joint Council for Clinical Oncology (JCCO) set the waiting time targets that is measured from the time that the decision to give radiotherapy was made to the first treatment session. Table 1 shows the waiting time targets for each category of patients.

Table 1: Waiting time targets

JCCO category	Description	Maximum acceptable waiting times
A	Emergency	2 days
B	Palliative	14 days
C	Radical	28 days

Linacs of high or low energy are treated as parallel machines. Each treatment on a linac is of fixed duration: 15 minutes on high energy linacs and 12 minutes on low energy linacs, apart from the first fraction which takes 5 minutes longer (due to patient induction). The capacity of each linac measured as the maximum number of sessions per day is calculated based on the working shifts that are different on weekdays and weekends, and the duration of sessions. A slot is reserved at the end of each weekday on each linac for emergency cases.

In this paper we will assume that each patient P_n finishes all processes prior to treatment sessions by the release date denoted by r_n . The radiographer has to book F_n treatment sessions described by the vector $[s_{n,f,m_n}]_{F_n}$, $f = 1,\ldots,F_n$, for each patient P_n .

The booking process has to satisfy the following constraints:

1. The first treatment session $s_{n,1,m_n}$ of patient P_n , $n = 1,\ldots,N$ has to be set after its release date r_n ;
2. Palliative (B) and radical (C) patients are not treated on weekends;
3. Emergency (A) patients can be treated on any day of the week;
4. Radical (C) patients do not start treatments on Fridays, so that at least two treatments are given before the first (weekend) interruption to treatment;
5. If the number of treatment sessions F_n is less than or equal to 5, the treatment must not have an interruption, i.e. the treatment must take place in a single week in F_n contiguous days;
6. If the number of treatment sessions F_n is greater than 5, patients can have a maximum of I_n^{max} interruptions – weekdays without treatment;
7. No two treatments can be booked on the same linac at the same time;
8. The capacity of each linac must not be exceeded;
9. Two sessions of one patient's treatment cannot be booked in the same day.

The following criteria are used to evaluate the quality of the booked treatments.

1. The number of patients who do not meet the waiting time targets:

   $C_1 = \Sigma U_n$ where

   $$U_n = \begin{cases} 1 & s_{n,1,m_n} > d_n \\ 0 & otherwise \end{cases}$$

2. The total length of waiting time breaches of the patients:

   $C_2 = \Sigma T_n$ where

   $$T_n = \begin{cases} s_{n,1,m_n} - d_n & s_{n,1,m_n} > d_n \\ 0 & otherwise \end{cases}$$

3. The number of interruptions of the scheduled treatments:

   $C_3 = \Sigma I_n$

   where I_n counts for patient P_n the number of adjacent days in the treatment which are defined as breaks of treatment process. These depend on the category and number of treatment sessions of the patient.

3 Methodology

The booking process consists of two phases: in the first phase patients are prioritised for booking, and in the second phase all of their required sessions are booked (scheduled). Scheduling is done separately for linacs of low and high energy. Therefore, a separate prioritised list of patients is maintained for high energy and low energy linacs.

1. The prioritisation of patients: in the first phase patients P_n , $n = 1,\ldots,N$, are prioritised for booking. The rule for prioritisation assigns high priority for all emergency patients (category A), while the remaining patients are prioritised by their due dates, i.e. Earliest-due-date (EDD) dispatching rule is used. Without loss of generality, we can assume that the patients are re-indexed so that vector $[P_n]_N$ presents a prioritised list of patients.

2. Booking: in the second phase, the required number of treatment sessions, F_n , are booked for each patient, starting from the patients with highest priority. Two algorithms are developed for treatment booking: As soon as possible (ASAP) and Just-in-time (JIT). They are described in more detail below.

3.1 ASAP algorithm

ASAP algorithm assigns to each patient from the prioritised list $[P_n]_N$ the earliest feasible start date $s_{n,1,m_n}$ of the first treatment (feasible in the sense that it does not violate constraints listed in Section 2). The pseudo-code of the *ASAP* algorithm is given in Figure 1. The first treatment $s_{n,1,m_n}$ cannot start before prior processes are completed (step 1). Emergency patients (category A) are booked on the first available day (step 2). Other patients have to be treated on weekdays (step 3). Patients given a course of treatment of five or less sessions are treated within one week without a weekend break; if this is not possible treatment start is delayed until the following week (step 4). Radical patients (category C) are not permitted to start on Fridays, so starts are delayed until the Monday (step 5).

Once a feasible starting date is found, step 6 ensures that there exists a feasible schedule for that start date, i.e. that there are linac slots available for all the treatment sessions with the allowable number of interruptions for that category of patient. If the original start date cannot provide a feasible schedule, the start date is moved forward one day, and the availability of linac slots is checked again.

```
For $n = 1,\dots,N$

  (1) $s_{n,1,m_n} = r_n$

  (2) If $C_n = A$ (emergency)
        go to (6)

  (3) If $s_{n,1,m_n}$ is a weekend day
        $s_{n,1,m_n}$ = next Monday

  (4) If $F_n \le 5$
        If all treatment sessions cannot fit into one week
          $s_{n,1,m_n}$ = next Monday

  (5) If $C_n = C$ (radical) and $s_{n,1,m_n}$ is Friday
        $s_{n,1,m_n}$ = next Monday

  (6) Test start date $s_{n,1,m_n}$ and book all treatment sessions
      $I_n = 0$
      $f = 1$
      do
        If capacity of linacs $V_{Hs_{n,1,m_n}}$ ( $V_{Ls_{n,1,m_n}}$ ) of energy $m_n$ =
        high (low) is not exceeded for day $s_{n,f,m_n}$
          $s_{n,f+1,m_n}$ is next_day ( $s_{n,f,m_n}$ )
          $f = f + 1$
        else
          $I_n = I_n + 1$
          If $I_n \le I_n^{max}$  // the number of interruptions is
          acceptable
            $s_{n,f,m_n}$ is next_day ( $s_{n,f,m_n}$ )
          else      // too many interruptions
            // new start date of the treatment is determined
            $s_{n,1,m_n}$ is next_day ( $s_{n,1,m_n}$ )
            go to (2)
      until $f \le F_n$
      return $[s_{n,f,m_n}]_{F_n}$     $n = 1,\dots,N$

next_day ( $s_{n,f,m_n}$ ):
  If $C_n = A$ (emergency)
    return next day of $s_{n,f,m_n}$
  else
    return next weekday of $s_{n,f,m_n}$
```

Figure 1: Pseudo-code of the *ASAP* algorithm

3.2 JIT algorithm

JIT algorithm assigns to each patient from the prioritised list $[P_n]_N$ the latest feasible start date $s_{n,1,m_n}$ of the first treatment. The idea is to consider firstly the day before the due date d_n (the due date itself is not used because of the risk of breakdowns on that date) and to check backwards for a possible start date of treatments. The pseudo-code of the *JIT* algorithm is given in Figure 2.

```
For $n = 1,\dots,N$

  (1) $s_{n,1,m_n} = d_n - 1$

  (2) If $C_n = A$ (emergency)
        go to (6)

  (3) If $s_{n,1,m_n}$ is a weekend day
        $s_{n,1,m_n}$ = Friday before

  (4) If $F_n \le 5$
        If all treatment sessions cannot fit into one week
          $s_{n,1,m_n}$ = week before on such a day so that all
          treatment sessions can fit in one week

  (5) If $C_n = C$ (radical) and $s_{n,1,m_n}$ is Friday
        If capacity of linacs $V_{Hs_{n,1,m_n}}$ ( $V_{Ls_{n,1,m_n}}$ ) of energy $m_n$ =
        high (low) is exceeded
          $s_{n,1,m_n}$ = Wednesday before
          // treat on Wednesday and Thursday, see constraint 4
        else
          $s_{n,1,m_n}$ = Thursday before
          // treat on Thursday and Friday, see constraint 4

  (6) Test start date $s_{n,1,m_n}$ and book all treatment sessions
      $I_n = 0$
      $f = 1$
      do
        If capacity of linacs $V_{Hs_{n,1,m_n}}$ ( $V_{Ls_{n,1,m_n}}$ ) of energy $m_n$ =
        high (low) is not exceeded for day $s_{n,f,m_n}$
          $s_{n,f+1,m_n}$ is next_day ( $s_{n,f,m_n}$ )   (next_day is given in
          Figure 1)
          $f = f + 1$
        else
          $I_n = I_n + 1$
          If $I_n \le I_n^{max}$ // the number of interruptions is acceptable
            $s_{n,f+1,m_n}$ is next_day ( $s_{n,f,m_n}$ )
          else      // too many interruptions
            // new start date of the treatment is determined
            $s_{n,1,m_n}$ is one_day_before ( $s_{n,1,m_n}$ )
            If $s_{n,1,m_n} < r_n$
              apply ASAP algorithm to patient $P_n$
            else
              go to (2)
      until $f \le F_n$
      return $[s_{n,f,m_n}]_{F_n}$     $n = 1,\dots,N$

one_day_before ( $s_{n,f,m_n}$ ):
  If $C_n = A$ (emergency)
    return previous day of $s_{n,f,m_n}$
  else
    return previous weekday of $s_{n,f,m_n}$
```

Figure 2: Pseudo-code of the *JIT* algorithm

The first treatment $s_{n,1,m_n}$ starts the day before the due date (step 1). Emergency (A) patients are booked on the first available day (step 2). Other patients have to be treated on weekdays (step 3). Patients given a course of treatment of five or less treatment sessions are treated within one week without a weekend break; if this is not possible treatment start is moved back to the week before (step 4). Radical patients must have two treatments before their first weekend break; therefore they start no later than Thursday (step 5).

Once a feasible starting date is found, step 6 makes sure that there exists a feasible schedule for that start date, i.e. that there are linac slots available for all the treatment sessions with the allowable number of interruptions for that category of patient. If the original start date cannot provide a feasible schedule, the start date is moved back one day, and the availability of linac slots is checked again. If no start date can provide a feasible schedule, then the *ASAP* algorithm is applied to the patient.

The main difference between the *JIT* and the *ASAP* algorithms is that *JIT* starts from the latest feasible start date and books backwards whereas *ASAP* starts from the earliest feasible start date and books forwards.

3.3 Objective function

Satisfaction grades are introduced to reflect the satisfaction of the radiographer with the value achieved for each criterion. Satisfaction grades take values from [0, 1] interval, where 0 and 1 represent full dissatisfaction and satisfaction with the achieved criterion value, respectively. The values of the criteria used to evaluate the quality of the booked treatments are of different nature. For example, criterion C_1 counts the number of patients (the value between 1 and P_n) while C_2 is expressed in days. Satisfaction grades enable aggregation of criteria values into a single measure.

In practice it is very difficult to book the treatments in such a way as to satisfy waiting targets for all the patients. In order to define the satisfaction grade of criterion C_1 (measures the number of patients who do not meet the waiting time targets) we introduce a parameter p which expresses the threshold of the acceptable percentage of the patients who do not meet the targets.

The satisfaction grades linearly decrease from 1 to 0 on the [0, p] interval. Parameter p has value 0%, 33%, 53% for emergency, palliative and radical patients, respectively (we used figures from the RCR's (2006) national audit to set the values for parameter p). The satisfaction grade of C_1 is calculated as the average of the satisfaction grades for all categories of patients.

The satisfaction grade S_2 of criterion C_2 (the total length of waiting time breaches of the patients) is calculated as the average of the patient satisfaction grades $S_{2,n}$, $n=1,\dots,N$. The patient satisfaction grade is defined for each category of patient; it has value 1 if the patient meets the waiting time target and linearly decreases to 0 when the waiting time is 2, 28 and 56 days for emergency, palliative and radical patients, respectively. As an illustration Figure 3 shows the satisfaction grade for radical patients.

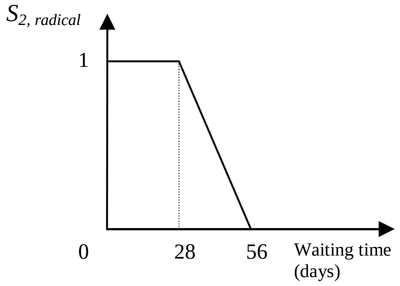

Figure 3: Satisfaction grade for waiting time of radical patients

The satisfaction grade S_3 of criterion C_3 (the number of interruptions) is calculated as the average of the patient satisfaction grades $S_{3,n}$, $n=1,\dots,N$ that is defined in the following way:

$$S_{3,n} = \begin{cases} 1 & I_n = 0 \\ 1 - \left(\dfrac{I_n}{I_n^{\max} + 1} \right) & I_n \le I_n^{\max} \\ 0 & I_n > I_n^{\max} \end{cases}$$

4 Results

This section reports on the experiments designed to evaluate the performance of the proposed algorithms. The algorithms were implemented in the C++ language and executed on a 2.4GHz Pentium 4 with 1024MB of RAM.

Real-world data about patient referrals provided by the City Hospital for the period January to March 2006 have been used in the experiments. The numbers of patients of different categories are presented in Table 2.

Table 2: Categories of patients, in the period January – March 2006

Patients	**Jan 06**	**Feb 06**	**Mar 06**
Emergency	6	6	9
Palliative	57	58	63
Radical	98	90	92
Total	161	154	164

Each algorithm was tested under three different load conditions: *Normal* load of the treatment booking system; *Light* load and *Heavy* load, which are 5% less and 5% more (in absolute terms on a week by week basis) than the *Normal* load, respectively. The percentages of already booked sessions in the treatment booking system when N

patients arrive for booking, under different loads are given in Table 3.

Table 3: Percentage loads of the treatment booking system

Week	Light	Normal	Heavy
1	90	95	98
2	75	80	85
3	70	75	80
4	65	70	75
5	60	65	70
6	55	60	65
7	50	55	60
8	45	50	55
9	35	40	45
10	25	30	35
11	15	20	25
12	5	10	15
>12	0	0	0

Figure 4 shows the percentage of patients late under the *Normal* load. For all load conditions, no emergency patients were late. Comparing the two algorithms, the main difference is in palliative patients, namely the *JIT* algorithm produces between 28% to 40% less late palliative patients than *ASAP*.

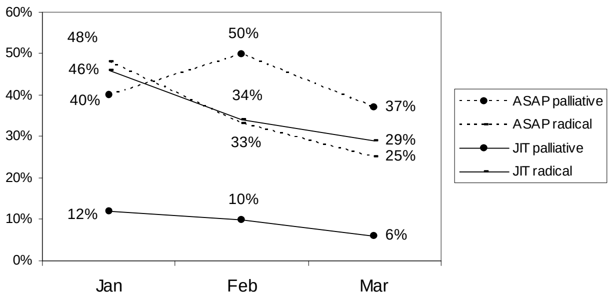

Figure 4: Percentage of late patients under the *Normal* load of the treatment booking system

Table 4 shows the satisfaction grades for the number of late patients (criterion C_1) under the *Normal* load, achieved by the *ASAP* and *JIT* algorithms. Only the number of late palliative patients is less than fully satisfactory. Satisfaction grades for criterion C_1 for all patient categories for all months (number of late patients) were equal to 1 (full satisfaction) for the *JIT* algorithm.

Table 4: Satisfaction grades for C_1 under the *Normal* load of the treatment booking system

Patients	**Jan 06**		**Feb 06**		**Mar 06**	
	ASAP	*JIT*	*ASAP*	*JIT*	*ASAP*	*JIT*
Emergency	1.00	1.00	1.00	1.00	1.00	1.00
Palliative	0.89	1.00	0.75	1.00	0.95	1.00
Radical	1.00	1.00	1.00	1.00	1.00	1.00
Average	0.96	1.00	0.90	1.00	0.98	1.00

Table 5 shows the satisfaction grades for breach length (criterion C_2) under the *Normal* load of the treatment booking system. Comparing the two algorithms, *JIT*'s satisfaction grades are 0.28 to 0.4 higher for palliative patients than *ASAP*. However, *ASAP* produces marginally higher satisfaction grades for radical patients. Finally, average satisfaction grades are higher for *JIT*.

Table 5: Satisfaction grades for C_2 under the *Normal* load of the treatment booking system

Patients	**Jan 06**		**Feb 06**		**Mar 06**	
	ASAP	*JIT*	*ASAP*	*JIT*	*ASAP*	*JIT*
Emergency	1.00	1.00	1.00	1.00	1.00	1.00
Palliative	0.60	0.88	0.50	0.90	0.64	0.94
Radical	0.85	0.81	0.90	0.87	0.97	0.92
Average	0.77	0.84	0.75	0.88	0.84	0.93

Figure 5 shows the percentage of late patients under the *Light* load of the treatment booking system. Similarly to the *Normal* load, *JIT* produces between 29% to 30% less late palliative patients than *ASAP*. However ASAP produces up to 11% less late radical patients than *JIT*.

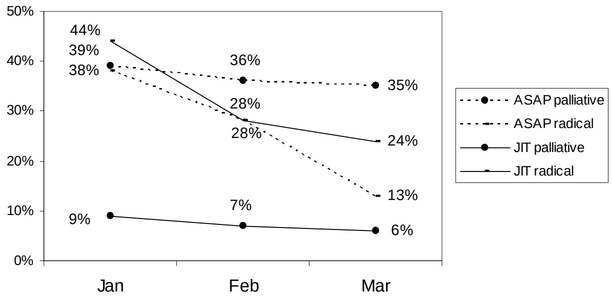

Figure 5: Percentage of late patients under the *Light* load of the treatment booking system

Table 6 shows the satisfaction grades for the number of late patients under the *Light* load, achieved by both algorithms. Again, only the number of late palliative patients, under *ASAP*, is less than fully satisfactory. A 5% reduction in load has resulted in a 3% to 27% increase in satisfaction grade for palliative patients.

Table 6: Satisfaction grades for C_1 under the *Light* load of the treatment booking system

Patients	**Jan 06**		**Feb 06**		**Mar 06**	
	ASAP	*JIT*	*ASAP*	*JIT*	*ASAP*	*JIT*
Emergency	1.00	1.00	1.00	1.00	1.00	1.00
Palliative	0.92	1.00	0.95	1.00	0.97	1.00
Radical	1.00	1.00	1.00	1.00	1.00	1.00
Average	0.97	1.00	0.98	1.00	0.98	1.00

Table 7 shows the satisfaction grades for breach length (criterion C_2) under the *Light* load. *JIT* produces between 43% to 48% higher satisfaction grades for palliative patients than *ASAP*, leading to less variability than under the *Normal* load. *ASAP* produces marginally higher satisfaction grades for radical patients. Again, average satisfaction grades are higher for *JIT*.

Table 7: Satisfaction grades for C_2 under the *Light* load of the treatment booking system

Patients	**Jan 06**		**Feb 06**		**Mar 06**	
	ASAP	*JIT*	*ASAP*	*JIT*	*ASAP*	*JIT*
Emergency	1.00	1.00	1.00	1.00	1.00	1.00
Palliative	0.61	0.91	0.64	0.93	0.65	0.94
Radical	0.91	0.85	0.94	0.90	0.99	0.95
Average	0.81	0.88	0.83	0.92	0.86	0.95

Figure 6 shows the percentage of late patients under the *Heavy* load. *JIT* produces between 27% to 41% less late palliative patients than *ASAP*.

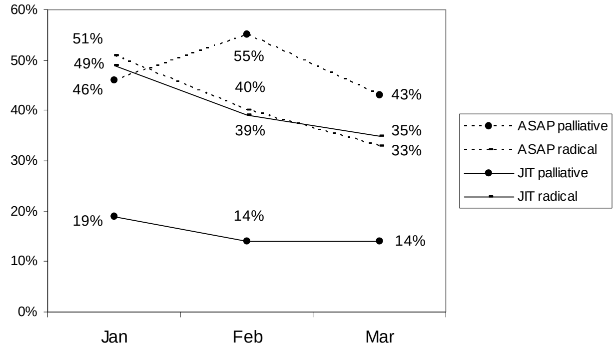

Figure 6: Percentage of patients late under the *Heavy* load of the treatment booking system

Table 8 shows the satisfaction grades for the number of late patients (criterion C_1) under the *Heavy* load. Under the *ASAP* algorithm, a 5% increase in load has resulted in a 9% to 11% reduction in satisfaction grade for palliative patients.

Table 8: Satisfaction grades for C_1 under the *Heavy* load of the treatment booking system

Patients	**Jan 06**		**Feb 06**		**Mar 06**	
	ASAP	*JIT*	*ASAP*	*JIT*	*ASAP*	*JIT*
Emergency	1.00	1.00	1.00	1.00	1.00	1.00
Palliative	0.81	1.00	0.67	1.00	0.85	1.00
Radical	1.00	1.00	1.00	1.00	1.00	1.00
Average	0.93	1.00	0.87	1.00	0.94	1.00

Table 9 shows the satisfaction grades for breach length (criterion C_2) under the *Heavy* load. *JIT* produces between 48% to 93% higher satisfaction grades for palliative patients than *ASAP*, showing more variability than under the *Normal* load. *ASAP* produces marginally higher satisfaction grades for radical patients.

Table 9: Satisfaction grades for C_2 under the *Heavy* load of the treatment booking system

Patients	**Jan 06**		**Feb 06**		**Mar 06**	
	ASAP	*JIT*	*ASAP*	*JIT*	*ASAP*	*JIT*
Emergency	1.00	1.00	1.00	1.00	1.00	1.00
Palliative	0.54	0.81	0.45	0.86	0.57	0.86
Radical	0.79	0.76	0.85	0.82	0.92	0.82
Average	0.71	0.78	0.71	0.84	0.79	0.88

The satisfaction grades for the number of interruptions, presented in Table 10, show little variation between either loads or algorithms.

Table 10: Satisfaction grades for C_3

Load	**Jan 06**		**Feb 06**		**Mar 06**	
	ASAP	*JIT*	*ASAP*	*JIT*	*ASAP*	*JIT*
Light	1.000	0.996	1.000	0.993	0.998	1.000
Normal	1.000	1.000	0.998	0.996	0.998	0.998
Heavy	0.996	0.998	0.996	0.994	0.994	0.998

We can conclude, based on the performed experiments that overall *JIT* achieves higher satisfaction grades due to its superior performance with palliative patients.

5 Conclusion and future work

This paper presents two algorithms that can be used in radiotherapy treatment booking; the *ASAP* algorithm which books forward from the earliest feasible start date and the *JIT* algorithm which books backwards from the latest feasible start date. Some practical constraints that arise in the booking process are described.

Our experiments on real-world data provided by the Nottingham University Hospitals NHS Trust indicate that *JIT* achieves higher satisfaction grades due to its superior performance with palliative patients. An interesting combination worth trying may be the *JIT* algorithm for palliative patients and *ASAP* algorithm for radical patients, and vice versa. In our future research work we will introduce adjuvant patients for whom radiotherapy is an additional treatment for cancer. The further differentiation of patients will take into consideration certain patient sites and introduce high priority cases among patients of the same category. The processes prior to treatment sessions have to be scheduled also.

In real-world treatment booking there is a need for rebooking because of “did not attends” (caused by patients forgetting, being on holiday and loss of the patients) and short notice cancellations (due to changes in condition, disease status and treatment plan). This can lead to the loss of valuable linac slots. It also reduces flexibility to accommodate acute/ urgent patients. Thus future research work will investigate the rescheduling of linac slots. Patient preferences for linac slots will also be taken into consideration.

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