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A simulation of a radiotherapy treatment system: A case study of a local cancer centre

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***Abstract*— This paper describes a study of a complex radiotherapy treatment system observed at a local cancer centre. In the system, patients undergo processing on several machines to complete their treatment regimen. Several parts of the process have disturbances that impede the flow of patients, adversely impacting patient waiting time and throughput. This study aims at understanding the treatment process, and identifying complexities and bottlenecks from the interactions between patients and human or machine resources using discrete-event simulation.**

***Keywords*— radiotherapy; discrete-event simulation**

I. Introduction

Radiotherapy involves the use of ionising radiation to treat cancer while minimising damage to healthy tissue. The ionising radiation may be delivered from a source at a distance from the patient's body, termed teletherapy, inserted in or near the tumour (i.e. brachytherapy), or ingested as a radioisotope solution, a method named unsealed sources therapy (UST). These methods involve several steps before the actual treatment commences.

Oncology centres aim to promptly treat patients recommended for radiotherapy. However, some patients wait for a long time before undergoing treatment. These prolonged waiting times thwart any likelihood of prompt cure or palliation of the disease. An estimated 120 000 people lose their lives to cancer annually in England [7]. Thus, several waiting time standards have been framed by the Joint Council for Clinical Oncology (JCCO) and the Department of Health (DH) to reduce further loss of life through the disease [4], [8]. These standards are difficult to meet because of bottlenecks created by the interactions between the patients and human or machine resources in the treatment system.

An audit conducted by Summers and Williams [14] in 2005 reported that the waiting times were worse and unacceptable compared to 1997 statistics. Oncology centres face the challenge of reducing these patient waiting times to improve their quality of service. One of these centres is the Arden Cancer Centre (ACC) at the University Hospitals of Coventry and Warwickshire NHS Trust (UHCW), Coventry, in England. It aims to reduce waiting times and maximise patient throughput while utilising its available resources to full capacity. This could be difficult to achieve because of disturbances normally involved in the system. These include patients not attending sessions, staff shortages, unavailability of doctors, machine breakdowns, and or continual surge in cancer patients. Therefore, a simulation model of the treatment system would help to understand the magnitude of bottlenecking in the fundamental steps of the process. The simulation model is developed with this respect, and as a first step towards development of radiotherapy patient scheduling algorithms.

The remainder of the paper is organised as follows. Section II surveys literature on simulation. Section III describes the radiotherapy treatment process at UHCW. Section IV discusses the development of the simulation model. Section V reviews the experimentation results. Lastly, Section VI provides concluding remarks.

II. Literature review

Simulation is a problem solving methodology that mimics a real world system over a period of time [2]. Literature has considerable spectra of real world problems analysed and solved using simulation models. These models provide invaluable information for decision making and also increase the problem solver's understanding of the system through experimentation [3], [9]. Simulation models can be continuous or discrete-event. Discrete-event simulation involves modelling a system whose state changes instantaneously whereas in continuous simulation, state changes continuously with respect to time [3], [9]. Pidd [9] includes an exposition of the distinction between the two. One archetypical discrete event simulation was reported by Chen et al. [3] for a chemical plant manufacturing process.

This paper discusses a discrete-event simulation of patient flow at a cancer centre. Numerous articles have been published on the application of discrete-event simulation on health-care problems. Jun and colleagues [?] extensively discussed literature on simulation of single or multi-facility health care clinics. However, it seems a few researchers have attempted to model cancer clinics. Sepúlveda and colleagues [12], [1] analysed patient flow and resource requirements for a new facility. However, unlike in [12], this paper solely describes the analysis of patient flow. The radiotherapy treatment processes could be viewed as a multi-facility healthcare environment that shares key resources such as doctors and radiographers.

Lowery [5] presented an introduction to simulation in health-care and clearly outlined the barriers to modelling in this environment. One issue of paramount importance is how the simulation model would be developed and implemented. Numerous computer simulation software packages are available on the market. Some of these include Arena, eM-Plant, Micro Saint, ProcessModel, SimScript, Simul8, and or Visual Simulation Environment [6]. In this study, Simul8, a discrete-event simulation computer package by Simul8 Corporation [13], was used in the development of the model. It is easy to use and supports stochastic simulation [9]. Furthermore, it allows the user to create an iconic representation of the real system being investigated by drawing objects directly on the screen.

III. Overview of the Radiotherapy Treatment System

The cancer centre is located at the UHCW premises. It has facilities for the three radiotherapy treatment methods; teletherapy, brachytherapy, and UST. Teletherapy is the most common form of treatment with circa 3000 patients treated yearly (according to 2005 data) while a handful are treated through unsealed sources and brachytherapy. All the steps of these treatment processes are carried out in three units of the centre (i.e. physics, planning, and treatment unit). Teletherapy patients go through all the three units. Brachytherapy and UST processes are only carried out in the physics unit. Figure 2 shows a high level view of the three processes. Furthermore, the physics unit provides essential technical support services such as commissioning, calibration, repair, and maintenance of machines.

The teletherapy process (see Figure 1) can be divided into four phases; consultation, simulation and imaging, pre-treatment, and treatment. The consultation phase commences the treatment process. A multi-disciplinary meeting of doctors discusses patient details from referrals. Either chemotherapy or radiotherapy is recommended. If radiotherapy, and the patient acquiesces, they are scheduled for the simulation and planning phase after a doctor establishes their treatment regimen (i.e. a treatment path to be followed by a cancer patient).

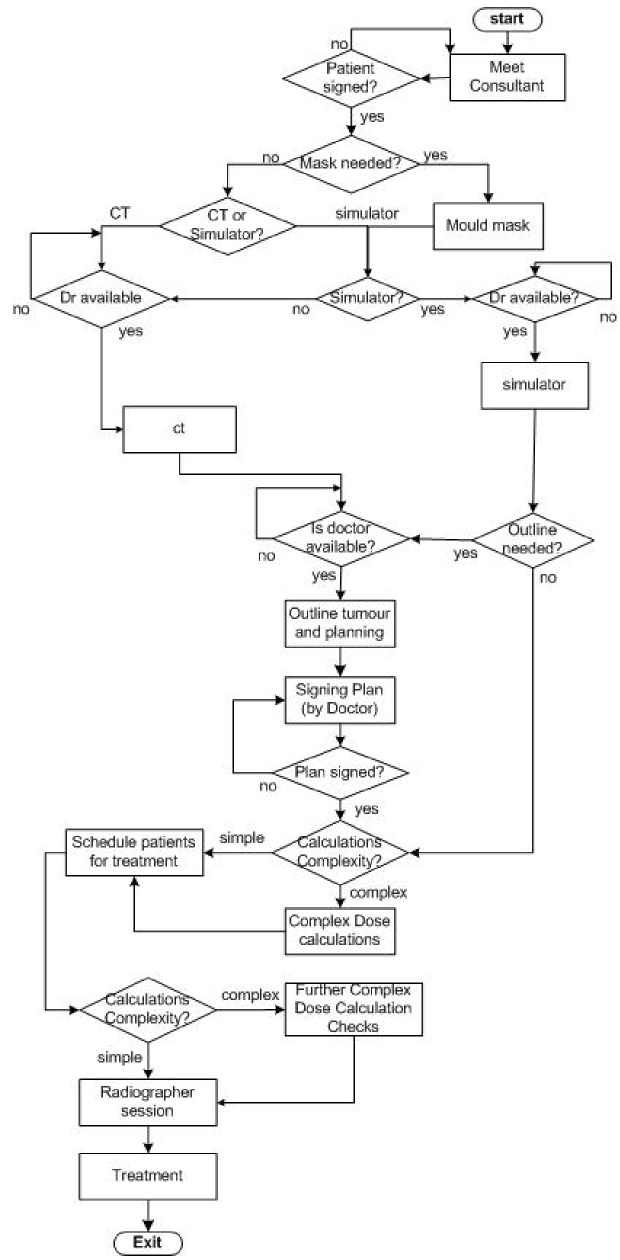

Fig. 1. Teletherapy process flowchart

In the simulation and planning phase, several machines are used for simulating and planning the patient's treatment. These are a mould room, computed axial tomography (CT) scanner, and simulator. Simulation and planning involves one or any combination of these facilities. All patients receiving radiotherapy treatment are required to be positioned accurately at each treatment session. Some cancers (such as head and neck cancers) require immobilisation devices to improve the accuracy of the positioning of the patient on the treatment machine. Therefore, patients requiring these devices visit

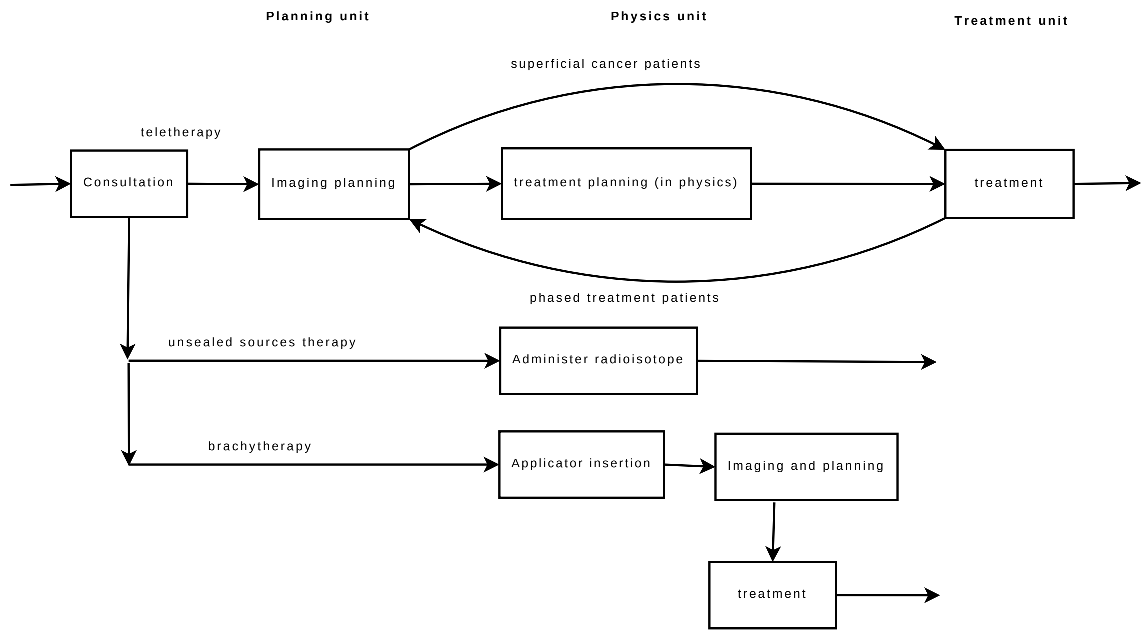

Fig. 2. High level flowchart of the processes

the mould room before either the CT scanner or simulator.

Treatment outline and planning involves determining the most appropriate angle and intensity of radiation beams. In the physics unit, physicists and dosimetry technicians determine the treatment plans, check them for errors, and calculate the radiation doses required based on details from simulation and planning phase. Some cancers (e.g. breast) require complex outlines and dose calculations. Complex dose calculations are performed and checked in physics. Further checks of these calculations are carried out by radiographers in the pre-treatment phase. In addition, simple calculations are also performed in the pre-treatment phase. Thus, depending on their complexity, some treatment plan calculations and checks may not be handled in the physics unit.

The pre-treatment phase also deals with scheduling patients on treatment machines depending on the dose (low or high energy) to be delivered and machine availability. Seven treatment machines are involved in this phase. These include five linear accelerators (linacs), a deeper X-Ray (DXR) machine, and betatron. The linacs treat complex cancers (e.g. breast) while the DXR and betatron are for other special cases. Patients taking the UST route are booked on a date when their doctor is available. The centre receives soluble radioisotopes such as Iodine (I-131) on standing orders. Others such as Phosphorus (P-32), Strontium (Sr-89), and Samarium (Sm-153) are ordered days before the treatment date. Thus, the treatment process involves consultation, appointment date booking, and then treatment delivery.

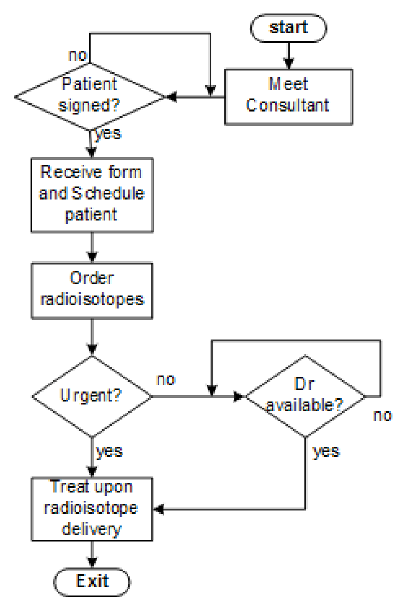

Fig. 3. UST process flowchart

There are two isolation rooms used to decontaminate patients (especially thyroid cancers) before being discharged. The UST process flowchart is illustrated in Figure 3.

After the consultation phase, brachytherapy patients have an applicator inserted next to their tumour. In the case of lung/bronchus and other cancers, the applicator is inserted in the physics unit's brachytherapy treatment room while cervix related cancers require an operation in the hospital's theatre. Standard plans and checks are performed by the doctor before the patient can be treated on the high dose rate (HDR) machine. The whole process is undertaken by physicists and technicians in the physics division. The brachytherapy process flowchart is shown in Figure 4.

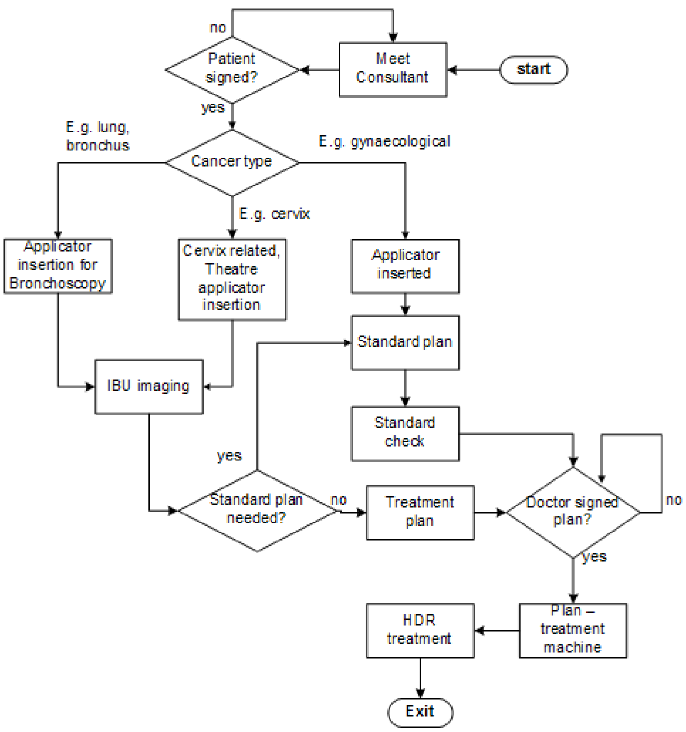

Fig. 4. Brachytherapy process flowchart

IV. Development of the Simulation Model

A. Data collection

TABLE I
TIME ESTIMATES

Item (minutes)	**Distribution**
Machine breakdowns (in days)	Exponential(3.98)
Treatment time	Uniform(15,20)
Scanning time	Uniform(25,30)
Simulator time	Uniform(25,30)
Planning time	Uniform(40,45)
Radiographer session	Uniform(10,15)
Patient booking	Uniform(5,7)
Radioisotope delivery	Uniform(12,15)
Applicator insertion	Uniform(5,7)

Data were collected from the ACC computer database system, observations, and by interviewing radiographers, physicists, technicians, and other personnel. Records from the computer database system had some details of patients treated in 2005. Probability distributions were estimated for several random variables including the time between machine breakdowns, processing time on the machines, and number of patients; arriving for consultation per day, urgent and non-urgent, for palliative or radical treatment, in or out-patient, attended to by own doctor in simulation and planning unit, and number of treatment phases. Table I shows some of the estimated probability distributions for some of the variables.

There are twelve doctors involved in the whole treatment system (i.e. all three processes). At least a doctor is available at any time of the day (i.e. Monday through Friday). For the rest of the staff, work commences at 9am and ends at 5pm although they at times work overtime to clear queued patients. There is a limit to the number of radiographers that should operate each machine. Table II summarises the staff complement at the centre.

TABLE II
HUMAN (STAFF) RESOURCES

Resource	**Units**
CT and Simulator Radiographers	5
Treatment unit radiographers	25
Pre-Treatment radiographers	3
Physicists	11
Dosimetry technicians	7
Engineering technicians	6

TABLE III
PHYSICAL (MACHINE) RESOURCES

Resource	**Units**
Linacs	5
CT Scanner	1
Simulator	1
Deep X-Ray (DXR)	1
Betatron	1
IBU	1
High dose rate (HDR)	1

The UST process requires services of a physicist and technician during a patient's treatment session. Staff in the physics unit is multi-skilled. So, they all can be involved in the teletherapy, brachytherapy, or UST processes. Similarly, the brachytherapy treatment method also needs a physicist and technician to operate the machines, HDR and integrated brachytherapy unit (IBU), plan checks, and treatment sessions.

B. The simulation model

The simulation model is divided into three parts representing teletherapy, brachytherapy, and unsealed sources processes. In earlier work at UHCW, Proctor [10], modelled the teletherapy process alone. This has been extended by including the brachytherapy and UST system because all the three treatment systems share human resources in the physics unit. Currently, the centre schedules patients on a first come first serve (FCFS) basis depending on whether it is a first definitive treatment or an additive to chemotherapy or other forms of treatment. Modelling all the treatment processes helps to determine the magnitude of the complexity of the radiotherapy patient scheduling.

The structure of the simulation model mimics all the phases in the real system. Work items (i.e. patients) processed at the consultation work centre, can take one of the three possible routes: teletherapy, brachytherapy, or UST. The teletherapy route involves the simulation and imaging phase where patients undergo the mould room work centre and subsequently either the CT scanner or simulator work centres. Upon exiting the simulation and imaging phase, patients from the simulator or CT scanner work centres could join the outline and planning queue, complex or simple calculations queues, or the treatment machine queues. Figure 5 shows a screen shot of the simulation model.

The UST route, illustrated in Figure 3, mainly comprises of three work centres that represent the radioisotopes involved in the process (i.e. Iodine (I-131), Phosphorus (P-32), and others like Samarium (Sm-153) and Strontium (Sr-89)). The I-131 is connected to the decontamination work centres whose services are also utilised by brachytherapy patients.

The brachytherapy model branches into three routes, the physics unit applicator insertion work centre, cervix related applicator insertion work centre (in theatre), and the bronchoscopy and endoscopy route. These work centres are linked to the queues of the standard plan and checks or treatment plan work centres. There is only one machine used in the treatment phase, the HDR. Iodine isotope seeds are used, thus, work items (patients) undergo the decontamination room work centres before being discharged.

V. Simulation Experiments

A. Overview of simulation model validation

Sargent [11] describes several methods of verifying and validating a simulation model. These methods include animation, historical data validation, face validity, comparison to other models, internal validity, extreme condition tests, turing tests, and traces. An anatomy of credibility and validity of simulation models by Law and Kelton [**?**] showed that some of these validation methods depend on the aims of modelling the system. Some of these methods were used to validate the simulation model. The process flowcharts illustrated in Figure 1, 3, and 4 and the historical data also availed in tracing the behaviour of the work items (i.e. patients) in various sections of the model. Table IV compares the average waiting time (in days) between the consultation phase and the commencement of a patient's fractionation scheme in the treatment unit.

TABLE IV
Comparison of real and model waiting time averages in days

Intent	Historical	Model
All	32.25	33.14
Palliative	15.52	17.27
Radical	42.37	42.67

B. Experiments

The simulation model shows excessive patient congestion on the queues for treatment machines (especially the linacs). During the runs, intermittent crowding of patients was evident on doctor queues and physics outline and planning queues, although not as significant as the linac queues. A plausible explanation of congestion on linacs was the unavailability of some machines decommissioned due to the 2005 migration to a new centre site. Furthermore, the sporadic crowding on doctor queues was due to their limited time in the system. However, some patients took the doctor bypass route (particularly the urgent ones). The varying statistics in Table V illustrate that some machines were not fully utilised. Of the high energy linacs, H3 was most utilised compared to H1 and H2. This could again be attributed to the disturbances caused by the migration to the newly built hospital premises.

C. Simulations of different scenarios

Proctor [10], discussed the reactions of the patient flow in different scenarios. Predictably, extending the human and physical resource shift hours, adding new treatment machine, and easing demand for doctors by patients increased the throughput for those treated within 14 days of commencing their treatment regimen. However, the report did not include a comparison of the waiting times such as illustrated in Table VI.

An extension of shift hours for both human and machine resources to the time window, 9am to 8pm, reduced

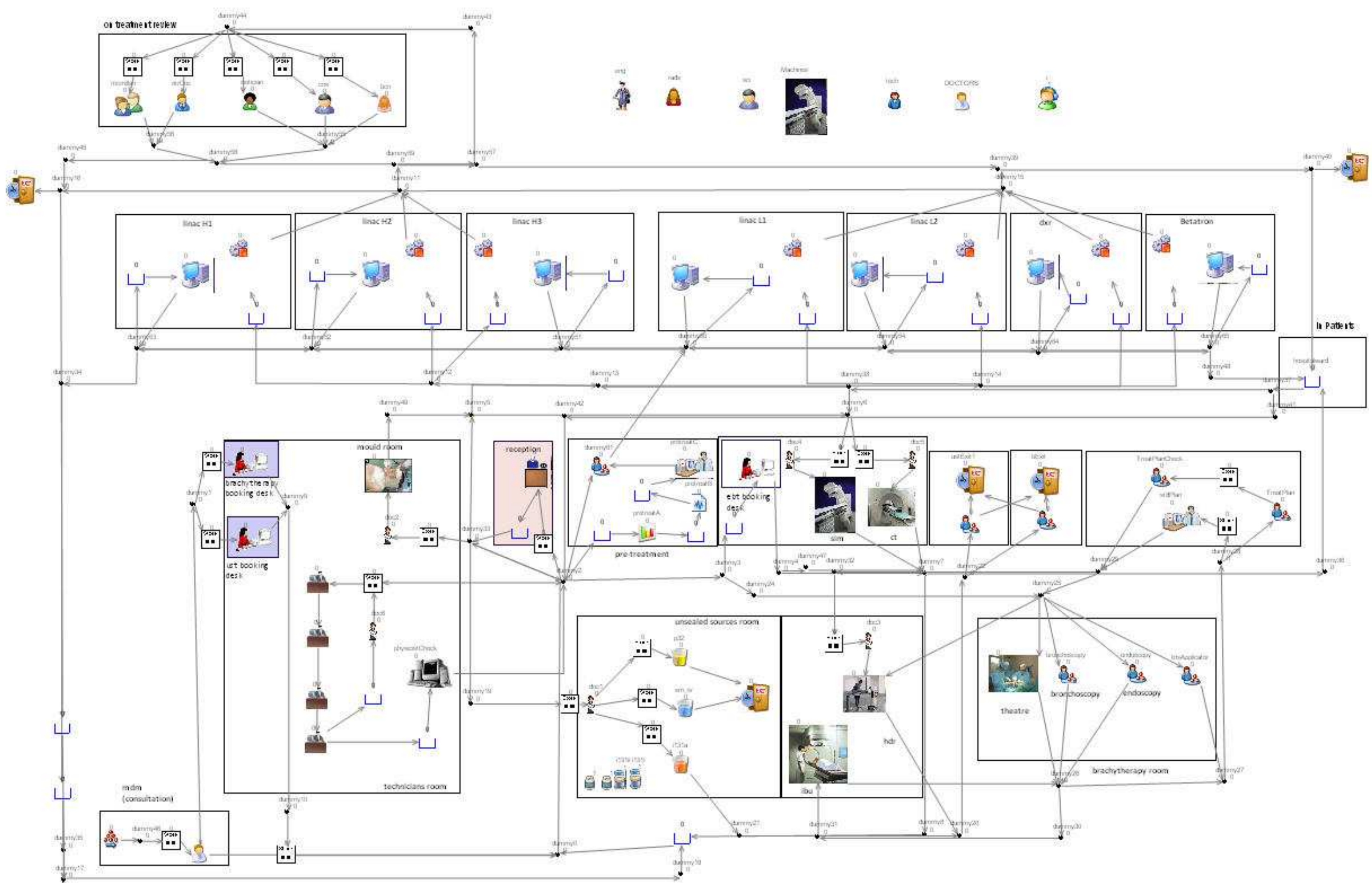

Fig. 5. Screen shot of the cancer centre model

TABLE V

MACHINE RESOURCE UTILISATION STATISTICS

Machine	Utilisation(%)
Linac H1	16.00
Linac H2	34.00
Linac H3	60.00
Linac L1	45.00
Linac L2	60.00
DXR	21.00
Betatron	1.00
High dose rate (HDR)	1.00
IBU	1.00
Mould Room	3.00

TABLE VI

COMPARISON OF MODEL AND SCENARIOS (IN DAYS)

Intent	Model	Reduced Staff	Extended hours
All	33.14	33.51	32.55
Palliative	17.27	17.35	17.09
Radical	42.67	42.98	41.47

the average time patients took to complete their first treatment dose. In this case, it was presumed that daily activity on all machines is uniform. This did not impact the intermittent crowding of patients for doctors but lowered average waiting times for the cancer categories significantly. Table VI compares the average waiting times of the model (see Table IV) with the results obtained after altering shift hours and radiographer staffing levels. When the staffing levels of radiographers in the various units was reduced, the average waiting times in Table VI lowered insignificantly because the model shared the available resources amongst the starved units (i.e. because staff is multi-skilled).

TABLE VII

COMPARISON OF MODEL AND SCENARIOS (IN DAYS)

Intent	Model	Doctor presence	Machine breakdowns
All	33.14	35.52	34.25
Palliative	17.27	19.36	17.39
Radical	42.67	45.06	43.77

The real treatment system permits doctor bypasses. A patient (e.g. emergency or urgent) does not necessarily have to be attended to by their own doctor. Thus, enforcing a no doctor bypass scenario on the model intensifies the patient congestion on their queues. Additionally, the average waiting time to treatment phase for the cancer categories degenerates to the extent shown in Table VII. A disturbance that impedes patient flow, mostly evident at the treatment phase is machine downtime due to breakdowns. When the model was set to automatically breakdown machines, the average waiting times worsened (see in Table VII).

VI. Conclusion

The use of discrete-event simulation models in the analysis of patient flow in cancer clinics is not a novel concept. Literature has case studies of the analysis of patient flow in emergency and other hospital departments. This study described an implementation of simulation modelling to analyse patient flow in a cancer centre's treatment processes. The results obtained from the Simul8 model show that the radiotherapy treatment system has intricate steps and points that bottleneck the movement of patients from consultation to the commencement of treatment, making it difficult to meet the waiting time standards.

The study of the cancer centre provided substantive evidence of the existence of bottlenecks in a radiotherapy treatment process. Various methods could be proposed to solve the problem of scheduling patients at a cancer centre. The future work on this study could involve the development and testing of novel methods for optimally scheduling patients on the existing machine complement using the JCCO and DH targets as constraints.

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