Workflow optimisation for multimodal imaging procedures

Fernandez-Gutierrez, Fabiola; Wolska-Krawczyk, Malgorzata; Buecker, Arno; Houston, J. Graeme; Melzer, Andreas

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Authors:

Fabiola Fernández-Gutiérrez, PhD (1)
Malgorzata Wolska-Krawczyk, MD (2)
Arno Bücker, MD (3)
J. Graeme Houston, MD (4)
Andreas Melzer, MD (1)

Affiliations:

(1) Institute for Medical Science and Technology, Division of Imaging and Technology, University of Dundee, Dundee, United Kingdom
(2) Clinic of Diagnostic and Interventional Neuroradiology, Saarland University Hospital, Homburg, Germany
(3) Clinic of Diagnostic and Interventional Radiology, Saarland University Hospital, Homburg, Germany
(4) Medical Research Institute, The Institute of Cardiovascular Research, University of Dundee, Ninewells Hospital and Medical School, Dundee, United Kingdom

Address for correspondence:

Fabiola Fernández-Gutiérrez
18 Leadmill Court
Leadmill Street
Sheffield
S1 4SA
Phone: +44 (0)77380 72016,
fabiola.fg@gmail.com

Abstract:

Objectives: This study presents a framework for workflow optimisation of multimodal image-guided procedures (MIGP) based on discrete event simulation (DES). A case of a combined X-Ray and magnetic resonance image-guided transarterial chemoembolisation (TACE) is presented to illustrate the application of this method. We used a ranking and selection optimisation algorithm to measure the performance of a number of proposed alternatives to improve a current scenario.

Methods: A DES model was implemented with detail data collected from 59 TACE procedures and durations of Magnetic Resonance Imaging (MRI) diagnostic procedures usually performed in a common MRI suite. Fourteen alternatives were proposed and assessed to minimise waiting times and improve workflow.

Results: Data analysis observed an average of 20.68 (7.68) minutes of waiting between angiography and MRI for TACE patients in 71.19% of the cases. Following the optimisation analysis, an alternative was identified to reduce waiting times in angiography suite up to 48.74%.

Conclusions: The model helped to understand and detect "bottlenecks" during multimodal TACE procedures, identifying a better alternative to the current workflow and reducing waiting times. Simulation-based workflow analysis provides a cost-effective way to face some of the challenges of introducing MIGP in clinical radiology, highligthed in this study.

Key words: Workflow, discrete event simulation, optimisation, MRI, TACE

1. INTRODUCTION

Advances in imaging information systems, navigating and tracking technologies are transforming the traditional intervention rooms in modern Multimodality Imaging Therapy Operating Systems (MITOS) or also known as hybrid Operating Theatres (OT)(1–3). These new designs follow mainly

two approaches. They can be based in one single room layout, containing all the surgical and imaging equipment; or have a set of adjacent rooms directly connected allowing the transfer of the patient and/or equipment among rooms. These suites try to avoid some usual patient safety incidents by means of reducing travel distances for patients and clinicians. In addition, when using adjacent rooms, the imaging equipment placed in separate suites could be used independently for diagnosis (4). Despite their multiple benefits, these new integrated OT are very expensive and therefore, they should be used in the most efficient and cost-effective way possible. Furthermore, when sharing facilities, as in the case of the adjacent rooms design, waiting times can become a critical challenge.

In general, extended waiting time is a common problem in health environments with highly demanded shared facilities (5,6). Simulation techniques such as discrete event simulation (DES) help to identify bottlenecks causing waiting times and understand and improve health protocols (7). DES models are computer programs that translate a system into a process flow represented by tasks and decision points. Every task may need certain human resources to be carried out and would have associated a certain time-to-finish. These tasks behave as random variables and DES models can accommodate the variability of the real system by modelling these times through statistical distributions. These statistical distributions are then used to generate random samples for the times needed to perform each of the tasks.

Recent studies on radiology departments support the application of simulation to improve machine usage and reduce waiting times for patients (8), scheduling policies (9) and radiotherapy planning process (10,11). Up to now, studies have examined departments at various levels of complexity. Johnston et al. (9) and Werker et al. (11) for example classified different patients types but did not applied optimisation analysis to compare workflow scenarios as Granja et al. (5) or Nickel and Schmidt (8) did. However, in these studies, decision points and tasks were modelled at a departamental level.

Previous studies on workflow for interventional radiology do not contemplate events and decisions taken within the procedures, which are considered blocks with an overall duration. Our framework contemplates the inherent variability within the interventions by modelling the interventions' workflow with higher detail. The framework is based on preliminary work to analyse in detail workflow for image-guided procedures (12) and extends it, presenting a workflow optimisaion approach for using DES for multimodal imaging environments. All the steps required in the implementation of this framework are described in the next section. These involved the description of the system's logic via a conceptual workflow, the data collection, detailing which tasks and decision points are to be included; the statistical analysis on the data, including the fitting of the statistical distributions and the model validation. In the optimisation analysis, a wide-accepted method is presented and several alternatives as "what-if" scenarios are compared to the current workflow. A case of study of Transarterial Chemoembolisation (TACE) procedure as multimodal image-guided procedure (MIGP) exemplar, involving Magnetic Resonance Imaging (MRI) and X-Ray, is presented to ilustrate the advantages of this approach. Multilevel information about diagnostic and interventional patients was combined to integrate the inherent variability of the intraprocedural phases. The model was implemented using real clinical data collected during the procedures, as well as using information gathered from questionaires in collaboration with the interventional radiology team at Saarland Medical Centre (Homburg, Germany). The model validation was done with the aid of the clinic and the scenarios considered for the optimisation analysis were also discussed with the clinical team. The scenarios were assessed defining a set of key performance indicators (KPI) and using a statistical ranking and selection procedure for simulation optimisation.

2. METHODS and MATERIALS

2.1. Overview of the multimodal imaging protocol for TACE

TACE is a recommended palliative therapy method of choice in the intermediate stage of hepatocellular carcinoma (HCC), which represents more than 90% of liver cancers (13). The procedure is characterised by a slow injection of a chemotherapeutic agent and oily emulsion of iodinated contrast agent in the tumour area, which has a temporary embolic effect leading to tumour necrosis. The Clinic of Diagnositic and Interventional Radiology in Saarland Medical Centre developed a new clinical protocol to investigate whether MR angiography, after transcatheter intraarterial contrast agent application offers the possibility to identify the treated liver parenchyma. The hypothesis was that this new protocol could allow visualisation of potentially new vascularisation or newly formed metastases (14). Hence, the interventional radiologist could change the primary therapy position of the catheter before the final treatment, which could be significant for optimal tumour targeting. However, large delays were observed when transferring the patient from the angiography suite to the MRI scanner room due to the high demand of MRI imaging in the hospital.

The clinic benefits of an two-adjacent-room-layout, with a MRI scanner suite placed across an angiography room, separated by a 3.7m wide corridor. The MRI room is equipped with a 1.5T wide bore (70cm) MR scanner (Magnetom AERA, Siemens, Erlangen, Germany). The angiography suite is provided with a sliding door to facilitate the transport of patients. Using these settings, the new procotol for a multi-modal imaging TACE (see Figure 1) can be divided in three main phases: cannulation of the target tumour vessel in the angiography suite, transfter to the MRI area and imaging, and transfer back to the angiography suite for possible repositioning of the catheter and final chemotherapy. The catheter cannulation phase consisted of the preparation of the patient, the access to the common femoral artery and the cannulation of the targeted liver area controlled by the HCC. Subsequent digital substraction angiography (DSA) is then performed to confirm the correct therapy position of the catheter. The second phase included the transfer to the MRI area, the preparation of the patient for MRI, the time for taking the scans and the transfer back to the

angiography room, where the last part of the protocol is carried out. In this phase, patients will likely need to wait if the MRI is occupied. The last phase consisted of possible repositioning of the catheter, chemotherapy and closing of the groin access before taken the patient out of the room.

FIGURE 1

2.2. Data collection

Records of 59 TACE interventions were collected from 47 male and 12 female patients with average age of 61.96 (35 – 85). Data was submitted via a website, application designed for data gathering and management of image-guided procedures. This website, although currently unvailable while being transferred to a different server, used a user friendly interface with data validation (e.g. no negative times or age allowed) and autocomplete function to speed up data submission. It also provided basic descriptive statistics of the data being able to plot times associated to a task, selecting one or more types of procedures (12). In addition to the age and gender of the patients, each record included other information about the patiens (height and weight), number and role of the clinical staff members participating in each intervention and time-based event registration. Table 1 presents the significant events registered per TACE intervention together with their average duration and the corresponding standard error in minutes.

TABLE 1

Information corresponding to MRI diagnosis times was gathered through a questionnaire completed by the MRI department clinical team at Homburg Saarland University Hospital. Table 2 contains information about minimum, maximum and most likely time of the most common MRI diagnostic procedures performed in the hospital. The times collected for the MRI diagnostic procedures included the positioning of the patient and scanning times. The preparation of the patient for the MRI was set to 10min in average. An extra 5min were considered to model the time needed to dismiss the patient from the MRI scanner room.

2.3. Model implementation and validation

The DES model was implemented on Delmia Quest software package for workflow modelling and simulation (Dassault Systèmes S.A., Vélizy-Villacoublay, France). The conceptual workflow as shown in Figure 1 was used to implement the logic for the DES model. The simulating model reads a proposed daily schedule of patients based on one TACE patient and seven MRI-diagnostic patients, usual patient number at that part of the radiology department. A TACE patient would be sent to the angiography room, and a MRI patient to the MRI suite. MRI patients will remain in the waiting area in case the MRI suite is occupied. Once the MRI suite is available and the room has been cleaned, the patient is prepared and proceeds for the MRI scanning. The TACE patient, once ready to be transferred, would wait on the operating table if the MRI is occupied. All these waiting times were collected during the simulations.

The software package EasyFit (http://www.mathwave.com/es/home.html, Dnepropetrovsk, Ukraine) was used to fit the TACE events into the best-suited statistical distributions, used then as input in the simulating model. The results are presented in Table 1 with their correspondent event. The Anderson-Darling goodness-of-fit test ($\alpha = 0.05$) was used to determined the best distribution fitting. The MRI diagnosis data set (see Table 2) was modelled using triangular distributions, method broadly accepted in cases when limited information is available (15).

TABLE 2

Validation of the model was done in multiple directions. On one side, since real clinical data was available for the part corresponding to the TACE procedure, we performed a variability analysis following the method for the Behrens-Fisher problem (16), for an unknown ratio of variance. This makes a comparison between the means and variances of the real system, e.g. tasks within the TACE procedure, and the output of the simulating model, using the so-called Welch 90% confidence interval (CI):

$$\bar{X}_1(n_1) - \bar{X}_2(n_2) \pm t_{f,1-\alpha/2}\sqrt{\frac{S_1^2(n_1)}{n_1} + \frac{S_2^2(n_2)}{n_2}} \qquad (1)$$

Where $\bar{X}_1(n_1)$, $S_1^2(n_1)$ and $\bar{X}_2(n_2)$, $S_2^2(n_2)$ are the means and variances of the two systems (real world and model) with n_1 and n_2 samples, respectively; and $t_{f,1-\alpha/2}$ is the Student-t for 100(1-α) CI and f-degrees of freedom, calculated by

$$f = \frac{\left[S_1^2(n_1)/n_1 + S_2^2(n_2)/n_2\right]^2}{\left[S_1^2(n_1)/n_1\right]^2/(n_1-1) + \left[S_2^2(n_2)/n_2\right]^2/(n_2-1)} \qquad (2)$$

To calculate the Welch CI, batches of 100, 300, 1000 and 3000 simulations were performed, each of the simulations containing 30 runs (1 run =1 TACE complete procedure). The number of runs per simulation was chosen artbitrarily but following the suggestions given in the simulation software's manual.The Welch CI was calculated for each batch until finding a CI that included zero, which was the necessary condition to validate the model against the real system.

Since no real clinical data was available for the MRI diagnostic workflow, this part was validated and verified through alternative methods (17). For instance, trace methods and animations, embedded in the DES model were used in order to debug the logic implemented for both the MRI and the TACE workflows. In addition, the clinical team was always involved in the validation of the whole conceptual workflow.

2.4. Simulation-based optimisation analysis

In agreement with the clinical team, 14 scenarios were formulated for the optimisation analysis (see Table 3). These scenarios were defined depending on three different factors:

- **Arrival time for the TACE patient**: first time in the morning or in the afternoon (12pm).
- **Interarrival time for the patients**: scheduling patients every hour or scheduling patients based on the most likely procedural duration. For this last case, an average time for preparation of 15 minutes was added in conjunction with the clinicians' experience.

- **Duration of the MRI diagnosis**. Three categories were defined: short procedure (duration less than 45 min), medium procedure (between 45 and 60 min) or long procedure (more than 60 min and less than the upper limit given for the defined MRI procedures in Table 2).

TABLE 3

The optimisation process consisted in simulating these scenarios and measuring three KPIs per scenario:

- **Overwork time**; defined as the difference between the 8h (usual working hours) and the overwork timeed due to the length of the procedures
- **Average waiting time**; defined as the average time that a patient needed to wait to start the procedure (TACE or MRI)
- **Waiting time in angiography suite**, defined as the average time that a TACE patient needed to wait for the MRI to be available

To assess which of the scenarios was the best for each key factor, a ranking and selection (R&S) method developed by Dudewicz et al.(18) for unknown variances was used. The method involves "two-stage" sampling for each of the scenarios (systems) analysed (14 in this case) (19,20). Firstly, $n_0 > 2$ replication per system were done, $n_0 = 20$ was chosen following the guidelines of the authors to choose a starting number between 10 and 30. For each system, the means $\bar{X}_i^{(1)}(n_0)$ and the variances were calculated for each KPI. The number of samples needed for the second sampling stage for the system i, N_i, was calculated as follows

$$\boldsymbol{N_i = max\left\{n_0 + 1, \left\lceil \frac{h_1^2 S_i^2(n_0)}{(d^*)^2} \right\rceil \right\}} \qquad \textbf{(3)}$$

Where $\lceil x \rceil$ is the smaller integer that is greater than or equal than the real number x, $S_i^2(n_0)$ is the variance of the system i, $d^* > 0$ is the smaller actual difference between the means of the systems that we care about detecting and h_1 is a constant dependent on n_0, the number of scenarios and the

least probability agreed to assure selecting the best system. This probability was established in a 90%. For the waiting times in the angio suite (TACE patients), $d^* = 300\ seg$ (5min) was chosen and for the waiting area, $d^* = 600\ seg$ (10min) for the overwork time. The h_1 value for this study was obtained from the tables in (18).

Once N_i was obtained, we performed $N_i - n_0$ more replications of each system, calculating the new sample means $\bar{X}_i^{(2)}(N_i - n_0)$. Then, we defined weights as

$$\boldsymbol{W_{i1} = \frac{n_0}{N_i}\left[1 + \sqrt{1 - \frac{N_i}{n_0}\left(1 - \frac{(N_i - n_0)(d^*)^2}{h_1^2 S_i^2(n_0)}\right)}\right]} \quad \textbf{(4)}$$

And $W_{i2} = 1 - W_{i1}$. Finally we calculated the weighted sample means

$$\boldsymbol{\tilde{X}_i(N_i) = W_{i1}\bar{X}_i^{(1)}(n_0) + W_{i2}\bar{X}_i^{(2)}(N_i - n_0)} \qquad \textbf{(5)}$$

Which we used to select the system with smallest $\tilde{X}_i(N_i)$ for each factor.

3. RESULTS

3.1. Model implementation and validation

Figure 2 shows a screen capture of the DES model implemented in Delmia Quest. The model includes the angiography suite and MRI scanner room layouts at scale, together with their respective control rooms and a waiting area for patients.

FIGURE 2

Table 4 presents the Welch 90% CIs (confidence intervals) calculated for each of the events recorded for the TACE procedure following the method described in Section 2.3. The Welch 90% CIs needed to validate the DES model (containing zero) were found when running batches of 1000 simulations (15).

TABLE 4

3.2. Simulating analysis

Following the optimising simulation method described in the previous section, the weighted means were calculated for each scenario and for each of the KPIs considered. Comparative results are shown in Figure 3. Scenario 2 (see Table 3) gave the best performance, while the worst case scenario was scenario 4. For the 'waiting time in angiography suite' the best result was obtained also with the scenario 2, while scenario 4 gave again the maximum value for the weighted mean. In the case of 'overwork time', several scenarios gave similar results, being the absolute minimum in the scenario 14 and the worst case scenario 9. Table 5 shows the 90% CI for the KPIs times in minutes for the scenarios that gave the best, second best and worst cases.

FIGURE 3

TABLE 5

Data from patients waiting in the angiography suite to be transferred to MRI during the TACE procedures was gathered as part of the study. It was observed that in the 71.19% of the cases, patients had to wait an average of 20 (± 20) minutes, with a maximum waiting time of 80 minutes, due to MRI being occupied for diagnostic patients. The optimisation analysis has shown that with scenario 2, which would be to schedule TACE patients as first appointment and scheduling MRI patients every hour with short diagnostic procedures first, would reduce the waiting times in angiography suite by a 48.74% in average. According to this scenario, the overall waiting time for MRI diagnostic patients is estimated to be minimal within the 90% CI of [20, 17] (min).

4. DISCUSSION

MRI environments appear to be one of the most demanded resources in hospitals. Several studies agree that improving the planning of MRI processes will reduce waiting times (21,22). Additionally, there are numerous efforts on introducing MRI as part of therapeutic procedures and not only as a diagnosis equipment (23–25). Simulation based analysis can be a powerful tool for an

optimal integration of MRI-guided or, in general, multimodal image guided procedures in the already saturated radiology departments. This study presented a framework for the use of DES in combination with an optimisation algorithm for better understanding and potential improvement of multimodal image guided procedures.

As case of exemplar, the framework was sucessfully applied to a multimodal image TACE protocol. Statistical analysis on the current workflow revealed large waiting times in the angiography area interfering with the MRI diagnosis workflow. A DES model of the current protocol was implemented and several scenarios, previously discussed with the clinical team involved in the study, were also simulated to study the impact of different changes in the workflow. The optimisation algorithm was used to select the best option for three KPIs, waiting time in angiography, total average waiting time and overwork time. This algorithm suggests that scheduling TACE patients early in the morning, scheduling patients in the MRI area every hour and setting estimated short MRI procedures first during the day (number 2 in Table 3) would be the optimal scenario to reduce the waiting time in the angiography suite up to 48%. This choice would be also the optimal to minimise the waiting times for MRI diagnostic patients. However, this option did not give the minimum overwork time. The algorithm estimated a similar alternative to minimise this time, although instead of scheduling patients every hour, they should be scheduled following their most likely duration time (number 1 in Table 3).

A comparison between the simulating results for overworked time and average waiting time for MRI patients with the real system was not possible since these times were not contemplated in the initial protocol. However, it would be possible to compare the estimation given by the algorithm with the real system if one of the alternatives would eventually be implemented. The current simulating model includes estimated times for patient preparation and cleaning times. Although, the clinical team agreed with the estimation as true representative of their working environment, detailed information about this procedures can be easily collected in case the model needs to be

updated in future studies. Other parameters considered are the transfer times to and from the MRI area (see Table 1), which could be potentially another source to optimise the current protocol but also other multimodal image protocols that involve MRI. In this case, staff training plays an important role to reduce this times (26).

For this study, it was also important to analyse the critical and basic steps of the MR intergration and to identify strategies for reduction of waiting and overworking times. These results have been taken into consideration in a new formed panel at the clinic of diagnostic and interventional radiology in Saarland Medical Center to be discussed and the adoption of any of these scenarios will depend on the feasibility of its implementation with resources available.

5. CONCLUSION

A framework to implement and optimise DES models in the context of MIGP has been presented. To illustrate its application, we used a multi-modal imaging protocol for a TACE procedure. The model helped to understand and detect "bottlenecks" during the interventions, identifying a better alternative to the current workflow and reducing waiting times. This framework provides a cost-effective way to face some of the challenges of introducing MIGP in clinical radiology.

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CONFLICT OF INTERESTS

Fabiola Fernández-Gutiérrez, Malgorzata Wolska-Krawczyk, Arno Bücker, J. Graeme Houston and Andreas Melzer declare that they have no conflict of interest

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TABLES and TABLE legends

Event	**Mean duration (Standard Error – SE) (min)**	**Fitted statistical distribution**	**Parameters**
Access	7.55 (2.39)	Lognormal	$\mu = 1.70$ $\sigma = 0.74$
Cannulation	42.22 (2.82)	Gamma	$\alpha = 3.87$ $\beta = 10.91$
Transfer to MRI suite	11.09 (0.94)	Lognormal	$\mu = 2.22$ $\sigma = 0.62$
MRI diagnosis sequences	16.02 (0.84)	Lognormal	$\mu = 2.71$ $\sigma = 0.356$
Transfer to angio suite	9.15 (0.83)	Gamma	$\alpha = 2.08$ $\beta = 4.40$
Cannulation after MRI	19.21 (3.81)	Lognormal	$\mu = 2.34$ $\sigma = 1.22$
Chemoembolisation	26.38 (2.29)	Lognormal	$\mu = 3.08$ $\sigma = 0.62$

Table 1. Descriptive statistics and statistical distributions of the duration (in minutes – min) of the events collected for TACE interventions, where α and σ are the shape parameters, and β and μ are the scale parameters of the distribution functions.

Type of MRI procedure	**Minimum (min)**	**Maximum (min)**	**Most Likely (min)**
Knee	20	60	30
Pelvis	40	60	45
Wrist	20	60	45
Whole Body	60	180	120

Neck	43	65	52
Angiography Abdomen	12	20	15
Angiography Pelvis and Lower Extremities	15	55	30
Cardiac	50	75	65
Thigh	35	115	65
Arthography Hip	40	60	42

Table 2. Procedure times gathered for the most common diagnostic procedures at the MRI department (Homburg Saarland University Hospital, Homburg, Germany).

TEST	TACE patient		Interarrival time		Duration MRI patients	
	Morning	Afternoon	Most likely time	Every Hour	Short first	Large first
1	X		X		X	
2	X			X	X	
3	X		X			X
4	X			X		X
5	X		X		Alternating short/long	
6	X			X	Alternating short/long	
7	X		X		Organising 3 blocks: Block 1: Procedures ≤ 45min Block 2: Procedures ≤ 60min Block 3: Procedures > 60min	
8		X	X		X	
9		X		X	X	
10		X	X			X
11		X		X		X
12		X	X		Alternating short/long	
13		X		X	Alternating short/long	
14		X	X		Organising 3 blocks: Block 1: Procedures ≤ 45min Block 2: Procedures ≤ 60min Block 3: Procedures > 60min	

Table 3. Scenarios (tests) studied during the simulation analysis.

Events	Welch 90% confidence interval (sec) [max,min]
Access	[85.09,-149.89]
Cannulation	[485.92,-221.92]
Transfer to MRI suite	[111.99,-145.59]
MRI diagnosis sequences	[39.26,-150.86]
Transfer to Angiography suite	[64.76,-147.56]
Cannulation after MRI	[789.48,-41.88]
TACE	[113.50,-419.50]
DynaCT	[24.55,-42.56]

Table 4. Welch 90% confidence intervals for the event in the TACE procedure when compared with the real system.

KPM	1	2	4	9	11	14
Overworked time	**[42, 32]**	[57, 47]	[50, 40]	[86, 78]	[49, 38]	[49, 39]
Average waiting time	[47, 43]	**[20, 17]**	[91, 87]	[25, 23]	[88, 83]	[32, 29]
Waiting time in angio suite	[19, 14]	[12, 9]	[90, 79]	[26, 21]	[24, 19]	[38, 31]

Table 5. KPIs and the respective 90% CI [max, min] for their times (minutes) for all the scenarios that gave the best, second best and worst cases. For each case, the 90% CI corresponding to the best alternative is shown in bold and underlined font.

FIGURE legends

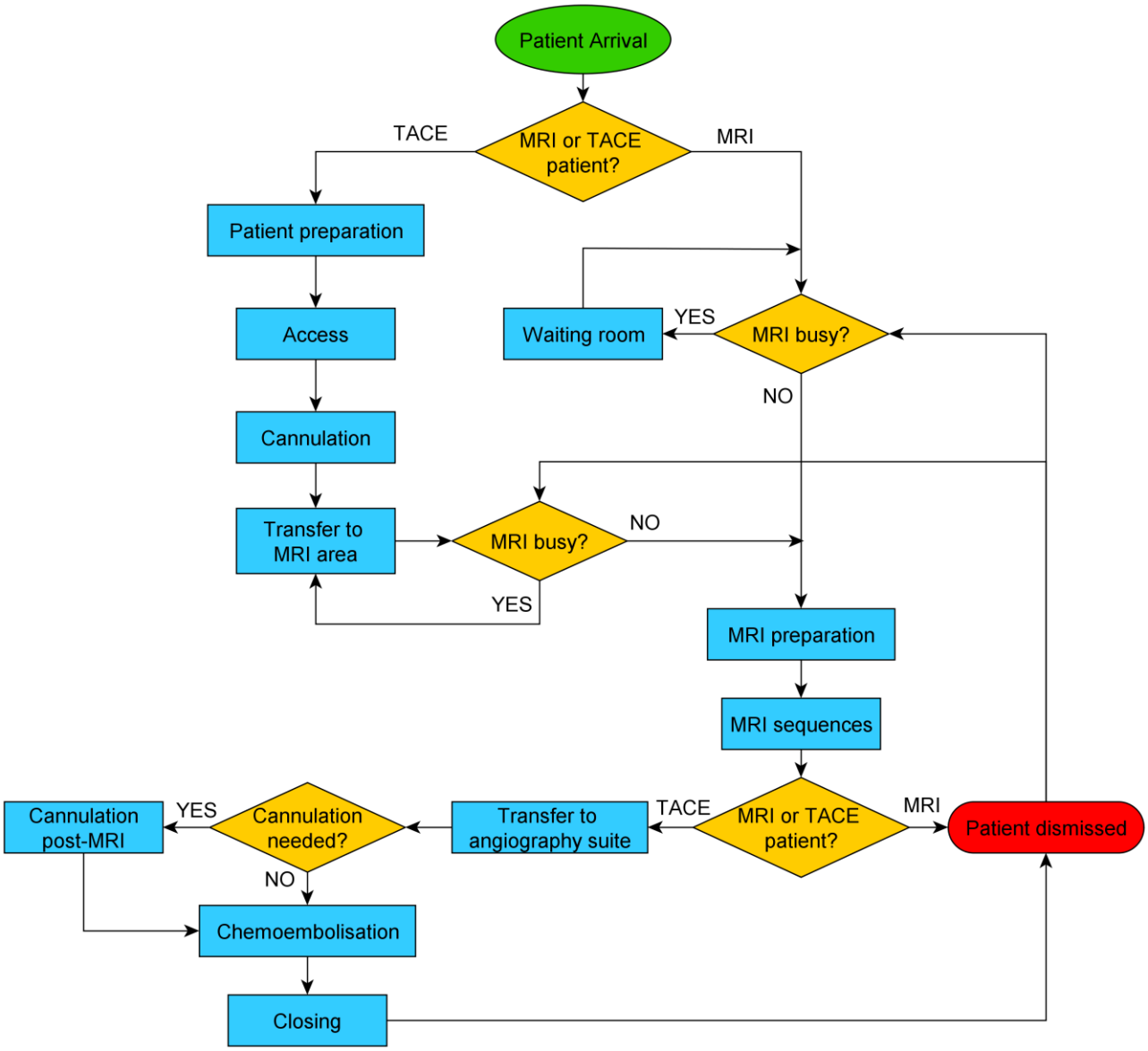

Figure 1. Conceptual workflow of the patients around the MRI area. Two groups are distinguished: patients for the TACE interventions and the MRI diagnostic patients at the clinic of diagnostic and interventional radiology in Saarland Medical Center (Homburg, Saarland, Germany).

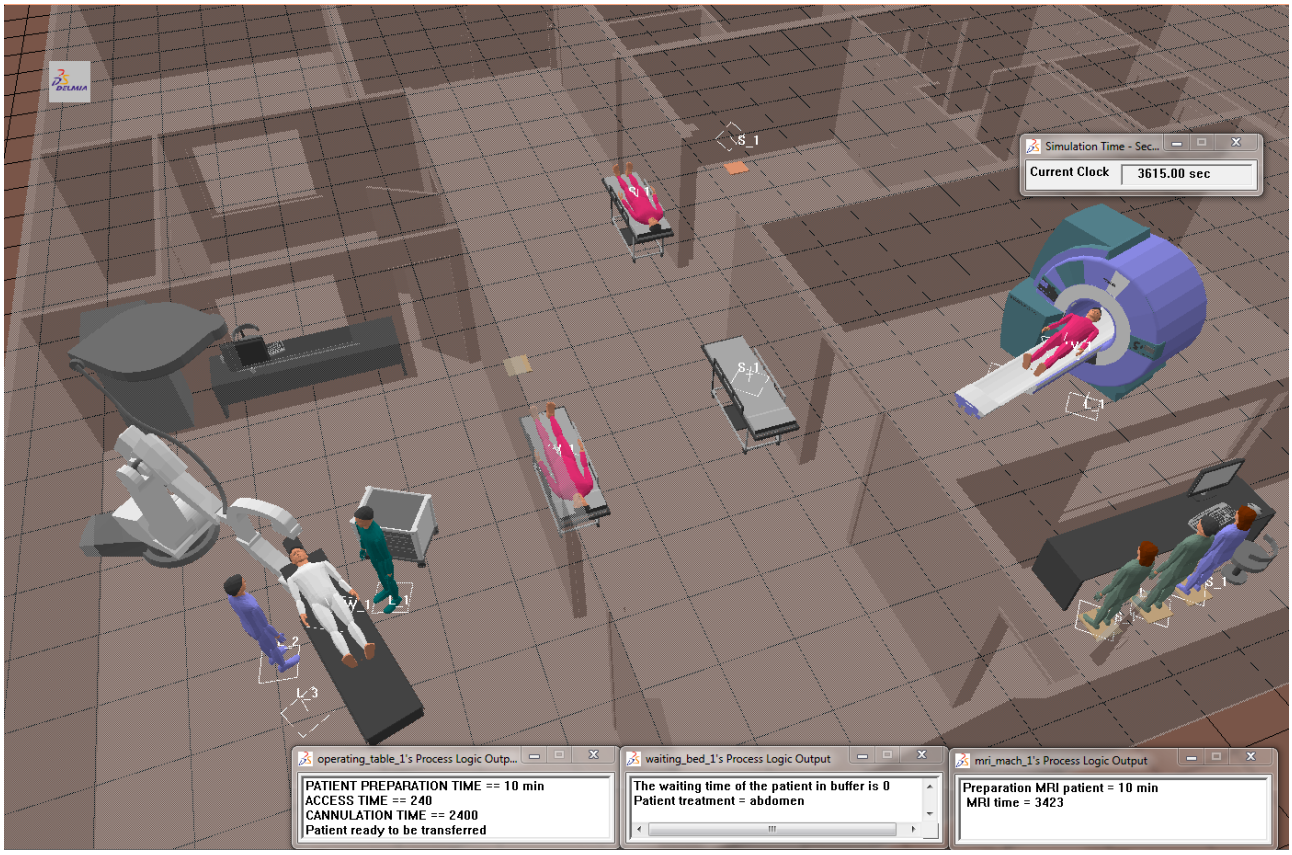

Figure 2. Screenshot during simulation of the DES model for TACE interventions and MRI patients implemented in Delmia Quest. The 3D environment corresponds to the facilities at the department of Radiology, Saarland Medical Centre (Homburg, Saarland, Germany).

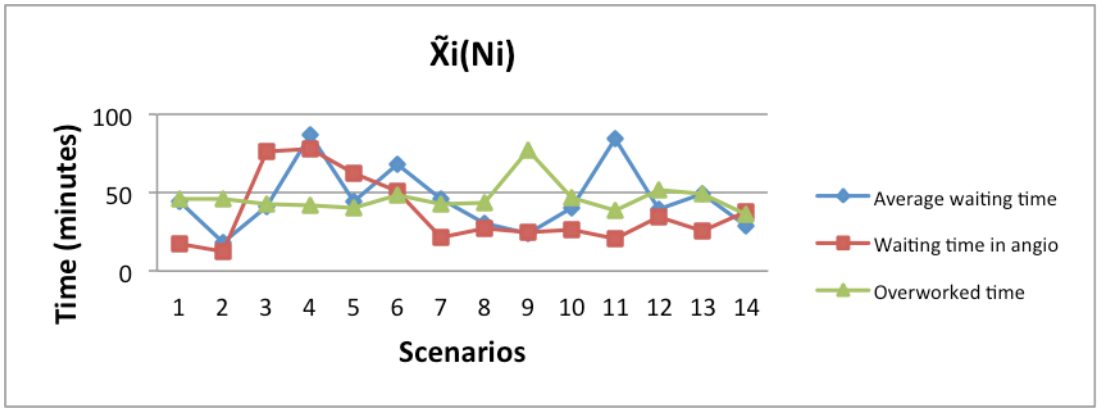

Figure 3. Weighted means ($\tilde{X}_i(N_i)$) calculated for each scenarios for the three key performance measures considered.