Risk-based Clinical Scheduling Tool for Congenital Cardiac Catheterization Procedures

Scheduler and Simulation Model

Technical Description and User Guide

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1 Objective/Purpose

The MITRE Corporation is working with the pediatric cardiac catheterization lab at Boston Children's Hospital (BCH) to develop a tool that enables hospital decision-makers to evaluate scheduling policies before implementing them. The aim of the work is to leverage predictive modeling and discrete event simulation to validate human-interpretable scheduling heuristics that decrease system-level risk, increase system-level efficiency, and are easily integrated into existing scheduler workflows. This framework can be used not only to evaluate the impact of scheduling protocol changes, but it can also capture the impact of an altered lab configuration, changes in case arrival rates, and changes in case population complexity. Although the framework is being prototyped at BCH, this is a generalized tool that can be utilized in complex care environments beyond the BCH pediatric cardiac catheterization lab.

2 Description

2.1 Case Files

Case files, which consist of either historical or synthetic cases, can be added into this tool in the form of JSON files. These cases should be separated into elective and add-on cases. Elective cases are scheduled in advance through the scheduler tool, while add-on cases arrive and must be fitted into the schedule during the simulation.

2.2 Schedules

The Schedules that are produced through this tool use the following scheduler framework. This framework was developed to show the resulting schedule when using a scheduling heuristic and a list of elective patient cases that arrive according to a specified distribution.

The scheduler framework utilizes a job-board based approach to assign arriving elective cases to a particular lab and day within the simulated scheduling time-period. A lab configuration file defines the number of labs that were open each day of the week, the number of case slots per lab each day, and the types of procedures that could be performed in each lab. Elective cases arrive in daily batches according to an inputted arrival rate distribution. The scheduler framework then assigns each case to a slot according to an inputted scheduling heuristic. These heuristics leverage the point-based scoring system, typically by setting point limits for cumulative case risk and/or duration at the lab or day level. The scheduler framework outputs a populated schedule and a metric to assess heuristic performance related to balancing case risk and time across the scheduling window. This metric, *Count of Unbalanced Schedule Days*, captures the number of days within the schedule that had a cumulative risk or duration score exceeding a specified daily tolerance.

Inputs	**Outputs**	**Metrics**

• Elective case population file • Elective case arrival distribution • Lab configuration • Scheduling heuristic	• Populated elective case schedule	• Count of Unbalanced Schedule Days

2.2.1 Point-Based Scoring System

Two predictive models were developed, one predicting case risk and the other case duration. Predictions were then used to assign cases risk and duration scores to be utilized by the point-based scoring system within the scheduler framework.

Case Risk Score

The probability of a case resulting in a discharge to the intensive care unit (pICU) was used to estimate case risk. A logistic regression model for pICU, called iCATCH, was developed as part of previous work at BCH. It leverages key predictors collected in pre-catheterization assessments and known to be associated with adverse events to model pICU[1]. Cases were then categorized into risk groups based on their associated iCATCH pICU value and assigned a risk score.

Case Risk Criteria	**Risk Level**	**Risk Score**
pICU < 0.1	Low	1
0.1 <= pICU < 0.3	Medium	2
pICU >= 0.3	High	3

Case Duration Score

Radiation risk score is a metric used by BCH to quantify risk related to radiation during a case, which in the pediatric cardiac catheterization setting is primarily determined by procedure length. At BCH, cases are grouped into one of three radiation risk categories based on procedure type[2]. For this analysis, a linear regression model having one feature, radiation risk category, was developed to predict case duration. Cases were then categorized into duration groups based on their radiation risk category and assigned a duration score.

Case Duration Criteria	**Duration Level**	**Duration Score**
Radiation Risk Category 1	Low	1
Radiation Risk Category 2	Medium	2
Radiation Risk Category 3	High	3

Case Complexity Score

An overall case complexity score was determined by summing a case's risk and duration scores, and therefore could range from 2 to 6 points.

Case Complexity Score Assignments

Risk Level	Risk Score	Duration Level	Duration Score	Case Complexity Score
Low	1	Low	1	2
Low	1	Medium	2	3
Low	1	High	3	4
Medium	2	Low	1	3
Medium	2	Medium	2	4
Medium	2	High	3	5
High	3	Low	1	4
High	3	Medium	2	5
High	3	High	3	6

2.2.2 Heuristics

There are three main heuristics developed and built into this tool as options when creating a new schedule.

Baseline

Each case is assigned to an available slot within the scheduling window without considering the risk or duration of other cases on the same day or in the same lab. This is essentially random case placement while still following lab configuration constraints.

Points Heuristic

Each case is assigned to an available slot within the scheduling window, however the cumulative case complexity score allocated to each day is constrained to a user-defined number of points. This heuristic only considers total complexity points per day and does not consider case order or case complexity scores at the lab-level. Cumulative daily complexity point limits can be modified in the scheduling rules configuration file using the "overall_limits" attributes.

Point Split Heuristic

Each case is assigned to an available slot within the scheduling window; however, the cumulative case risk score and cumulative duration scores are constrained separately. The cumulative risk and duration scores can be constrained at either the day or lab-level to a user-defined number of points. This heuristic alone does not consider case order at the lab-level. The day or lab-level duration and risk point limits can be modified in the scheduling rules configuration file using the “point_limits” and “which” (equal to “lab” or “day”) attributes.

Case Reordering

The order of cases throughout the day in and across labs can also be considered as an addition to any of the three above heuristics. If case order is considered, cases are reordered alternating from lowest to highest risk score in one lab and highest to lowest in the next to avoid running higher risk cases simultaneously. To reorder cases based on risk, select the “Order cases within labs” checkbox on the front-end interface when creating a schedule.

2.3 Experiments

This tool can be used to run experiments for each created schedule. The experiments tab utilizes a discrete-event simulation model of the BCH pediatric cardiac catheterization lab that was developed to evaluate the performance of scheduling heuristics by simulating schedules generated by the scheduler framework.

Although this simulation was developed to simulate the BCH pediatric cardiac catheterization lab, the customizable inputs allow it to be used for other hospital or surgical situations. This simulation incorporates stochasticity into lab processes including when cases started, the duration of cases, turnover time between cases, whether an adverse event occurred, and whether a case was discharged to the ICU. The simulation also provides logic for the handling of adverse events, scheduling of cases that arrive during the simulation (add-on cases), and pushing of non-emergency cases. System-level performance metrics capturing risk and efficiency are tracked to analyze the impact of scheduling heuristic and lab configuration changes.

Two system-level efficiency metrics are tracked. The first, *Count of Weekdays with Time After EOD*, captures the number of days within the simulation that had procedure time run past a specified end-of-day time. For BCH this was 5pm, but it could vary based on the surgical suite being simulated. The second, *System Average Time After EOD*, captures the actual amount of procedure time that was spent after the designated end-of-day time and is averaged across all weekdays in the scheduling window. These metrics capture the number of long operating days and the amount of operating overtime that could be expected from a particular schedule. In this way, they are used as a proxy to measure provider burnout and to evaluate the impact a scheduling heuristic has on system-wide efficiency.

One system-level risk metric tracked is *Total Lab Minutes Spent at High pICU Risk*. Within the simulation, system pICU is captured by finding the joint pICU given all cases occurring at each minute of time. If the system-level pICU reaches a threshold equivalent to the joint probability of two high pICU risk cases occurring simultaneously, then the overall system is at high pICU risk. This metric captures how well a schedule balanced out risk over time and evaluates the impact that a scheduling heuristic had on the system-wide risk.

Inputs	**Metrics**
• Distributions for stochastic components	• Count of Weekdays with Time After EOD
• Operating department logic	• System Average Daily Time After EOD

- Add-on case population file
- Add-on case arrival distribution
- Populated elective case schedule
- Total Lab Minutes Spent at High pICU Risk

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3 User Guide

This user guide describes how to run the tool including system requirements, getting set up, setting the model parameters, and outputs.

3.1 Getting the Tool Set Up

Refer to the README.md in the Grace Scheduling Tool on GitLab for the most up to date setup instructions for this tool. Some system prerequisites are

Docker and Docker Compose

Base Images:

- python:3.9
- gradle:7.4.2-jdk17
- node:18

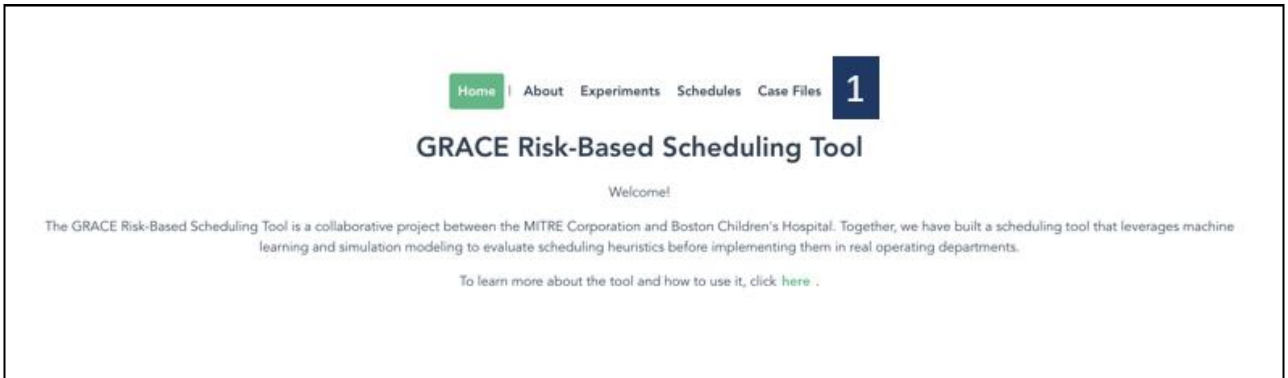
3.1.1 Requirements and Running the Model

The front-end interface supports case file upload, schedule creation, and schedule simulation. Model inputs and results can also be visualized within the tool. After generating a case file run, schedule run, or simulation experiment run, the page will have to be refreshed to see the details populate in the results table. When generating a case file run or schedule run, the user will see a spinner and will be directed to wait until the run is complete. File uploads and schedule creation are relatively quick processes. Simulation experiments take longer, so these run in the background. A user can submit multiple simulation experiment runs in sequence. These runs will be added to a job queue, and the status will show as "Running" or "Queued" in the experiments results table. Always refresh the page to see the most updated version of any table on the interface.

More detailed information on model inputs, additional performance metrics, and log files are tracked and stored using an MLFlow server and database. The user can view these details, as well as delete or rename model runs, by navigating to the MLFlow dashboard at the following url address: http://localhost:5000

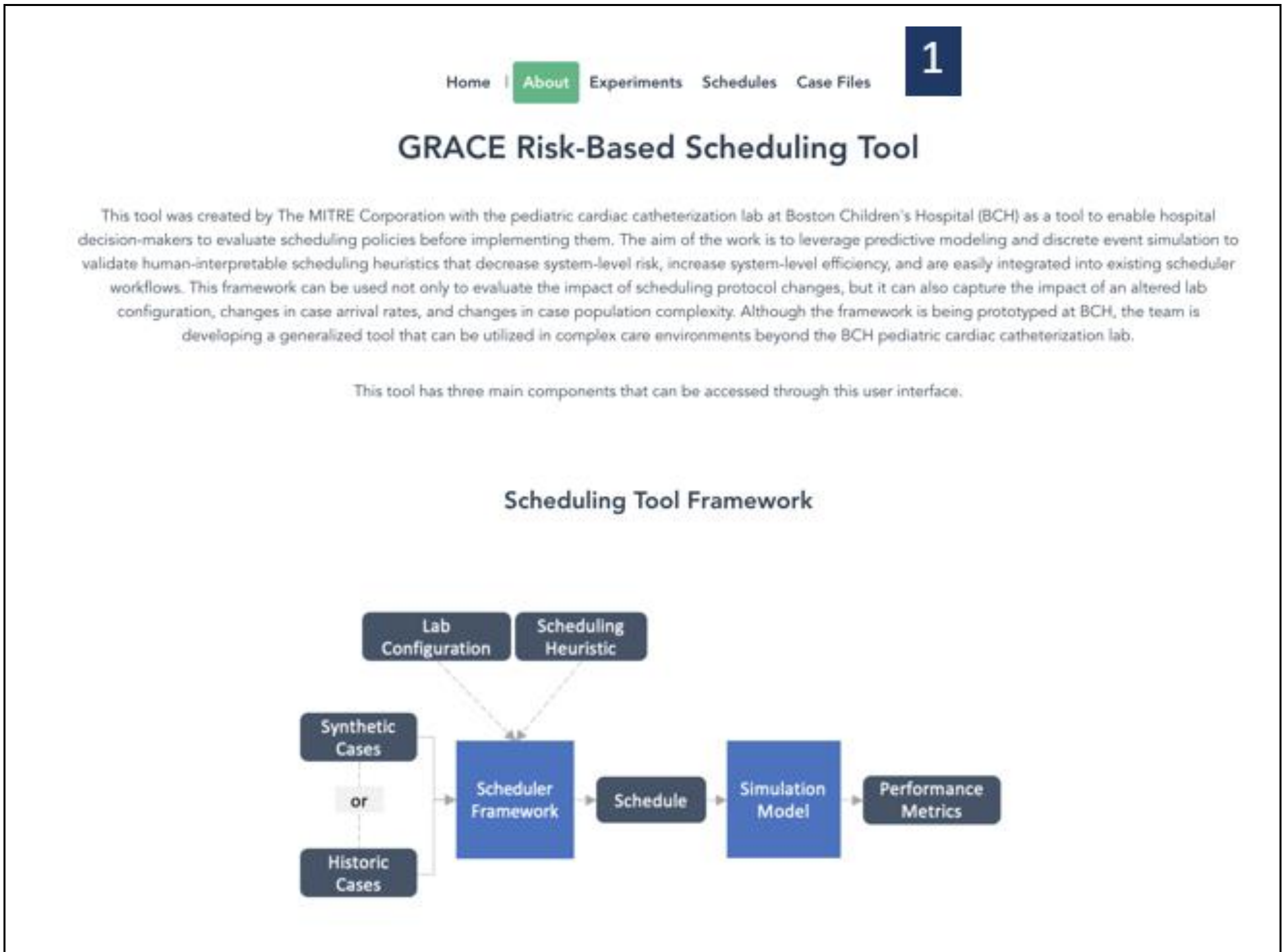
More details for using MLFlow can be found in the MLFlow docs.

3.1.2 Screenshots of Tool Interface



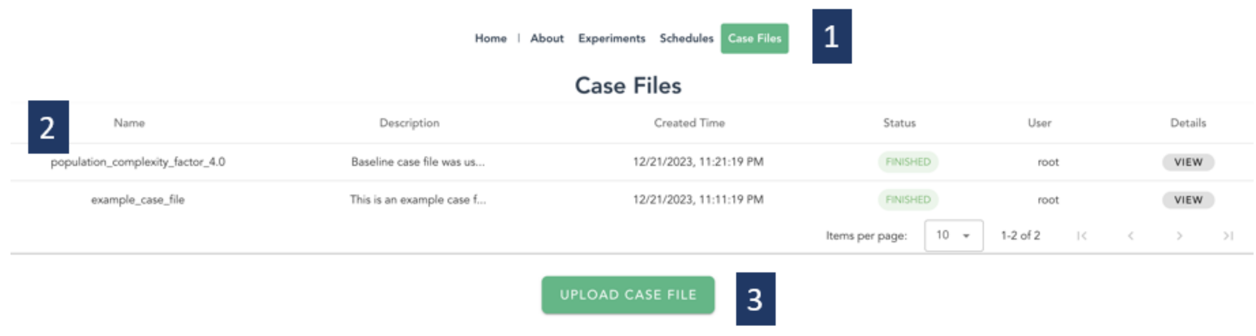
	Legend
1	Navigation Bar – Use this to switch between pages of the UI. This page is a general introduction to the tool and a link to more documentation.

Figure 1. Home Page



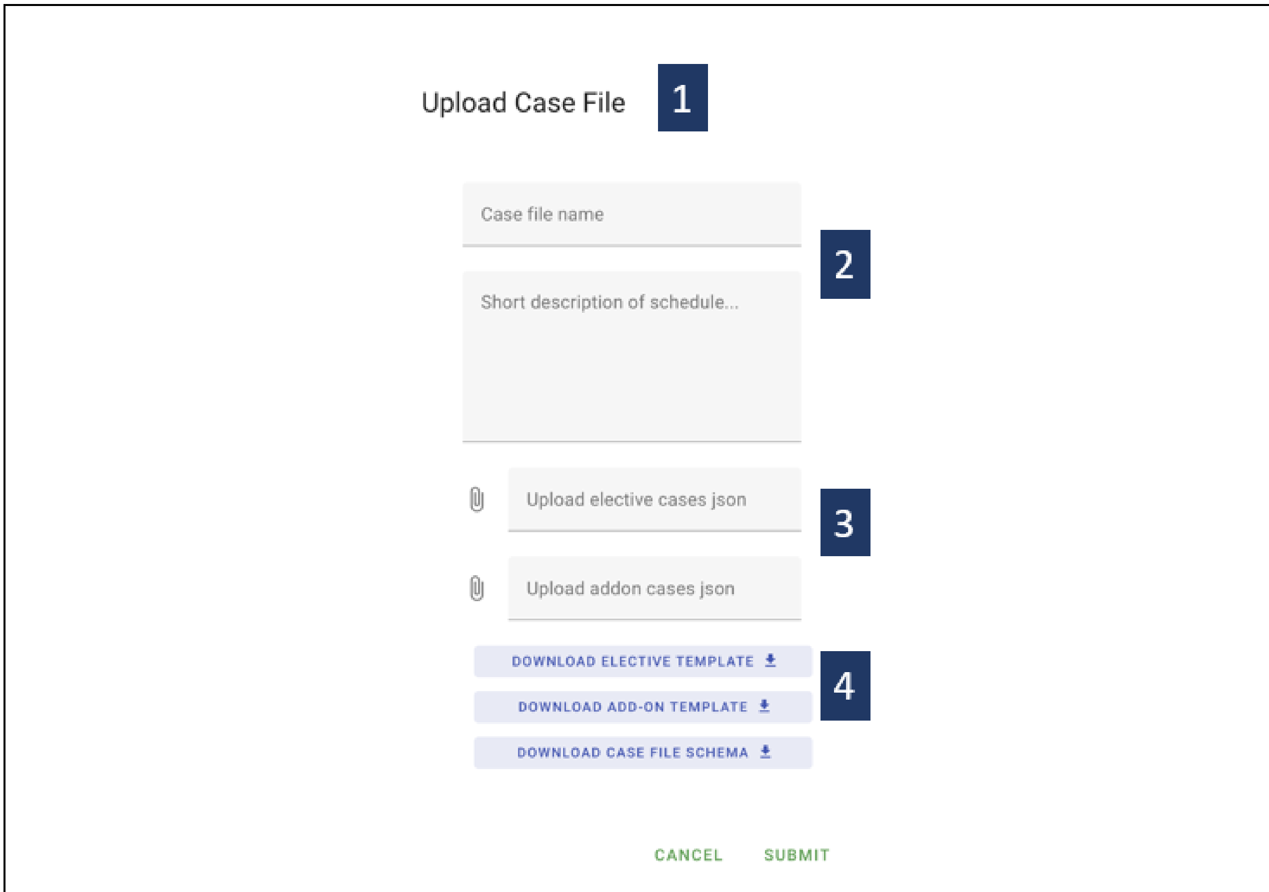
	Legend
1	Navigation Bar – Use this to switch between pages of the UI. This page provides a summary of the tool capability.

Figure 2. About Page



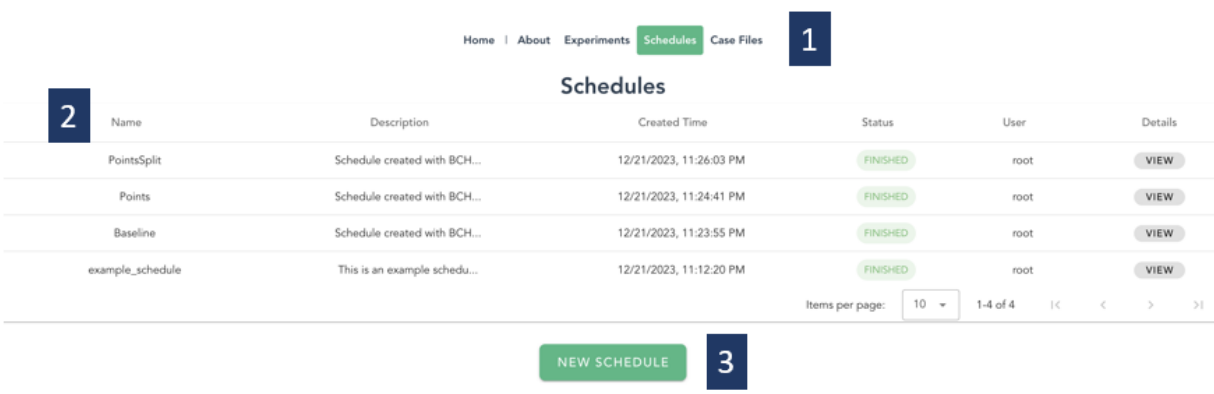
	Legend
1	Navigation Bar – Use this to switch between pages of the UI. This page is used for uploading case files.
2	Case File List – This is a list of all the case files that have been uploaded including the name, description, creation time, status, which user uploaded it, and a button to view details of the files.
3	Upload Case File Button – Click this button to create a new case files record in the pop-up. More detail in Figure 4.

Figure 3. Case Files Page



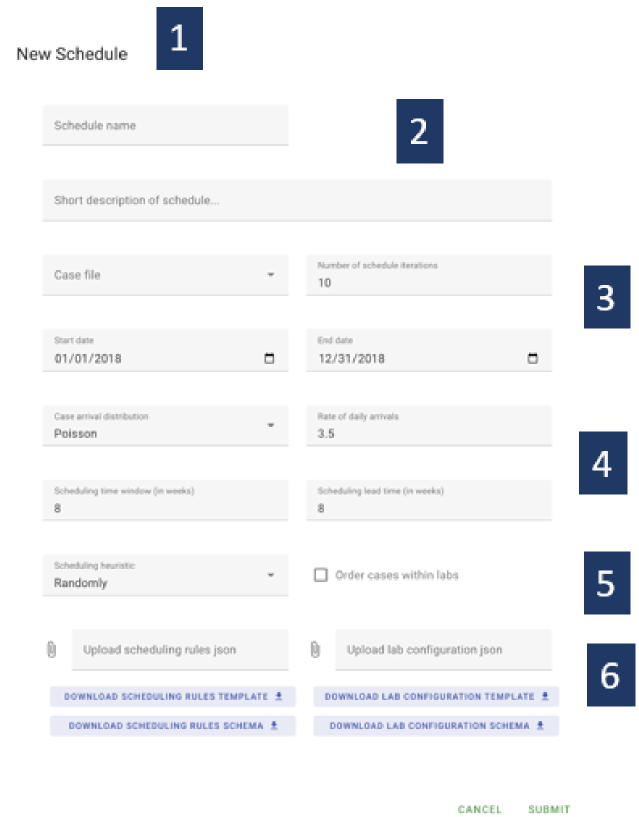
	Legend
1	Upload Case File Pop-up – Use this pop-up to input information about and upload case files to be used in the scheduler and simulation.
2	Case Description – Use these two input boxes to enter a name for the case files and a short description if desired.
3	JSON file upload – Use these two boxes to upload the JSON files for elective and addon cases.
4	Case File Templates – Download the base templates and schema to check the formatting of input files.

Figure 4. Upload Case Files Pop-up



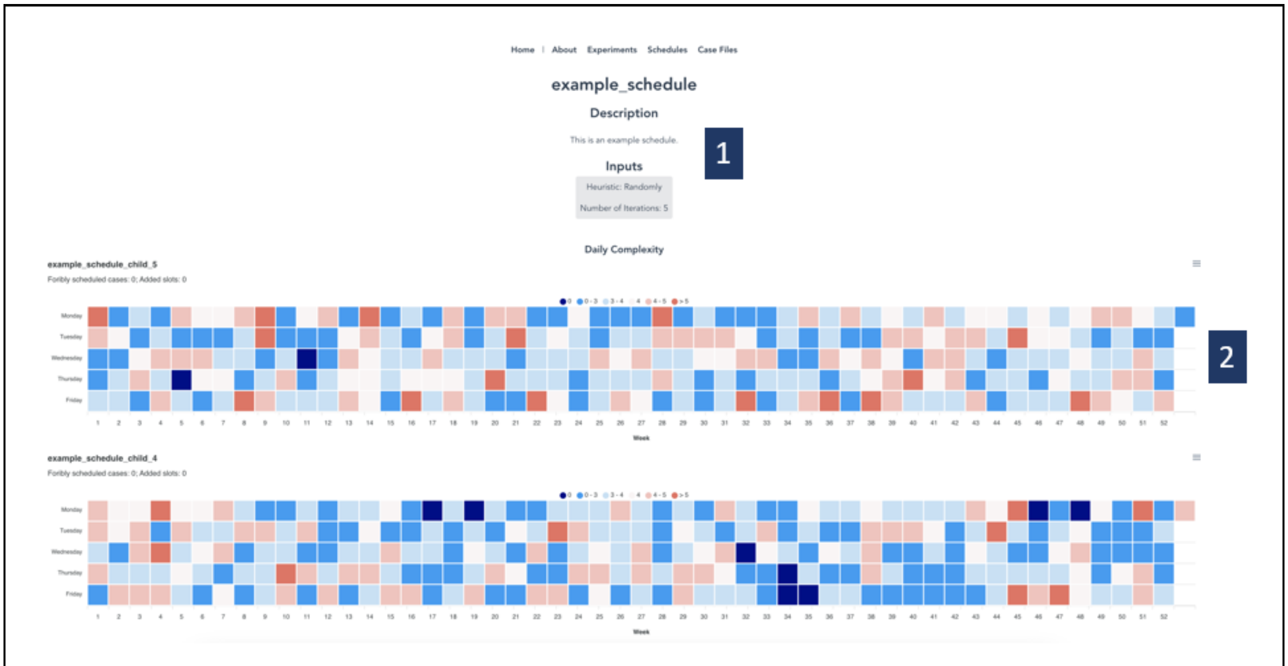
	Legend
1	Navigation Bar – Use this to switch between pages of the UI. This page is used for creating and viewing schedules.
2	Schedules List – This is a list of all the schedules that have been created including the name, description, creation time, status, which user uploaded it, and a button to view details of the schedule. The status of a schedule can be finished, failed, running, or queued. The details of the schedule from the view button can be seen in Figure 7.
3	New Schedule Button – Click this button to create a new schedule in the pop-up. More detail in Figure 6.

Figure 5. Schedules Page



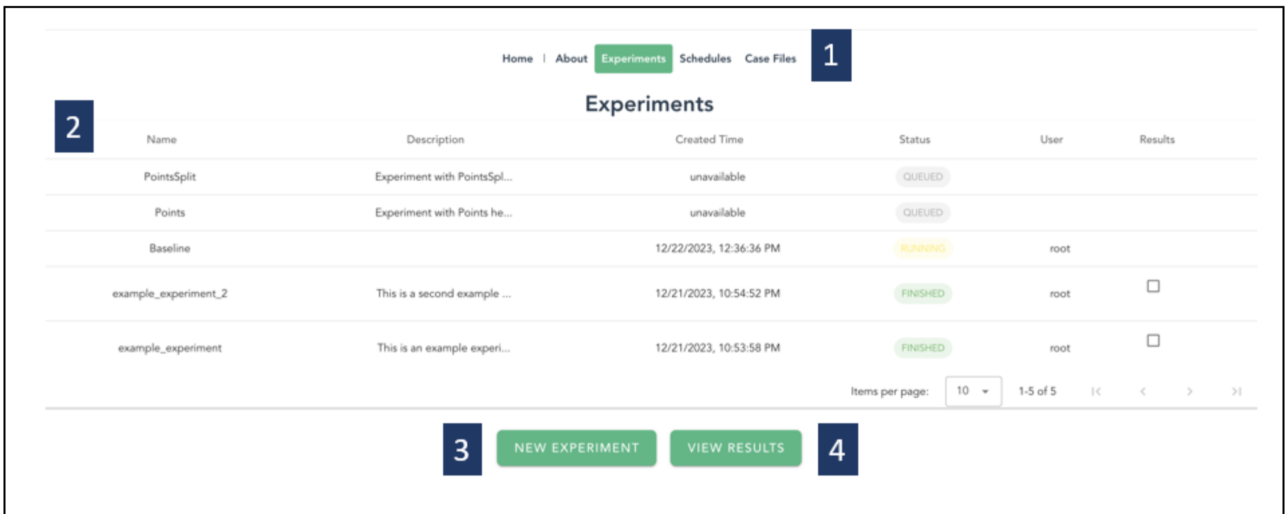
	Legend
1	New Schedule Pop-up – Use this pop-up to input parameters to run a new schedule.
2	Schedule Description – Use these two input boxes to enter a name for the schedule and a short description if desired.
3	Schedule Timing Inputs – Use these four boxes to input the case file to be used, the number of schedule iterations, and the start and end dates of the scheduling period.
4	Schedule Run Inputs – Use theses boxes to input schedule run information like the elective case arrival distribution and arrival rate, schedule time window for each case, and the lead time (time between elective case arrival and start of scheduling window) for each case.
5	Heuristic Input – Select the desired heuristic from the drop-down menu and click the checkbox to have the scheduled cases ordered according to risk level if desired.
6	Upload Scheduling Config – Use these two boxes to upload the scheduling rules and the configuration files. The templates and schemas can be downloaded to check formatting.

Figure 6. New Schedule Pop-up



	Legend
1	Schedule Details – This is general information about the schedule run that was selected to view.
2	Schedule Heatmap – This heatmap shows the average case complexity for each day in a run. There is a separate heatmap for each iteration of the schedule.

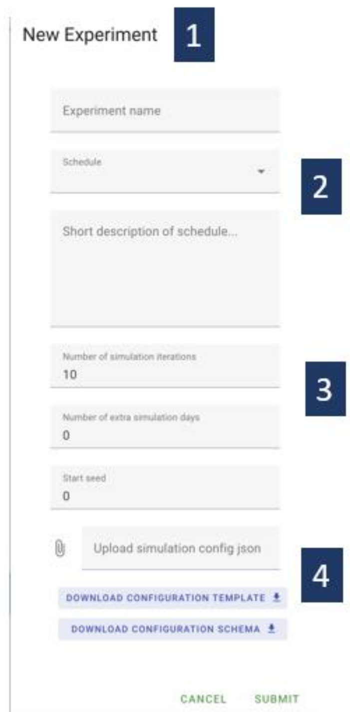
Figure 7. View Schedule Page



	Legend
1	Navigation Bar – Use this to switch between pages of the UI. This page is used for running experiments.
2	Experiments List – This is a list of all the experiments that have been run including the name, description, creation time, status, which user uploaded it, and a check box to view results. The status of an experiment can be finished, failed, running, or queued.

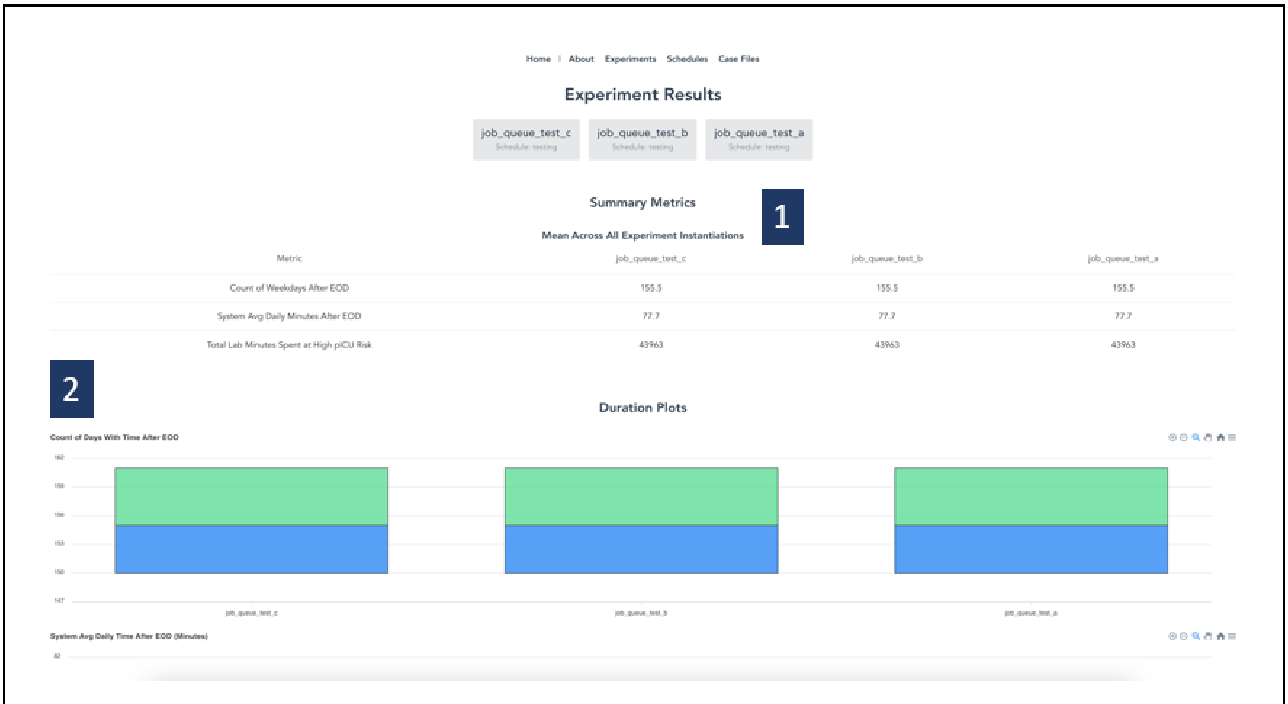
3	New Experiment Button – Click this button to run a new experiment in the pop-up. More detail in Figure 9.
4	View Results Button – Use this button to compare experiment runs. Select the experiments to compare by selecting the results checkbox in the rows of the experiments. More detail in Figure 10.

Figure 8. Experiments Page



	Legend
1	New Experiment Pop-up – Use this pop-up to start a new experiment.
2	Experiment Description – Use these three input boxes to input an experiment name, pick a schedule to use, and an experiment description if desired.
3	Experiment Parameters – Use these three boxes to specify the number of iterations (this is the number of simulation runs per iteration of the schedule), the number of additional days to run after the schedule ends (cool-down period), and a start seed.
4	Simulation Config– Upload the simulation configuration file here. The configuration template and schema can be downloaded to check formatting.

Figure 9. New Experiment Pop-up



	Legend
1	Experiment Summary Metrics – A table showing the duration and risk metrics for each experiment run being compared.
2	Experiment Metrics Boxplots – Three boxplots showing the distribution of each metric across all experiment iterations.

Figure 10. Experiment Results Comparison