Simulation of Laboratory

Group 9

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1. Background

1.1. Introduction

Severn Pathology in Southmead Bristol handles an extensive volume of samples, processing approximately 25,000 samples each week. Of these, around 500 are urgent samples received daily, often requiring priority handling to support timely patient care for those in critical need. Urgent samples typically originate from patients within the hospital, including those in the A&E department, where rapid turnaround times are essential to inform immediate treatment decisions. In contrast, routine samples, which come from external GP practices or patients in non-urgent situations, follow standard processing timelines. Given the critical nature of urgent samples, ensuring they are prioritized over routine samples is imperative. However, achieving this consistently presents challenges, especially when factors such as pod transport system downtime and high sample volumes impact turnaround times (TAT). Our goal in this study is to optimize the laboratory's urgent sample pathway, focusing on minimising delays and maintaining TAT within a 60-minute target from collection to result availability. By addressing the factors that influence TAT, we aim to support Bristol Southmead Hospital in delivering high-quality, prompt care for patients requiring urgent medical attention.

1.2. Research Objectives

This study focuses on identifying and mitigating factors affecting the urgent sample pathway to improve outcomes:

- **Adhere to a 60-Minute TAT:** Deliver results within 60 minutes of sample collection.
- **Streamline Booking:** Ensure samples are booked within 16 minutes of arrival for prompt processing.
- **Evaluate Pod System Downtime:** Assess its impact on TAT and implement alternative transport strategies.
- **Focus on Six Critical Tests:** Improve TAT adherence for the following:
    - **Haematology:** Full Blood Count (FBC), Clotting Screen (CSC), D-Dimer (DIMN).
    - **Biochemistry:** Liver Function Test (LFT), Troponin (TNI), Urea and Electrolytes (UE).

1.3. Problem Statements and Aims

1. Collect data on TAT across each stage of the urgent sample pathway focusing on factors that contribute to delays.
2. Investigate how pod system downtime affects TAT and analyse alternative strategies to mitigate delays during pod malfunctions.
3. The diagram below is based on the patient's entire process from start to finish in GP, and the consultation process that patients must follow.

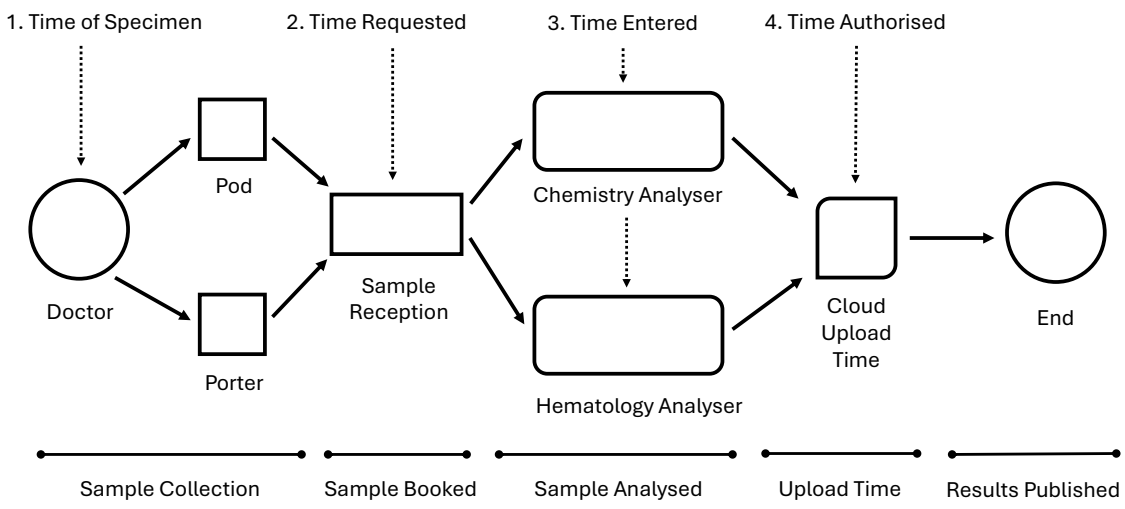


Figure 1. The figure depicts the workflow of a blood sample from collection by a doctor to the publication of results. The process begins with **Time of Specimen**, where a sample is collected and sent to the lab via either a **pod system** (an internal pneumatic transport) or a **porter system** (manual transport). Upon lab receipt, the **Time Requested** phase starts as the sample is booked at **Sample Reception**. The sample is then directed to either a **chemistry analyser** or a **haematology analyser** for testing (**Time Entered**). Following analysis, results are uploaded via a cloud-based system for authorisation and publication (**Time Authorised**). The entire process, from sample collection to result publication, highlights key time points for tracking turnaround efficiency, focusing particularly on steps from **Time Requested** to **Time Authorised** within the lab.

2. Data Collection and Analysis

2.1. Using Visualisations to Determine the Research Area

From the data collection we were able to see the general picture of the data that we were supposed to be working with. Below the graphical representation of the types of samples and their average hourly distribution during the day:

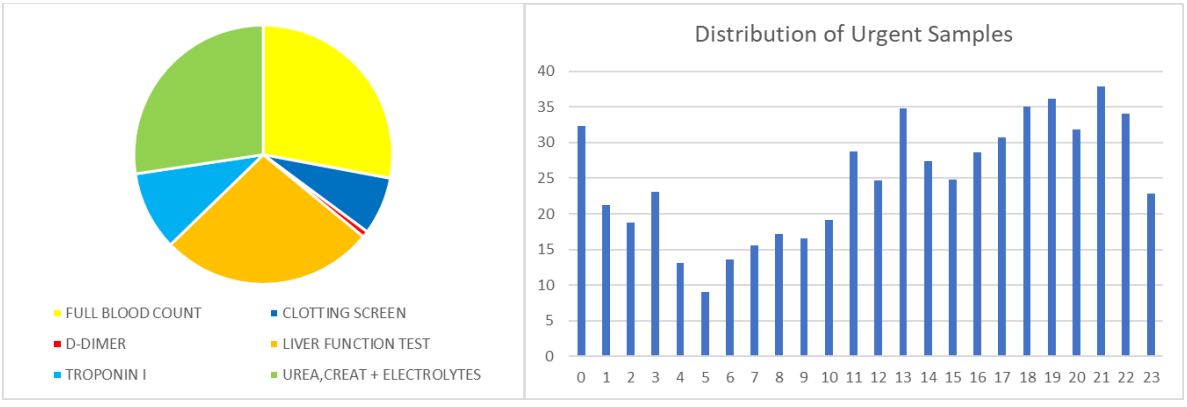


Figure 2. *The pie chart illustrates the distribution and frequency of specific test types received in the laboratory. The proportions represent the relative occurrence of each test:* ***Full Blood Count (yellow), Clotting Screen (blue), Liver Function Test (green), Urea, Creatinine + Electrolytes (light green), Troponin I (light blue),*** *and* ***D-Dimer (red)****. This data highlights the variability in test demands, with Full Blood Count and Urea, Creatinine + Electrolytes showing higher frequencies compared to less frequent tests like D-Dimer.*

Figure 3. The bar chart depicts the distribution of urgent samples received over a 24-hour period. The **X-axis** represents the hours of the day, while the **Y-axis** shows the frequency of samples received. The data indicates peak activity during hours **16:00 to 22:00**, highlighting these as the busiest times for urgent sample submissions, with a lower frequency observed between **01:00 and 06:00**.

2.2. Data and Variables

Data for this study were sourced from Severn Pathology, Southmead Hospital, Bristol, focusing on the urgent sample pathway over a 24/7 period. Approximately 500 urgent samples are processed daily, with key variables including TAT, POD breakdown frequency, and sample test volume. Staff availability in sample reception and porters' shifts were also considered. Team member Muhammad Hussain collected and analysed the data, covering all stages of the pathway. High-priority tests—FBC, CSC, DIMN, LFT, TNI, and UE—were flagged for their critical role in diagnosing and managing urgent patient conditions efficiently.

2.3. Activity Flow Diagram

The laboratory system is structured to handle the receipt, registration, analysis, and final upload of results to the system, with specific processing stages for chemical and haematology analysers, which can be seen in Figure 4. The following are the main components of the system, which are based on the data gathered and the model that has been created:

- **Entities:** Patient Samples.
- **Activities:** Entry (Doctor's request), Sample Routing Decision, Pod System, Driver System, Registration, Chemical Analysis (Chemical Analyser), Haematology Analysis (Haematology Analyser), Final Upload (Upload results).
- **Resources:** Pod Machine (1), Car Driver (1), Registration staff (2).
- **Events:** Sample request arrivals from doctor (entry point), Processing through Pod or Driver System for transportation, Registration of samples, Routing of samples to analysers based on type, Completion of analysis (Chemical or Haematology), Upload of results, Completion of the sample workflow.
- **Queues:** Pod System, Driver System, Registration, Chemical Analyser, Haematology Analyser, Final Upload.

Duration: The simulation is conducted over a one-week period, with operations running continuously for 24 hours each day.

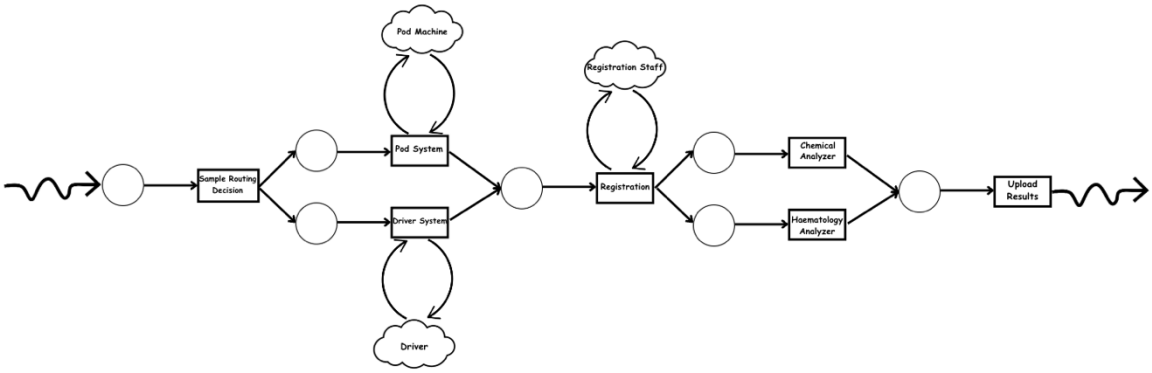


Figure 4: Activity Flow Diagram

2.5. Distributions and Model Parameters

Time Dependent Distribution

The data indicates that the number of samples entering the laboratory varies throughout the day, reflecting fluctuations in laboratory activity based on the doctors' orders. To accurately simulate the distribution of sample counts and assess the laboratory's busyness, we conducted an in-depth analysis. This involved aggregating the total number of samples entering the laboratory each hour over a seven-day period to derive average hourly counts. Below is the simplified version of the data we used to create the distribution functions:

Date/Time	SUM
AVG	
00	30.5
01	20.625
02	19.375
03	22.625
04	13.625
05	9.125
06	12.75
07	14.625
08	15.25
09	15.5
10	21.375
11	26.5
12	25.375
13	34.125
14	25.75
15	26.625
16	29.625
17	32.71429
18	33.25
19	33.375
20	33.375
21	37.625
22	31.75

Figure 5

Utilising these calculated averages, we implemented a Poisson distribution function to model the laboratory's hourly workload. The lambda values for the Poisson function were set based on the average sample count divided by 60 minutes to reflect the typical flow within an hour. Here is an example of how we structured the function:

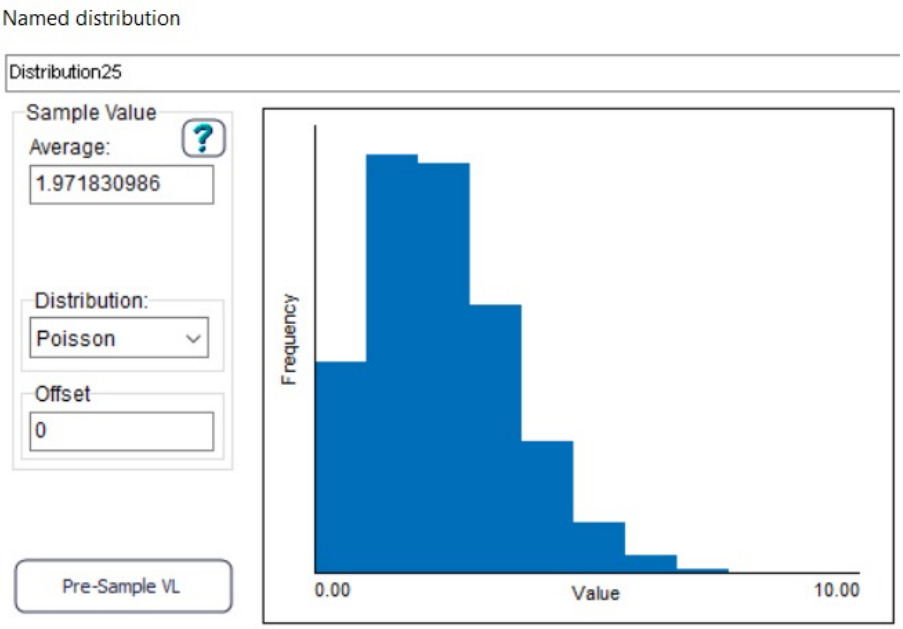


Figure 6

We combined individual Poisson distributions into a cohesive set of Time Dependent Distributions named "dst_sample_count_hourly." This structured approach allows for a detailed simulation of the hourly sample count based on the historical data, providing a robust framework for modelling the laboratory's workload dynamics effectively.

Probability Profile Distribution.

The calculated probabilities for labelling based on test type were used to create a custom Probability Profile Distribution, labelled `dst_label_type`, which assigns a numeric identifier (from 1 to 6) to each sample according to its likelihood. This method ensures accurate statistical representation of sample frequencies and is further detailed in the “Labels” section.

Normal Distribution

Normal distributions were applied to model the time requirements of various activities in the laboratory. For the Registration activity and the Driver system, normal distributions were utilized with an average of 1 minute and a standard deviation of 0.25, and an average of 20 minutes with a standard deviation of 5 minutes, respectively. These settings were based on feedback from laboratory personnel responsible for sample registration, who reported that the registration process typically takes about 1 minute. Similarly, both analysers were modelled using normal distributions with an average processing time of 25 minutes. A standard deviation of 5 minutes was incorporated to account for variations in processing times due to fluctuating workloads.

Exponential Distribution

When modelling the "Upload Results" activity, it was observed that most uploads to the system are completed very quickly. However, to create a precise simulation, we determined that setting an Exponential upload time of 0.1 minutes accurately reflects real-life conditions. This decision is supported by recorded instances where factors like network delays, system performance fluctuations, and variations in file sizes occasionally prolong the upload process.

Pod System Breakdown Distribution

The pod system's breakdown behaviour was modelled using data collected from the laboratory's **"Reporting Downtime"** log, maintained by staff. By analysing five weeks' worth of data, we derived the following distribution functions to simulate breakdown intervals and repair times:

- **Time Between Breakdowns:** Modelled as an **exponential distribution** with an average time of **1,080 minutes (18 hours)**. This reflects the average operational period between breakdowns.

- **Repair Time:** Modelled as a **normal distribution** with a mean of **240 minutes (4 hours)** and a standard deviation of **90 minutes (1.5 hours)**, capturing the variability in repair durations.

These distributions were implemented into the simulation to reflect realistic operational challenges and assess the impact of pod system downtime on overall workflow efficiency.

3. Simulation

3.1. Overview

The model was developed around four distinct phases, each representing a distinct event in the system's workflow. These phases—**time of specimen**, **time requested**, **time entered**, and **time authorized**—served as the foundation for modelling the activities in the system.

- **Time of Specimen**: This phase captures the first activity (after entry), where the doctor sets the sample for delivery to the lab.
- **Delivery Routes**: Samples follow the routing decisions activity, in which it is determined which one of the two delivery methods they enter. Generally, 80% of the samples were transported via the pod system, while 20% were delivered by a driver. However, the routing is subject to change if the pod machines break down, for instance, or if the driver is unavailable.
- **Time Requested**: Upon arrival at the lab, each sample undergoes registration to prepare for analysis. Two staff members were assigned to always perform this task. At this stage, the routing decision determines whether the sample proceeds to either the haematology or chemical analyser by using labels.
- **Time Entered**: This phase involves the processing of the sample by its designated analyser (represented as separate activities).
- **Time Authorized**: Following analysis, the sample data is uploaded to the cloud, after which the sample exits the system, completing its journey.

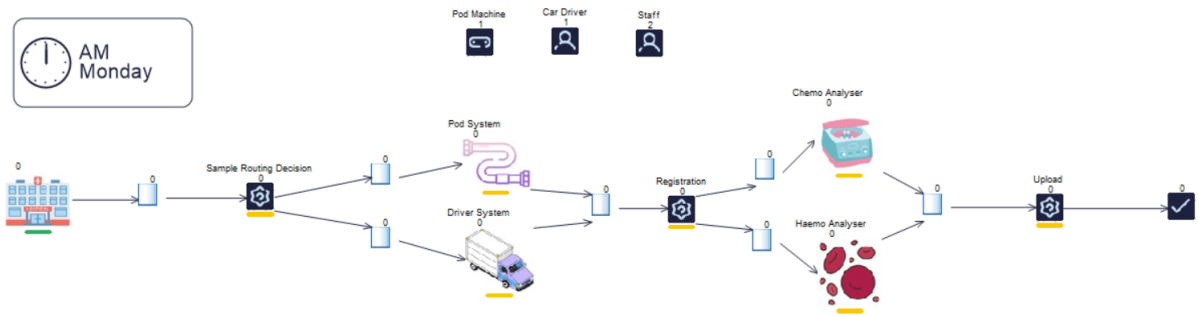


Figure 7 Simulation Model

3.2. Clock Properties

In configuring the clock properties for our laboratory simulation, we have established a timing framework that operates around the clock, reflecting the 24-hour activity common in laboratory settings. The simulation extends over a complete week, running continuously each day to encompass the full range of operational dynamics.

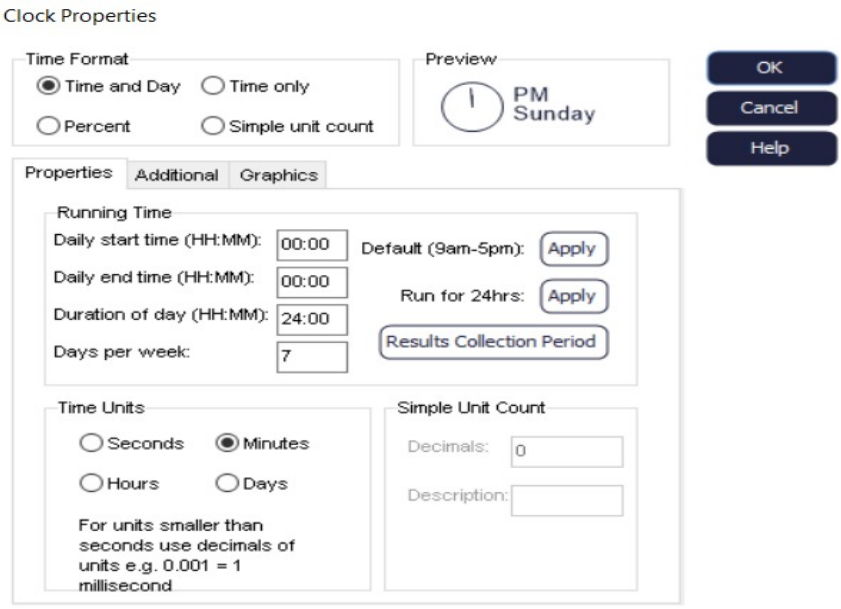


Figure 8

Time Format and Running Time:

- **Time Format**: We have selected the "Time and Day" option, enabling us to track both the hour of the day, and the day of the week.
- **Daily Operation**: The simulation starts and ends at midnight, running continuously for 24 hours each day, over a 7-day period.

Time Units:

- **Primary Unit**: Time was set to minutes, facilitating precise tracking and analysis of time-sensitive laboratory processes.

This setup ensures our simulation accurately reflects the temporal patterns and demands of a real-world laboratory environment.

3.3. Visual Logic

1. We have implemented a simple visual logic code (fig.9) which translates numeric identifiers for test types into textual descriptions within the simulation. This transformation occurs just before samples exit the “Registration” activity, enhancing readability and making simulation results easier to understand and analyse.

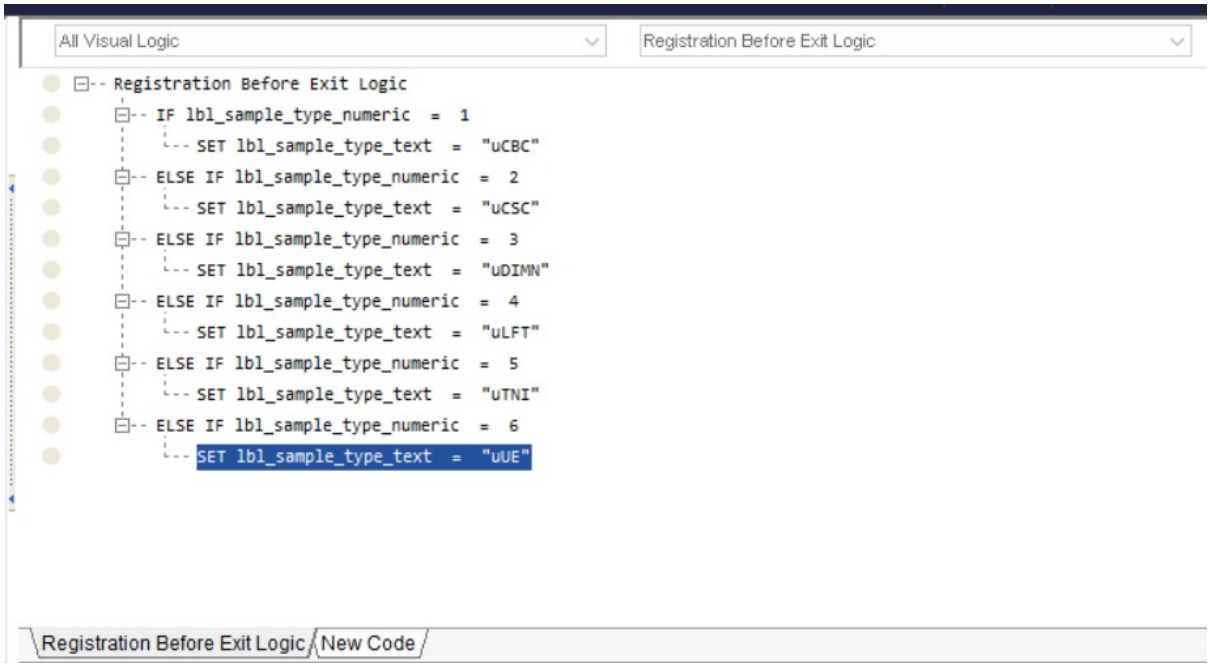


Figure 9: Visual logic code translating numeric identifiers into textual descriptions

2. Our other code (fig.10) calculates and formats the elapsed time for a sample within the simulation. This refinement is crucial as the Turnaround Time (TAT) in our data, captures the interval from a sample's entry into the laboratory (noted at pre-registration), to the moment results are uploaded into the system (excluding transportation time). The code executes two principal functions:

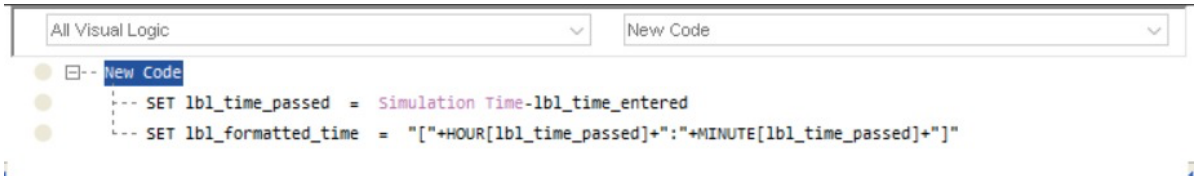


Figure 10: Visual logic code for elapsed time

- **Calculation of Time Passed:** Determines the duration from the entry point to when the results are uploaded, recording this data in 'lbl_time_passed'.

- **Formatting Time:** This duration is transformed into an interpretable format, displaying hours and minutes, which is then stored in 'lbl_formatted_time'. The formatted results are subsequently utilized in an Excel spreadsheet, for further calculations and data analysis.

3.4. Flow of Simulation

As mentioned, TAT should be 60 minutes. However, the data reveals delays in many samples, with some samples take much longer than the expected 60-minute TAT. The collected data indicates when samples enter each activity, providing the statistics needed to assess the delays.

1) Logistics

The origin of the patient's blood sample is the hospital, whilst the following procedures occur in the lab. Samples are transported from the hospital to the lab in one of two ways: the pod system or a driver. The pod system is preferred since it's both quicker and cheaper. However, it's unreliable due to frequent breakdowns, therefore it can't fully replace the driver. In our model, the 'sample routing decision' activity divides into two routes to determine how the sample is transported to the lab.

2) Laboratory

Upon arrival to the lab, the samples must be registered, wherein the samples (from both driver and pods system) are manually booked by the employee, so when there is a high density of incoming samples, a queue forms. After registration the samples undergo analysis, which ideally completes within an hour. As mentioned, there are six test types, three of them are to enter the chemical analyser, whilst the other three are to enter the haematology analyser. We have another routing decision to represent this, determined by the label given to each sample. The process is automated and requires no additional resources. However, there's a limit of 36 sample spaces in each analyser; when more samples are to be analysed, queues can form. Once analysis is complete, the results are automatically uploaded.

3) Resource

The model has three resources: pod machine, driver and registration staff. Whilst the pod system is an activity, the pod machine resource represents its functionality. One of the goals of our simulation is to understand the impact the pod system's reliability has on the efficiency of the whole system. There is only one driver to transport the samples, they can be affected by several factors e.g. traffic. Hence, the driver system is not as efficient as the pod system, but valuable, nonetheless. Two employees work on the registration to book all the urgent samples, always.

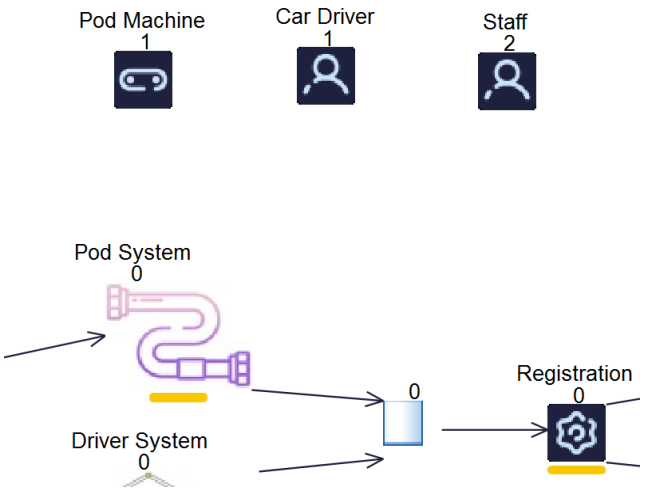


Figure 11: Resources

3.5. Labels and their Distributions

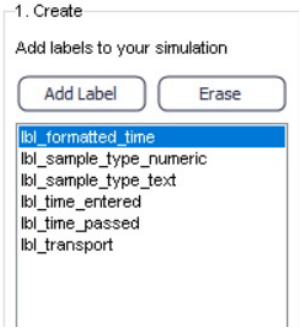


Figure 12: the labels for the simulation

Distribution of Test Types in the Simulation

In our simulation, the entry point is marked as the stage where the doctor takes blood samples from the patients. This stage simulates the routine procedure in which doctors request specific laboratory tests. Within this framework, there are six types of tests: uCBC, uCSC, uDIMN, uLFT, uTNI, and uUE.

To accurately represent the flow of samples through the lab, we have calculated the probability distribution for each test type based on empirical data, which was done by averaging the distribution of each test type over the seven-day period and further refined into 24-hour segments. The resultant probabilities for each test type are as follows:

1. uCBC: 0.30515
2. uCSC: 0.08101
3. uDIMN: 0.00635
4. uLFT: 0.25585
5. uTNI: 0.09118
6. uUE: 0.26046

These probabilities were then utilized to create a custom probability profile distribution (fig.13), labelled `dst_label_type`, which assigns a numeric identifier (from 1 to 6) to each test type based on their respective probabilities. The labelling mechanism, `lbl_sample_type_numeric`, ensures an accurate and dynamic distribution of the test types throughout the simulation, allowing precise modelling of laboratory operations and the handling of various test requests that occur each hour.

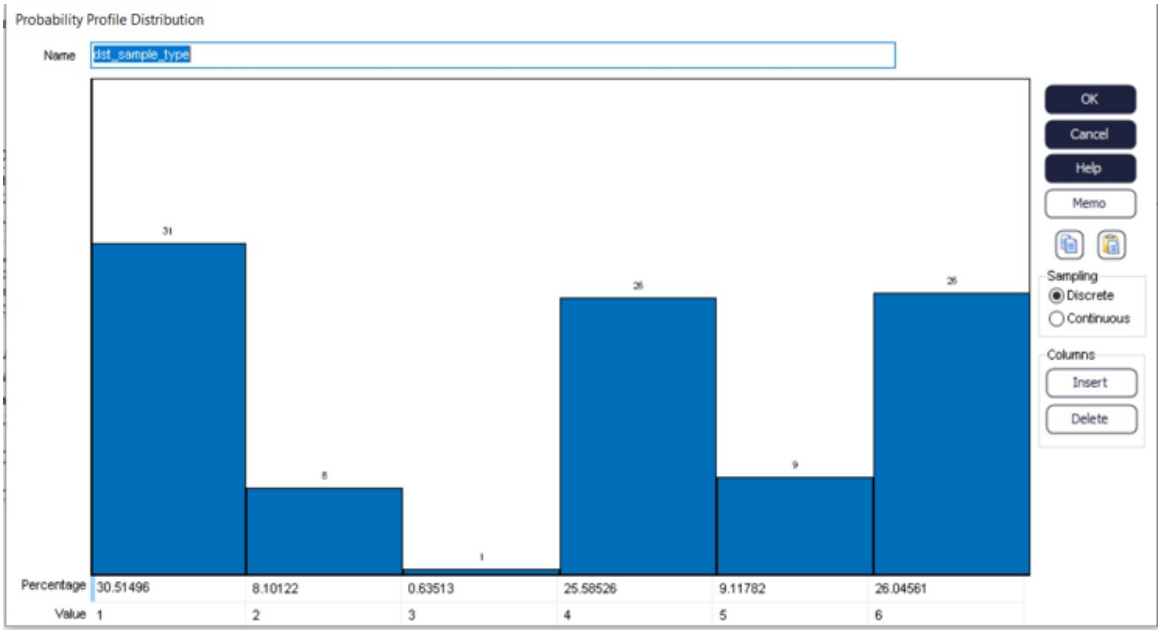


Figure 13: probability profile distribution

Additionally, `lbl_sample_type_numeric` was used in the routing logic of the registration activity to determine which tests should be sent to the appropriate analyser (fig.14).

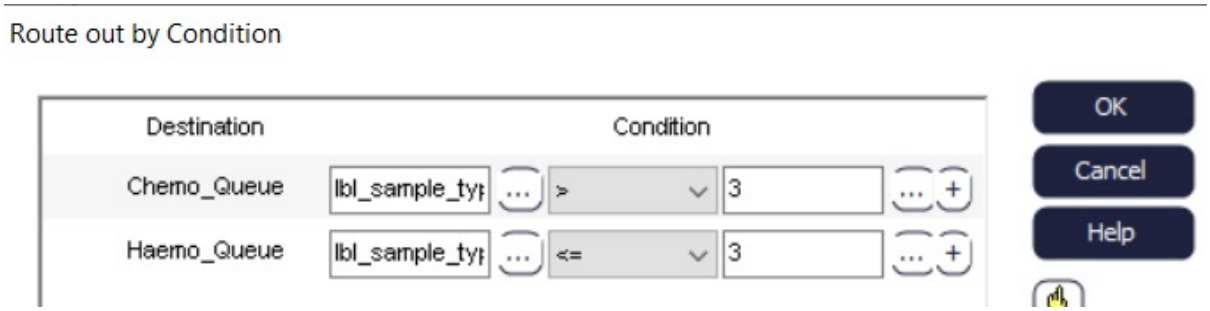


Figure 14: Conditional routing

Transportation Labelling and Routing Strategy

In the simulation, transportation methods for samples from the hospital to the laboratory were also characterised using a probability profile distribution, due to the lack of direct empirical data. After consulting the laboratory staff, it was decided that approximately 80% of the samples are transported via a pod system, while the remaining 20% are delivered by drivers. This distribution was incorporated into our simulation under the distribution `dst_Transport` and labelled as `lbl_Transport`.

With both the test type and transportation labels configured, we established a label-based routing system. Samples are first routed based on their `lbl_Transport` value to either the pod system or driver. Following this, samples are then directed to the appropriate analysers based on their `lbl_sample_type_numerical` values, ensuring

each sample is processed correctly according to its designated test type and transportation method. This setup optimises the workflow and reflects realistic operational procedures within the laboratory.

Additionally, recording the entrance time of each sample into the laboratory was crucial, implemented using the labels 'lbl_time_entered' and 'lbl_time_passed' to calculate the TAT for each sample. For better analysis and reporting, the numeric sample type labels ('lbl_sample_type_numerical') were converted into text-based descriptions using 'lbl_sample_type_text'. The 'lbl_time_passed' was also reformatted into a more readable format with 'lbl_formatted_time'. These conversions streamlined data interpretation and enhanced the clarity of analytical outputs.

SIMUL8 Flow File Version 1.00

ID	Time	lbl_transport	lbl_sample_type_numeric	lbl_sample_type_text	lbl_time_entered	lbl_time_passed	lbl_formatted_time
1	62.51116	1	6	uUE	24.56273	36.3784	36
2	62.61707	1	5	uTNI	27.21216	33.83488	33
3	62.75271	1	2	uCSC	35.13021	26.05247	26
4	62.827	1	1	uCBC	37.61033	23.64664	23
5	62.94016	1	6	uUE	39.77122	21.59891	21
6	66.60549	1	6	uUE	23.33846	41.697	41

Figure 15: *The generated results from the Simul8 simulation, providing a detailed overview of the sample data for enhanced understanding.*

3.7. Batch Processing and Sample Handling

To find best batching sizes and intervals, we engaged with staff and collected operational data. This analysis helped in identifying the most efficient batching configurations based on real-time usage and demand patterns.

Batching in Simulation Systems

- **Pod System**: Manages batches ranging from 5 to 15 samples per unit, adapting to changing workloads for optimal efficiency.
- **Driver System**: Utilises batching intervals between 10 and 36, enhancing logistical operations and reducing system idle times.
- **Analysers**: Both the Chemistry and Haematology analysers implement batching, ensuring continuous operation and preventing bottlenecks due to sample influx.

The implementation of batching provides a realistic modelling environment.

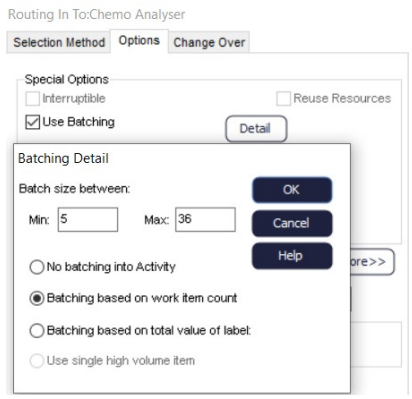


Figure 16: batching of chemo analyser

4. Simulation Experimentation and Results

Our primary goal was to evaluate how the pod system's braking mechanism impacts the process efficiency, specifically focusing on the time metrics associated with lab sample handling and result dissemination. We aimed to keep the TAT under 60 minutes. To achieve this, we employed a systematic approach by labelling each sample to track its progress and subsequently analysing the data through a dedicated spreadsheet to compute the average time.

The simulation results were calculated by averaging the label, "lbl_formatted_time", and the resulting figure (41 minutes) indicates that our objective of maintaining an operational TAT of less than 60 minutes has been met effectively, demonstrating that the system functions within the expected parameters under normal conditions.

Regarding the impact of pod machine malfunctions, our findings are as follows (fig.17):

- When the pod machine operates without interruptions, the average time for doctors to receive patient results is approximately 73 minutes.
- Conversely, when the pod machine experiences breakdowns, this average time extends to 87 minutes.

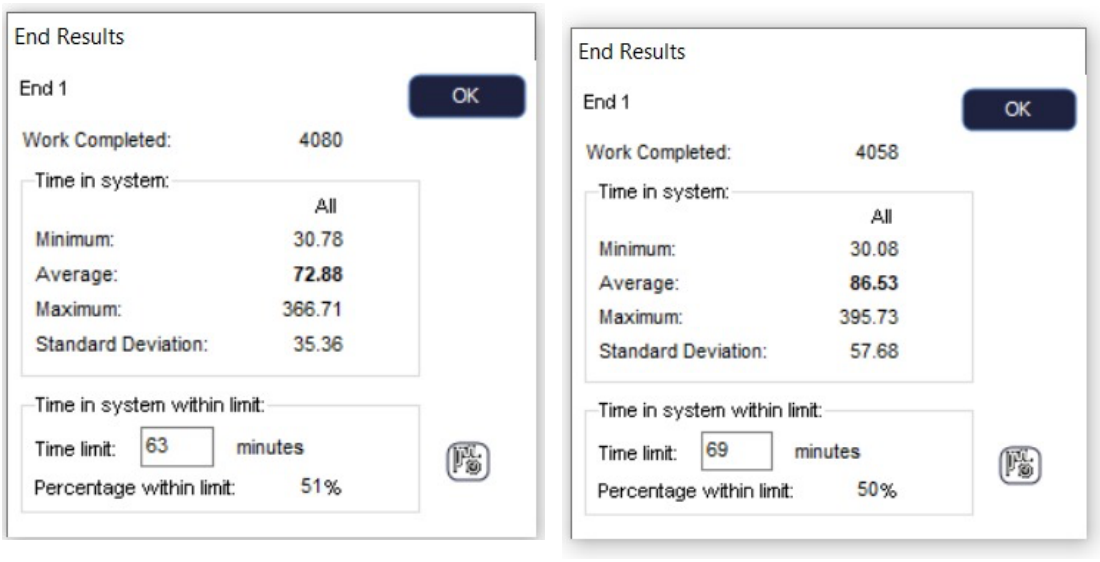


Figure 17: average time of a sample in the whole system when no breakdowns occur (left) and when pod machines break down (right).

Considering the urgency and critical nature of these lab results, the additional delay caused by pod machine breakdowns is significantly impact the overall efficiency of our system and delaying hinder timely medical decision-making. This emphasises the significance of maintaining robust and reliable machinery within our operational framework to ensure quicker healthcare delivery.

4.1. Key Findings

We opted for a 95% confidence level for our analysis, ensuring that each confidence interval reflects the range in which the true mean is expected to fall, with 95% certainty. Using the Key Performance Indicator (KPI) calculator, we analysed the simulation model's performance and included confidence intervals where necessary for meaningful insights into variability and reliability. The following findings summarise the system's performance.

1) Activity Analysis

Sample Generation and Routing

- Sample Generation:
  - The "Doctor Requests Sample" activity generated a total of 4,161 samples over the simulated week, with a confidence interval of [4,096.20, 4,197.80].
- Sample Routing Decision:
  - The work rate of this activity was notably low at 4.12%.
  - This aligns with its limited functionality. Its primary role was to redirect samples to the driver system during pod system breakdowns, bypassing the default transportation labels.

Pod System and Driver System

- Pod System:
  - Operated for 29.71% of the time, with 55.49% of its time spent in a waiting state.
  - Breakdown-related stoppages accounted for 14.80% of the time, reflecting reliability challenges.
  - Completed 509 batches, with a confidence interval of [497.57, 605.23].
- Driver System:
  - Compensated for pod system failures but had overall low utilisation.
  - Completed 106 batches, with a confidence interval of [102.97, 136.63].

Analysers

- Haematology Analyser:
  - Operated at 67% utilization, handling a moderate workload.
  - Completed 268 batches of samples, with a confidence interval of [259.08, 277.72].
- Chemistry Analyser:
  - Operated at 81.63% utilization, handling a larger proportion of workload.
  - Completed 326 batches of samples, with a confidence interval of [320.22, 332.58].

2) Queue Analysis

- Chemo Queue
    - Average Queue Size: 3.01; Max Size: 19; Average Time: 12.22 min; Max Time: 37.05 min.
    - Only 43.93% of samples queued for less than 10 minutes, indicating significant delays.

- Haematology Queue
    - Average Queue Size: 1.66; Max Size: 14; Average Time: 10.20 min; Max Time: 34.60 min.
    - Better performance than chemo but still experiences delays with 53.69% meeting the 10-minute limit.

- Transportation Queues
    - Pod System: Efficient overall with 96.08% under 10 min, though breakdowns cause occasional extreme delays (Max: 312.88 min).
    - Driver System: Well-managed with 82.22% under 10 min but struggles during pod failures.

- Registration Queue
    - Efficient with 92.36% processed under 10 minutes. Peak queue size reached 26.

3) Resource Utilisation Analysis

- Car Driver
    - Utilisation: 97.66%, with a 95% confidence interval of [97.18%, 98.12%], indicating high demand and minimal capacity for additional workload.
    - Observation: The system heavily relies on the driver, especially during pod breakdowns.

- Pod Machine
    - Utilisation: 98.26%, with a 95% confidence interval of [96.64%, 98.43%], showing critical usage with little spare capacity.
    - Observation: Any downtime risks significant delays.

- Registration Staff
    - Utilisation: 20.55%, with a 95% confidence interval of [20.11%, 20.72%], indicating ample capacity to handle surges.
    - Observation: Staffing is not a bottleneck in the current setup.

Summary

The system demonstrates high reliance on the Pod System and Driver System, with both operating near full capacity and prone to delays during breakdowns. Key bottlenecks lie in sample transportation and queue management, particularly for the

chemo queue. Conversely, registration staff have ample flexibility to handle demand. To improve overall performance, adding redundancy to transportation systems and addressing pod reliability issues is recommended.

4.2. Suggestions for Improvement

Based on the findings from the simulation, the following recommendations are proposed to address bottlenecks and enhance the system's performance:

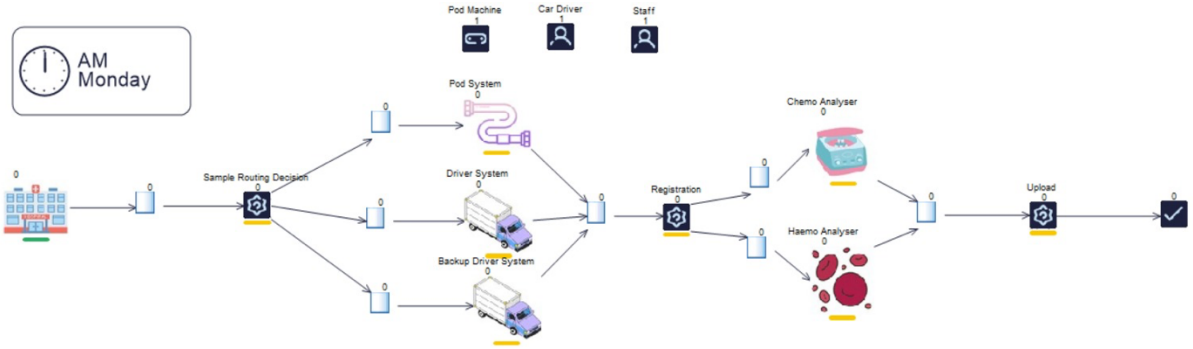
1. Increase Pod System Reliability
   - **Action:** Implement predictive maintenance schedules and monitor pod system performance to pre-emptively address potential issues.
   - **Expected Outcome:** Minimise breakdown-related stoppages, reducing the 14.80% downtime and improving overall system efficiency.

2. Optimise Driver System Utilisation
   - **Action:** Deploy an additional driver during periods of pod system downtime or high workload to manage transportation delays effectively.
   - **Expected Outcome:** Reduce the strain on the driver system during pod failures and maintain timely sample deliveries.

3. Review and Adjust Batching Strategies
   - **Action:** Fine-tune batching sizes and intervals for the pod and driver systems to better match sample arrival patterns and workload fluctuations.
   - **Expected Outcome:** Improve transport efficiency, reduce idle times, and maintain timely sample delivery to the laboratory.

4.3. Proposed Enhancements and Their Impact

A separate simulation was conducted to evaluate the impact of the proposed suggestions, ensuring reliable and actionable results. The changes implemented included reducing registration staff from two to one, optimising batching configurations, and adding a second car driver to support transportation demands during pod system malfunctions. These adjustments yielded significant improvements in system performance.



Registration staff utilisation increased to 40.87% (95% CI: 40.23%–41.51%), highlighting a more balanced workload without creating bottlenecks. Optimised batching configurations enabled the two car drivers to work efficiently, enhancing transportation reliability and minimising delays. The average time in the system decreased to 75.54 minutes (95% CI: 72.12–78.96), reflecting faster processing and improved overall throughput.
These results confirm the effectiveness of the proposed changes in optimising resource allocation, reducing system delays, and improving operational efficiency.

5. Conclusion

The simulation analysis highlights the strengths and limitations of the current laboratory workflow at Severn Pathology. While the system generally meets the 60-minute TAT target (the time elapsed between when samples enter the lab and results are uploaded) under normal conditions, pod machine breakdowns significantly increase the time for doctors to receive results (the time from sample request to result upload), from **73 minutes to 87 minutes**—a **19.2% increase**. This delay underscores the system's vulnerability due to the high utilisation of critical resources, such as the pod machine (98.26%) and car driver (97.66%), during periods of increased demand or equipment failure. Conversely, the underutilisation of registration staff (20.55%) suggests an opportunity for better resource allocation.

To enhance efficiency, targeted improvements are recommended, including increasing pod system reliability, optimising driver utilisation, and refining batching strategies. Implementing these changes will reduce bottlenecks, improve transport reliability, and ensure the prompt delivery of results, supporting high-quality patient care.