A Process Simulation Model for a Histopathology Laboratory

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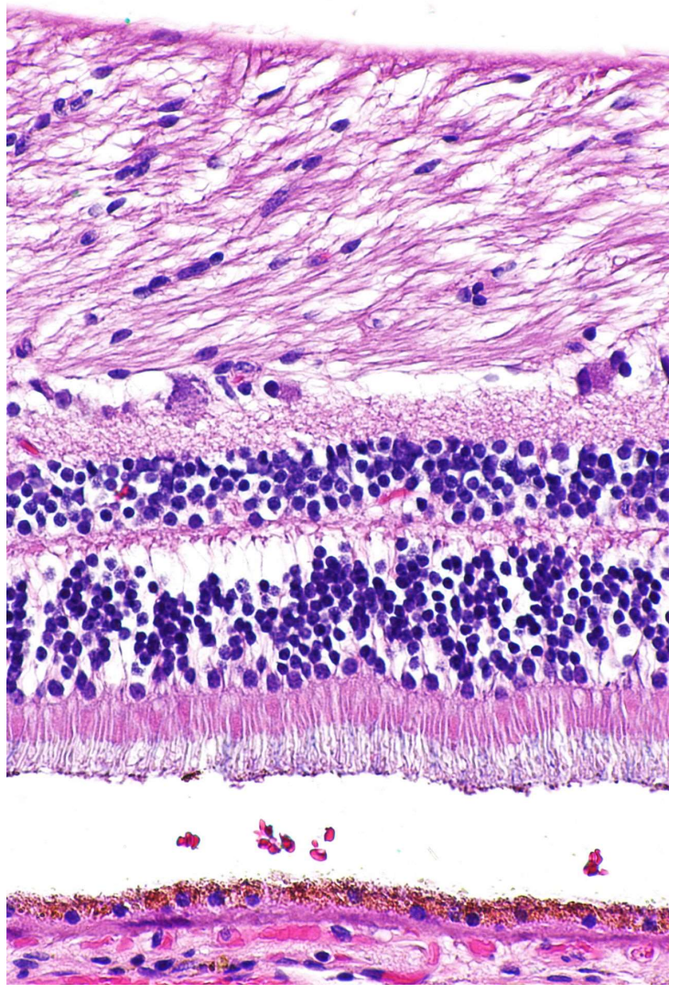
Introduction



- Histopathology = microscopic examination of (stained) tissue samples for study & diagnosis of disease
- Especially critical for cancer screening
- Yet:
  - NHS England, 2022/3 – only 70.2% of cancer diagnoses delivered within 4 weeks
  - Compare with guideline: 90% within 10 calendar days (Royal College of Pathologists, 2013)
- Brown 2004: 80% of lab time is non-value-adding
  - (Case study of histopathology lab in Leicester, UK)

Process Simulation

- Identify bottlenecks in the process
- Estimate key performance indicators (KPIs)
  - Mean turnaround time (TAT) (reception to diagnostic report)
  - % specimens with TAT < n days
  - Mean lab TAT (excludes reporting stage)
  - % specimens with Lab TAT < n days
- Scenario analysis
  - E.g., staffing levels / shift scheduling

Outline

1. Overview of modelling process
2. Simulation model features
3. Results and scenario analyses
4. Discussion

Process modeling

- What are the steps? What order? How long do they take?
- Obtain data from:
  - Workshops
  - Lab observations (shadowing)
  - Review of Standard Operating Procedure (SOP) documents
- For simplicity:
  - Focus on core processes
  - Focus on standard stains (hematoxylin and eosin / H&E)

Process Modelling (2)

- Object Hierarchy
  - Specimen
  - Block
  - Slide
- Tasks operate on any of the above, or batches of these
- Specimens collated before transfer between stages
  - Easier tracking

Stages:

1. Specimen reception
2. Cut-up
3. Processing
   1. Decalcification (sometimes)
   2. Processing machine
   3. Embed & trim
4. Microtomy
5. Staining
6. Labelling
7. Scanning
8. Block/quality check
9. *Reporting*

Lab turnaround time

Total turnaround time

Simulation Model

- Discrete-event simulation model
  - Implemented in Arena
  - Entities created, worked on, disposed by navigating a flowchart
  - Flowchart blocks include Seize/Delay/Release/Batch/Set Attributes/etc.
  - Input/Output blocks for connecting to Excel spreadsheets
    - Model parameters
    - Simulation results (KPIs)
  - Plots for work-in-progress counters (overall / per-stage)

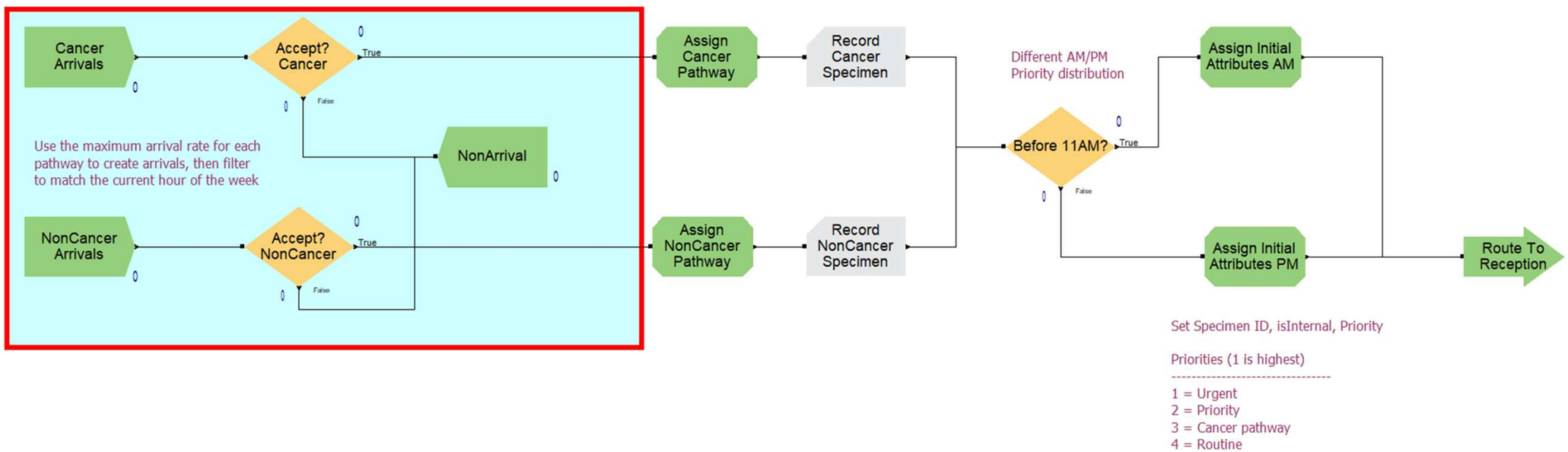
Selected Model features

Attributes of a Specimen

- Unique ID#
- Priority: 1-4, critical/priority/routine cancer/routine non-cancer
- Start/End timestamps for each stage
- Internal/External request
  - Affects duration of reception tasks
- Cut-up category
  - Affects cut-up duration and staff requirements
- Block and slide type
  - Affects processing machine duration, etc.
- # of blocks (created during cut-up stage)

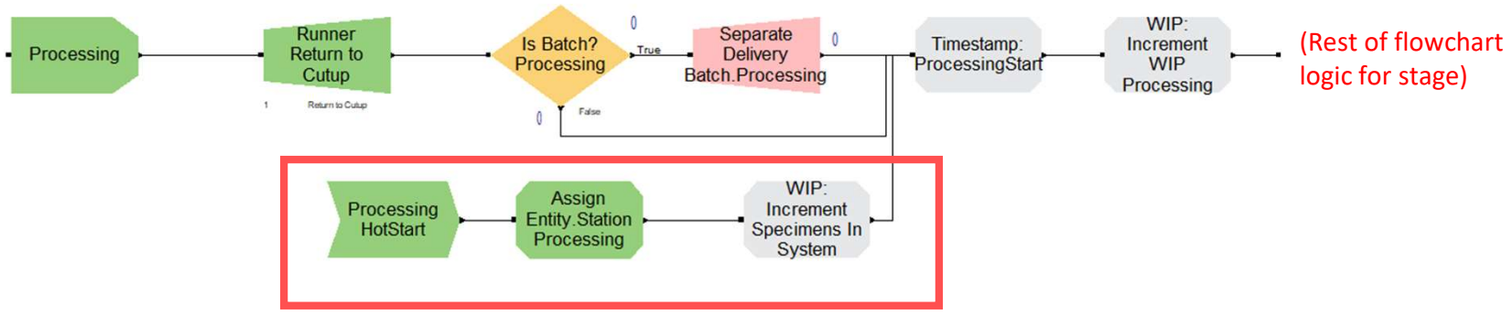
Specimen Arrivals

- Excel table → Arena schedule
- Hourly rates, defined over one week (cyclical)
- Separate rates for cancer/non-cancer pathway specimens
- Rejection sampling used to create time-varying Poisson processes



Simulation hot-start

- Bootstrap initial simulation state
- Read specimens from Excel file (one sheet per stage)
- Each sheet contains, for each specimen, timestamps for completed stages + attribute values set so far
- Related: early exit points for studying parts of simulation model in isolation
  - Triggered manually by modifying simulation settings



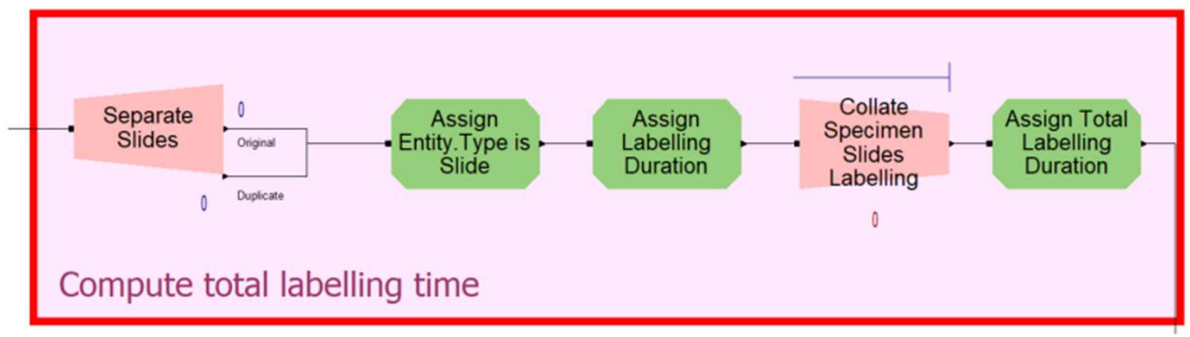
Task durations

- Three-point estimates → triangular distribution
- Exception: machine tasks
  - Constant duration
- For machine tasks:
  - Loading time
  - Machine time (unstaffed)
  - Unloading time

- Can be defined per specimen/block/slide/batch
- Batching/collation times not explicitly defined; combined with preceding task

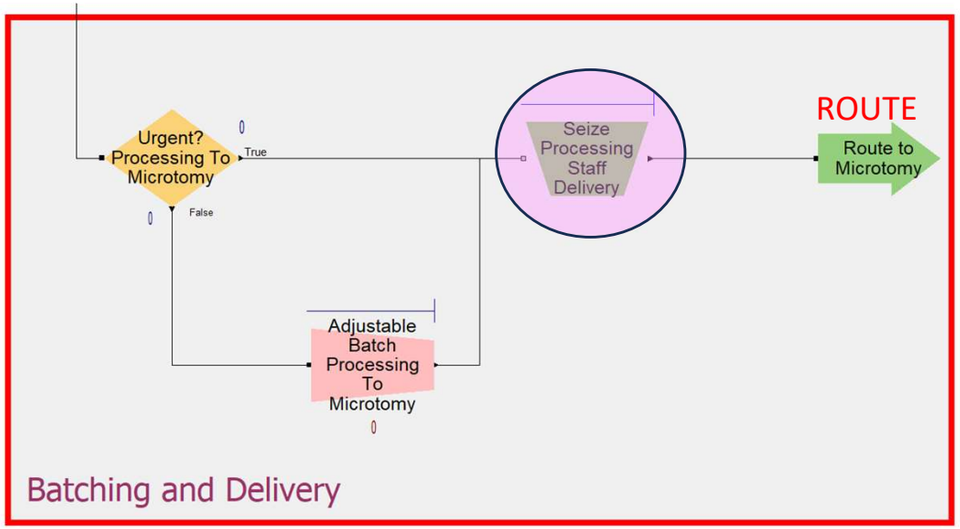
Task duration based on # of subcomponents

- Example: slide labelling
- Ensure all slides of specimen are labelled together, but duration depends on number of slides
- Steps
  1. Split Specimen into correct # of slides
  2. Assign random task duration for each slide based on distribution
  3. Collate slides based on Specimen ID#
  4. Assign total duration by summing across all slides in collated group
- Works because Arena can retain attributes of group members in a collation, while still treating collation as ordinary specimen object

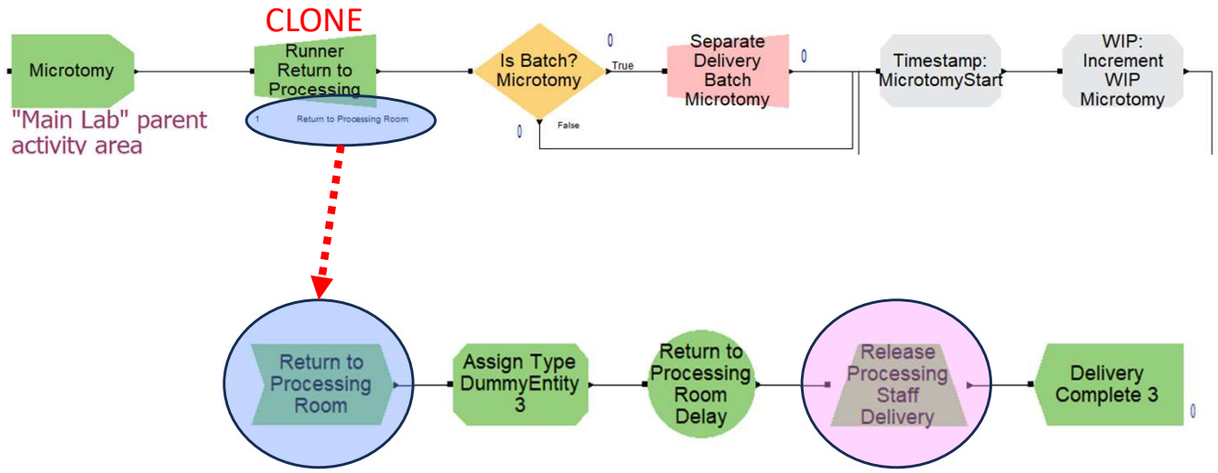


Delivery between stages

- Originating stage
  - Urgent specimens are unbatched
  - Other specimens are batched, but with a time limit
  - ROUTE block has an associated delay (read from Excel file)



- Receiving stage
  - CLONE block triggers runner's return trip
  - Specimen continues on main path
  - Delivery batches separated



Time-triggered batch jobs (1)

- Example: machine processing of wax blocks
  - Series of chemical processes
  - Except for urgent specimens, left to run overnight
  - Each batch contains up to 36 or 300 wax blocks depending on type
  - Need time-based gate to delay machine load / start
- Need to:
  - Batch specimens based on how many blocks can fit in a job
    - Blocks from same specimen cannot be split across batches
  - Release incomplete batches before end-of-day

Time-triggered batch jobs (2)

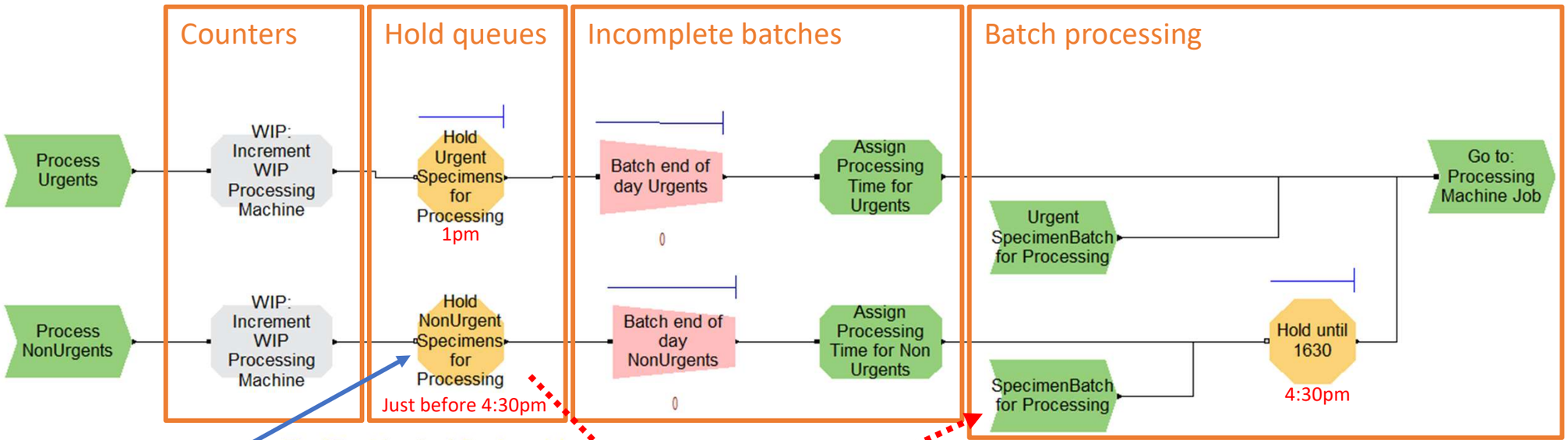
Signals triggered at 1pm, just before 4:30pm, and at 4:30pm

Choose 1 of 3 hold queues based on specimen attributes:

1. Small surgical blocks
2. Large surgical blocks
3. Mega blocks

Time-triggered batch jobs (2)

Signals triggered at 1pm, just before 4:30pm, and at 4:30pm



Choose 1 of 3 hold queues based on specimen attributes:

1. Small surgical blocks
2. Large surgical blocks
3. Mega blocks

The "Batching Logic" submodel will remove specimens from these hold queues when a batch can be completed. Remaining batches will proceed to the end-of-day pathway.

Completed batches from the "Batching Logic" submodel rejoin here.

Time-triggered batch jobs (3)

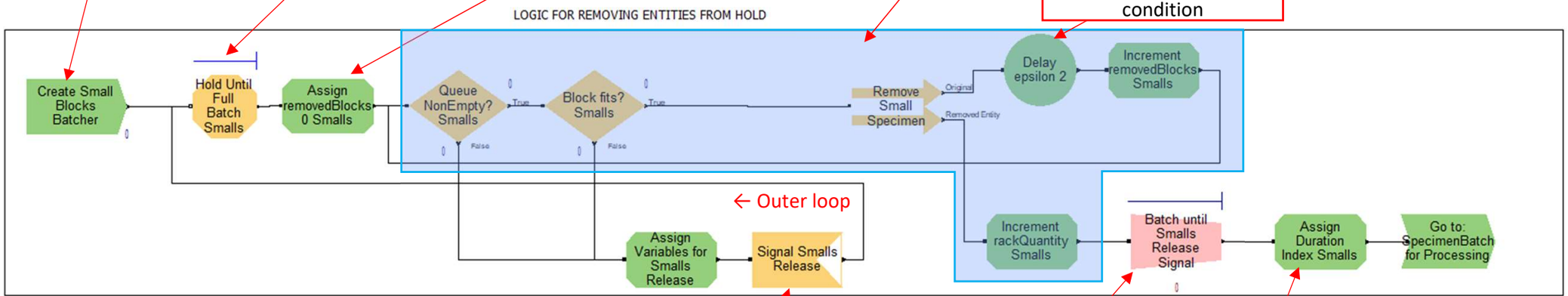
Create batcher entity for each hold queue (1 per processing machine program)

Hold until full load (sum of #blocks of specimens ≥ limit)

Counter for number of blocks taken from queue (reset to 0)

Inner loop:
While (all of) current specimen's blocks fit in machine batch, move specimen to batch and update batching variables

Tiny delay avoids race condition

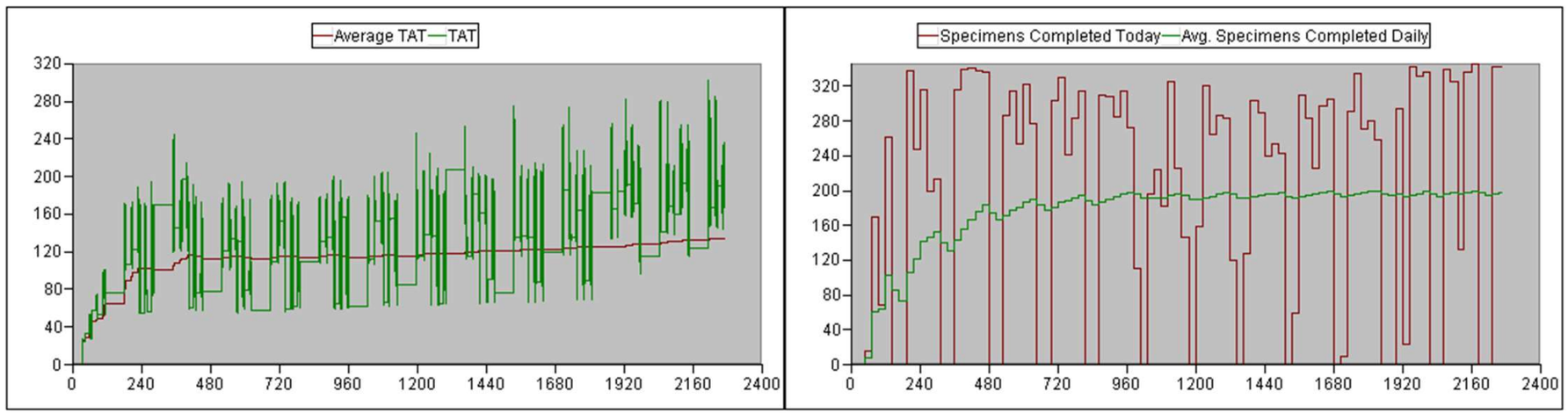


Inner loop exit condition:
When all outstanding blocks have been added to machine batch or next specimen can no longer fit, release the current batch

Processing machine duration read from Excel parameter file

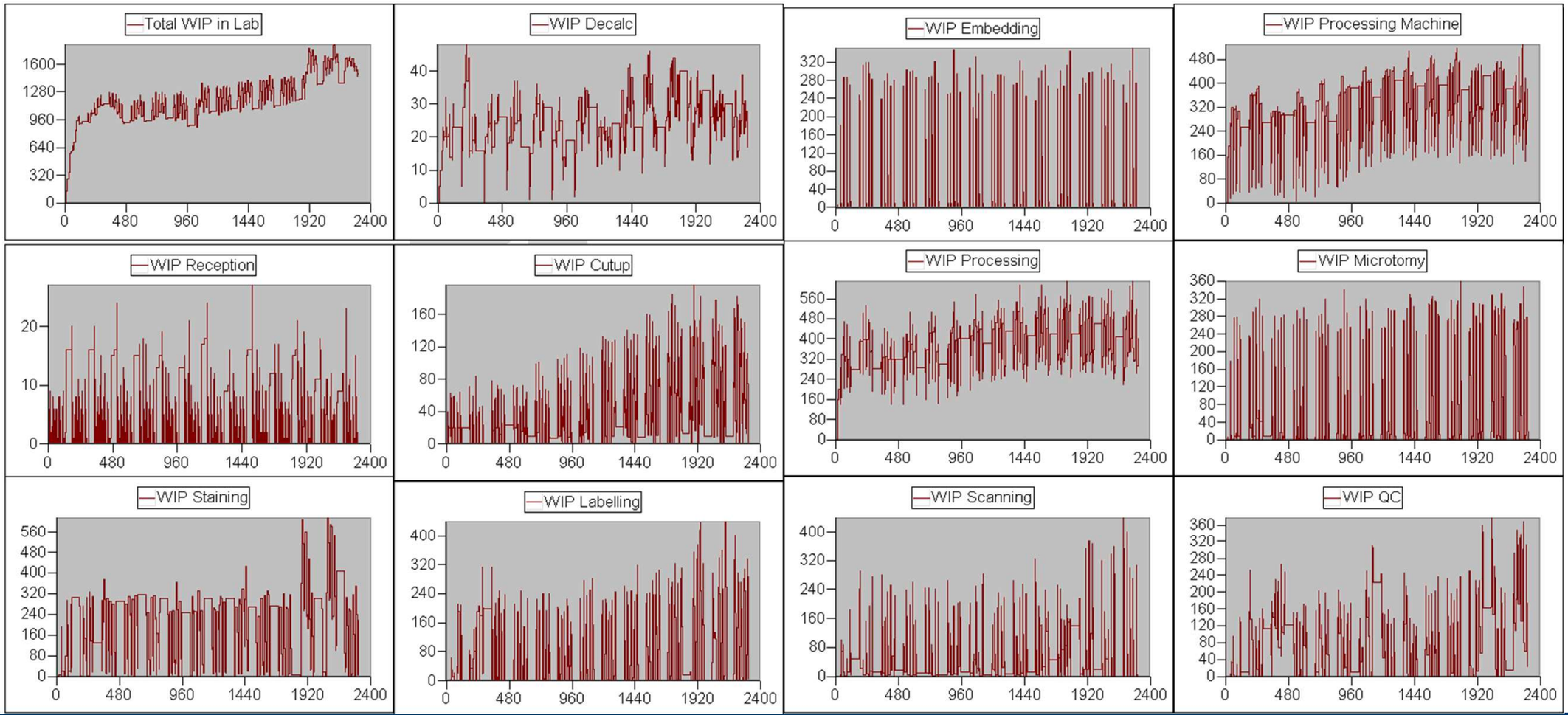
Results & Scenario Analyses

Plots: Turnaround time and throughput



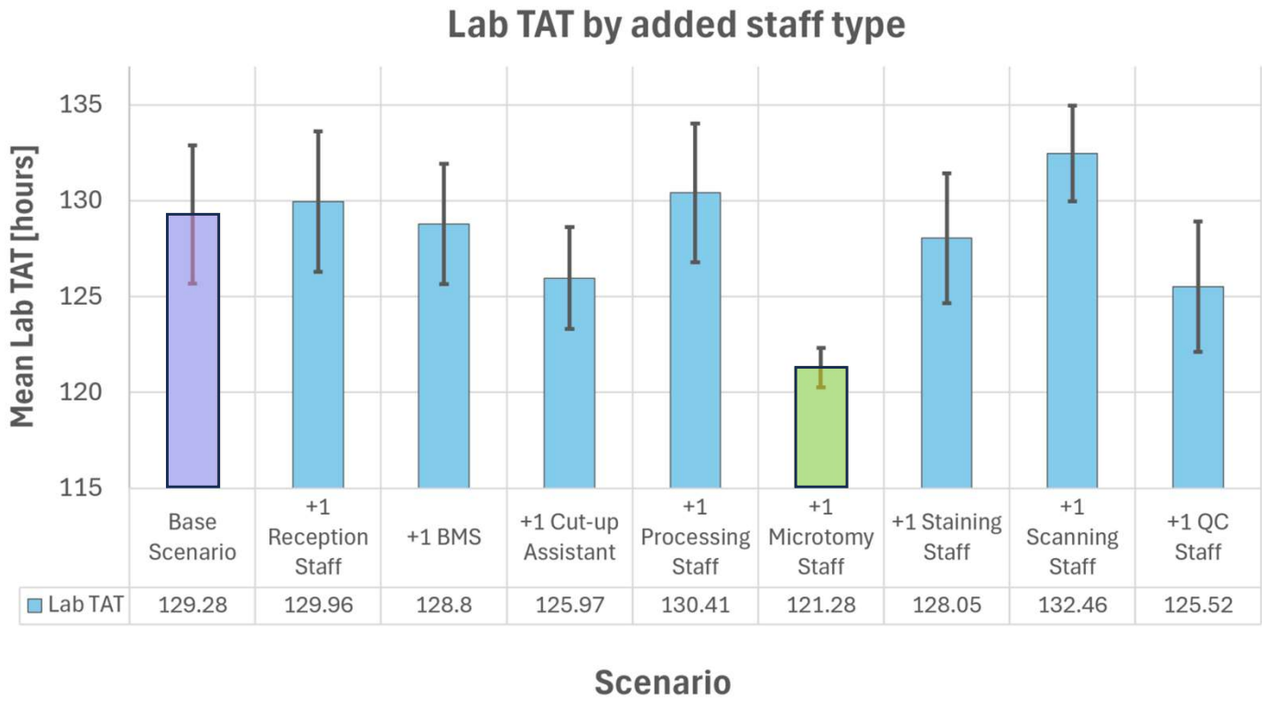
Mean TAT of about 140 hours; about 200 specimens completed daily

Plots: Work-in-progress



Scenario: adding one more staff

- Staff levels are defined in Excel for each staff type (nine types in model)
- Error bar shows 95% confidence interval of mean
- +1 Microtomy staff only scenario with significantly lower mean lab TAT compared to base scenario (no overlap of confidence interval)



Discussion

Summary

- Simulation model for KPI estimation, scenario analyses (what-if comparison)
- Can hot-start simulation with bootstrapped initial state
- Can handle batching with attribute-based batch size
  - i.e., total number of blocks among all specimens in batch
- Can handle simultaneous tasks
  - Delivery runners return to base while specimen continues along main path

Future work

- Improved arrival modelling
  - Current: time-varying Poisson processes (single arrivals)
  - Batched arrivals based on courier deliveries
  - Federate lab model with logistics model?
- Effect of specialities on cut-up, reporting stages
- Full implementation of specimen priorities
  - Currently, only urgent vs. non-urgent considered
- Data integration
  - Staff rotas
  - Building layout → travel time computation
  - Building state → e.g. if lift down / access door malfunctioning, need to take longer route (if one exists)
- Inventory management
  - Effect of low stock on processes / lab throughput

Thank you!

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