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Nations

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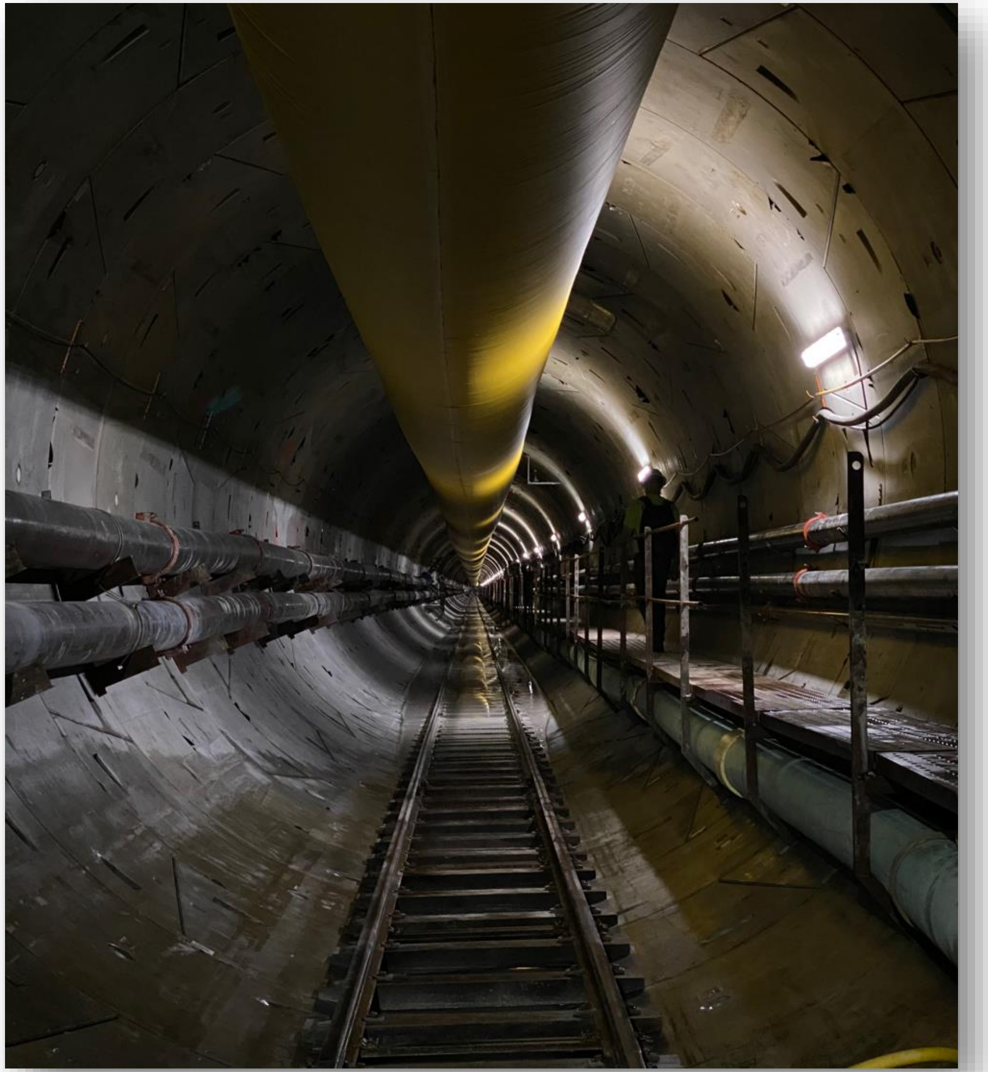

Analysis of Concurrent Activities in TBM Tunneling Operation

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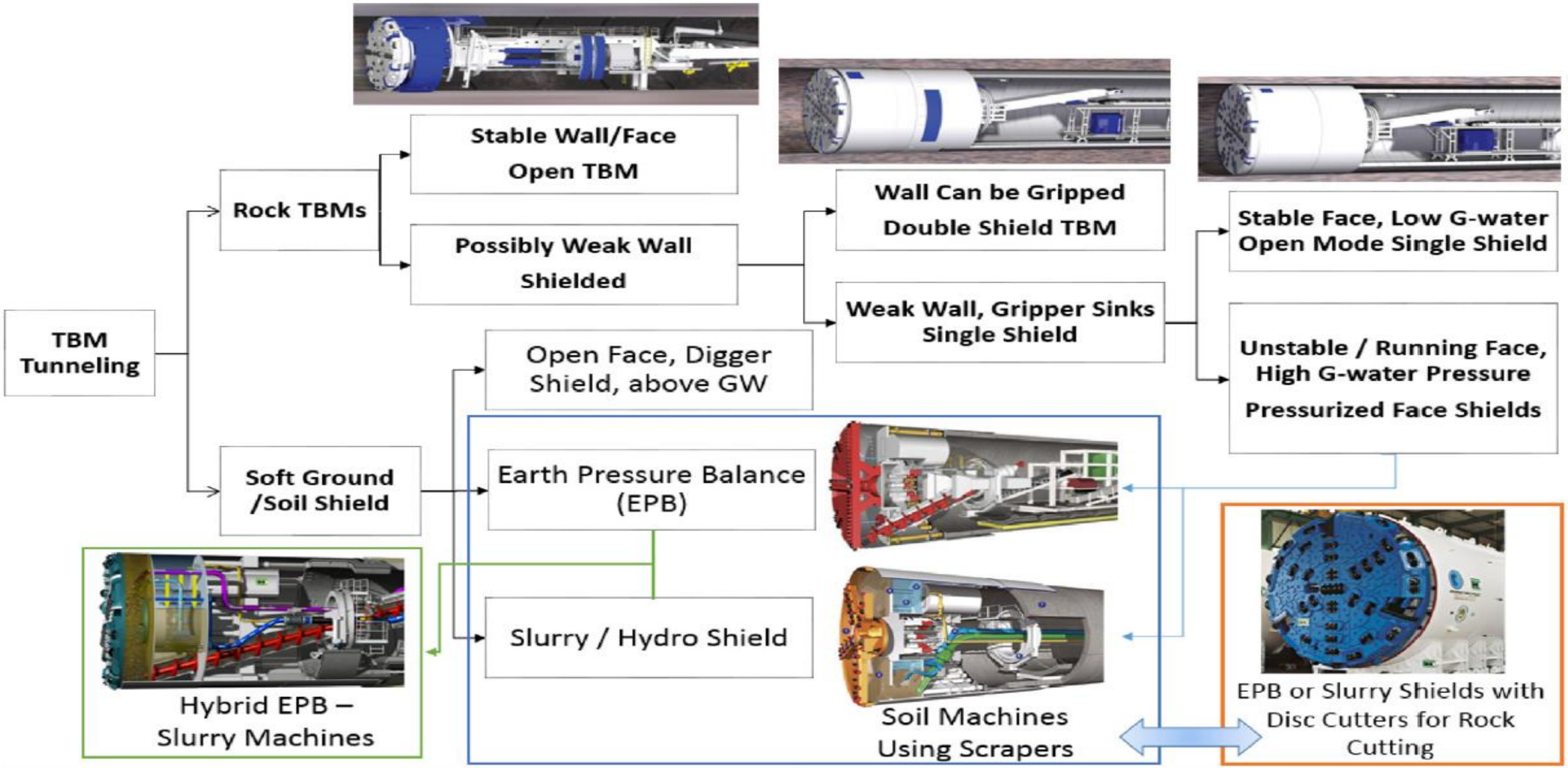
COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

May 23-24, 2023

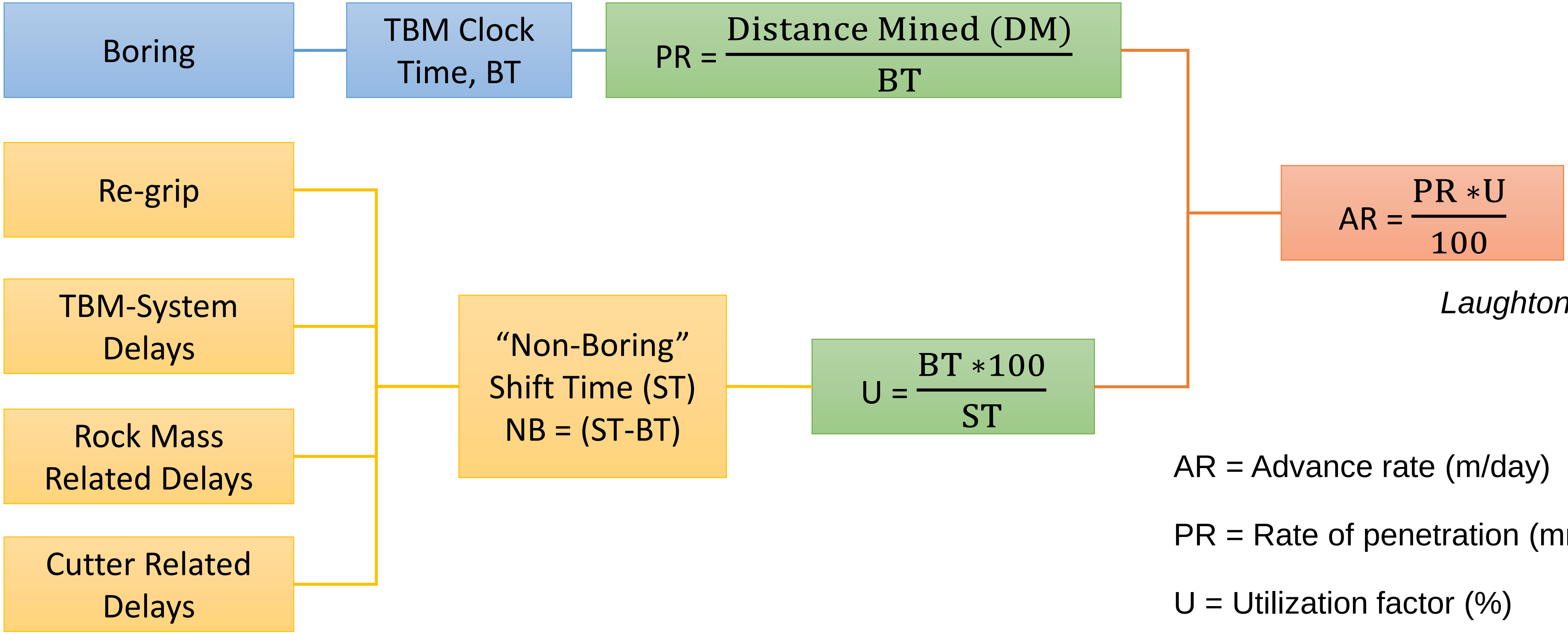
Introduction

TBM Types



TBM Tunneling
Rock TBMs
Stable Wall/Face
Open TBM
Possibly Weak Wall
Shielded
Wall Can be Gripped
Double Shield TBM
Weak Wall, Gripper Sinks
Single Shield
Stable Face, Low G-water
Open Mode Single Shield
Unstable / Running Face,
High G-water Pressure
Pressurized Face Shields
Open Face, Digger
Shield, above GW
Soft Ground
/Soil Shield
Earth Pressure Balance
(EPB)
Slurry / Hydro Shield
Hybrid EPB –
Slurry Machines
Soil Machines
Using Scrapers
EPB or Slurry Shields with
Disc Cutters for Rock
Cutting

Introduction



Laughton, 1998

AR = Advance rate (m/day)

PR = Rate of penetration (mm/min)

U = Utilization factor (%)

Utilization factor is the percentage of boring time per total time.

Introduction

Advance rate

$$AR = Penetration\ rate \times Machine\ utilization\ rate = PR \times U$$

Penetration rate

$$PR = \frac{Distance\ mined}{Boring\ time}$$

Machine utilization rate

$$U = \frac{Boring\ time}{Total\ time}$$

$$U\ (\%) = \frac{T_b}{T_b + T_s + T_g + T_t + T_{sp} + T_{br} + T_{ut} + T_{ch} + T_m + \cdots} \times 100$$

$$U\ (\%) = \frac{T_b}{T_b + T_{Scheduled} + T_{Unscheduled}} \times 100$$

T_b= boring Time
T_s= Segment Installation Time
$T_g = Ground\ Troubleshooting$
$T_t = Transportation\ Time$
$T_{sp} = Delays\ due\ to\ Supplies$
T_{br}= Unexpected Breakdown
$T_{ut} = Utility\ extension$
$T_{ch} = Cutterhead\ inspection$
$T_m = Maintenance\ Time$
$T_{Scheduled} = Scheduled\ delays$
$T_{Unscheduled} = Unscheduled/unexpected\ delays$

TBM Utilization Rate

Utilization rate is impacted by:

01
Geological conditions

02
TBM Type

03
Back system

04
Site set up

05
Workflow

06
Logistics

07
Management of operation

08
Skill level of contractor and crew

These parameters are:

- Unique
- Uncertain
- Hard to quantify

Literature Review

Timeline

1991 **CSM Model**

Unreliable for present-day projects
Project-specific
Overestimates utilization rate
Not able to detect bottlenecks

1998 **NTNU**

Developed based on Scandinavian rock
Unreliable for present-day projects
Constant value used
Not able to detect bottlenecks

1999 **Abd-al Jalil**

Only estimates the total downtime and can’t identify bottlenecks
Unreliable for present-day projects

2000 Q $_{TBM}$
Requires detailed data-set as input
Indirect estimation of utilization rate
Not able to detect bottlenecks

2007 RME
Based on hard rock TBMs
Indirect estimation of utilization rate
Not able to detect bottlenecks
The database used for open type TBM and Single shield TBM is limited

2012 Farrokh et. al.
Incapable recreating parallel activities
Deterministic approach
Some parameters are adopted from previous models

2016 NTNU-Modified
Project-specific
Deterministic approach
Constant value assigned based on No. of tracks for several activities
Not able to detect bottlenecks

2020 DES Model (CSM2020)
Current version is only applicable for DS, SS and open machines
Incapable of directly incorporating geological parameters in the estimation
Developed based on limited database for TBM type, back-up systems and ground conditions

Objectives of the Study

Improvement of the DES model

01

The final goal is to develop a TBM utilization rate model that is

- Flexible and reliable
- Considers various site set ups
- Different tunneling activities and their relations
- Stochastic

02

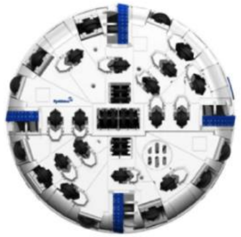
A Discrete Event Simulation Model is:

- Data-driven
- Process interaction approach

03

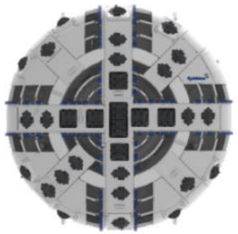
- Expanding the existing database
- Introducing new activities to the model
- Redefining their interaction based on TBM type

Open TBM

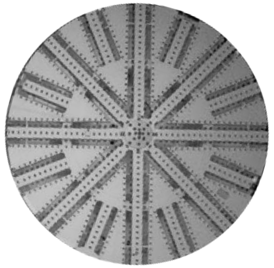


Double shield TBM

Single shield TBM



EPBMs

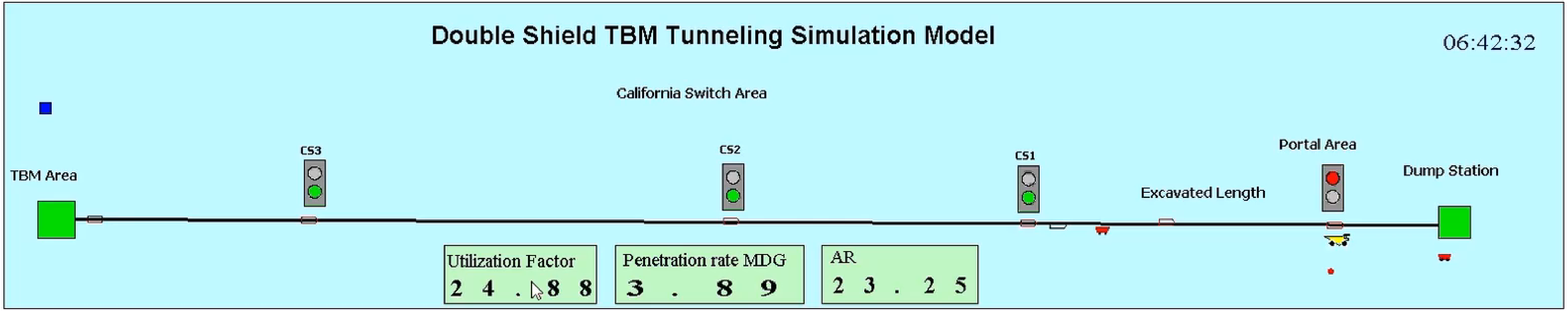


Slurry TBM

The Potential of DES Simulation in Improving the TBM Performance

Be able to account for :

- Geology
- Machine type
- Machine size
- Site Set Up
- Alignment (grade, curves. . . .)

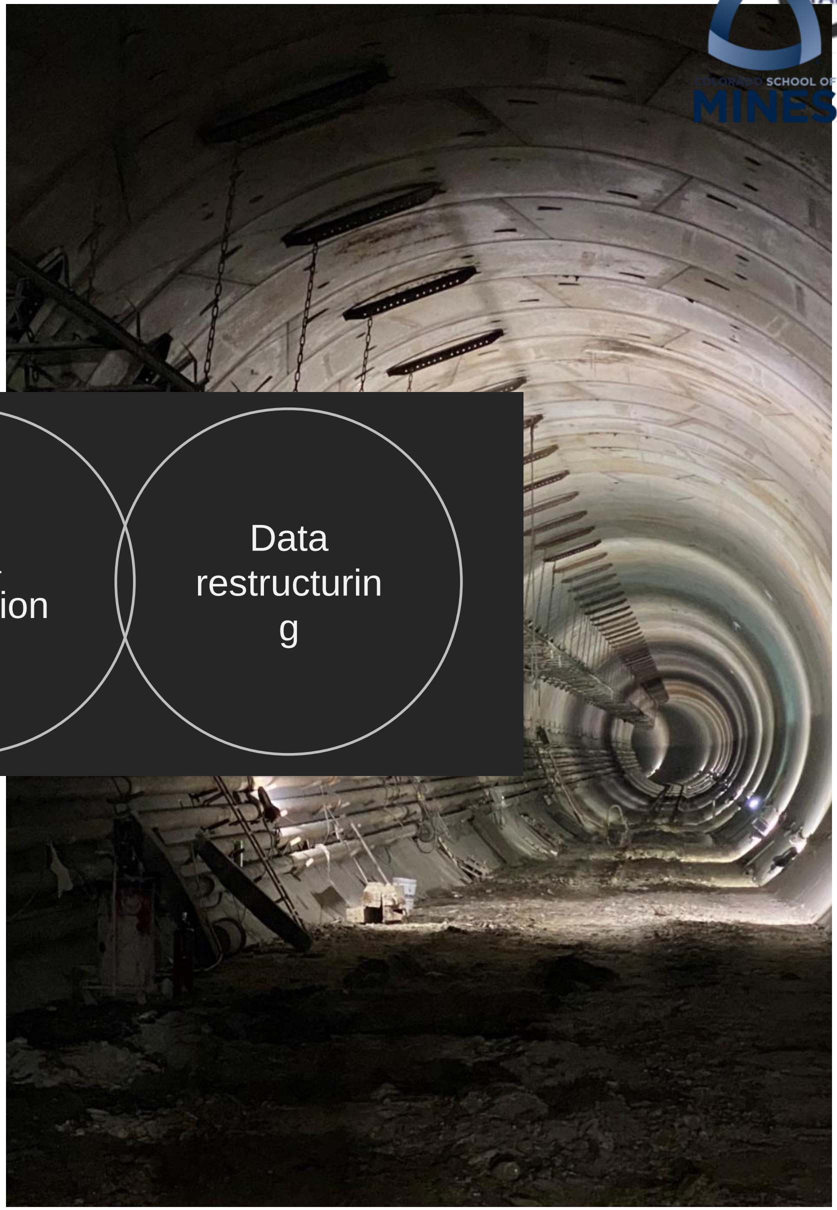


Case studies

Input data preparation

Data preparation Process

- Data Collection
- Data cleaning
- Data integration
- Data restructuring



Data Collection

Binni Tunneling software

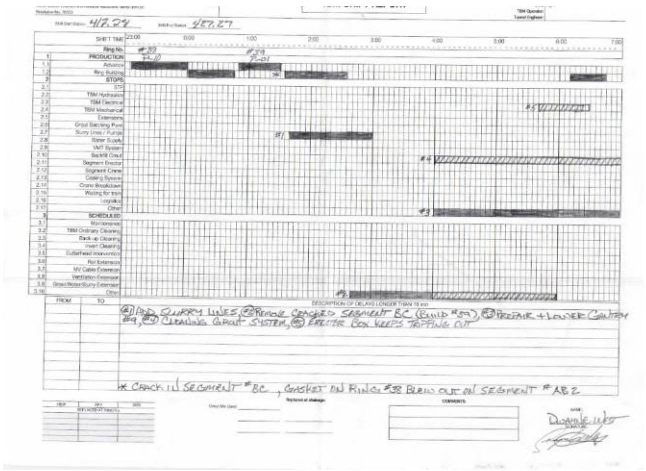
Advantageous

- Exchange data within different platforms
- Real-time collaboration between team members
- Real-time access to data helps in decision making
- Tracking consumables and activities efficiently
- Simpler customized reports

Disadvantageous

- No built-in platform for data analysis
- Inconsistent data acquisition and reporting between different projects
- Specific reports need to be produced manually
- The primary setting of the software requires expert knowledge
- No template for report preparation

Manual

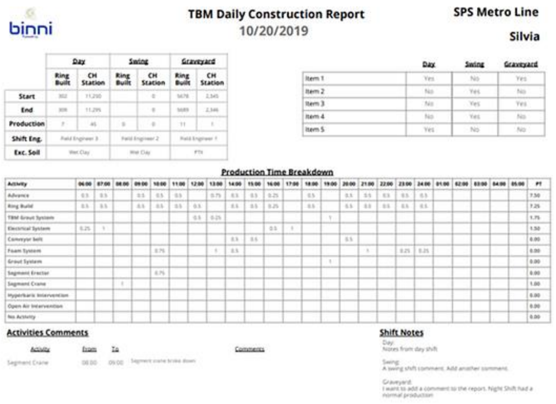


Advantageous

- Shorter learning curve phase
- No software/hardware
- Lots of experience in manual data recording

Disadvantageous

- No framework, not consistent
- Possibility for huge errors
- Delayed access to data
- Time-consuming



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Data restructuring

The data structure needs to match the model structure

DATABASE: On the basis of day

DES Model : On the basis of stroke (excavation cycle)

- Time distributions
  - Hour per day
  - Hour per stroke
- Frequency of occurrence
  - Overestimation or underestimation

mmddyy	chainage_from	chainage_to	weekday	advance	cum_advance	segments_installed	cum_segments_installed	strokes_no	net_boring	lowering_pipes	ring_building	cracks_on_segments	probe_drill
2019-04-18	17.10	18.44	5	1.34	18.44	0	4		4.50		0.0	0	0
2019-04-19	18.44	19.02	6	0.58	19.02	1	5		0.75		6.3	5	0
2019-04-20	19.02	19.82	7	0.80	19.82	1	6		2.83		2.7	0	0
2019-04-21	19.82	19.82	1	0.00	19.82	0	6		0.00		0.0	0	0

This analysis allows to prepare more accurate input data for the model:

- Time distributions
  - Hour per occurrence
- Time between breakdowns

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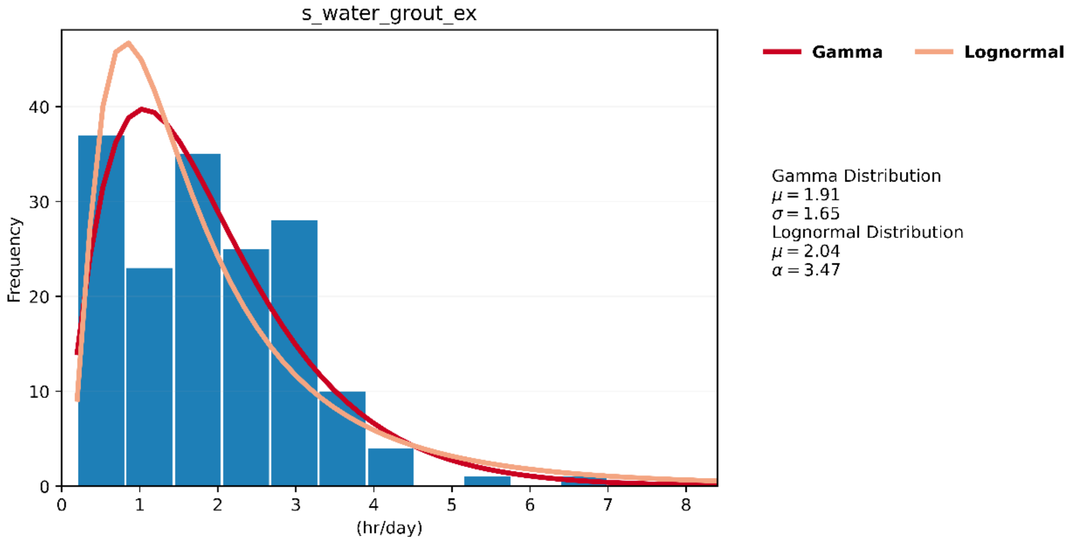
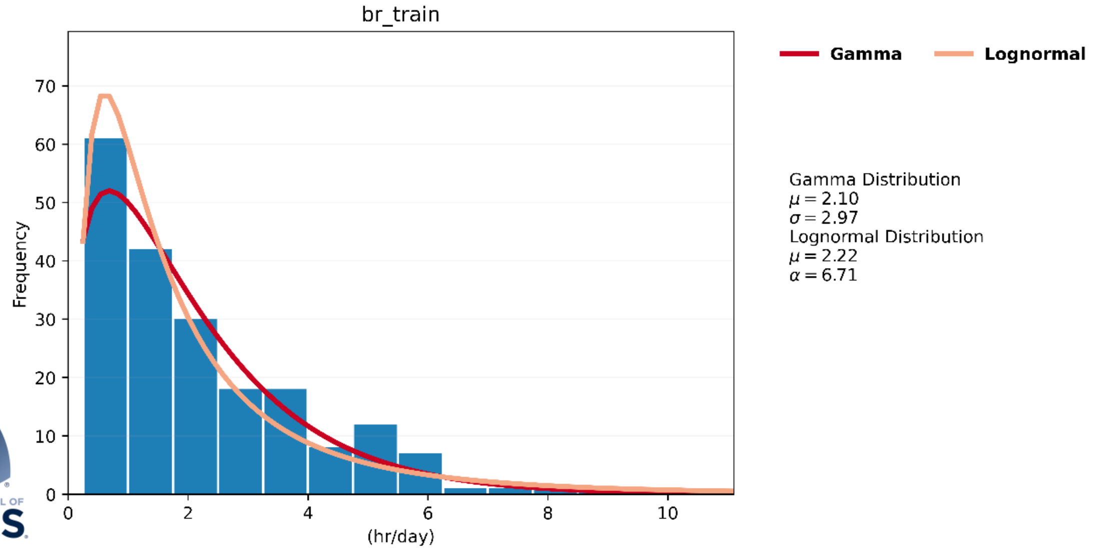
Input Data-Duration of Activity

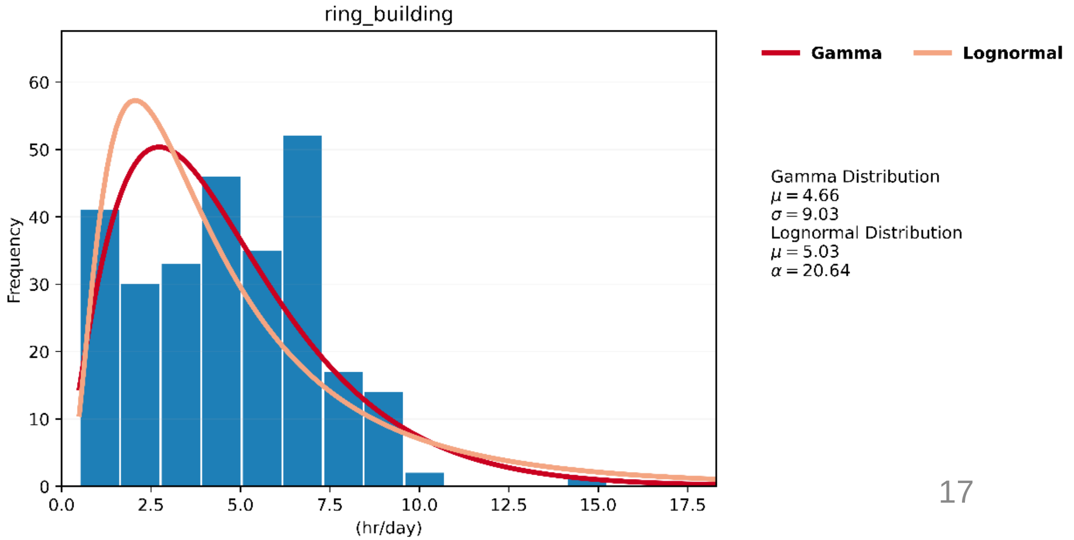
Time distributions

The raw data (activity times) needs to be defined and processed. The parameters should be able to represent the system behavior in the model.

The data might need to be treated differently depending on the model set-up.







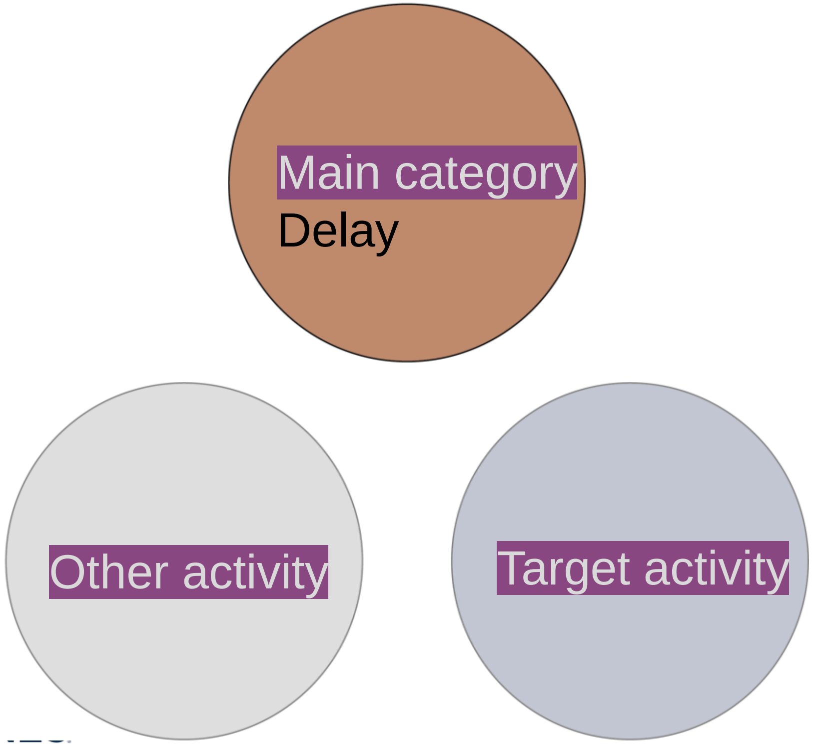
Frequency of Occurrence

Types

- Each cycle, Such as “Boring”
- Chance, Such as “Breakdown of equipment”
  - Probability of occurrence
  - Time between failure
- Schedule, Such as “Cutterhead intervention”
- Distance, Such as “Utility extension”

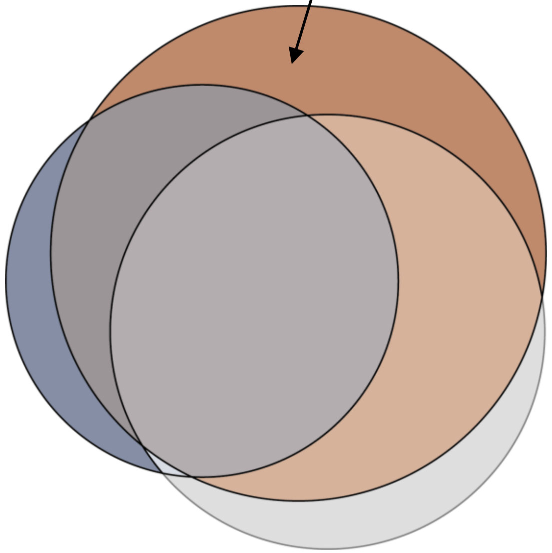
Probability of Occurrence for overlapping activities

- The ‘target activity’ and ‘other activity’ can happen concurrently.
- The main category contains the delays causing by one of ‘target activity’ or ‘other activity’

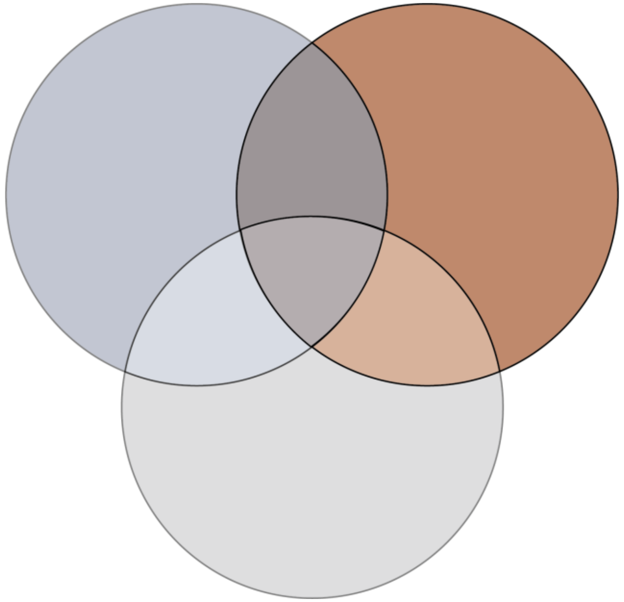


- When the categories are overlapped, the result should look like this:

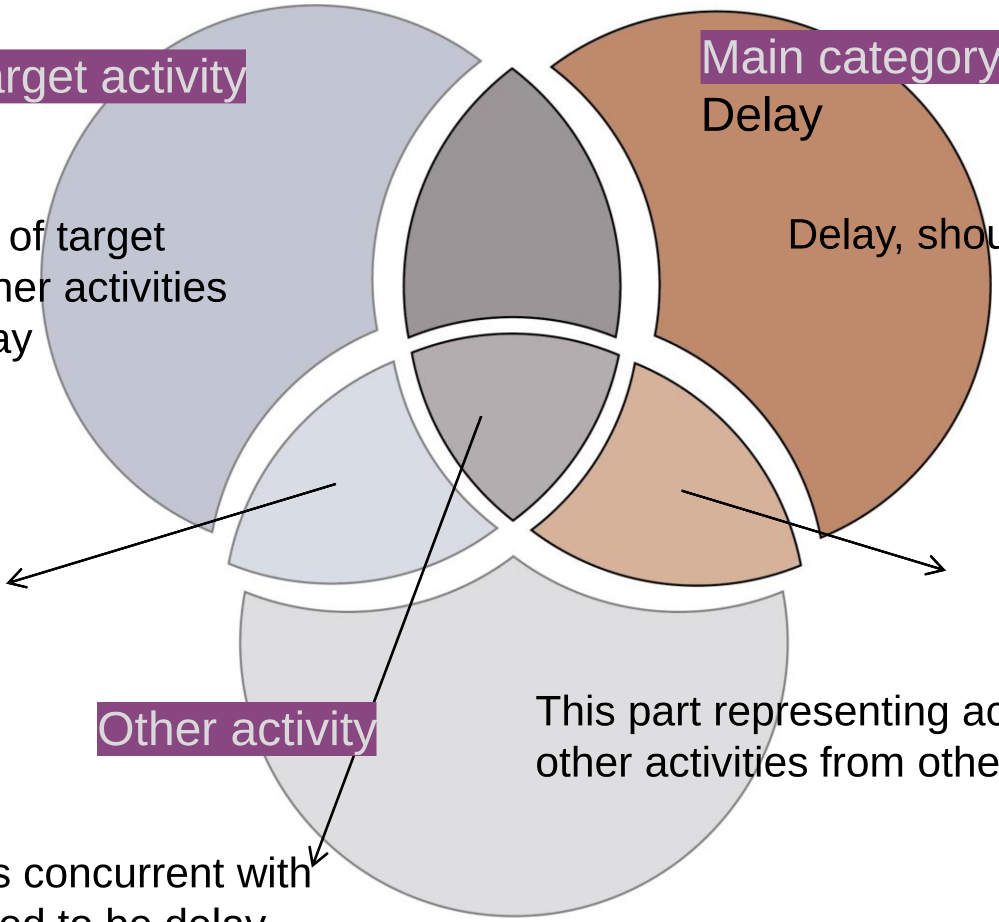
This part technically should be zero. But it is not probably due to reporting errors.



- But for simplicity and clarity assuming the following case:

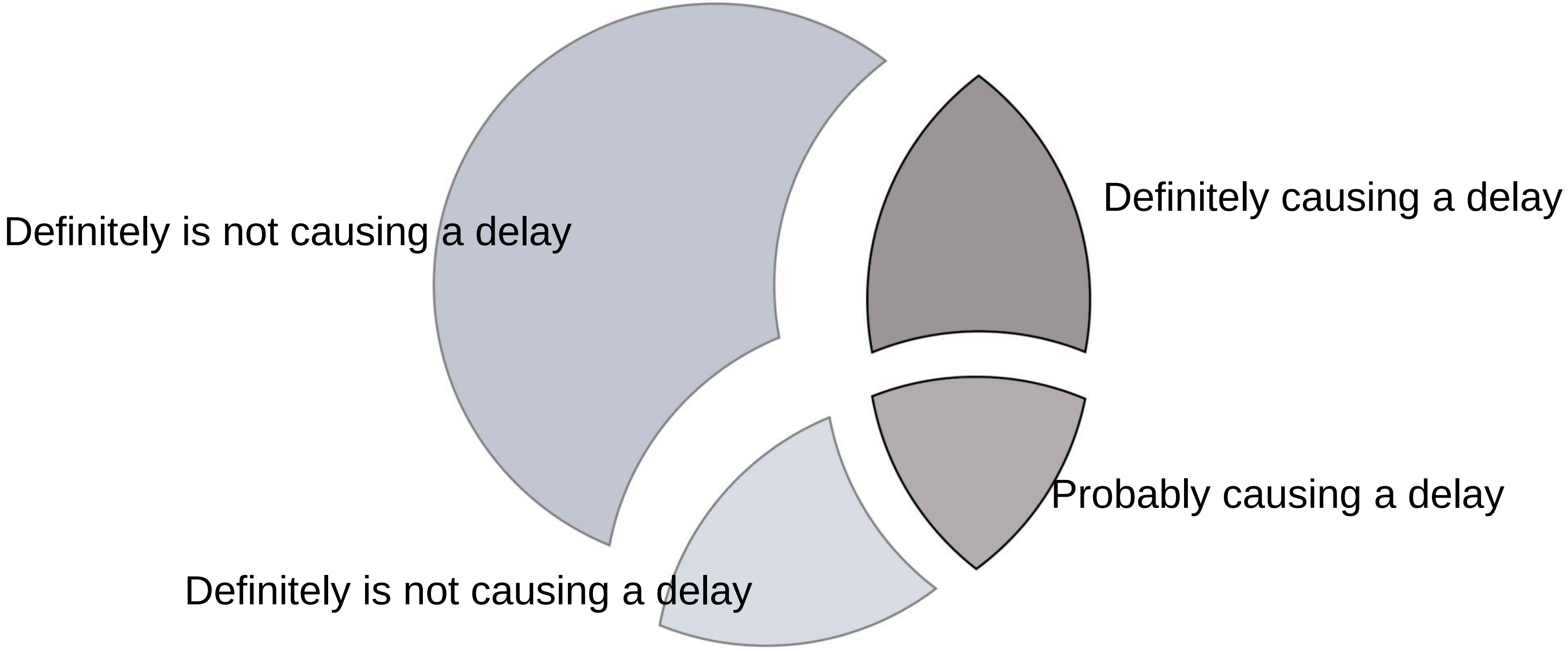


Probability of Occurrence for overlapping activities



Probability of Occurrence for overlapping activities

Each activity can be divided into three groups



Data Structure

Main Categories

- Advance (Boring)
- Ring Build
- Maintenance
- Breakdowns And Other
- Support
- Booster Installation
- Rail Switch Installation
- Cutterhead Intervention
- No Activity

Maintenance → Subcategory

- Backfill Grouting System
- Conveyor Belt (TBM and Tunnel)
- Foam System
- TBM and Backup
- Segment installation equipment
- Tunnel Mucking / Track Repair
- Other (not listed above)

Breakdowns And Other → Subcategory

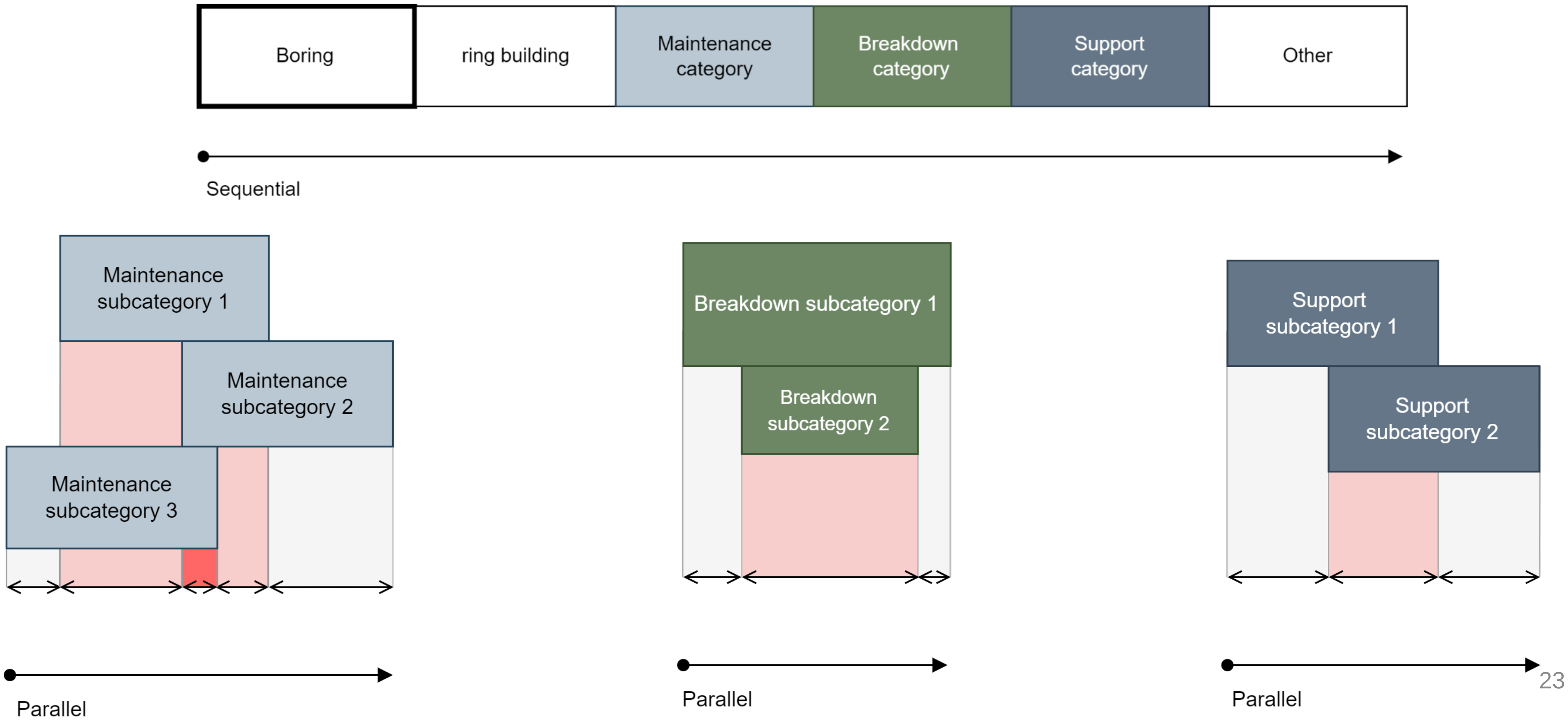
- TBM and Backup failure
- Utility failure
- Remedial Grouting
- Segment Failure
- Train Delay
- Other (not listed above)

Support → Subcategory

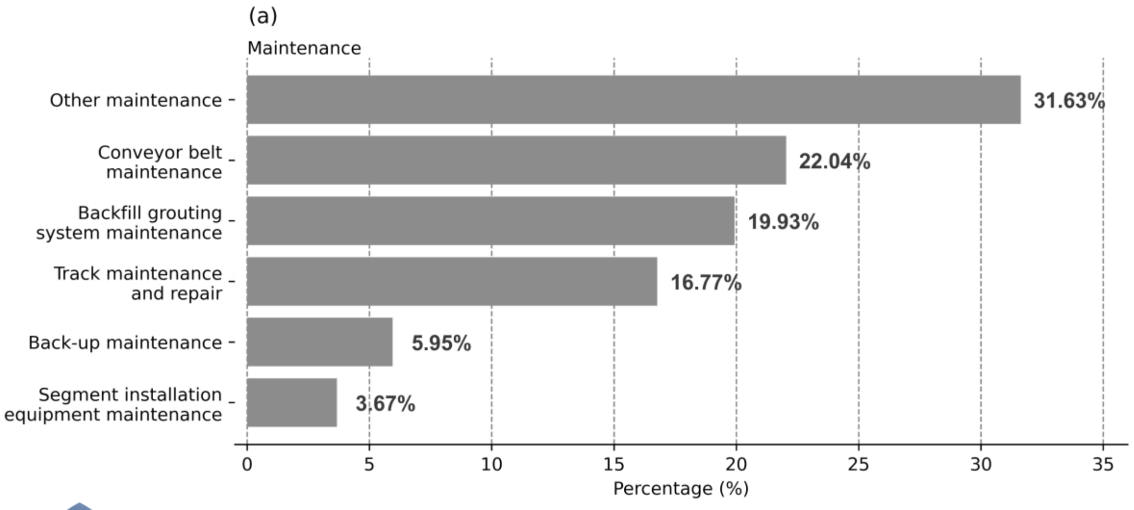
- Consumable Supply
- Guidance System (VMT)
- Safety Meeting
- Logistics
- Utility installation
- Other (not listed above)

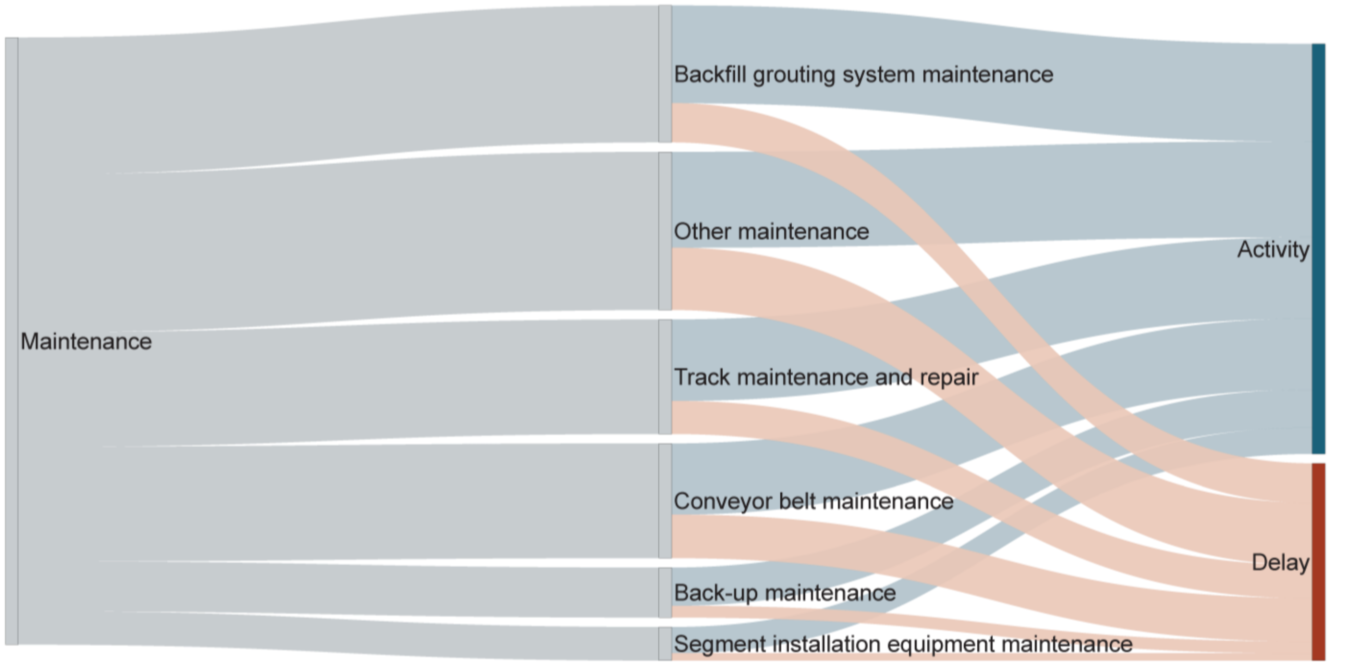
Data Structure

Recorded times in TBM Operation Shift Report
The recorded times can be considered as activity times

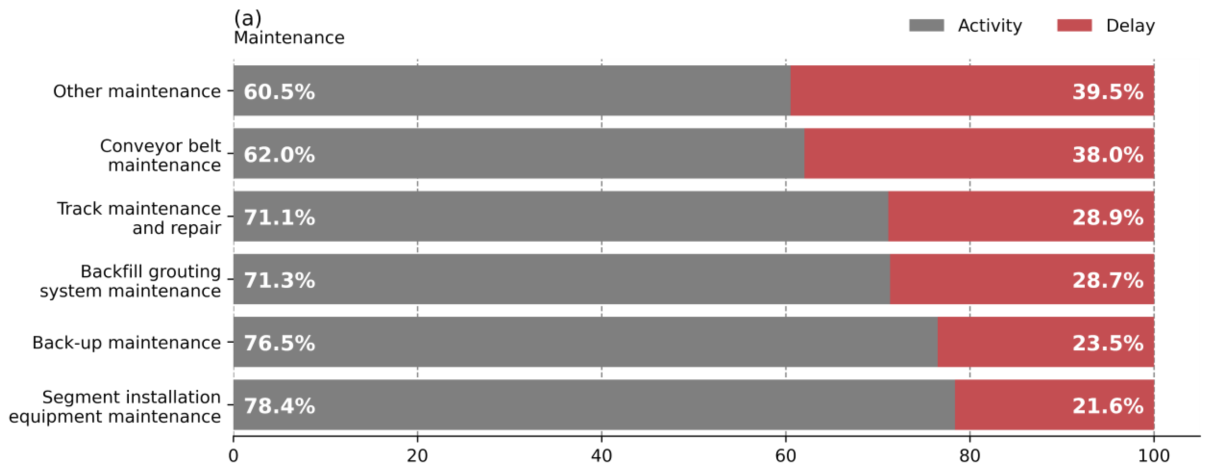


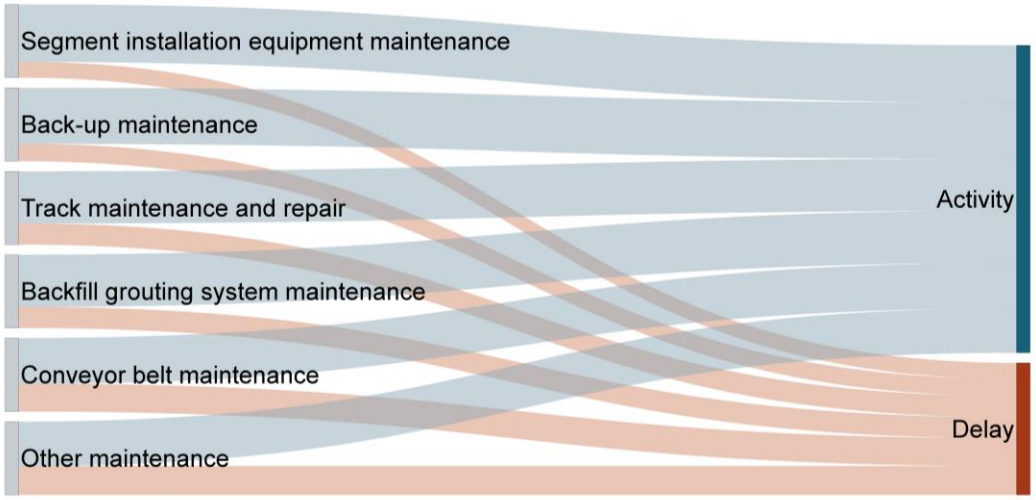
Maintenance and subcategories

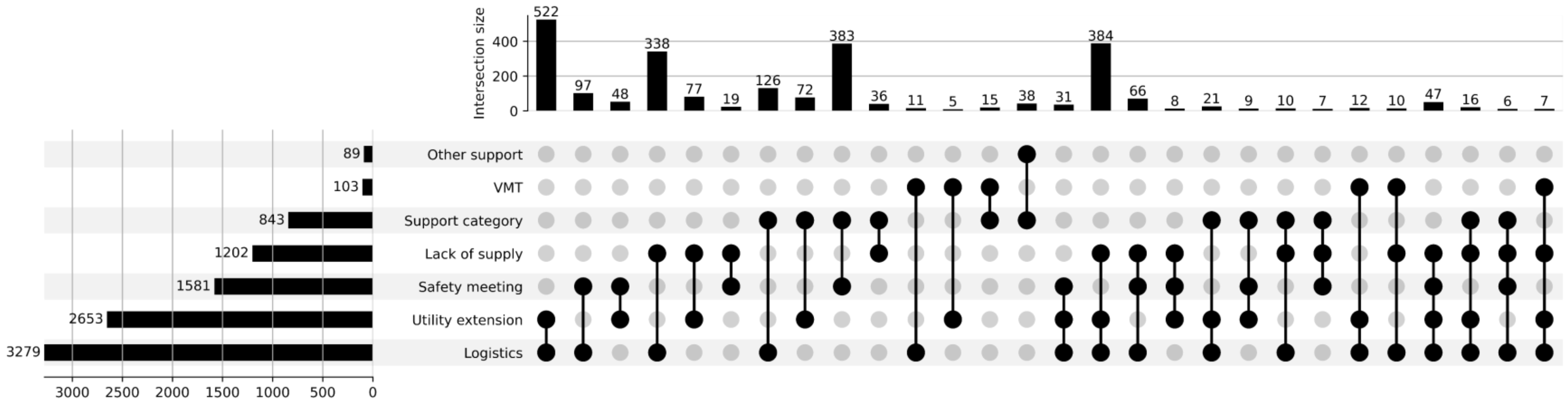




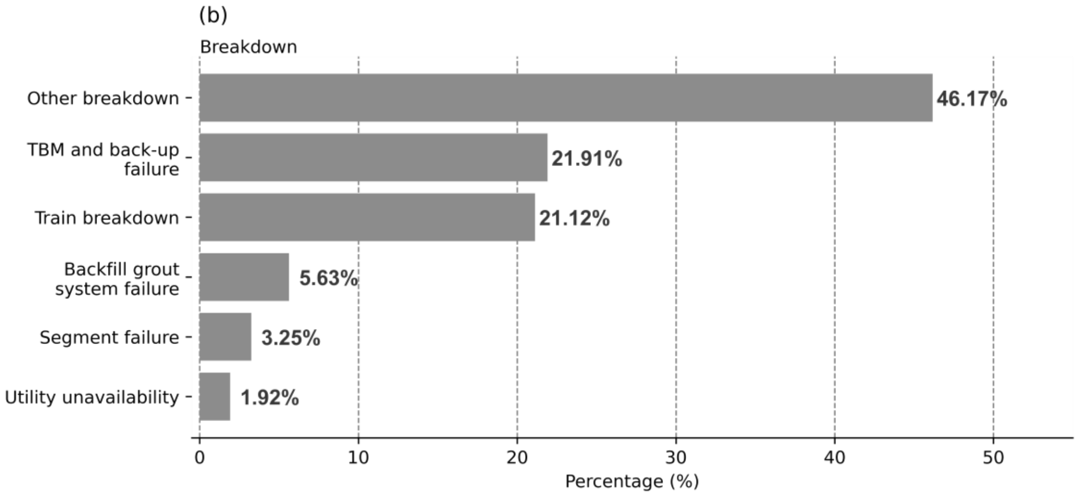
Maintenance and subcategories

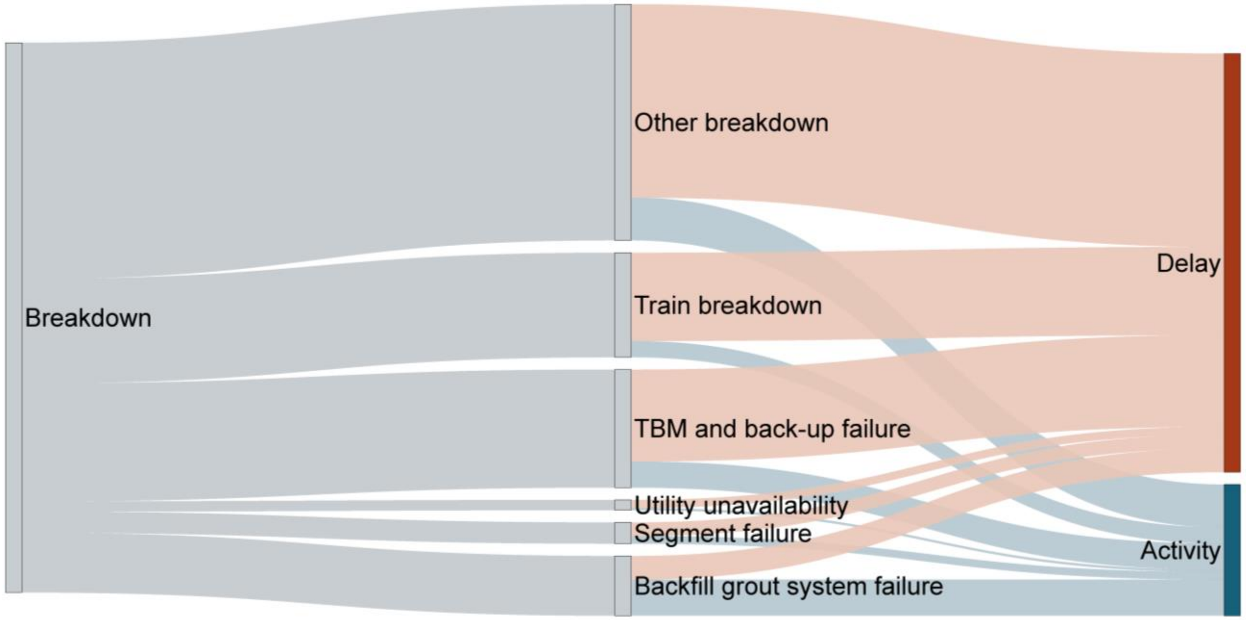




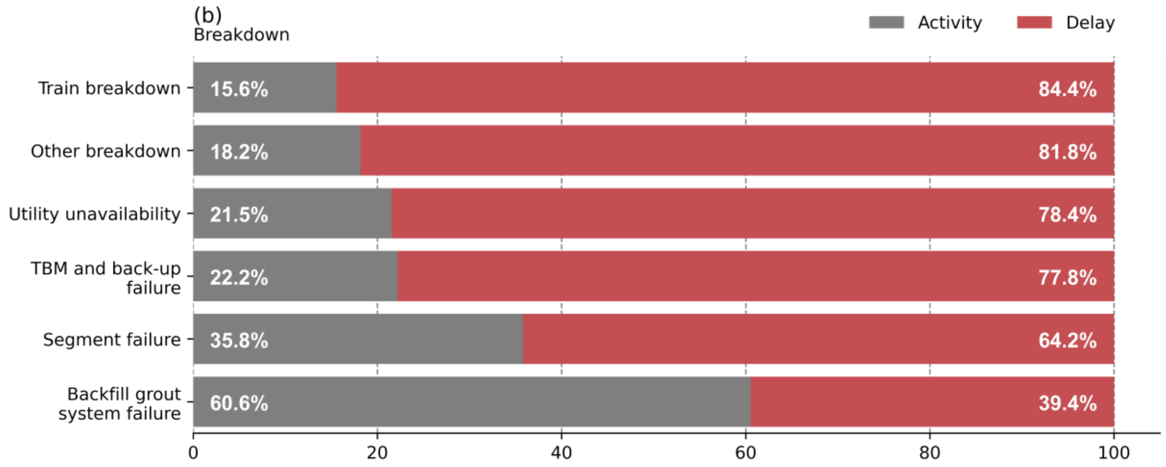


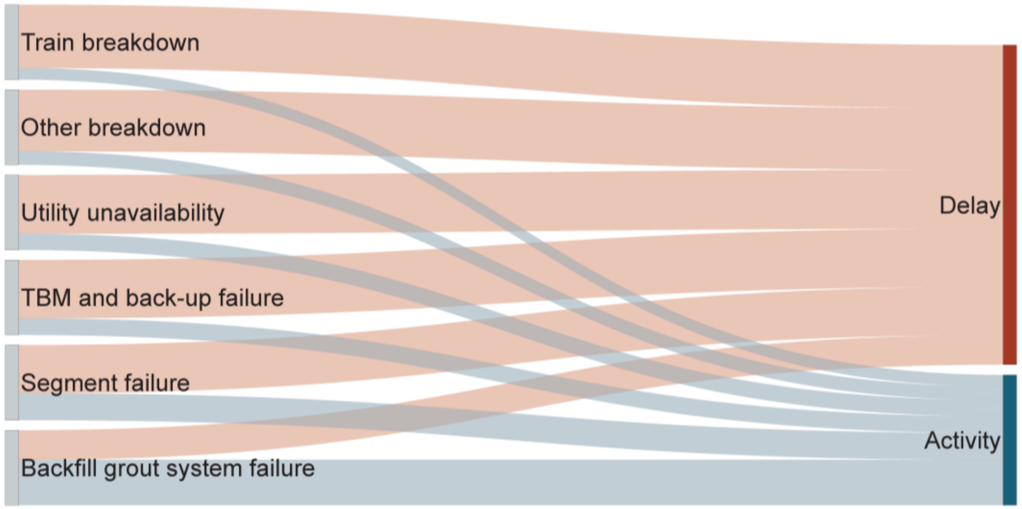
Breakdown and subcategories

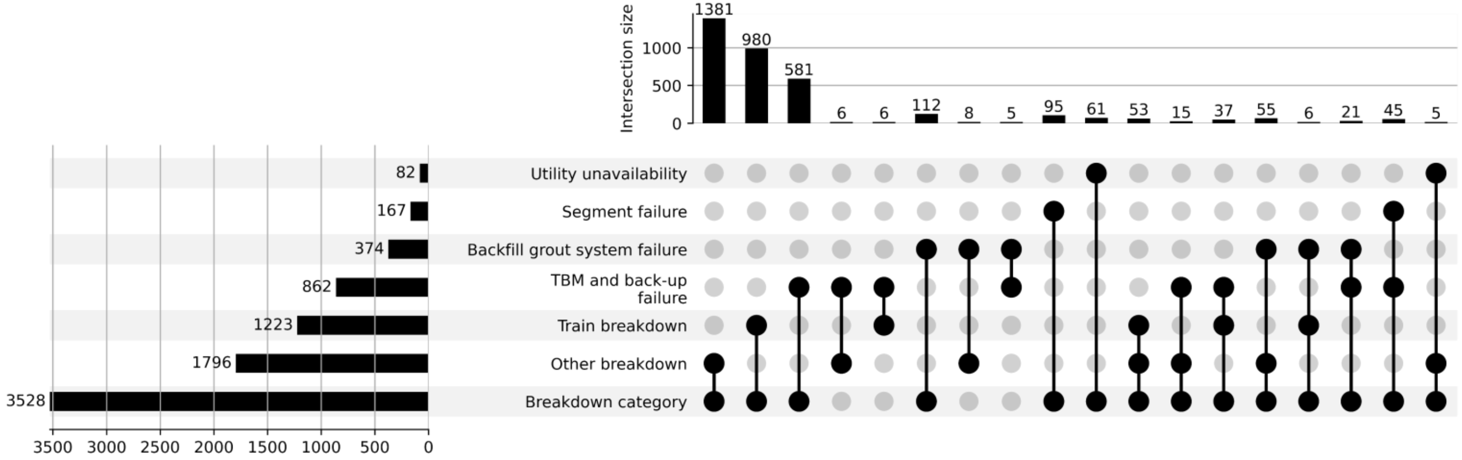




Breakdown and subcategories

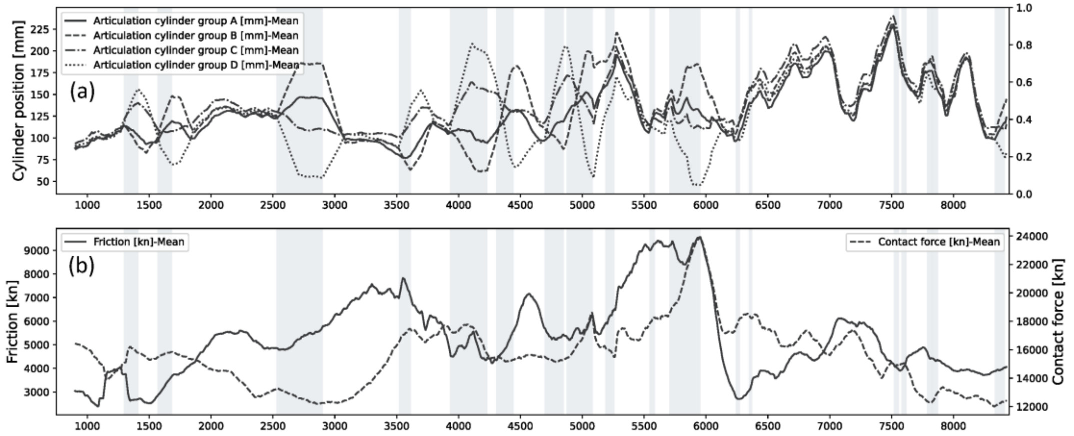


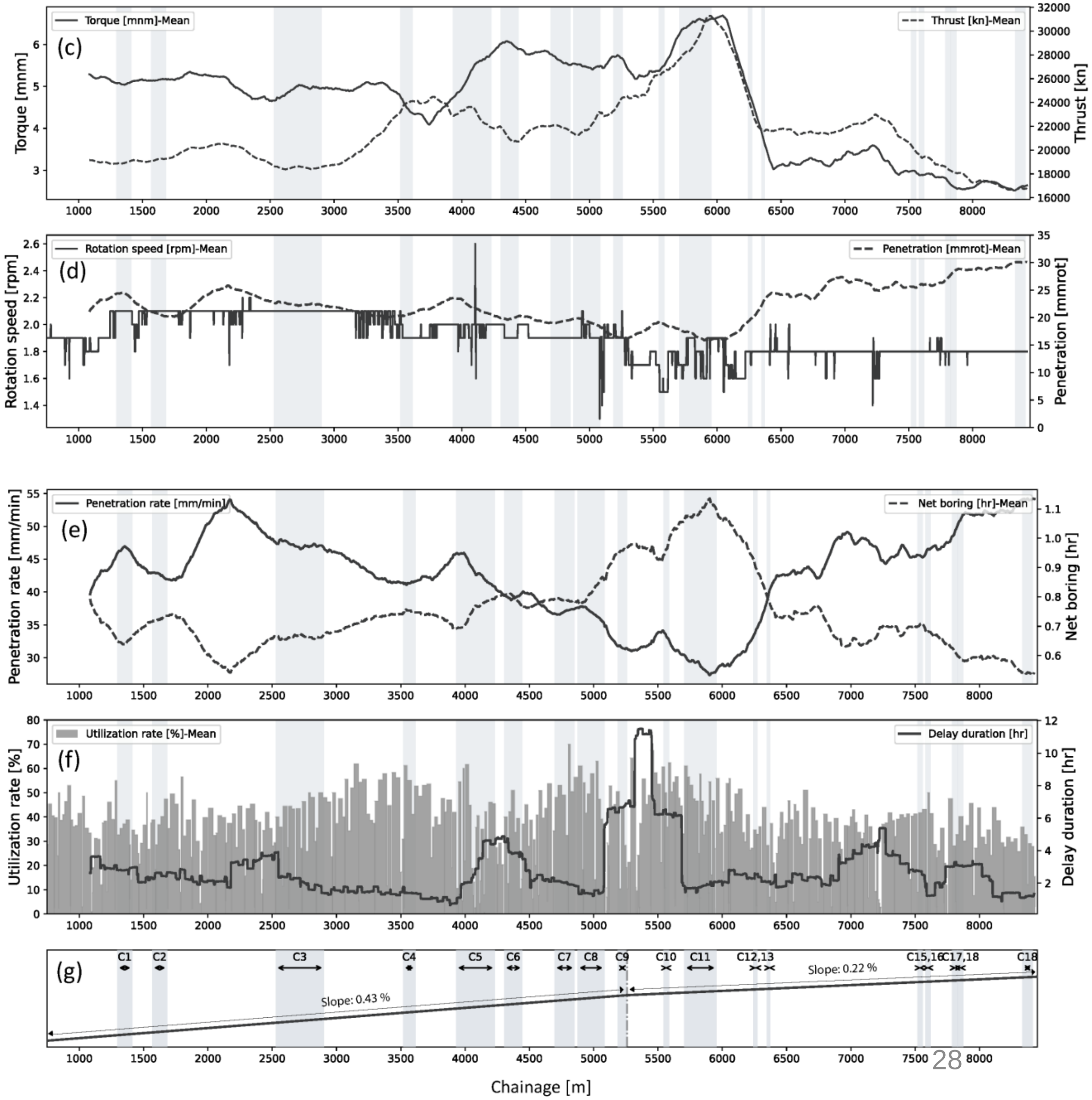




Impact of curves on TBM Performance

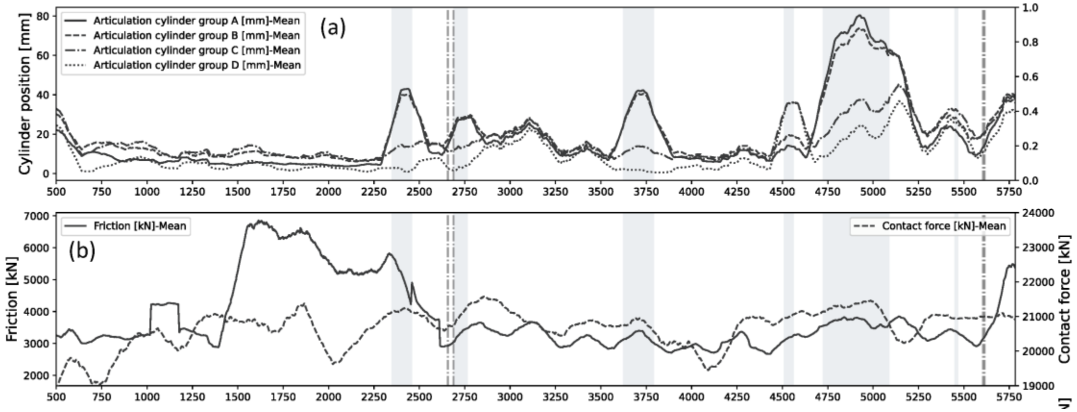
Project 1

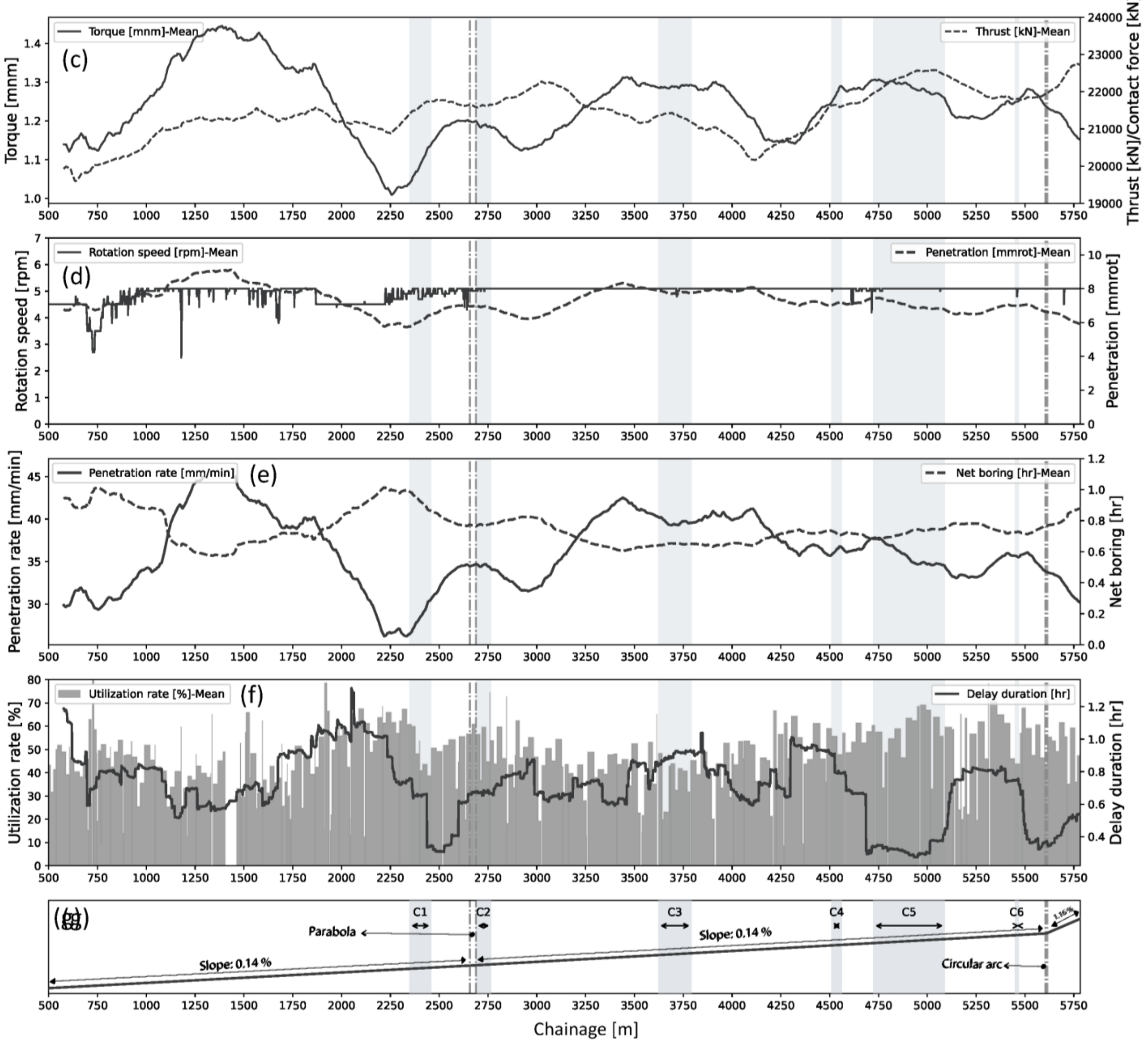




Impact of curves on TBM Performance

Project 2

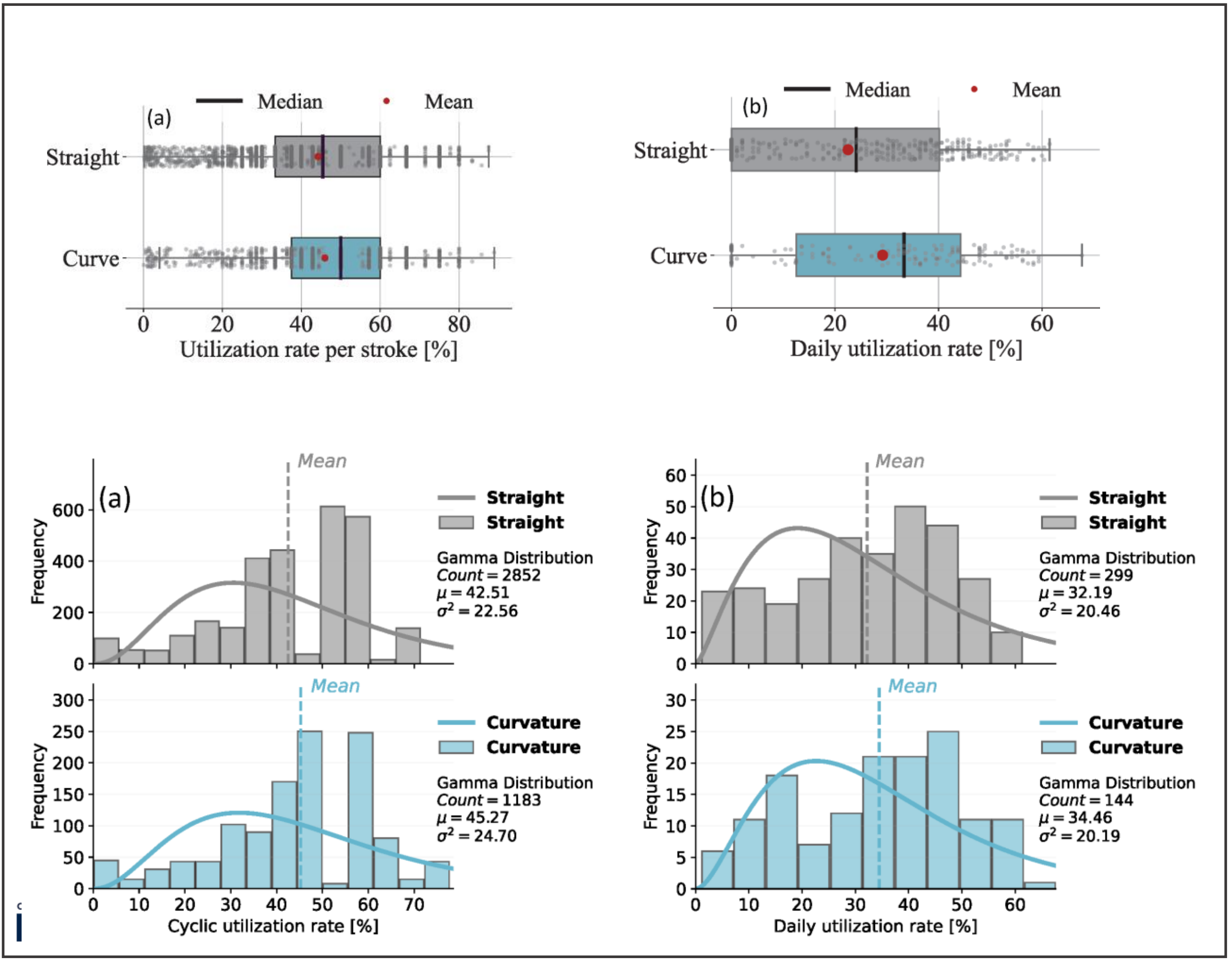




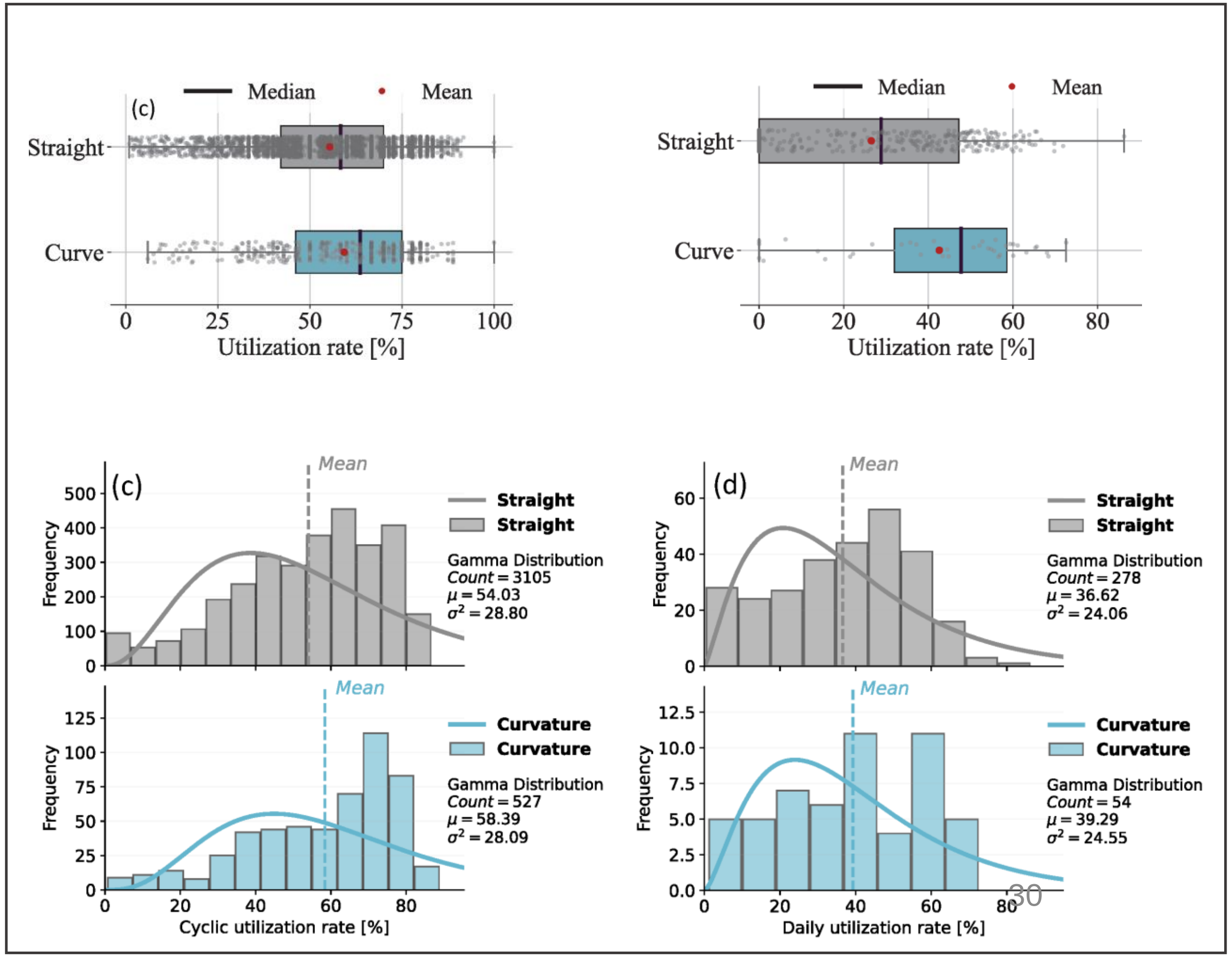
Impact of curves on TBM Performance

The utilization rate

Project 1



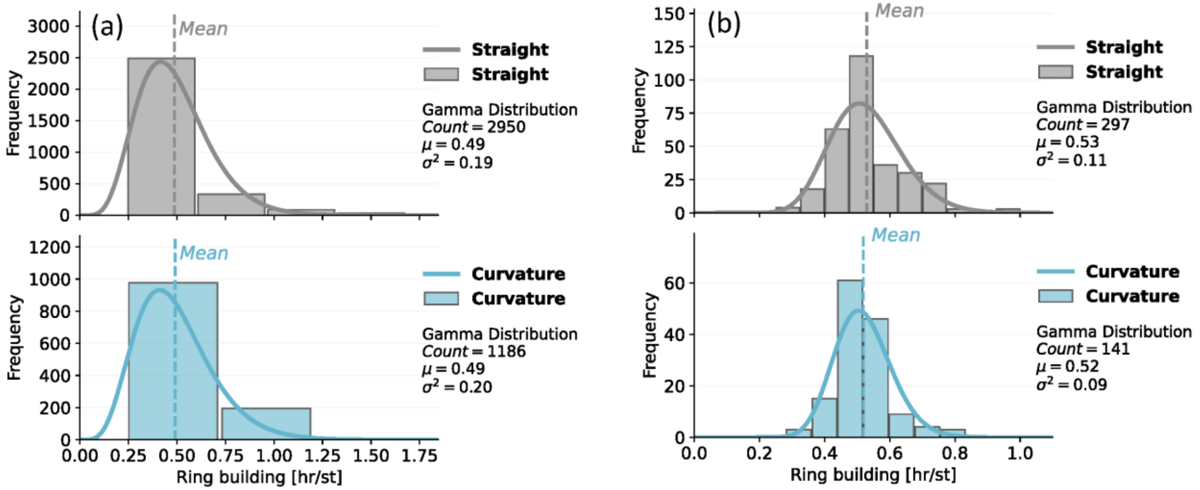
Project 2



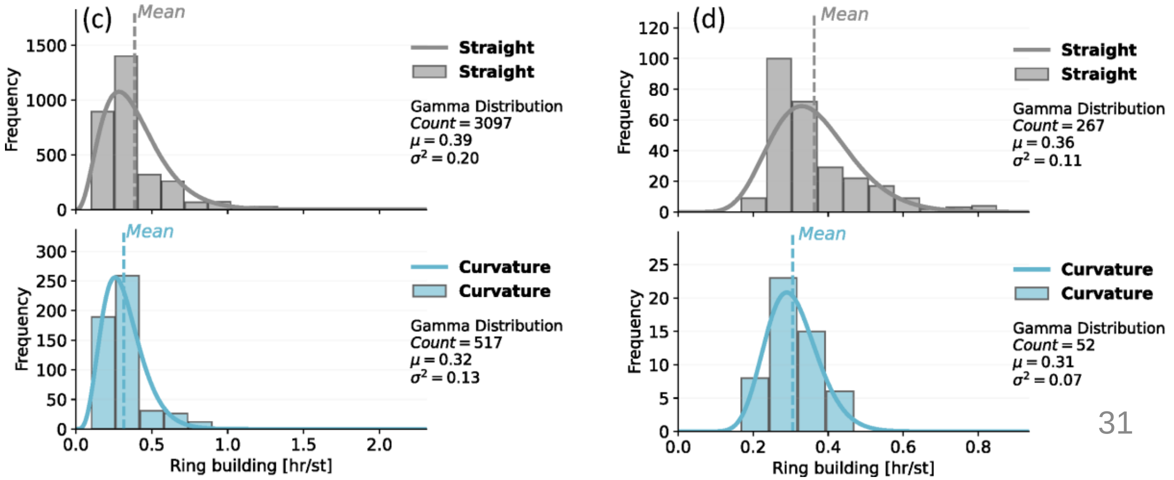
Impact of curves on TBM Performance

Ring building

Project 1

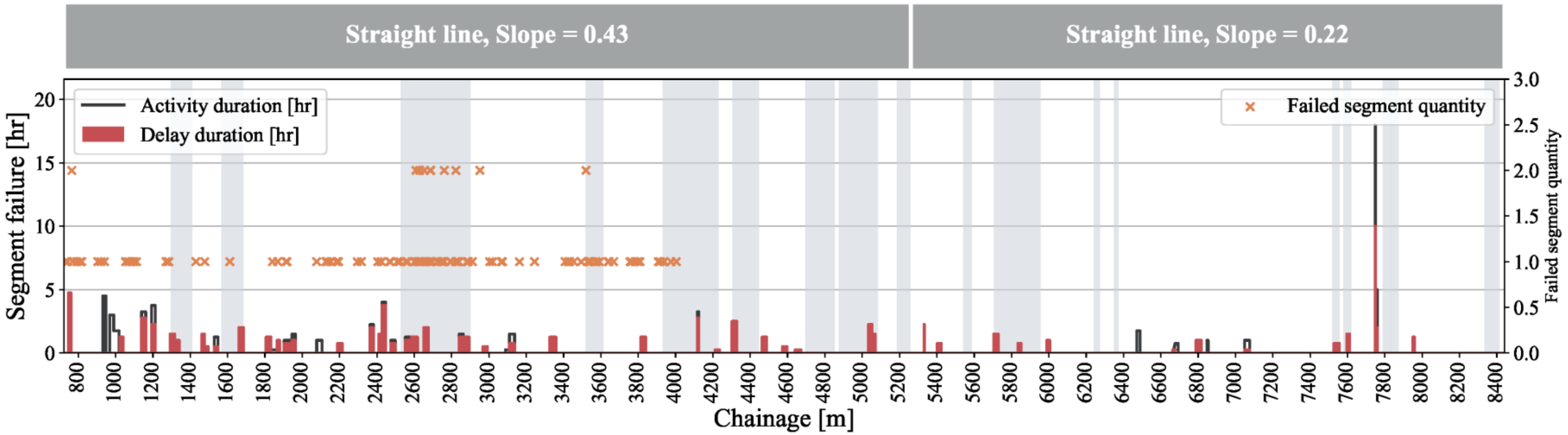


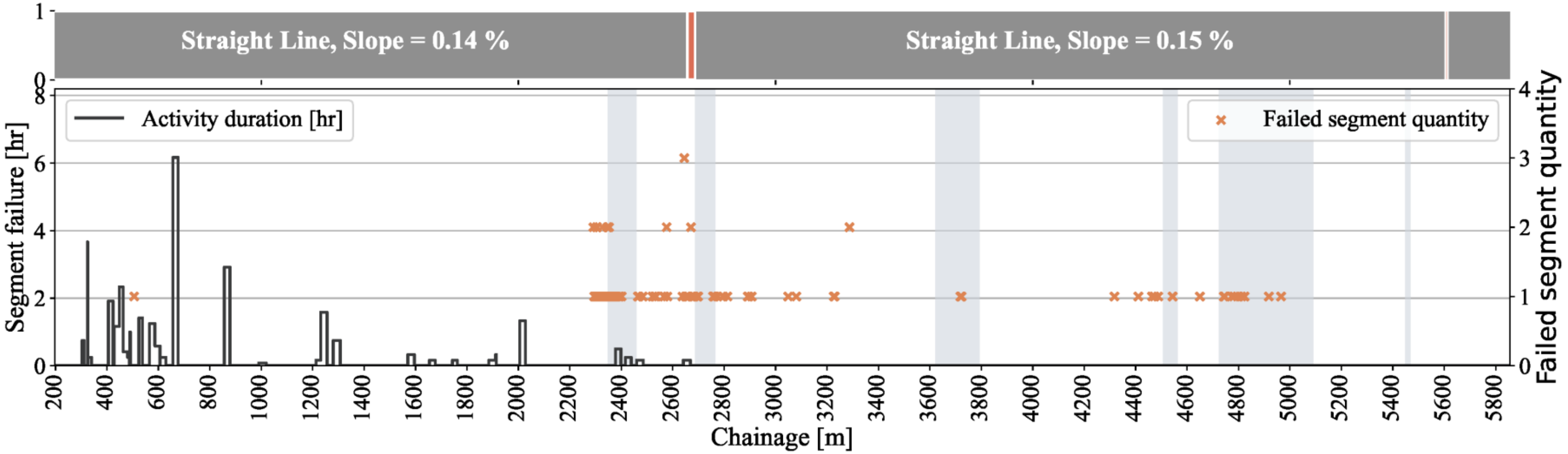
Project 2



Impact of curves on TBM Performance

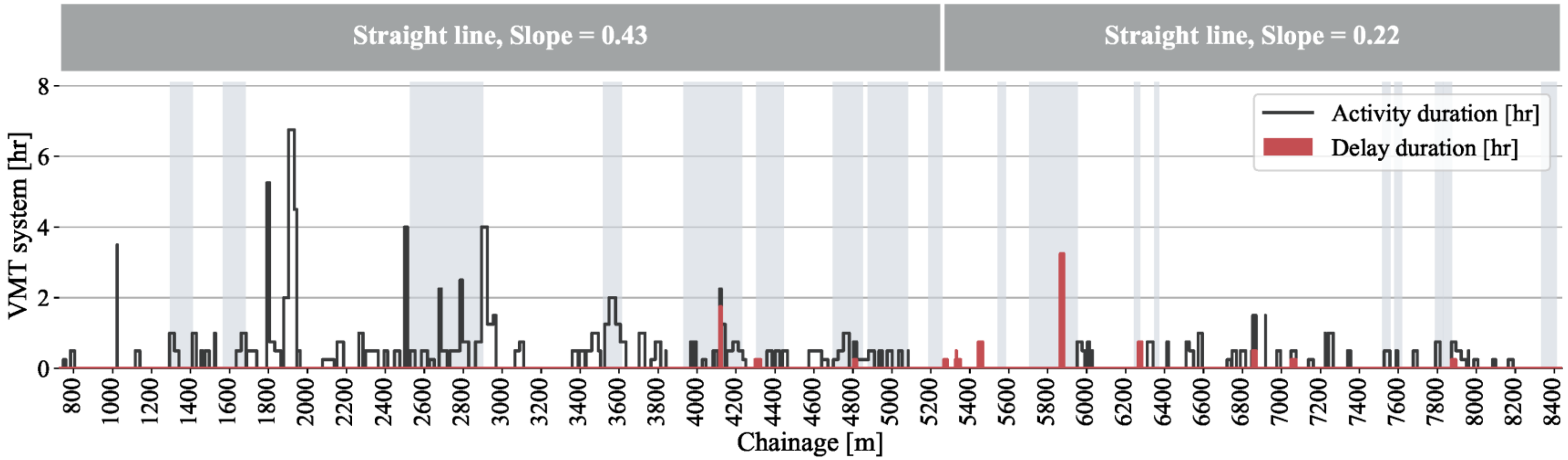
Segment failure

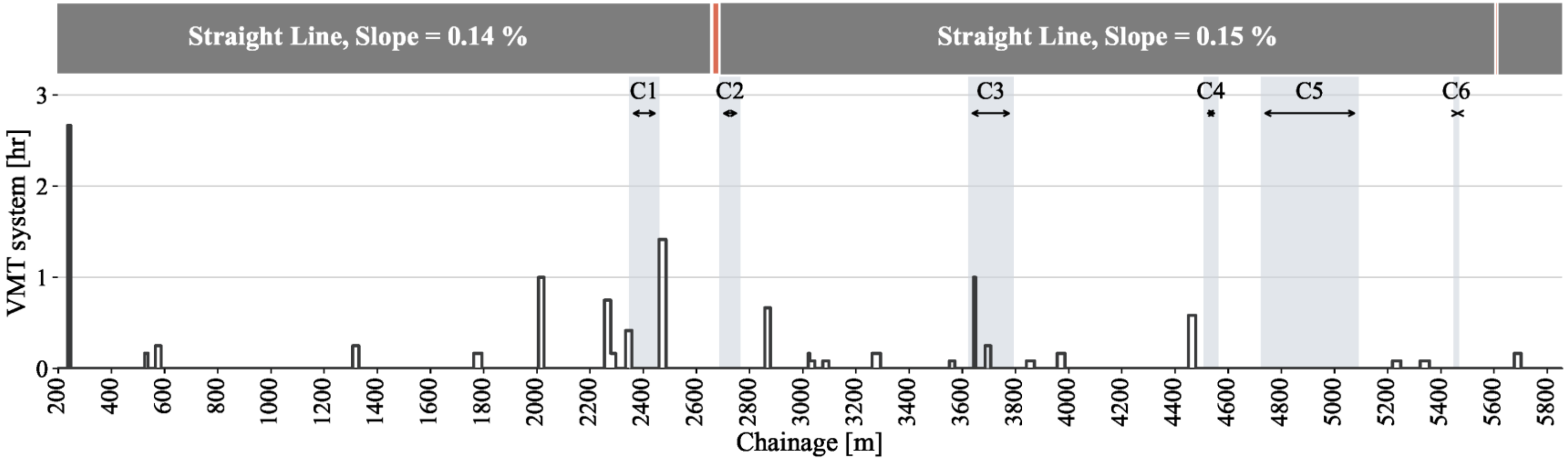




Impact of curves on TBM Performance

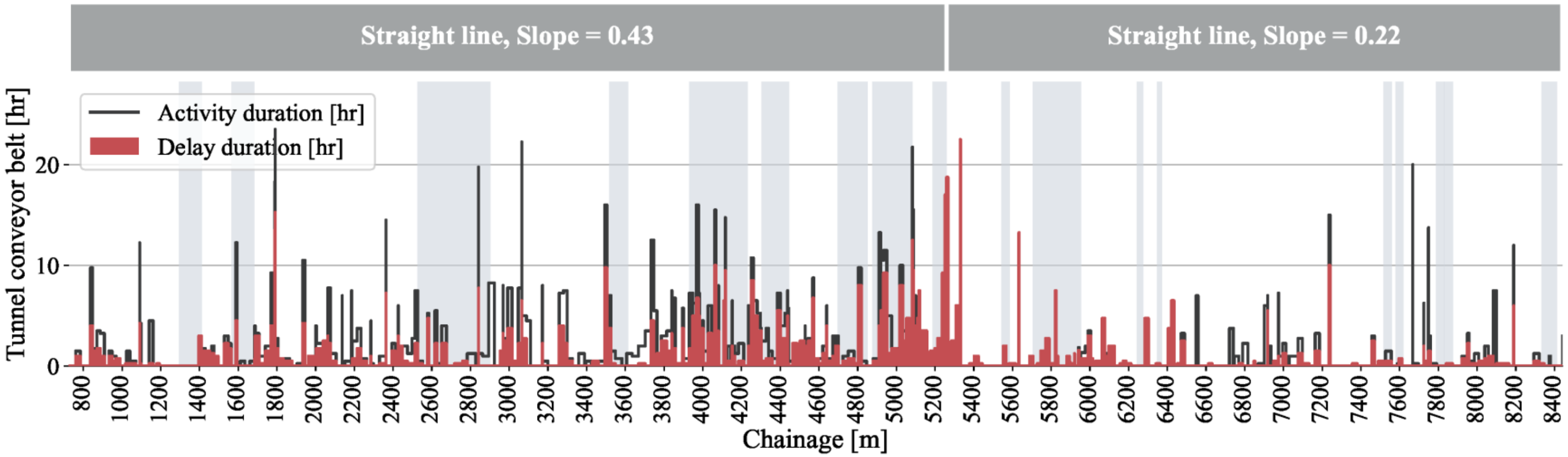
Surveying

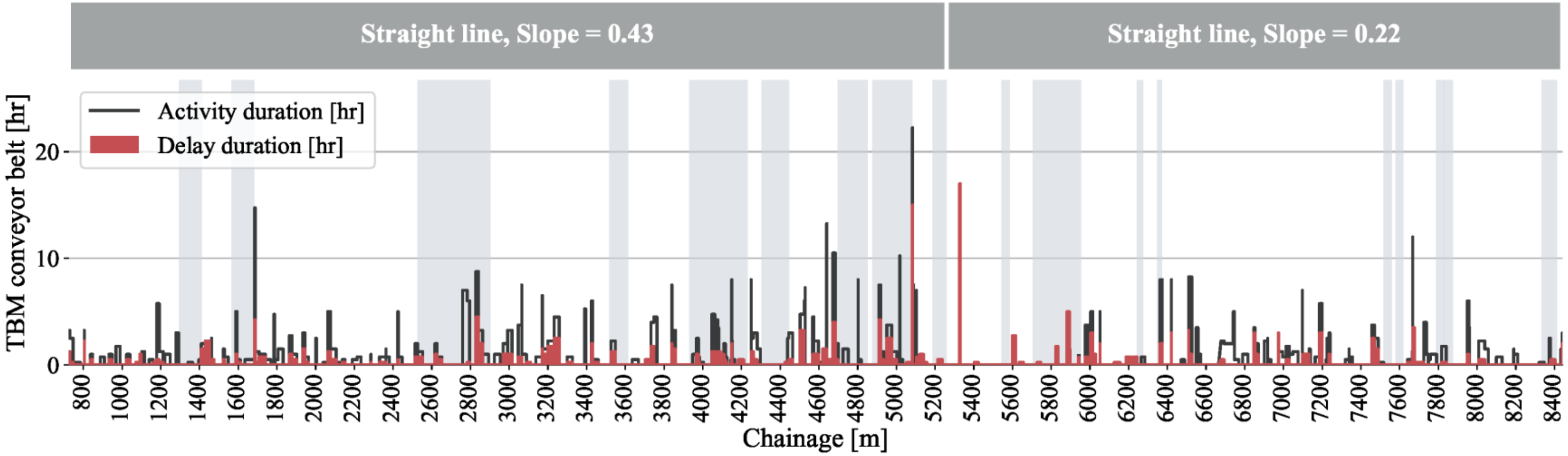




Impact of curves on TBM Performance

Conveyor belt





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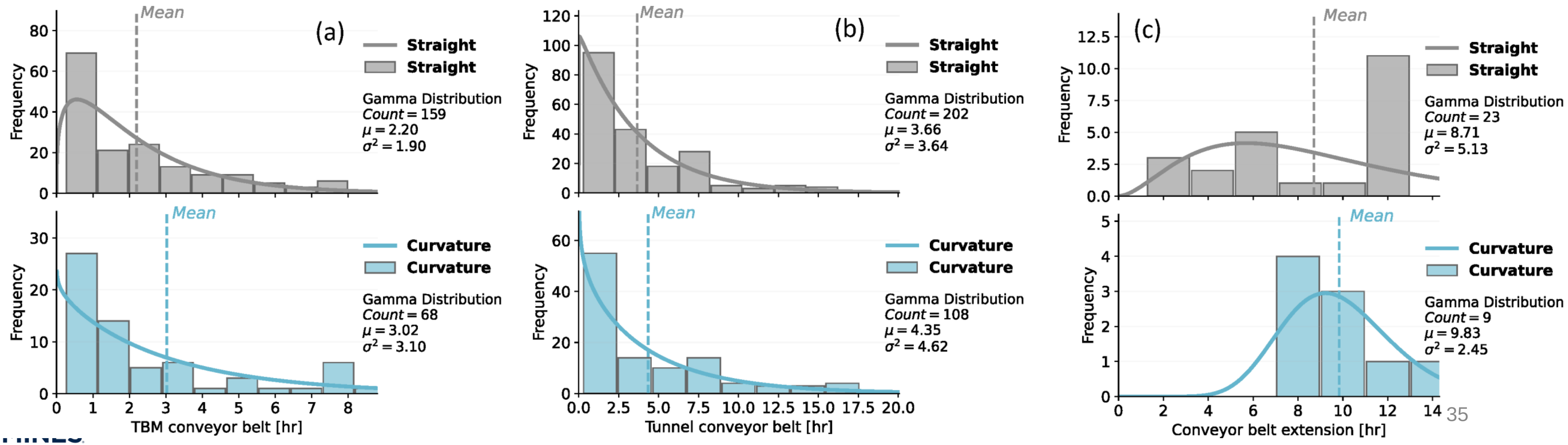
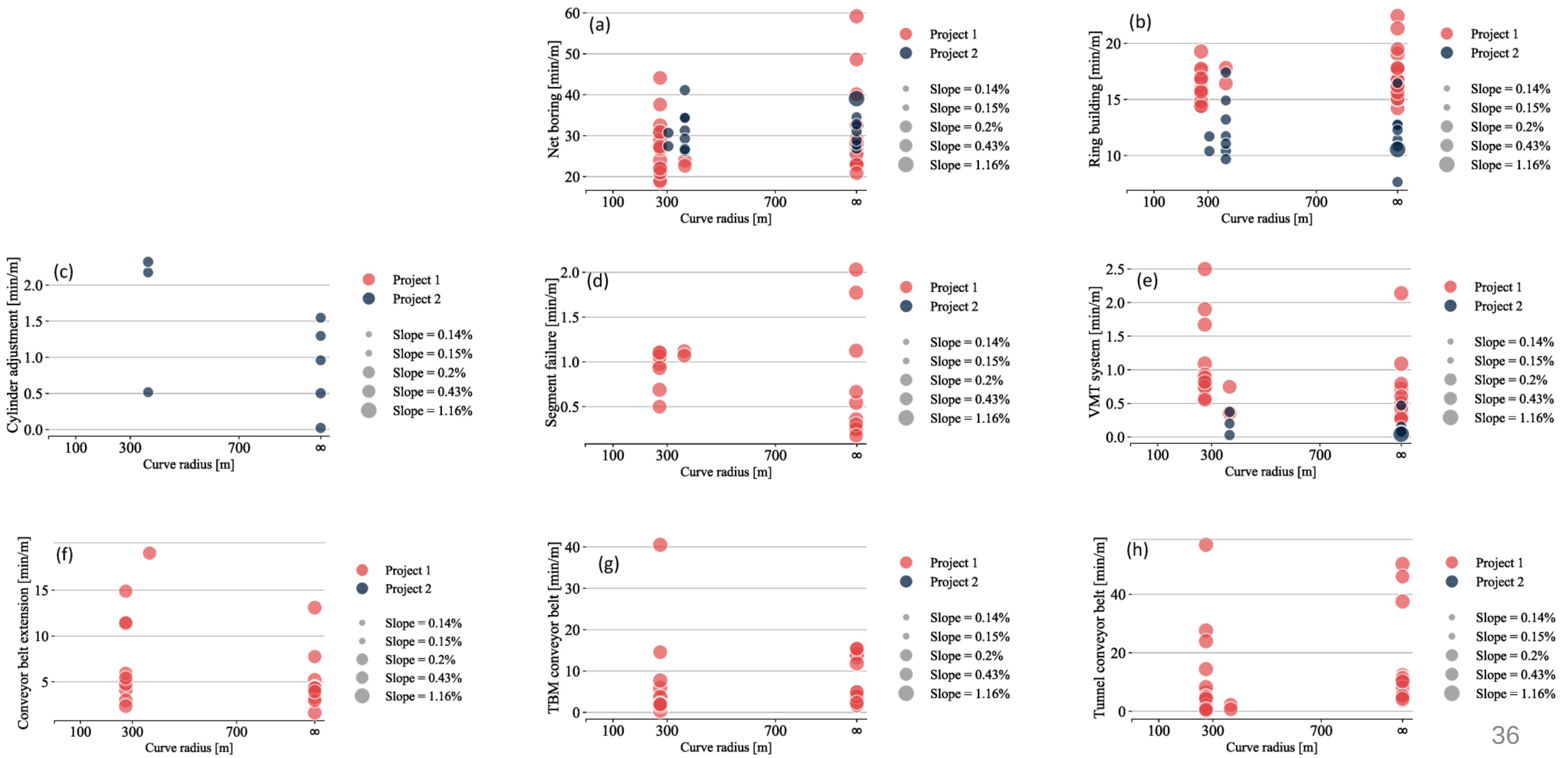
Impact of curves on TBM Performance

Conveyor belt



Impact of curves on TBM Performance

Cumulative activity duration vs. Curvature radius



DES Model

DES Model for estimation of utilization rate

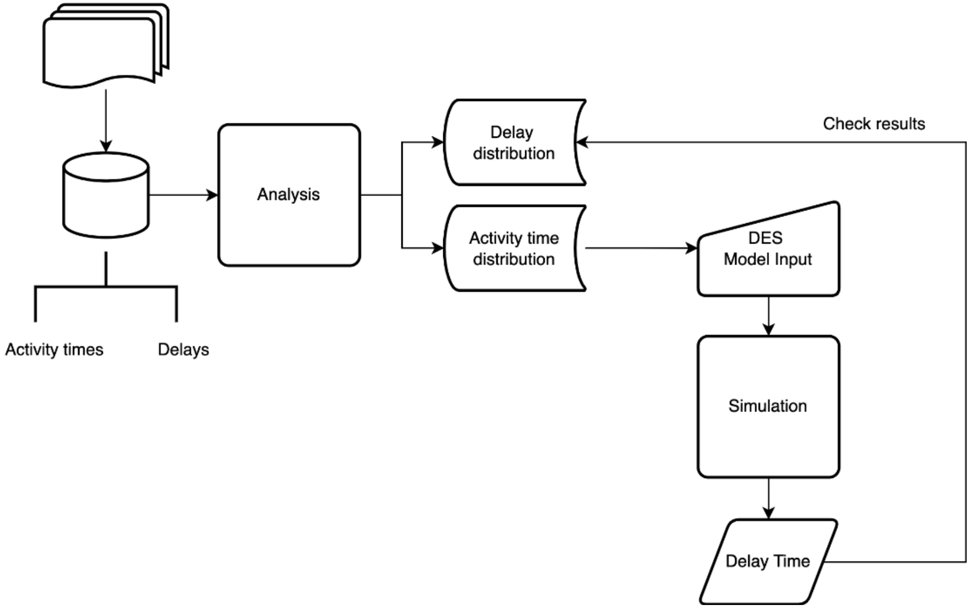
The final goal is to develop a TBM utilization rate model that is

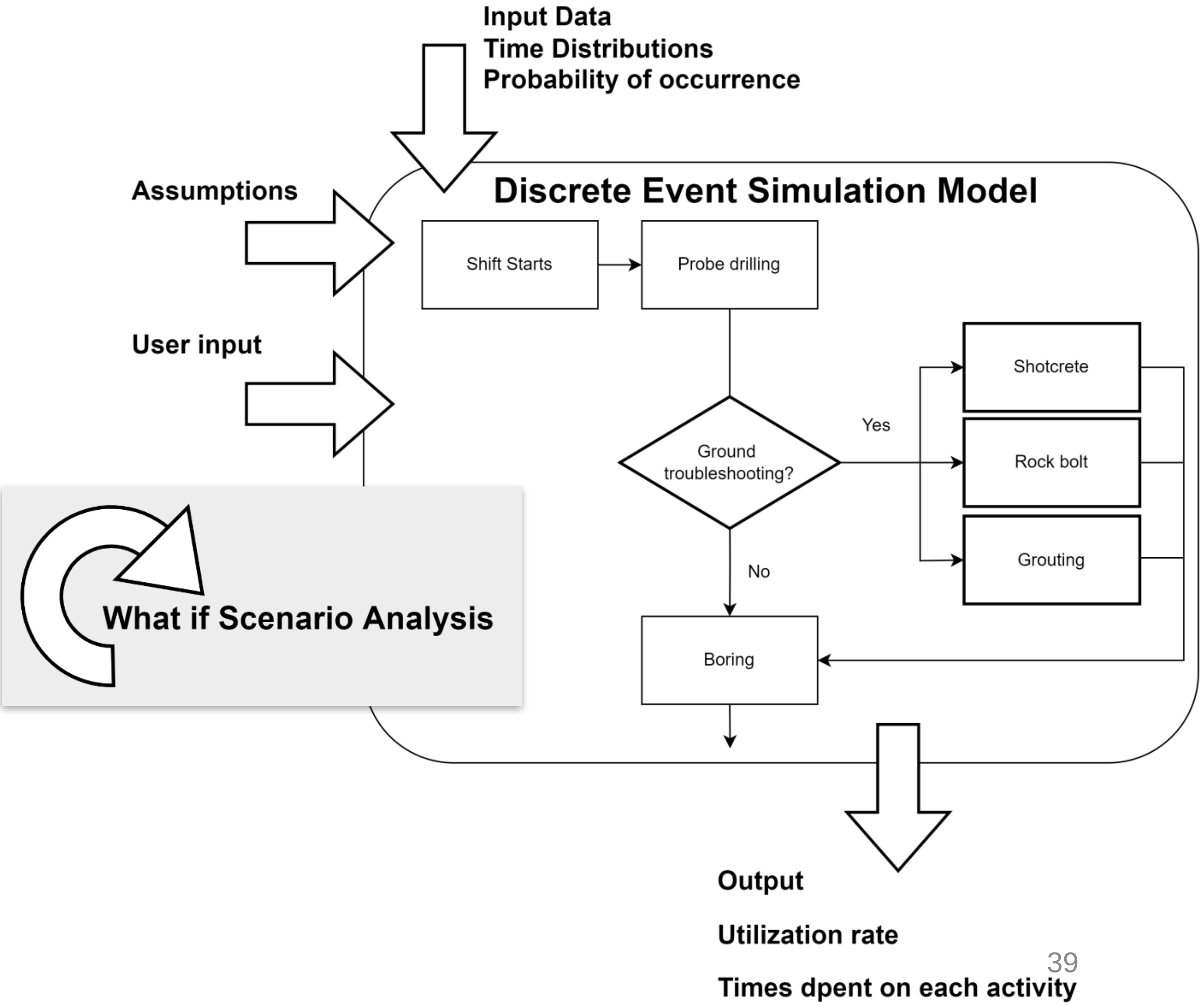
- Flexible and reliable
- Considers various site set ups
- Different tunneling activities and their relations
- Incorporates Stochastic nature of the activities

A Discrete Event Simulation Model is:

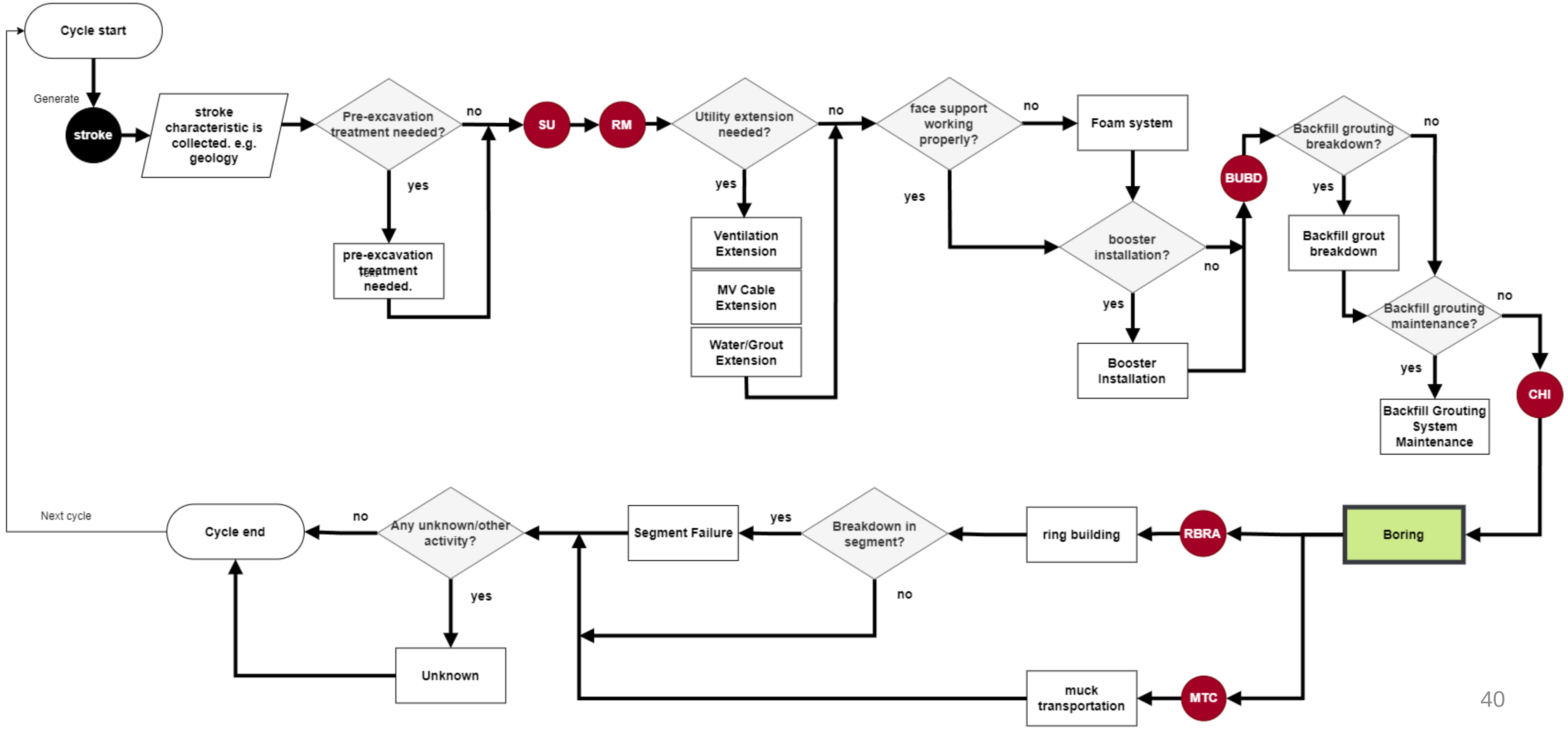
- Data-driven
- Process interaction approach
- Allows analysis of tunneling operation
- What-if scenarios
- Identify bottlenecks
- How tunneling would go if parameters changes
- Takes uncertainty

DES Model for estimation of utilization rate



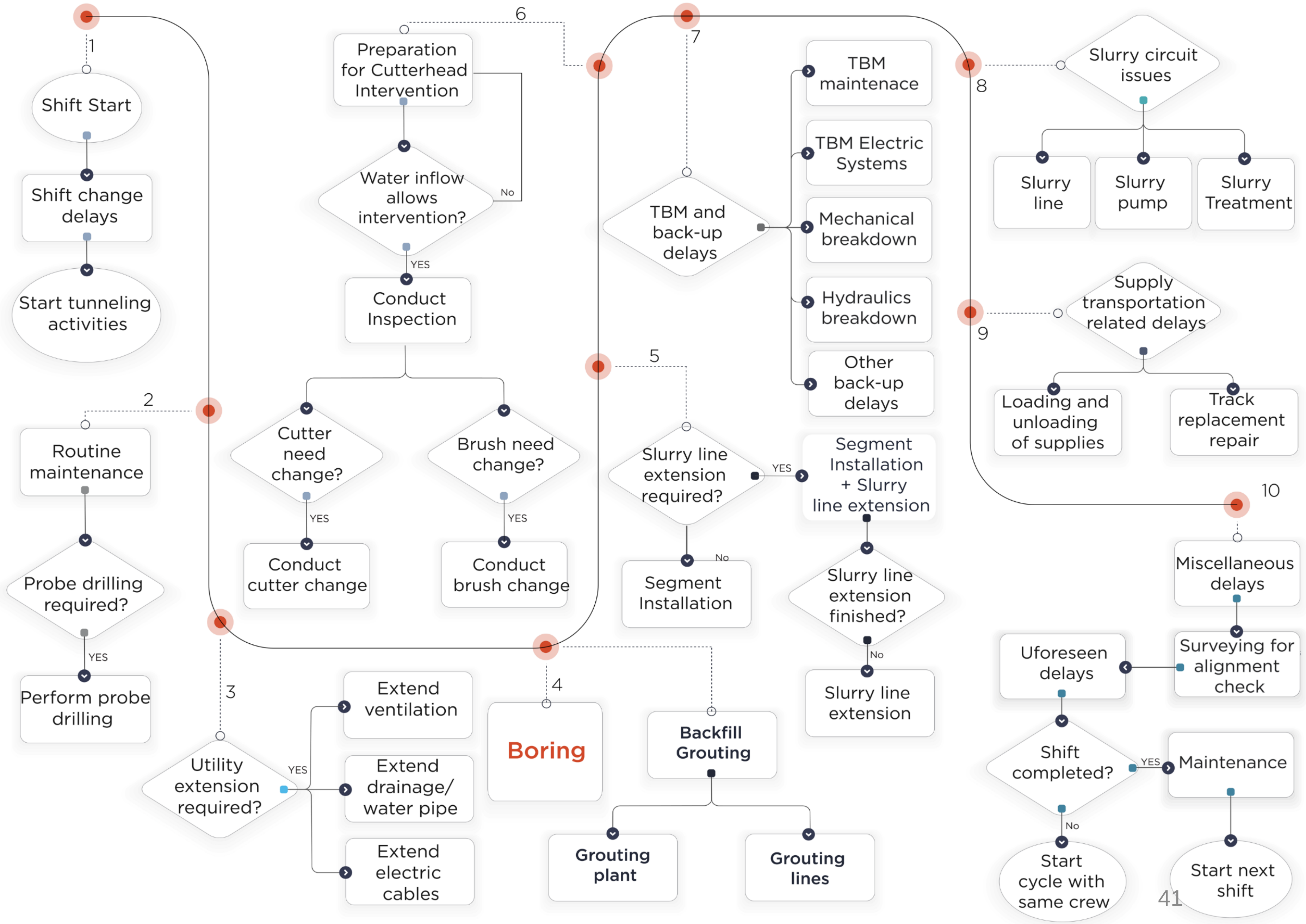


DES Model for estimation of utilization rate in SimPy



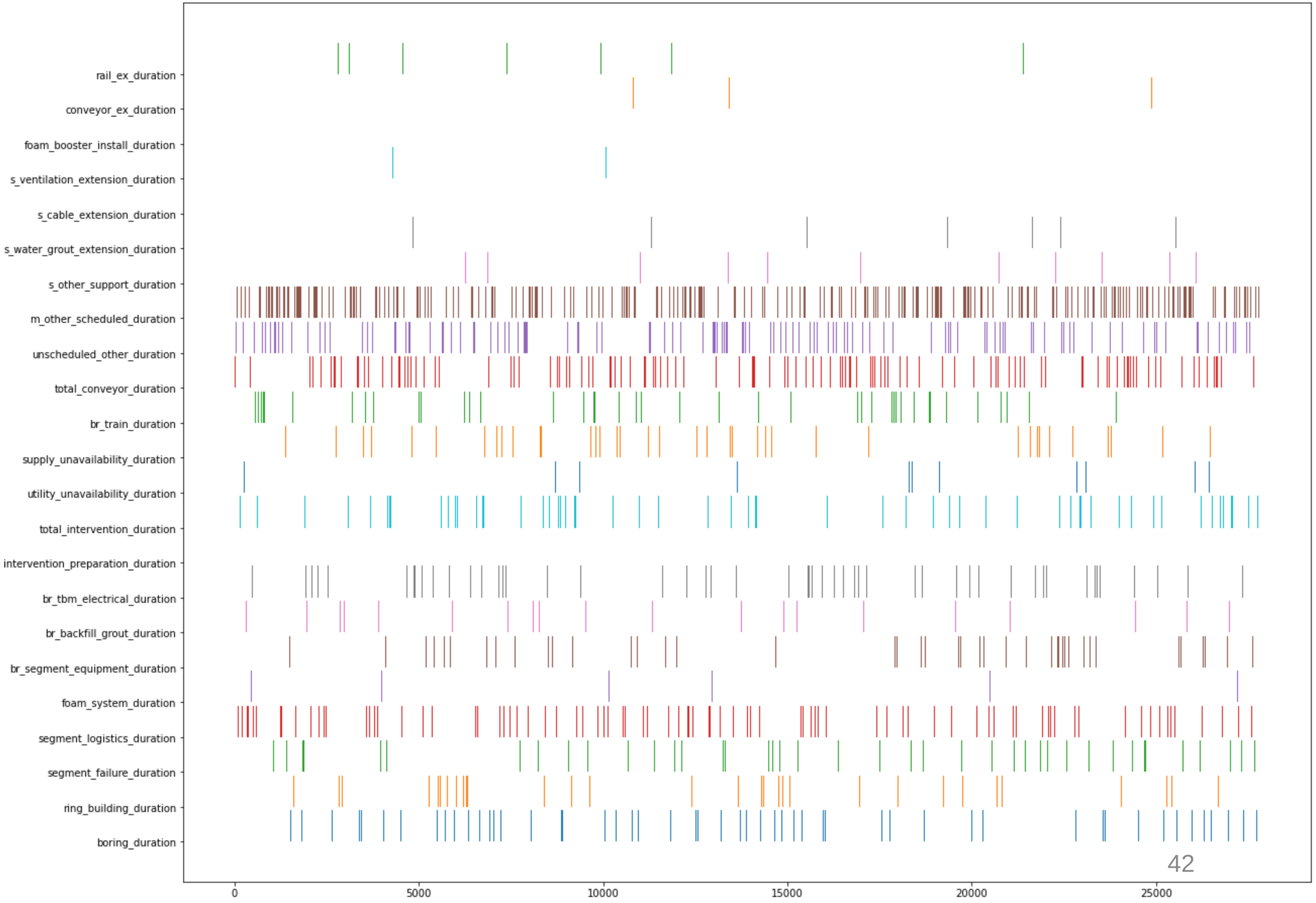
DES Model

For MATLAB Code
For slurry TBM

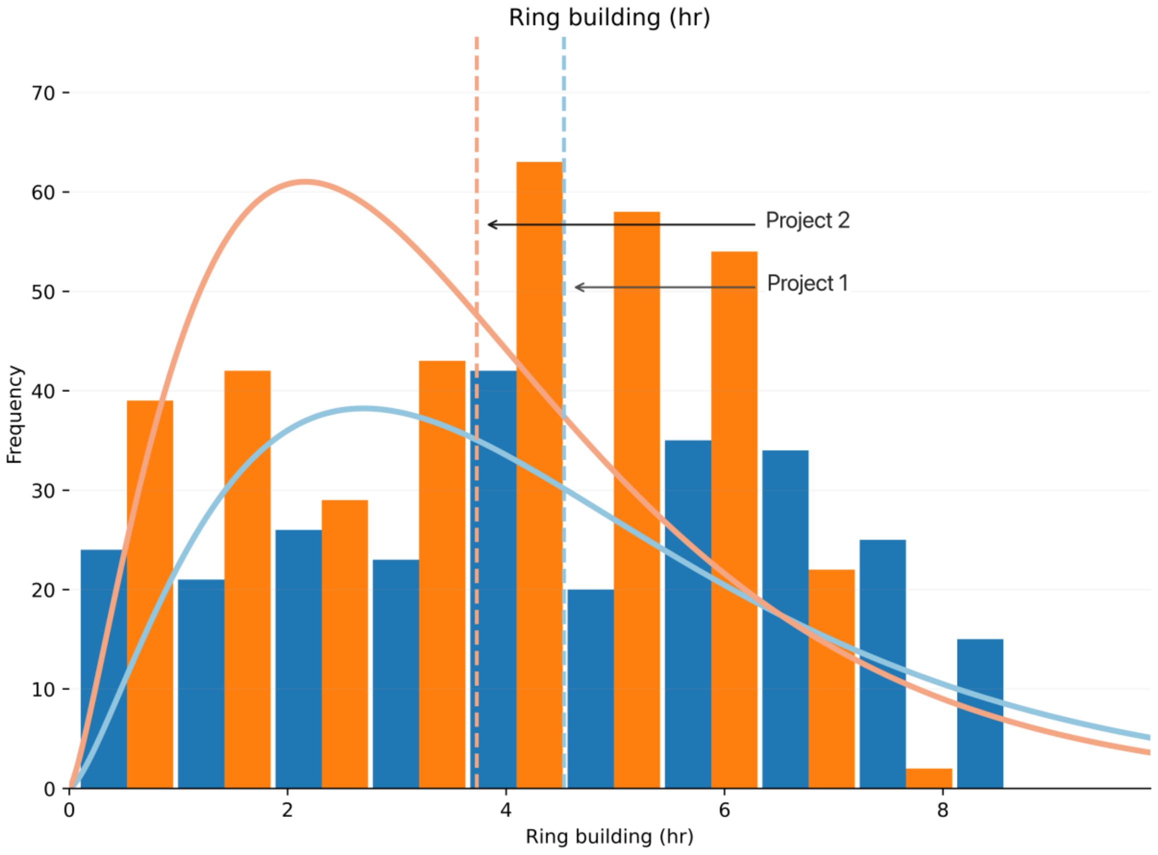


DES Model Output

- Start and end time of each activity
    - Activity duration
- Waiting for resources
    - Resource utilization



Sensitivity of Single Shield TBM Utilization rate to the Segment Installation Time



Case study	Diameter (m)	Length	
		Total (m)	Simulated (m)
Project No. 1	8	8,127	4,342
Project No. 2	5.8	7,468	5,778

Conclusions

- It is critical to analyze the activity times of a TBM operation to understand the time allocation for each activity and the overall workflow
- This analysis allows the contractor/operator to identify the bottlenecks in the operation and remove them to increase utilization rate and daily advance rates
- Discrete Event Simulation (DES) allows for comparing different scenarios to see if the operation can be improved by changing the workflow and site setting
- DES allows for more accurate, stochastic based prediction of the machine utilization.

Thanks for your attention