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SIMULATION CASE STUDY: MODELLING DISTINCT BREAKDOWN EVENTS FOR A TUNNEL BORING MACHINE EXCAVATION

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ABSTRACT

Tunnel Boring Machine (TBM) tunneling projects are frequently hit with delays which can cause adverse effects, extending schedules and incurring additional costs. This paper outlines a case study to show how simulation can be effectively used to analyze productivity performance of a project with emphasis on delays from equipment breakdowns and unexpected conditions. Data collected from this project under a Method Productivity Delay Modelling study, completed by a consulting firm, was collected and prepared to model delays on a combined discrete event continuous tunneling simulation model. Calibration was done to the theoretical tunneling model to ensure the results would be reflective of the actual construction project and to measure the effectiveness of the delay modelling. Sensitivity analysis was conducted to distinguish the most unfavourable delays to a tunneling project, allowing further analysis into the results of the mitigation of these delays on project duration and hypothetical costs.

1 LITERATURE REVIEW

Simulation has been successfully applied to modelling construction operations as an effective tool to assist decision-making in a wide range of operations in construction (AbouRizk 2010), since the first construction simulation tool, CYCLONE, introduced by Halpin (1977). CYCLONE was developed to model processes based on discrete event simulation technique, which is an effective method in simulation of construction projects. A number of simulation systems have been developed based on CYCLONE, including RESQUE (Chang and Carr 1987) and Stroboscope (Martinez and Ioannou 1994), which are General Purpose Simulation (GPS) tools, which can represent almost any process. Further advancements to simulation techniques for construction applications include Special Purpose Simulation (SPS) to facilitate modelling of specific type of projects, for example, through Simphony (AbouRizk and Hajjar 1998) which was developed specifically for modelling construction processes. Other advancements include 4D modelling methods and Construction Synthetic Environment (COSYE) (AbouRizk and Hague 2009), amongst others.

These simulation systems have been applied to tunnel construction. Touran and Toshiyuki (1987) predicted tunnel advance rate in soft rock with CYCLONE. Ioannou (1988) presented a geologic prediction model for tunneling and risk reduction modelling as well as planning and simulation approaches to augment those predictions. Ruwanpura (2001) forecast soil types and soil families along a tunnel path using Simphony Special Purpose Simulation. Likhitruangsilp and Ioannou (2003) presented a stochastic methodology, based on discrete event simulation, to evaluate tunneling performance. Einstein (2004), and Haas and Einstein (2002) described and innovative simulation system for tunnel construction simulation, called Decision Aid for Tunneling. Chung, Mohamed, and AbouRizk (2006) applied Bayesian updating methods and developed a simulation-based productivity model for utility tunnel construction operations. Al-Bataineh (2008) planned tunnel construction by modelling different construction scenarios with Simphony. A general purpose simulation was developed using Simphony for modelling space, logistics, and resource dynamics with genetic algorithms for optimizing the layout based on various constraints and rules (Zhou et al. 2009, Zhou et al. 2008). Marzouk et al. (2010) applied simulation for planning microtunnels projects and estimating project time and cost for construction.

The works presented in the literature thus far do not critically assess the impact of delays on construction progress. The challenge is to be able to collect real data from a project and use it in the simulation process in such a manner where causes of delays are properly modeled and incorporated. This case study attempts to fill this gap in the literature, and can act as an example for researchers and practitioners attempting similar approaches in the future.

2 CASE PROJECT BACKGROUND

The tunnel studied is one segment of a larger municipal project. Note, the data has been scaled for confidentiality. The TBM tunnel is approximately 700 m. The tunnel constructed used the M100 TBM (M17). The project timeline was approximately one year. A consulting company conducted the project management and provided resident engineering and production planning services throughout the project. Daily progress reports were collected in order to assess productivity, notes on the day's issues and details of the shifts (hours, crew size, etc.). Concurrently, delay assessment was being completed on a monthly basis as part of monthly reporting. The technique used was Method Productivity Delay Modelling (MPDM), which was done on a monthly basis and summarized in monthly reports. This technique is summarized in the section below, MPDM Background and Analysis.

2.1 Delay Definition

A delay, in the context of this paper and consistent with the definition in Adrian and Boyer (1976), can be defined as any interruption to the progress of tunneling. That is, any event or situation for which tunneling must cease, outside the normal operation of the tunneling cycle. The most common example of a delay is the breakdown or failure of equipment. For example, during operations, the TBM may break down mechanically, have hydraulic leaks or run into rocks, voids and unfavorable geotechnical conditions. When this occurs, we witness a delay in tunnel progress.

2.2 MPDM Background

Method Productivity Delay Modelling (MPDM) is a technique utilized to measure, predict and improve a project's productivity (Adrian & Boyer 1976) in relation to the amount of delay experienced. The details of all delays on the project are categorized, recorded and tracked to develop an in-depth understanding of the impact of delays on the project. This is extremely useful in measuring and predicting the productivity of the project as the actual productivities can be compared to idealistic or non-delayed productivities. The ideal productivity is by definition the productivity during which no delays occurred and represents an actual maximum possible productivity attained during the project.

2.3 Project Delay Information

As part of the engineering services provided by the consultant, detailed delay information was tracked throughout TBM tunneling. Any delay that occurred was recorded, with details of its nature and the duration of the delay. Delays were categorized based on the type of issue that occurred. This data provided the required inputs for a Method Productivity Delay Model assessment.

The MPDM study found that an ideal productivity for the project was 0.45 m/hr (production without delay) and an overall production of 0.34 m/hr. These metrics were obtained by comparing the production cycles (days/shifts) during which a delay did or did not happen. It is important to note that routine surveying and track extension work was not considered a delay in the MPDM study. Given below are the production summary and metrics of the actual project.

2.4 Data Preparation

Using the MPDM progress tracking compiled by the consultant, the details of the delays were analyzed. In order to extract practical data from the MPDM study, some data manipulation was required. Production and delays were tracked on a daily basis, with shift duration for the day noted. Shift times varied from 8 hour shifts to 23 hour shifts, so in order to normalize the delays against the project timeline, the cumulative project duration was calculated. For example, rather than having a TBM breakdown on one day during a 10 hour shift, the TBM breakdown was noted to have occurred at a time of 180 hours into the project. The result of this step allowed transferring the delay information to the simulation model.

For each type of delay, the average duration and average time between delays for each category were calculated. These were required inputs to embellish the base model with rational delay information. The delays were then fit to exponential distributions to represent the duration and inter-arrival times. The delay data is detailed in Table 1, with color coded severities for each delay.

Table 1: Summary of delay information.

	Delay Durations (Hours)			Time Between Delays (Hours)			
Delay or Breakdown Type	*Distribution*	*Mean (hr)*	*Minutes*	*Distribution*	*Mean (hr)*	*Minutes*	**Number of Delays**
TBM	Exponential	3.85	231.06	Exponential	117.00	7020.00	17
TBM Hydraulic	Exponential	4.84	290.11	Exponential	90.41	5424.55	21
Cleaning TBM	Exponential	5.33	319.92	Exponential	341.50	20490.00	6
TBM Electrical	Exponential	3.63	217.50	Exponential	231.13	13867.50	8
TBM Water System	Exponential	4.50	269.88	Exponential	415.50	24930.00	2
Surveying	Exponential	3.83	230.00	Exponential	341.50	20490.00	6
Weather/Crane	Exponential	4.00	240.12	Exponential	424.50	25470.00	1
Rocks	Exponential	3.77	226.11	Exponential	88.18	5290.59	13
Other and Miscellaneous Delays	Exponential	2.88	172.50	Exponential	419.75	25185.00	4
Voids and PVC asbuilts	Exponential	7.31	438.46	Exponential	58.29	3497.50	13

2.5 Base TBM Model and Parameters (No Delays)

AbouRizk and Hague (2015), detail a discrete event simulation model which was used as a starting point for the base model utilized for analysis. The model is shown in Figure 1. The models are standard process interaction models developed with Simphony. Trains are created as the flow entities that are processed through modelling elements to describe the tunneling operation. For example, the train captures the "track," "travels" to the TBM where it is loaded, then "returns" and repeats the cycles as shown in Figure 1. The general purpose model illustrated represents the schematic laid out in AbouRizk and Hague (2015).

To further develop the base model, the excavation and train travelling cycles were replaced with continuous simulation techniques. This facilitates a better understanding of the excavation process, and the behavior of the train cycle. This model was used to establish an experimental baseline for the TBM tunneling of the project. It is shown in Figure 2.

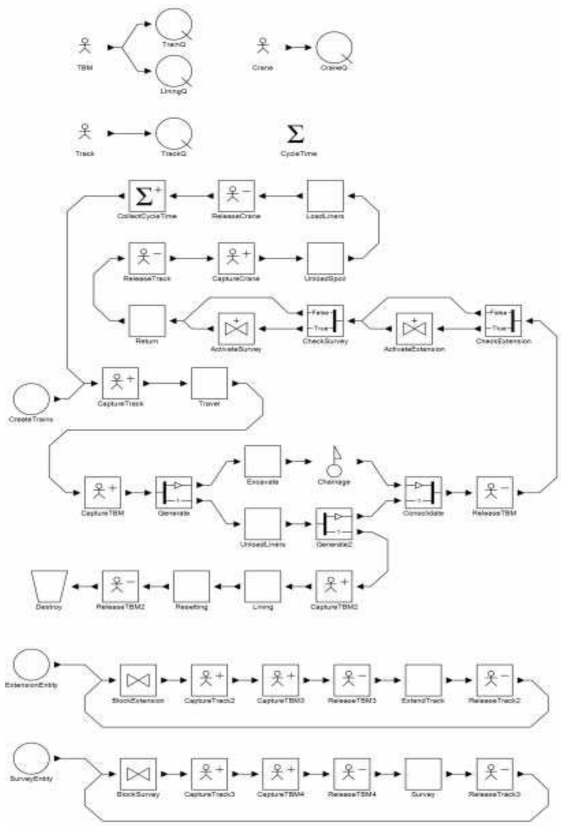

Figure 1: Discrete event simulation of TBM tunneling project (AbouRizk and Hague 2015).

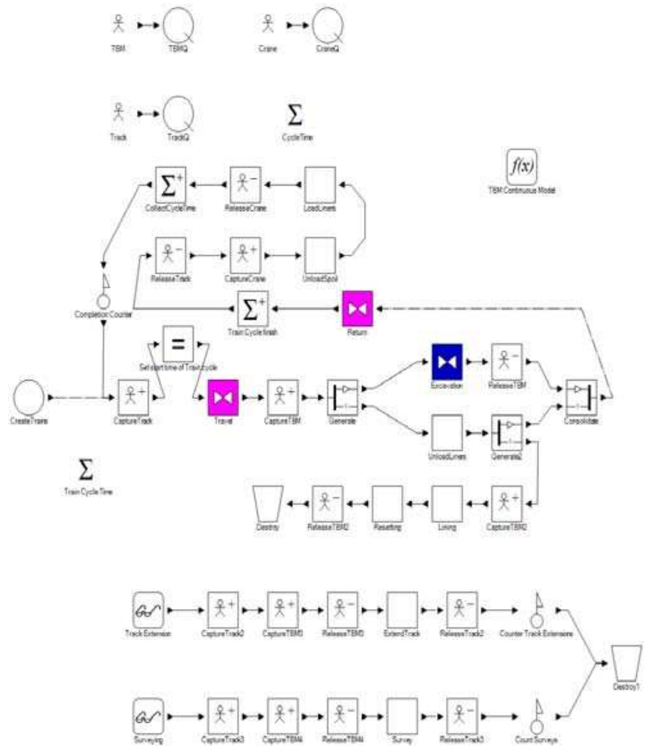

Figure 2: Modified discrete event model.

The modification in Figure 2 uses a combined discrete event continuous modelling approach. The *f(x)* component is the continuous model that simulates the TBM advancement through 1 m of tunnel. This modelling strategy is more accurate than the discrete event process, especially when breakdown events occur.

2.6 Parameters and Assumptions

The parameters utilized, outlined in Table 2, represent the project conditions on the tunneling project, which were utilized in the modified model described above. Specifically, a length of approximately 700 m of TBM tunneling and an average non-delayed productivity of 0.45 m/hr, assuming uniform ground conditions throughout, were used. All typical tasks were based on 1 m of advancement and ground conditions are assumed constant. The tunneling rate was calculated based on ideal (non-delayed) productivity detailed in the MPDM study.

Table 2: SA1A project parameters.

Parameter	Value
Tunnel length	700 m
Non-delayed production tunneling rate	0.45 m/hr
Train travel to TBM	4 km/hr
Train return	3.5 km/hr
Unload liners	15 minutes
Unload spoil	15 minutes
Load new liners	6 minutes
Install liners	24 minutes
Reset TBM	15 minutes
Surveying done every 90 m	8 hours
Track extension every 6 m	4 hours

3 MODEL CALIBRATION

It is important to note that due to any discrepancies between the model and the actual construction process, we must account for an adjusted "practical" penetration or excavation rate. This means that even though the data states an ideal production rate of 0.45 m/hr, the model completion time using this value may be offset due to inconsistencies in the model activities versus actual construction. Another reason for this relates to the fact that the ideal production is based on *penetration of the TBM*, while we are manipulating the actual excavation rate. The penetration rate takes into account the rest of the construction cycle within the metric and not simply the excavation. In order to account for this, we must find an adjustment factor to calibrate the base model.

To develop a representative model, calibration is required to converge the model completion time to the actual completion duration. This can be done by experimenting with the excavation rate as described above. The results of the calibration process are given below.

At a calibration factor of 1.85, the associated completion time was found to be approximately 1563 days, which is within 0.06% of the actual construction completion time associated with an idealized production rate of 0.45m/hr. These details are outlined in Table 3 below.

Table 3: Non-delayed model calibration.

<table>
<tr><td colspan="3">No-Delay Calibration</td><td></td></tr>
<tr><td rowspan="2">Actual Construction</td><td>Production Rate (m/hr)</td><td colspan="2">Associated Completion Time (hours)</td></tr>
<tr><td>0.45</td><td colspan="2">1562.222</td></tr>
<tr><td rowspan="7">Base Model Experimentation</td><td>Model Excavation Rate x Calibration Factor</td><td>Associated Completion Time (hours)</td><td>Production Rate</td></tr>
<tr><td>0.45*(0)</td><td>2276.8</td><td>0.309</td></tr>
<tr><td>0.45*(1.1)</td><td>2135.566</td><td>0.329</td></tr>
<tr><td>0.45*(1.3)</td><td>1918.316</td><td>0.366</td></tr>
<tr><td>0.45*(1.5)</td><td>1759.05</td><td>0.400</td></tr>
<tr><td>0.45*(1.75)</td><td>1611.065</td><td>0.436</td></tr>
<tr><td>0.45*(1.85)</td><td>1563.133</td><td>0.450</td></tr>
</table>

3.1 Breakdown Embellished Model

Based on the delay data prepared from the construction of the TBM tunnel on the construction project, it is possible to model the individual delays based on the data shown in Table 1. The embellishment to the modified continuous tunneling model above was completed by representing each individual delay, as shown below in Figure 3.

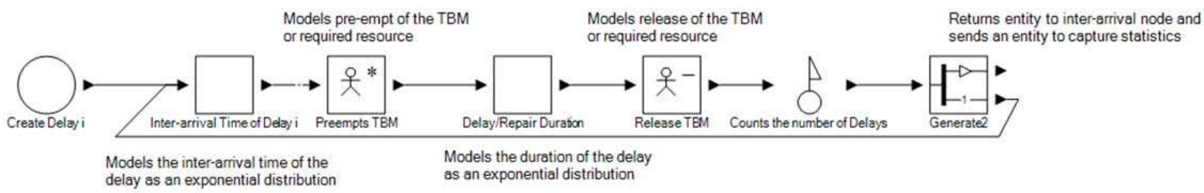

Figure 3: Schematic of the modelling of the delays/breakdowns.

The delays are linked to the modified model under the pre-empt of the TBM, and thus, all delays extend the project duration. The complete delay embellishment model is summarized below in Figure 4, which is compiled under a composite element in the primary discrete event model.

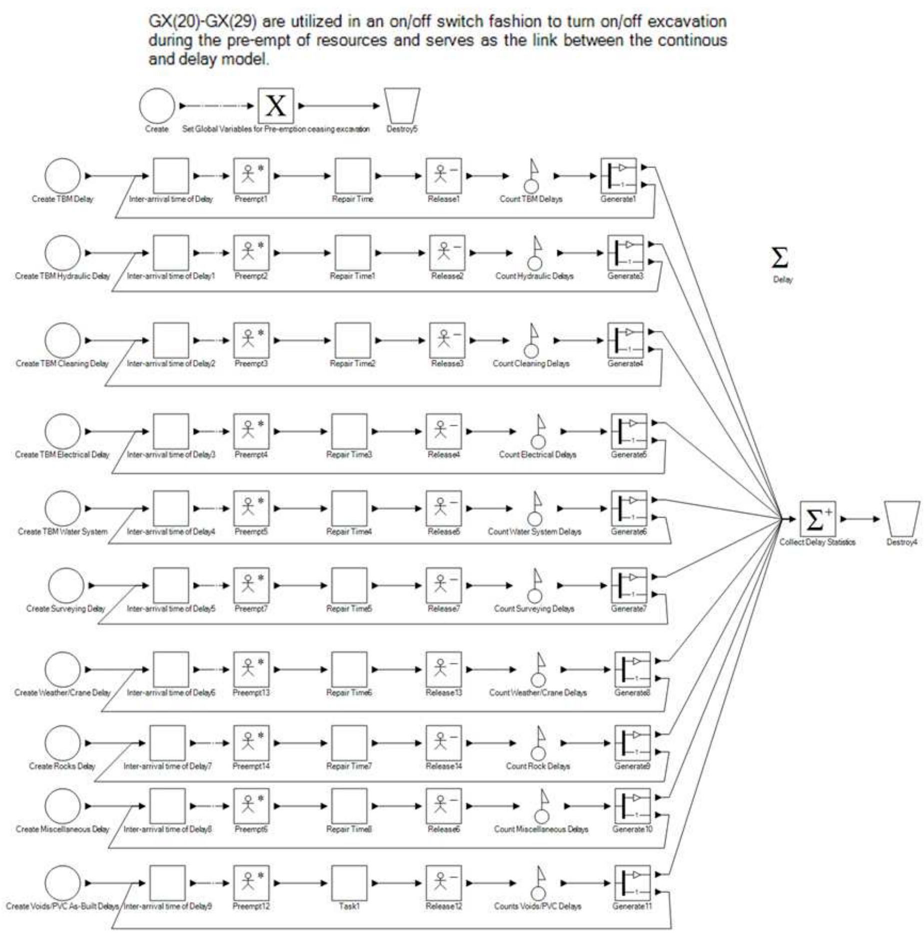

Figure 4: Modelling of all project breakdowns and delays.

3.2 Delay Embellished Model Calibration

Just as was the case in the base model, it is important to note that due to any discrepancies between the model and actual construction process, we must account for an adjusted "practical" penetration or excavation rate. This means that even though the data states a production rate of 0.34 m/hr, the model completion time using this value may be offset due to inconsistencies in the model activities versus actual construction. In order to account for this again, we must find an adjustment factor to calibrate the embellished model.

To develop a representative model, calibration is required to converge the model completion time to the actual completion duration. This can be done by experimenting with the excavation rate as described above. The results of the calibration process are given below. Due to the stochastic nature of the delay modelling, 50 runs were done for each calibration test, and the average reported.

At a calibration factor of 2.75, the associated completion time was found to be approximately 2070 days, which is within 1% of the actual construction completion time associated with an idealized production rate of 0.34 m/hr. The high value indicates that the delay embellished model has a few possible issues, the first of which may be the excavation rate, which may have been estimated too low relative to actual construction. The second irregularity could be related to another piece of the construction operation modelled, such as the track extension, routine surveying, or activities related to spoil movement or tunnel lining. Lastly, the modelling of the delays could be overestimated, causing the duration to be skewed, due to exponential modelling where delays may be sampled at higher than expected repair durations. This requires further investigation. The delayed calibration details are outlined in Table 4.

Table 4: Delayed calibration.

Actual Construction	*Production Rate (m/hr)*	*Associated Completion Time (hours)*	
	0.34	**2049**	
Base Model Experimentation	Model Excavation Rate x Calibration Factor	Associated Completion Time (hours)	Production Rate
	0.45*(0)	3428.412	0.205
	0.45*(1.5)	2731.856	0.257
	0.45*(1.75)	2536.74	0.277
	0.45*(2)	2396.37945	0.293
	0.45*(2.25)	2267.307	0.310
	0.45*(2.5)	2156.162	0.326
	0.45*(2.75)	**2067.86**	**0.340**

4 RESULTS OF SIMULATION

Now that the model has been calibrated to ensure it is representative of the actual construction process, the results can be explored. The embellished model was run 100 times to obtain the following summary data (Figures 5 and 6). The summary statistics are provided in hours for convenience. Given on the left is the overall project duration histogram. Shown on the right is the histogram of the average mean of delay times for 50 runs.

Mean Duration	2,067.86	hours
Standard Deviation	110.13	hours
Production Rate	0.3400	m/hr

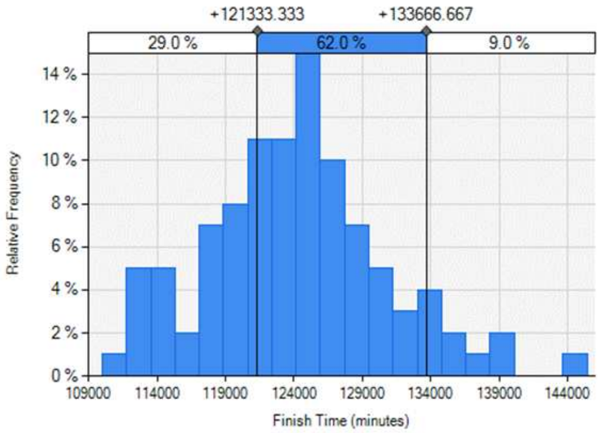

Figure 5: Histogram of project duration.

Mean Duration	6.97	hours
Standard Deviation	0.92	hours

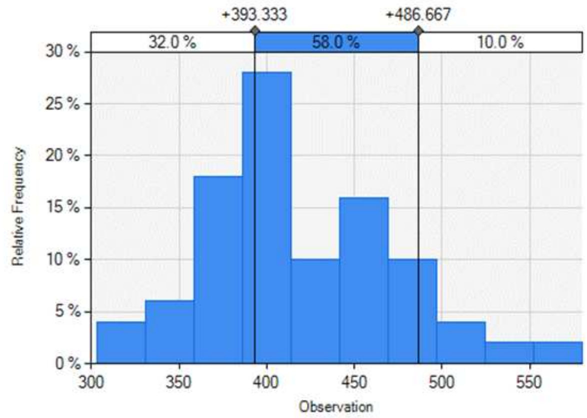

Figure 6: Summary of delays.

4.1 Comparison of Simulation Delay Data to Actual Delays

To evaluate the success of the modelling of the delay events, a comparison was done to assess the details of the actual delays versus the statistics of the modelled delays. Given below in Table 5 is a summary of the comparison.

Table 5: Comparison of construction and simulation delay counts.

Delay or Breakdown Type	Actual Construction Number of Delays Experienced	Simulation Model Number of Delays Experienced (Mean)	Evaluation
TBM	17	16.00	Acceptable
TBM Hydraulic	21	20.94	Acceptable
Cleaning TBM	6	5.72	Acceptable
TBM Electrical	8	7.70	Acceptable
TBM Water System	2	4.66	Needs Optimization
Surveying	6	6.02	Acceptable
Weather/Crane	1	4.86	Needs Optimization
Rocks	13	21.76	Needs Optimization
Other and Miscellaneous Delays	4	4.84	Acceptable
Voids and PVC As Built Delays	13	30.40	Needs Optimization

As seen above, the majority of delays were modelled accurately with the exception of water-system, weather/crane delays, rock delays, voids and/or PVC as built delays. These were over-estimated and thus occurred more frequently than expected based on actual construction. The most likely reason for this relates to the small sample size used to formulate the representative distributions. In the future, these delays should be reviewed and further background data obtained to establish more representative functions to model the delays.

Deviations in the simulation model versus the actual construction are captured within the calibration factor, which includes the need for optimization of certain delays. In future work, the modelling of the imprecise delays can be improved and further overall convergence of the project's details can be done.

4.2 Delay Sensitivity Analysis

After calibrating the embellished model, we can assume it is a reasonable estimate of actual project information. At this stage, we can begin to analyze the effects the specific delays have on the construction duration directly. In order to conduct sensitivity analysis, each specific delay can be removed from the simulation to show what would happen if this delay did not exist. This facilitates a better understanding as to which specific delays are causing the most time extension to the project, and should thus be mitigated. The results of the sensitivity analysis conducted are summarized below in Table 6, which details of the production and duration differentials for the exclusion of each delay type.

Table 6: Sensitivity analysis.

	Production Rate	Mean Project Duration (hours)	Production Rate Gain	Average Duration Differential	Estimated Financial Impact ($20,000/Day)*
All Delays Included	0.340	2070.41	-	-	-
Type of Delay Removed					
TBM	0.346	2030.817633	0.007	39.592	$65,987.28
TBM Hydraulic	0.358	1965.397633	0.018	105.012	$175,020.61
Cleaning TBM	0.346	2033.161767	0.006	37.248	$62,080.39
TBM Electrical	0.343	2048.2472	0.004	22.163	$36,938.00
TBM Water System	0.343	2050.5865	0.003	19.824	$33,039.17
Surveying	0.342	2056.9477	0.002	13.462	$22,437.17
Weather/Crane	0.342	2054.083333	0.003	16.327	$27,211.11
Rocks	0.352	1996.076933	0.013	74.333	$123,888.44
Other and Miscellaneous Delays	0.341	2061.783983	0.001	8.626	$14,376.69
Voids and PVC As Built Delays	0.382	1839.4329	0.043	230.977	$384,961.83

* Based on average of 12-hour shifts

Based on the sensitivity analysis done, three delays stood out as the most promising in terms of cost savings. The estimated financial impact was derived from an approximate hypothetical cost of $20,000 a day, with a day being a 12-hour shift. It is important to note that of the three delays, the rock and voids/PVC as built delays were found to be over-estimated in terms of the number of delays that occur. Their sensitivity remains significant but the magnitude may be overestimated. In order to better gauge the effects of these delays, they can be scaled back based on the actual behaviors of the delays. The rock delays were overestimated by approximately 40%, while the voids/PVC as built delays were over by approximately 60%. Thus, we can take approximately 40% and 60%, respectively, of the estimated financial impacts for these delays. Even after accounting for the over-estimation, these two delays remain among the top three major delays based on potential financial and schedule impact.

5 IMPROVED EMBELLISHED MODEL WITH "ABILITY TO AVOID" APPLIED

Depending on the delay, we can attempt to reduce the duration of repair as well as the frequency of delays occurring. These hypothetical improvements were explored using the embellished model to identify the potential financial impacts of mitigating these three major delays. Multiple cases were analyzed to assess what type of schedule and financial savings could be achieved. Due to the inaccuracy of the rock and void/PVC delay inter-arrivals, they were modified prior to this analysis so that their baseline inter-arrivals are increased by 40% and 60% respectively (to reduce the occurrences of delays). This results in more accurate and significant conclusions. No additional modifications were made to the hydraulic delays. The procedure for this analysis involved decreasing the mean duration and increasing the mean inter-arrival time of delays, thus reducing the downtime and preventing their occurrence. Modifications of 10%, 25%, and 50% were made to assess the impacts.

5.1 Impact of Results

Summarized below in Table 7 are the results of the three cases of process improvement whereby the down-time and arrival time of delays was modified by 10%, 20% and 50%. As seen below, the results show that if the delays could in fact be mitigated to these extents, there is significant potential for schedule improvement and financial savings. By attending to the three major delays on the project and reducing the severity by 50%, there is a potential cost saving of almost $0.5M, and a reduction in workdays of 24 days. With a 25% reduction, the results remain significant with approximately $0.38M and 19 days saved. Lastly with a 10% reduction in the severity of the three major delays, there is potential to save $0.25M and 13 work days.

Table 7: Summary of the impacts of delay mitigation.

Delay Avoidance	Production Rate Increase (m/hr)	Approximate Workdays Saved (based on 12 hr shifts)	Estimated Financial Impact ($20,000/day)
Delays reduced 10%	0.027	13	$254,233.67
Delays reduced 25%	0.042	19	$380,401.11
Delays reduced 50%	0.056	24	$486,355.39

6 VALIDATION AND VERIFICATION OF SIMULATION VERSUS REAL WORLD DATA

The constructed model went through multiple stages of validation and verification during its development and completion. The fundamentals of the model are based on a schematic given by AbouRizk and Hague (2015), providing inherent conceptual validity. Following the continuous model modifications, the model was validated by a member of the consulting company, who provided input and verification of project parameters. The model was built to replicate the actual construction of the case project as a basis to effectively model the delay breakdowns, and thus, once calibrated, had another layer of inherent validity.

Once the delay modelling had been added to the model, another meeting was held with the consultant to validate the layout of the breakdown occurrences and obtain input and suggestions for improvement. In analyzing the results and calibrating the model to better replicate actual construction and delay data, the delay embellished model has been continuously improved and verified. The model was shown to output results within 1% of actual data with regards to project duration and associated productivities as detailed in the calibration section of the report, serving as a data validation technique.

7 CONCLUSIONS AND FUTURE WORK

The modelling of the delays and breakdowns which occurred on the case project provided a basis for the legitimacy of distinct breakdown modelling, provided there is sufficient construction data to do so. Once calibrated, the delay model displayed results which indicated it was an effective representation of the construction operation. The data output displayed a significant accuracy for the majority of delay events predicted when compared to construction data, with the exception of a few delay types. A valid and verified overall simulation model allowed optimization analysis to be done. It was found that if the three major delays could be mitigated by a certain percentage (10%-50%), there was compelling evidence that financial benefits of $0.2-0.5M could be earned and approximately a month of schedule reduction could be realized.

In future work, the delay data should be enhanced by collecting summaries from multiple similar projects in order to strengthen the projections of delay details. Further work will be put into optimizing the overall model to better match actual operations, in an iterative manner. This will mean less calibration will be required and even more meaningful and accurate results can be achieved. Lastly, financial analysis will be done to enhance the understanding of the costs of tunnel construction in order to strengthen the financial projection validity of the model.

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