STATES:

SIMULATION TOOL FOR AUTOMATED TUNNELING ESTIMATION AND SCHEDULING

Submitted by:
SMA Consulting
230 Sun Life Place, 10123 99 St.
Edmonton, AB T5J 3H1
www.smaconsulting.ca
T 780.484.3313
F 780.497.2354

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Introduction

Every construction project is uncertain: setbacks, unexpected discoveries, and equipment failures all have the potential to cause significant delays and cost overruns. Tunneling projects are a special case, where all of the above-ground risks of a typical construction project apply, as well as the significant uncertainties of ground conditions and the difficulty of quickly recovering from setbacks. Because tunnelling tends to be linear in nature, having very few work faces, any issues encountered can lead to significant delays and costs.

THE CHALLENGES OF TUNNELING

Tunnel construction faces several unique challenges given its physical context, the specialized equipment and expertise required for accomplishing it, its susceptibility to the influence of weather and other risks, and the constraints it faces in terms of work approach.

Tunneling through a variety of ground conditions greatly affects the speed at which progress is made. Loose, flowing sand can require special conditioning to permit equipment like a tunnel boring machine to pass through safely. Boulders encountered often need to be broken down manually, and, if large enough, these can seriously damage the machine. Geotechnical information describing the types of soil, presence of water, probability of voids or boulders, is absolutely essential when

Software Highlights

- Powerful, state-of-the-art tool for project planning and optimization
- Produces reliable CPM schedules and cost estimates for tunnel projects
- A virtual space for exploring project variables and optimizing the approach
- Provides detailed and integrated decision-making information early in the planning phase
- Makes it easier to plan recovery from setbacks and unforeseen obstacles

planning tunneling work; however, geotechnical uncertainties continue to be one of the highest risks faced and can radically upset a project's schedule and budget.

Ground settlement can also complicate tunneling work. As workers cut through the earth, the ground becomes disturbed, shifting and resettling, which can lead to sinkholes, surface cracks, and destruction of critical infrastructure like utility lines and highway overpasses.

When ground conditions are bad enough, tunnel boring machines can actually become stuck and require an emergency shaft for removal. Sometimes equipment simply cannot be retrieved due to its depth or placement under critical existing infrastructure (e.g., major highways, rail lines, etc.) and has to be buried. As TBMs cost in the tens of millions, this could be very costly.

Extreme cold or wind conditions can also upset the progress of a project by necessitating temporary site shut downs. Excessive rain can slow work or even bring it to a halt as sump pumps within the tunnel struggle to keep the area dry.

There are few options available to project managers and planners if an obstacle is encountered – whether it is known or unknown. Alignments are more or less set; ground conditions permit modification with only varying success and at a high cost; the methods for tunneling are limited, and alternatives typically require expensive and non-local expertise. To overcome these issues requires creativity and a reliable understanding of the impact of different options that traditional approaches cannot usually provide.

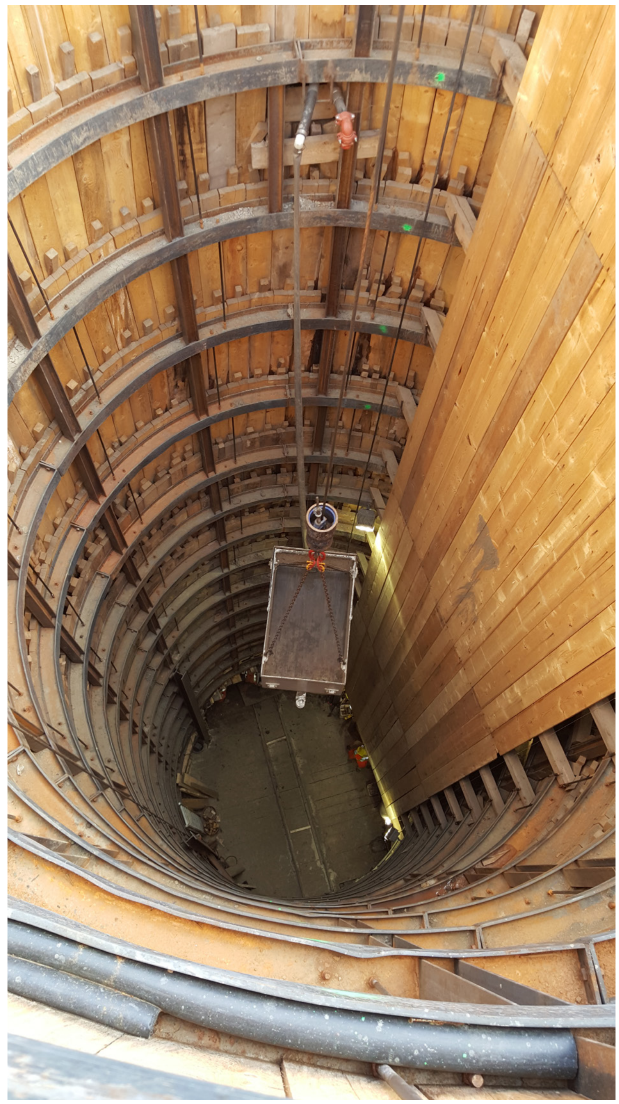
TUNNELING EXPERIENCE

SMA has 20 years of experience on major tunneling projects for the City of Edmonton and other municipalities. These projects and others have given us a comprehensive understanding of how tunneling projects are designed and managed, and what parts of that process have the greatest risks. Through careful planning and management, state-of-the-art simulation tools, and our experience on previous tunnels, SMA has helped the City of Edmonton complete tunnels at increased productivity and under budget.

Throughout our experience, we have also maintained a close relationship with the University of Alberta, advancing research into tunnel simulation. We have also spent more than 2000 hours collecting exhaustive data from tunnel projects, studying production with different tunneling methodologies and equipment.

Meeting Client Needs with Added Value

- Gives owners a sandbox to test and optimize project approaches and to plan responses to project challenges
- Integrates library of previous data and provides a platform for integrating lessons learned and performance information from past projects for future work
- Simplicity and speed-of-use makes it an effective decision-support tool



IDENTIFYING A NEEDED SERVICE

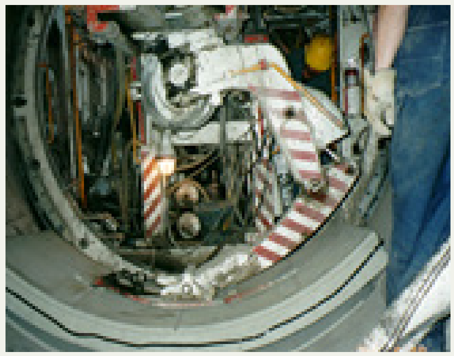
Our experience has shown us that a comprehensive and detailed planning process is the best method of ensuring a successful tunneling project that is completed on time and on budget, in line with the Construction Industry Institute's "Front End Planning" best practice. Construction planners rely on project plans, construction schedules, and cost estimates to select between various preliminary designs, but the process of creating these plans and estimates involves significant uncertainty. Typically, these tools cannot provide the kind of truly detailed picture that can take intricate project variables into account, especially once setbacks occur. They are also time-consuming to prepare and their accuracy relies largely on project team experience. We believe that if the right tools were available, project planners and managers could optimize their designs more easily and with more accuracy, and better respond to setbacks as the tunnel is being built.

Shaft

Tail Tunnel

Liners at Ground Level

Liners Lowered into Tunnel



TBM Installing Liners

Finished Section of Tunnel

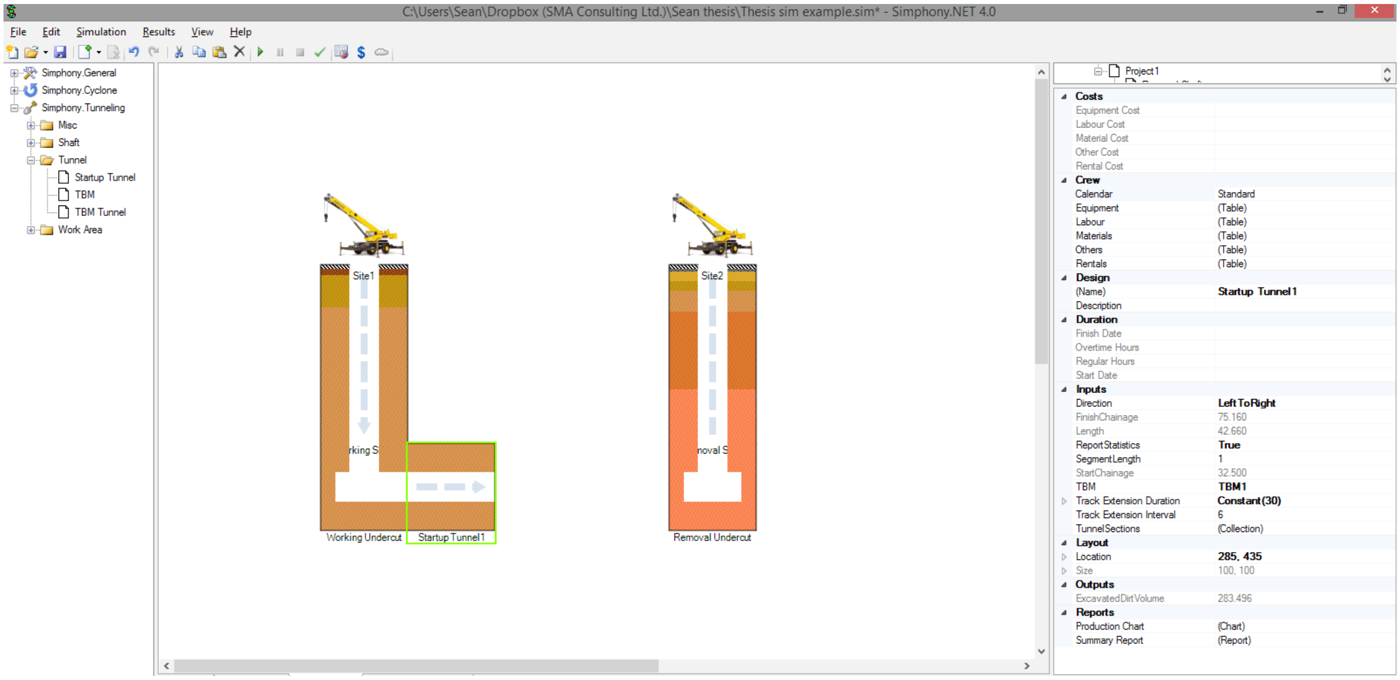
THE PROCESS OF TUNNEL CONSTRUCTION

Typical tunnel construction begins with the excavation of a shaft down to the depth of the tunnel. A tail tunnel is then usually excavated, the TBM is lowered into the tunnel, and tunneling begins. With each cycle, the TBM excavates a certain distance, then installs liners. Excavated material is removed in muck carts. The liners are lowered by the same crane and travel to the tunnel face on the same rails. Once the tunnel is complete, the TBM is removed.

In response to this clear need, SMA has developed STATES (Simulation Tool for Automated Tunneling Estimation and Scheduling), a simulation environment that powerfully predicts the course of any tunnelling project. It integrates historic data, statistical inference, and process interaction simulation modeling with our extensive experience on tunneling projects and uses these as a framework to analyze future projects. Every project begins with unique variables such as geotechnical conditions, productivity, budget, and schedule constraints. STATES integrates these variables into a model that can be modified in a virtual space, and it uses combined continuous–discrete event simulation and Monte Carlo techniques to provide probabilistically accurate outputs for testing various scenarios and returning detailed schedule and budget estimates. By using STATES, project planners can gain unprecedented information in the early phases of a project and can generate numerous scenarios to determine the optimal approach. For instance, on a current project SMA is using STATES to develop 12 unique scenario schedules and cost estimates at the detailed design phase. Providing this degree of comprehensive analysis using traditional estimation methods would take on the order of 2-4 months; STATES can achieve this in a single week, with far more reliable results.

SUCCESSFUL IN THE FIELD

SMA has used STATES on a number of tunneling projects, with significant quantifiable benefits. It was used to determine the ideal construction approach and tunnel lining material on W12, to quickly respond to setbacks on W13, to optimize the approach to SA10A, to quantify damages in the North LRT Tunnel claim, and to generate numerous scenarios for SW4, allowing a high degree of project optimization. Some of these case studies are explored in detail below. With each added project, we have advanced the software and created an even stronger underlying framework for future project simulation. STATES is under constant refinement to keep pace with the current state of the art in construction simulation.



The Project level of STATES, where users can create and edit the various work packages of the project.

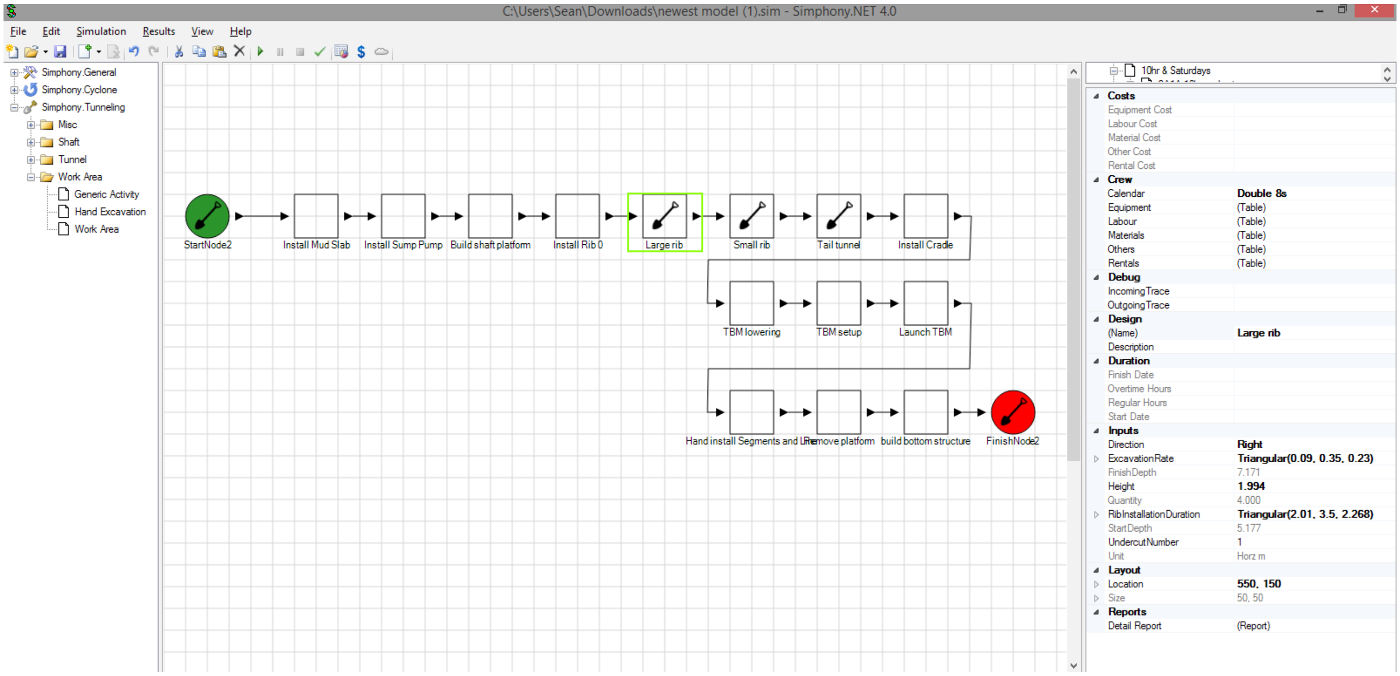
Using STATES

STATES was built using the state-of-the-art *Simphony.NET* engine, a powerful construction simulation platform which was developed at the Hole School of Construction at the University of Alberta. *Simphony.NET* is designed for use in numerous domains and supports different modeling constructs to that end. *Simphony* supports Discrete Event Simulation, where a system is modeled as a sequence of discrete events taking place over time, as well as continuous and combined modeling approaches. Tunnel construction is an ideal situation to employ this form of simulation, because the construction process is generally linear and includes repetitive sub-processes. In the case of a tunnel, a discrete event could be, for example, starting a new phase of the tunnel, starting a new TBM excavation cycle, a machine breakdown, or hitting unexpected ground conditions. At each of these events, the simulation model can be directed to respond in particular ways, generating different scenarios and accompanying budgets and schedules for the sub-phases and total scope of the tunnel. The continuous modeling includes the TBM's advancement through the ground and the travel times of muck carts. Accuracy of the model depends on the quality of the data used to estimate durations and costs. Variables are sampled from distributions fitted to collected data through Monte Carlo techniques; inaccurate assumptions can lead to untrustworthy results. A large portion of STATES's development has been devoted to gathering and integrating multiple data sources, including independent time studies, the Method Productivity Delay Model (MPDM) tool, City cost estimate databases, details of tunnel construction methodologies, productivity of different equipment, typical weather patterns, and many others.

STATES now offers a quick turnaround time and cost-effective service to the client, while also providing them with more accurate predictions – one previous director of Drainage Design and Construction described STATES as "uncannily accurate." The simulation environment is very flexible and can be integrated with any basic service that a client may require, such as estimating, scheduling, pre-project planning, or constructability reviews.

Monte Carlo

Monte Carlo simulation is a computerized mathematical technique that can be used for quantitative project analysis. The power of the simulation comes from the ability to essentially "run" a scenario or set of events thousands of times, varying the conditions each time. Each scenario "completion" is called an iteration. For each iteration in a Monte Carlo simulation, the value of a given event is randomly selected from defined distributions and calculations are performed. With STATES, each project variable is defined as a distribution, which is sampled for use in the discrete event simulation.



The Work Package level of STATES, where users can create, edit, and arrage the various tasks that make up a work package.

A USER-FRIENDLY APPROACH

STATES is a user-friendly tool intended for practitioners who are knowledgeable in their field, but not necessarily experts in simulation itself. The interface allows the user to easily model a project using "project components" that closely resemble the elements that they are familiar with. The project components are created as objects in a visual space, like desktop icons, and are then linked together in event chains that model the project. STATES was developed with several key functions in mind:

- It is easy to use without significant knowledge of simulation
- It provides more accurate results for estimating and scheduling than current systems
- It provides that information in a ready-to-use industry standard format
- It is efficient to use, requiring far less time than manual estimation and providing a higher-quality result
- It provides a medium that allows for sensitivity analysis, scenario planning, and experimentation

Innovation

- The only tool of its kind in Canada
- Has resulted in nearly a dozen academic journal and conference papers
- Developed as part of multiple master's and doctoral theses at the University of Alberta
- Brings sophisticated statistical and mathematical techniques to bear on problems traditionally solved using past experience and rules of thumb
- Built using the *Simphony.NET* engine developed at the University of Alberta
- Represents the state-of-the-art in tunnel planning technology
- Integrates a number of cutting-edge simulation approaches into a cohesive model for practical use

SIMPLE DRAG & DROP INTERFACE

Projects are modeled in STATES according to their work breakdown structure (WBS), a hierarchical organization of project tasks. Detailed information about each work package is added as components and parameters. Work packages in a tunnel project would include tasks such as shaft removal, creating the undercut for the TBM, and creating the startup and TBM tunnels. Each work package consists of work task elements that have their own schedules and costs.

Users begin modelling with the two parent-level objects in STATES: the TBM that will be used, and the project itself. By clicking on the TBM element, the specifications of the TBM can be added, as well as data for modelling the frequency of breakdowns and other relevant variables. Clicking on the Project element allows users to enter key information about the project such as a name and start date. Double-clicking on it takes users one level deeper into the project, where the work packages of the tunnel are defined, beginning with the two surface sites of the tunnel: the working shaft site and removal shaft site. Next, users add the shaft elements below the two working sites, and key variables such as shaft shape and soil conditions can be added to those objects. Other elements such as the tail tunnel, the tunnel itself, and any undercuts can then be added.

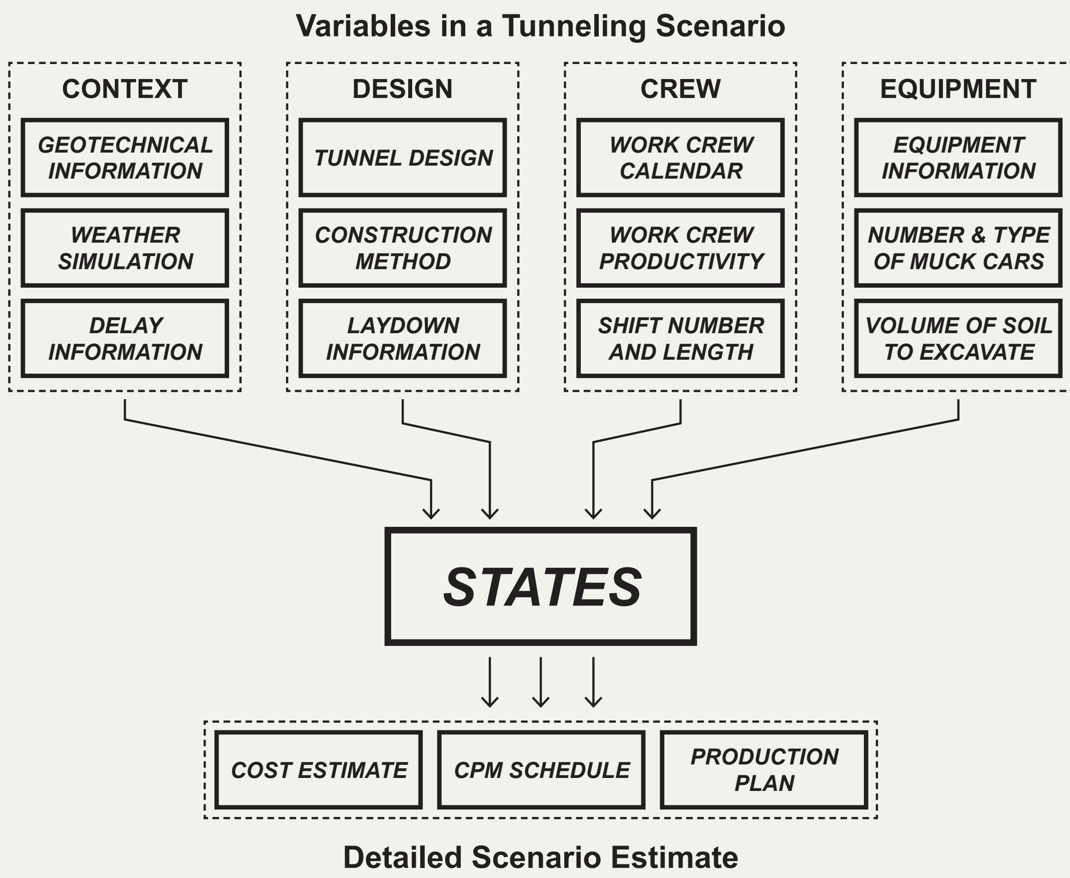


Diagram of STATES Inputs and Outputs

After defining these elements, users can access the lowest level of the simulation by double-clicking on one of them. Here, the user can drag and drop elements representing the actual work tasks that comprise a work package and connect them together in the order that they will occur during tunnel construction. Tasks can be defined to take place in parallel as well as linearly. This flexible approach allows the user to explore different approaches for constructing the tunnel, instead of limiting them to one predefined sequence.

COST INFO

Once these generic work task elements exist, users can input data into them such as details about the work crew and what schedule they will work on. STATES is integrated with a tunnel cost database, SmartEST, which plays a key role in estimating the direct costs of the project. When defining new labour crews, the user inputs information such as the position of a worker and the quantity of a task into SmartEST; however, the user can simply select "import from SmartEST" and use predefined crew data. This database, assembled from City historic data and the many tunneling projects SMA has experience on, is a strong asset for producing quick estimates in the early project planning phases.

MONTE CARLO SIMULATION

Once the user has defined all of the work packages of the project, as well as the task elements that comprise them, they can run the simulation. STATES makes use of Monte Carlo sampling to test a single scenario multiple times. For instance, a single tunnel construction scenario may be simulated 'n' times, allowing different setbacks to occur each time the tunnel is 'built' in the simulation. The resulting projections from this robust iterative process are much more accurate, reflecting the far larger pool of data that is generated by building the same tunnel numerous times.

THE RESULTS

The final data generated by a simulation is automatically formatted as industry standard cost estimates, network schedules, and production plans. Once preliminary designs have been produced, construction planners rely on their cost and schedule estimates to guide them in selecting a design. The simulation, here, is a tool for the construction planner to rapidly and accurately produce the cost and schedule estimates for any preliminary design, or to analyze an in-progress tunnel, to optimize their decision making process. Project costs and schedules are generated in a Work Package model, consistent with industry standards. The structure of the model allows planners to alter particular work packages if their costs are projected to be much higher than expected.

STATES significantly reduces the development time and consistency of creating budget and schedule estimates, compared with standard estimation and scheduling practices. Further, the cost and schedule estimates are both more accurate and more accurately linked, because they are developed from the same base model. In typical practice, different people would develop the cost estimate and the schedule estimate using their own proprietary base models.

We hope this brief summary begins to convey the significant advance that STATES represents for tunneling. The ability to conveniently model tunnel scenarios, then quickly simulate them and generate highly detailed budget, schedule, and production plan estimates is unprecedented for construction planners and managers.

Case Studies

SMA developed STATES based on its extensive experience encountering and solving problems faced by tunneling projects. The software's development has been repeatedly adjusted to respond to the needs we've encountered on projects, and STATES has already been used with great success on a number of projects.

CONSTRUCTION METHOD DECISIONS ON W12

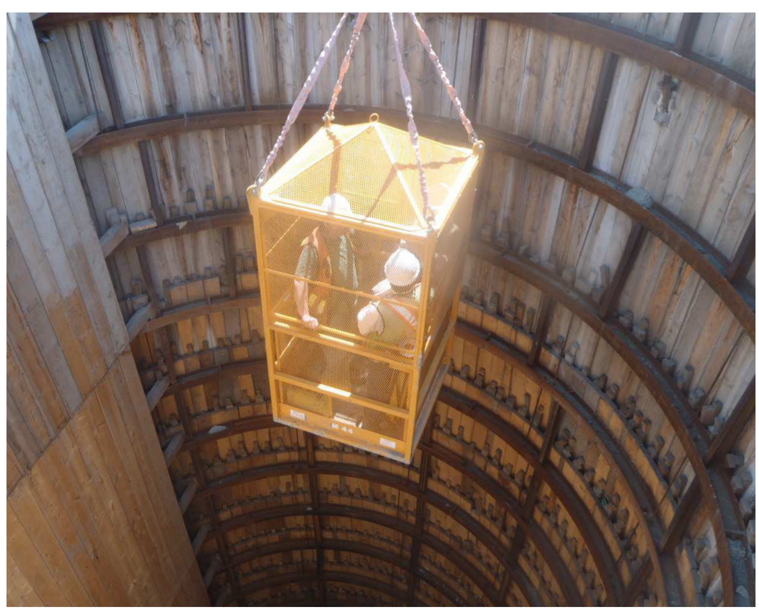
STATES was used to optimize the W12 tunnel construction. W12 is a 1135m syphon tunnel under the North Saskatchewan River connecting Northwest Edmonton to the Goldbar Wastewater Treatment Plant. The optimal tunneling approach needed to be chosen early in the project, and we used STATES to simulate the three approaches that had been identified. Two of the approaches used an 80m deep material handling shaft, and the simulation allowed us to see just how negatively this impacted productivity. The fact that the shaft would also require a specialty hoist, and that the hoist would have no redundancy in case of breakdown, further emphasized the added risk to these two methods. STATES confirmed that the third approach, using two-way tunneling, was the optimal one.

Later in W12, SMA used STATES to simulate what type of secondary liner should be used in the tunnel. It was vital that the pipes had zero infiltration from the sensitive underground conditions they passed through (an area with abandoned coal mines and trapped methane gas), and so this choice was a very significant one. Cast-in-place concrete, precast pipe sections, steel pipes with lining, or HOBAS pipe were all options. We gathered all of the relevant data through consultation with the project team and a literature review, and then made various assumptions for the purpose of the simulation model: shift length, tunnel length, average production, distance between pumping wells, duration of concrete pouring activities, duration for track installation, time for grouting, and so forth. The data from the simulations was analyzed, and it was clear that the HOBAS pipes were the best choice. They performed very well on the project, and pressure tests confirmed zero exfiltration (and thus zero infiltration).

OPTIMIZING PRODUCTIVITY ON W13

The W13 tunnel is a component of Edmonton's West End Sanitary Sewer (WESS) project, running for 1km with a diameter of 2.3m. The tunnel was constructed to mitigate a critical bottleneck in the system that was inhibiting future growth and had contributed to flooding in 2004. While the project initially seemed straightforward, major setbacks occurred such as sticky clay clogging the Tunnel Boring Machine, and hitting and abandoned concrete pipe near the end of the project.

Once it became clear that the project was suffering and may not meet its schedule, SMA performed Method Productivity Delay Modelling (MPDM) within STATES. Through careful observation of tunnel progress over a month, we quantified delays and observed their causes (eg. equipment breakdown, encountering boulders, etc.), and then built a model from the information.



The W12 Shaft

Analyzing the model results allowed us to implement solutions such as weekend shifts, proactive weekly maintenance on the TBM to identify problems before they led to equipment failure, and a new soil conditioning agent for dealing with the clay. These strategies led to an impressive tripling of productivity (defined as the number of meters of tunnel excavated per day). Despite these setbacks initially leading to projections that the project would be 30% over budget, using STATES and MPDM gave us the necessary data to respond to the setbacks. While it took slightly longer than planned to finish W13, the project was completed under budget.

IMPROVING THE PROCESS ON SA10A

The SA10A tunnel will be part of the South Edmonton Sanitary Sewer system, servicing a previously undeveloped area. STATES was used to simulate the entire construction phase of this tunnel, encompassing the following work packages: working shaft, working undercut, startup tunnel, tunnel excavation, removal shaft, removal undercut, connection tunnel, and wet/dry well shaft. Information from previous tunneling projects was used to define the characteristics of the TBM, and the geotechnical conditions of the site were added to the model. 6 scenarios were developed, all based off of a 10 hour shift with two trains to remove excavated material and a switch in the working shaft area. The scenarios were run, and generated a variety of budgets and project completion dates.

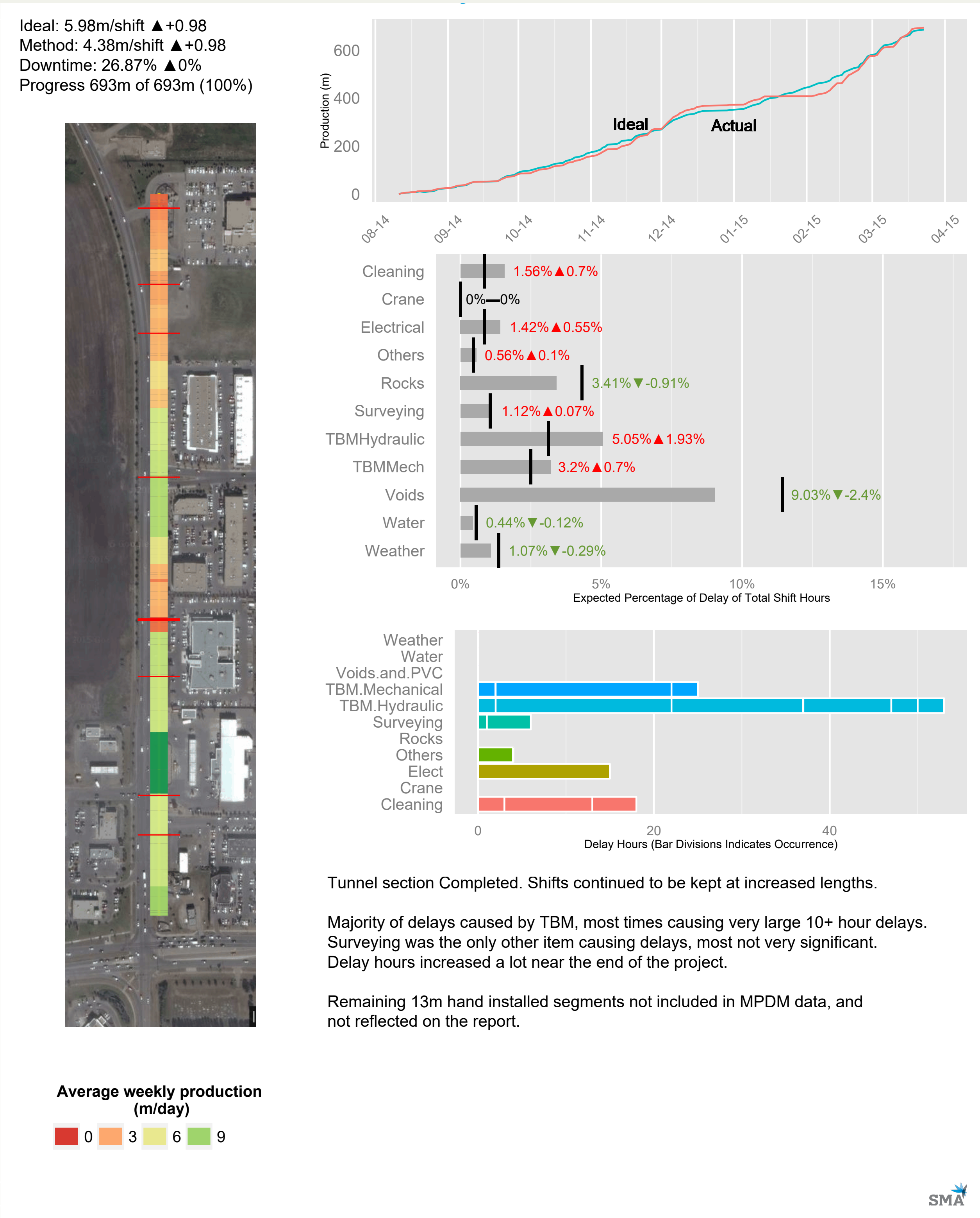
Complexity

- Uses discrete-event simulation, Markov chain modelling, Monte Carlo sampling, distribution fitting, and other statistical analysis techniques
- Integrates hundreds of variables into the model
- Based on thousands of hours of data collection
- Developed and refined over several years
- Integrates information from over a dozen tunneling projects

The detailed results from the simulation allowed us to confidently recommend that the City begin the project with a single 10 hour shift combined with the productivity targets of scenario 2, then switch to a single 8 hour shift to save costs once excavation had proceeded past the clay till soil layer, and the situation had been re-evaluated and re-simulated reflecting the additional information the crew would have. This approach will prevent the team from getting behind early on the project, creating a rushed atmosphere, and will instead give them some buffer time in case of unforeseen setbacks.

DESIGN OPTIMIZATION ON SW4

The City of Edmonton's SW4 project is a 1.5 km, 2920 mm in diameter sanitary tunnel currently just beginning construction in



Data Gathering and Refinement using Method Productivity Delay Modeling

The method productivity delay model technique, or MPDM, was developed by Adrian et al. in 1976 to enable construction firms to measure, predict, and improve construction productivity. The process is straightforward: during a construction production cycle, the observer notes the amount and types of delays which occur. Analysis of the data can show the effect of delays, and can help target improvements toward the delays which have the most impact on productivity. The data itself is also invaluable for simulation; with each project, the simulation techniques are improved. The use of MPDM on tunneling projects also allows for STATES tunnel simulations to be updated partway through the project for forecasting purposes, which increases accuracy. SMA strives to integrate the MPDM technique into all tunneling projects; future plans for STATES will involve more real-time updating and further ongoing linkage with the MPDM data. A sample MPDM and productivity/forecasting dashboard for a tunnel project is shown above.

Southwest Edmonton. 780 m of the tunnel alignment is curved; the survey requirements and construction challenges of curved tunneling make this extremely difficult to model. STATES was used during the design phase to test and evaluate 12 different scenarios before the project team settled on the final option, including examination of different combinations of shift lengths and one-way vs. two-way tunneling. When SW4 is complete, it will provide critical sanitary service to new developments in southwest Edmonton.

Social and Economic Benefits

- Supports the construction of tunnel projects that are reducing flooding
- Optimizes tax dollars spent on municipal infrastructure

Environmental Benefits

- Supports the construction of tunnel projects that are helping remove millions of litres of Combined Sewer Overflows from the North Saskatchewan River
- Helps planners optimize the environmental impact of the tunneling projects

Conclusion

STATES is a robust, state-of-the-art simulation platform unique in Canada for planning and managing tunneling projects. The use of simulation allows STATES to both create highly accurate budget and schedule estimates, and to forecast how likely a project is to meet them. STATES synthesizes SMA's extensive experience in tunneling and construction simulation into a single powerful, predictive tool, giving the client unprecedented decision support information to make their projects more efficient and effective. This new paradigm allows services such as value engineering and constructability reviews to have multiple project scenarios quickly developed for them, allowing construction planners and managers to make better informed decisions. Updating the simulation during construction allows managers to better gauge the real progress of their tunnel, with new forecasts for completion date, productivities, and costs reflecting how the project has developed to date.

STATES has been used on more than twelve projects totalling close to $200 Million in capital costs. SMA continues development of the tool; for instance, we are currently incorporating a higher degree of detail for the types of delays that can be experienced during tunneling to allow for better delay projection using Markovian Chains and Baysian updating techniques. Optimizing STATES for monitoring ongoing tunnel construction is another priority.

Our confidence in STATES comes from the many projects on which it has been successfully deployed and its major contributions towards increased efficiency and critical problem solving. This versatility highlights the many ways in which it can be used to optimize future tunneling projects of all varieties, in all phases of the project. Optimal projects that meet their budgets and schedules are rewarding for everyone involved: planners, managers, workers, and taxpayers.