The Application of Front End Planning and Special Purpose Simulation Templates to Drainage Tunnel Construction

by

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Preface

Some of the research conducted for this thesis has been published or will be published, and represents collaborative work done by Dr. Simaan AbouRizk, Steven Hague, and Dr. Yasser Mohamed at the University of Alberta, as well as industry collaborator Junhao Zou of the City of Edmonton.

A summarized version of Chapter 2 was submitted as Newstead, S., Zou, J., and AbouRizk, S. (2015). "Examination of application of front end planning." *Proc., International Construction Specialty Conference*, CSCE (submitted).

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A version of Chapter 4 will be submitted as a paper in the Construction Research Congress 2016.

The thesis follows a multiple-manuscript format as the research method was applied to two different problems from industry.

Abstract

The Construction Industry Institute (CII) has a best practice under the heading "Front End Planning" (1995) that is meant to ensure that projects are as complete, as optimized, and as certain as possible throughout the project life cycle. In order to demonstrate this, the Project Definition Rating Index (PDRI) was optimized to suit underground drainage tunnel construction. The rating index has been successfully used for 2 of 3 key area workshops to demonstrate the usefulness of this tool to both the case study and the construction industry. A special purpose simulation template was created for use in the simulation environment Simphony, specifically for underground drainage tunnel construction. This proved to be extremely helpful in the front end planning of the case construction project to confirm alternate construction alignments, construction methods, and what type of shifts and crews were necessary to meet a targeted construction budget and schedule deadline. The selected model was then updated throughout the construction phase of the project to confirm the necessary crews and schedule to complete the project within the deadline and budget.

Acknowledgements

I would like to thank Dr. AbouRizk for the enormous amount of time and effort that he has spent with me to help me complete this thesis. Without his support, guidance and structure I would have never put this together. I am the luckiest student/son in-law to have had the training and wisdom that he has provided me over the many years that I have known him and have been doing my masters. It truly has been an honor to be given the opportunity of a lifetime to work with him and absorb the infinite amount of knowledge that he has.

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A large part of me being able to physically and mentally write this thesis is due to my beautiful wife Hala AbouRizk-Newstead. Her love and support drove me to complete this master's program. The months leading up to completing this thesis she has been so supportive, absorbing my highs and lows that come with this large undertaking. She has given me the perfect atmosphere that any husband could ever ask for.

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1 THESIS INTRODUCTION

Underground pipe installation typically has two installation methods, trenchless and open cut. The open cut method of installation is suitable (cost effective) to installation depths typically less than 7 meters. Open cut construction requires a large amount of surface area to complete, as a 2:1 slope for a typical open cut angle is typically required. The surface disruption to road traffic and interference with shallow utilities often makes trenchless construction more desirable even though it may have a higher unit cost. Trenchless construction is suitable for many depth applications, but is constrained by the type of ground that is present.

Trenchless excavation methods vary between hand excavation and machine excavation. For the purpose of this thesis, I will focus on the machine excavation application, and in particular, the tunnel boring machine (TBM) application. Hand excavation or Sequential Excavation Method (SEM) is also used to excavate small sections of the tunnels that have a smaller diameter of pipe being installed. SEM is used for the excavation of the undercut/working area of the TBM tunnels, as this is required to be a two-staged or benched SEM section to accept the TBM for assembly. The TBM excavation is an open-face machine that uses large hydraulic pistons to push itself forward through the excavation alignment. The TBM head rotates and the large teeth on the front cut into the ground and pull the soil into the TBM on a conveyer system. Once on the conveyer system, a belt moves the soil to the back of the machine where a train and muck car system is waiting. Each of the muck cars on the train fills with what equates to one fully excavated meter. At this point, the TBM will stop excavating and install concrete segmental liners while the full train takes the soil back to the working shaft where a crane is waiting above ground to lift and dump the muck cars' soil. While this is happening, a secondary train has started to proceed to the TBM from the working shaft and the process repeats itself.

The planning of this process takes place over several months through several workshops until a construction method is chosen and funding is obtained. The project team is assembled and resources are committed to the project. The design is then produced to substantial completion, and an estimate and schedule are formed. The project team then comes to agreement about the final schedule and estimate and the project is passed into the construction phase. The remaining design work is finished during the construction phase. Once the project is near the completion of the construction phase, the project team then assembles a commissioning plan for the project to be put into service. The construction then concludes and as-built data is surveyed and recorded to be added to records. A project close out meeting is performed and lessons learned are captured.

[redacted] Goals and objectives

The overarching goal of this research is to enhance planning and control of utility tunnel construction projects.

There are two specific objectives:

- Adapt the CII Project Development Rating Index (PDRI) and project alignment best practices through simplification and integration with current project management processes for utility tunnel construction.

- Automate the production of tunnel plans (estimates and schedules) through special purpose simulation modeling to enhance the accuracy and reliability of such plans.

[redacted] Scope

The scope of this thesis is limited to the planning and control of utility tunnel construction. Although the concepts investigated and the methods used apply to other types of construction, limiting the scope to utility tunnel construction enables achievement of the stated objectives as both require close association between the development work and the immediate application area in order to be meaningful.

[redacted] Approach

The research project starts with a literature review and an exploration of how planning and control of tunnel projects are accomplished in industry. The results of the literature review are documented in two separate chapters. The understanding of how planning and control are done in industry will be achieved through careful assessment of a recently completed project in which the author was involved, the West Edmonton Sanitary Sewer System Stage: W13, and through an ongoing project, the South Edmonton Sanitary Sewer System Stage: SA1A project, which involves two contractors: The City of Edmonton internal forces and the Shanghi Construction Group Canada (SCGC). This understanding is also complemented by the author's own experience in this area of application, which spans five years, and his prior interactions and discussions with experts in the field. The outcome of this phase is an understanding of the life cycle of tunnel construction projects (design, construction, tender and operations), and a reasonable work breakdown structure that can be adopted and applied as needed in the thesis. The WBS is foundational for proper project management, and therefore, critical for this research. Since numerous projects have been completed in this regard, I will adopt the latest one that is most aligned with this research, that of Moghani (2013) and Ghaznavi (2013). The findings of this part of the research are also documented in two separate chapters, as well as in the case study chapter.

Once the literature has been reviewed and the practice understood, the research will focus on the first objective of the thesis: that of adapting the PDRI and project alignment best practices from CII to this application area. The PDRI had been derived for industrial construction and later adapted to building construction works. The rationale for adapting the PDRI and Alignment best practices is that CII research had shown that through their applications in industrial construction, savings were achieved and reliability of project delivery was enhanced. The specific methods for this phase are as follows:

- Explore the use of the PDRI concept for planning the work from phase to phase to ensure healthy project transitioning. This is completed by studying the CII best practice as applied to other construction disciplines (industrial and building construction), and then re-deriving the same for the application area.
- Since the output of this study will be project criteria that need to be tracked to feed the overall project health index known as the PDRI, a tool will be composed (a simple spreadsheet) that provides input on the health of the project. This will be deployed in Excel for ease of use. Although the method

requires benchmarking to define the thresholds for various PDRI indexes, this will not be fully completed in this study, as numerous projects need to be tracked and recorded prior to such derivation, thus requiring more time than available in this research. I will, however, commence the benchmarking exercise and set it up for future completion.

- Investigate the CII project alignment concepts and integrate them into the project planning and control processes currently in use in industry to enhance project performance. I believe that current practices of value engineering, risk analysis and management, constructability reviews and similar processes provide the medium for incorporating alignment principles, thus enhancing the project without significant increase in effort.

The second objective of the research explores the use of simulation as a service to facilitate the provision of accurate plans (estimates and schedules and resource plans) in a less intrusive manner. To achieve this objective, I undertake the following:

- Adapting the special purpose modeling concepts to enable the delivery of standard services required in industry, namely: estimates, schedules and work plans. I achieve this by:
    - Studying the SPS tunneling approach and determining what is required to enable its use as a service.
    - Developing the required extensions to the SPS template.
    - Applying them to a demonstration project for proof of concept.
- The TBM penetration, the breakdowns, etc.

Finally, the final phase of the research is a case study where I apply the findings of the research to an on-going project in shadow of current practices. I will also use this case study to validate the revised SPS template.

[redacted] Thesis organization

The thesis is presented in a paper format. It includes two papers and one case study paper. In addition to the three chapters, there is an introduction and a conclusion chapter.

Specifically, the thesis is organized as follows:

- Chapter 1 is the introduction.
- Chapter 2 focuses on adaptation of front end planning for tunnel planning.
- Chapter 3 focuses on the use of simulation as a service.
- Chapter 4 is a case study.
- Chapter 5 is the conclusions.

[redacted] Contributions

The following are the contributions of this thesis to the body of knowledge and to practice:

- Simplified the PDRI for small diameter utility tunnel construction by selecting applicable factors through understanding of how drainage projects are run and understanding how drainage and design construction (DDC) works (following their processes).

- Conceptualized and implemented a modeling strategy to make simulation more practical for tunnel planning and to better facilitate its use as a service. For simulation to be practical in planning it needs to be harmonized with planning tools commonly used in construction, especially estimating and scheduling.
- Enriched special purpose simulation (SPS) tools for tunneling with what is required to produce a full estimate and a full schedule. The integration of the SPS with estimating was done with SMARTEST, and for scheduling, through MS Project. To achieve this, a WBS had to be common to the simulation model as well as to the estimate and the schedule. Those were integrated by having the modeling elements in the SPS template have all physical parameters required for estimating, having all resources used in the simulation link directly to those in the estimate.
- Studied and analysed historical data that was collected from various projects to understand the nature of interruptions during work flow and documented those in statistical distributions and probabilities for breakdown events.

2 THE APPLICATION OF FRONT END PLANNING TO DESIGN AND CONSTRUCTION OF UTILITY TUNNEL CONSTRUCTION

[redacted] Introduction

A project can be defined as a unique, one-time operation designed to accomplish a set of objectives in a limited time frame. For example, building a bridge, designing a new product, software development, and implementing an ERP system.

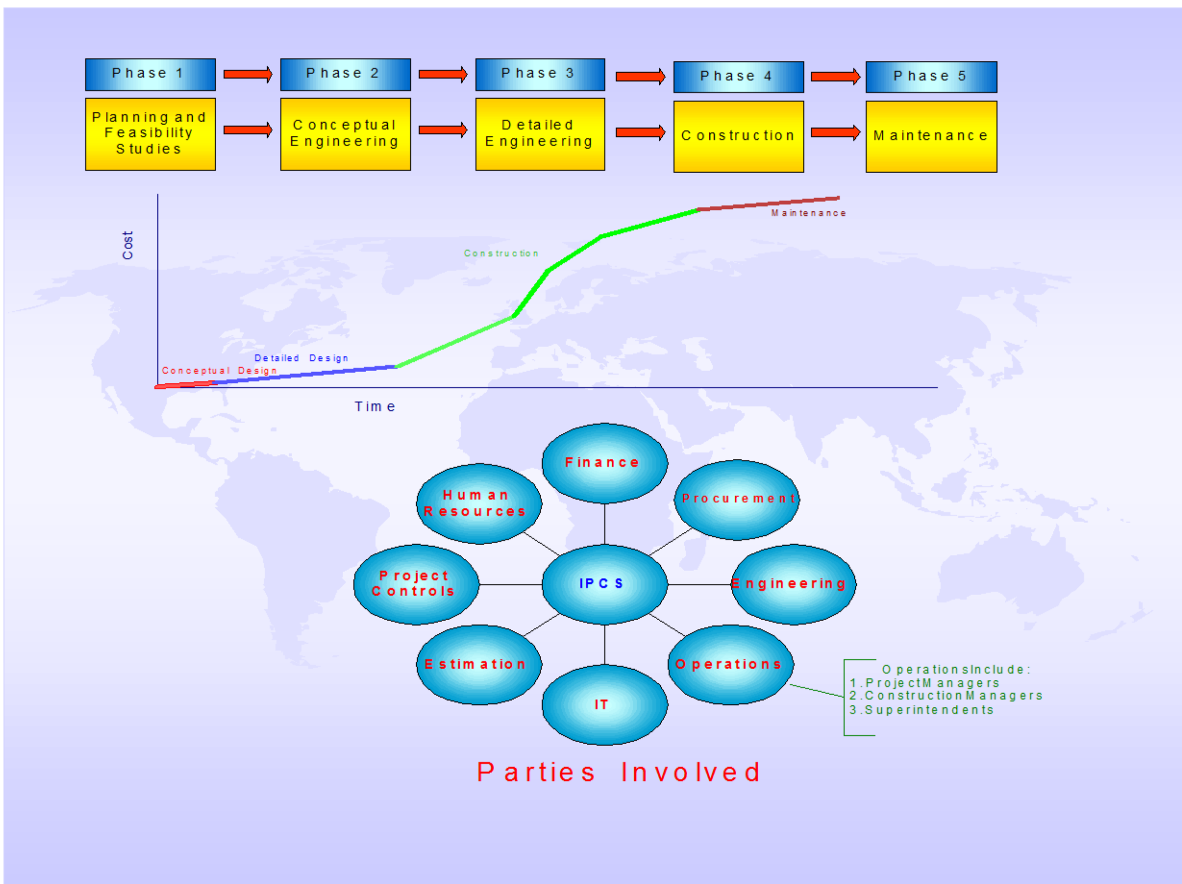

Figure 1: Phases of a construction project

Utility tunnel projects, like most other construction projects, follow a life cycle, as shown in Figure 1. The project purpose is generally to provide a medium for drainage, water, power, gas and other utility services underground. Tunnel projects can be constructed using an open cut method if they are reasonably shallow (approximately less than 7 meters deep), or through trenchless methods using a tunnel boring machine (TBM) or the sequential excavation method (SEM). The first step in the life cycle is to develop a concept design. The concept generally assesses feasibility of various alternatives for the design, and details critical elements of the project while also providing high level estimates and schedules for the project. The deliverables of the concept design vary widely as there are no specific standards that spell out required deliverables from a concept design. The experience of the author indicates that at concept, generally some alternative design options have been provided, including basic hydraulic analysis, sizing options for the tunnel, horizontal/vertical alignments, open cut and trenchless methods for construction. Those alternatives would have been vetted, but at a high level (not much detail in the design). Cost Engineering Standard (AACE, 2012) shows that in general, only 15% of the design effort would have been expended at this stage of the design, and therefore, it is not possible to include many details. A recommended option is generally provided along with approximate costs within 50% accuracy and a high level schedule.

The second phase of the design is the preliminary design phase. In this phase more than 30% of design resources are generally expended, and subsequently, the expectation is that more than 30% of the design has been completed. Deliverables of this phase generally include a geotechnical report, tunnel sizing resulting from the hydraulic analysis (in case of drainage), final alignment (horizontal and vertical), various connections, construction method(s), and the locations and basic design of the shafts, along with detailed cost estimates within 30% accuracy and a schedule. The preliminary design is a critical stage of the design process as most significant aspects of the project are determined at this stage.

The detailed design phase follows preliminary design and focuses on detailing the preliminary design to the level required for contractors to produce shop drawings. A detailed design generally has all information required to produce the desired final product. The detailed design would normally also include details that facilitate the installation of the TBM for trenchless construction, the potential site layout, all permits and authorization, specifications related to materials used (e.g., precast panels), all geotechnical investigations, environmental reports, etc. In essence, all contract material is ready after this stage, including drawings and specifications.

The tendering phase is sandwiched between the detailed design and construction phases. This is an important phase of the project where the owner and its engineer decide on who will build the project, as well as at times whether to order specific equipment and material if they are outside the scope of the contractor's work.

The construction phase involves preplanning and construction activities. It also includes producing all shop drawings and designing all temporary structures. Planning activities include site layout, site servicing, construction strategies, control budgets, baseline schedules, crews and resourcing strategies, etc. Those can be generally structured as a project execution plan.

Once construction is complete the hand-over activities take place and the project is commissioned.

One of the main challenges associated with improving tunnelling projects is reducing uncertainty. This, in general, can be achieved through obtaining more information to facilitate better decision making and by ensuring that all necessary analysis and designs have been properly and fully completed and that the deliverables are appropriate as one moves from one stage to another in the project life cycle. One can think of these as gates where checks and balances are put in place to ensure that when the project moves from one stage to another, it is as complete and as certain as it could possibly be.

The Construction Industry Institute (CII) has a best practice under the heading "Front End Planning" (CII, 1995) that is meant to ensure that projects are as complete, as optimized, and as certain as they can be throughout the project life cycle. The CII best practice applies to all types of construction, but generally leans towards large industrial projects. In their studies, CII has shown that increasing effort at the earlier stages of the project (front end planning), and as early in the life cycle as possible, showed a greater chance of achieving project success. Of those projects that included front end planning, cost savings for the projects ranged from 6% to 25% and schedule savings of 6% to 39% (CII, 1997).

Front end planning commits resources required to complete a project in a given amount of time. For this to happen, a team must be created that has a perfect blend of field experience and construction knowledge. This team must dig up sufficient information to get a proper understanding of what challenges the project at hand faces. Once this has happened, the information should be presented to the owner who must commit the required resources to the project (CII, 1997).

[redacted] An overview of the demonstration subject – Drainage Design and Construction

The City of Edmonton's Drainage Design and Construction (DDC) branch specializes in the construction of underground infrastructure for Edmonton. DDC has over 100 years of tunneling experience, and continuously incorporates new tunneling technologies to improve project time and cost efficiency. DDC acts as the prime contractor or sub-contractor in providing underground infrastructure for construction firms and private developers. DDC's design services include designing underground infrastructure that includes structures such as pump stations, manhole shafts, and sewer trunks. DDC's other design services include neighborhood renewal projects, flood prevention programs, and new infrastructure expansion projects. DDC's construction services include open cut/small diameter trenchless tunnel installation with various technology including pilot tube micro tunneling, pipe bursting, and pipe ramming. DDC provides large diameter tunnel installation utilizing Tunnel Boring Machines, and hand excavation methods.

DDC fabricates and maintains all of its equipment with its own staff, shop, and personnel. DDC also purchases all of its materials from local suppliers for its underground infrastructure services. The main source of its precast tunnel material is procured and coordinated through a local supplier.

[redacted] Objectives

The objective of this part of the research is to study the CII front end planning approach and investigate its applicability to utility tunnel construction. The CII methods were developed for industrial construction projects. In order to carry this investigation and transfer this approach to drainage tunnel construction I apply it to Drainage Design and Construction (DDC) at the City of Edmonton, which currently does not use this best practice for its projects. Using such a demonstration will provide insight to others on how to apply the best practice to various areas of construction application. The contributions will be in the transfer of the best practice principles to a smaller organization in a discipline that the best practice was not intended for.

To facilitate front end planning, CII has developed two key processes that provide efficient information gathering for the project team and owner. These are 1) Alignment, 2) Project Development Rating Index (PDRI).

Alignment is most successful at influencing a project's success when adapted to the project at the earliest point. Alignment of an organization is three-dimensional, such that there is a top to bottom dimension, cross organizational dimension, and the project life cycle dimension. The organization should ensure that the proper culture, execution process, information, and tools exist to allow alignment to take place. Once barriers to alignment have been removed, 10 critical alignment issues exist that make up the alignment effort score. The alignment effort score has been positively shown to lead to overall project success (CII, 1997).

PDRI is a checklist supported with an evaluation process to ensure that the project is ready to pass the various gates during the life cycle. The focus is on the project scope being sufficiently defined as the design matures to minimize risk of failure and maximize value to the owner. PDRI includes numerous criteria that are checked at each gate during the project life cycle and given a score. The various criteria have weights associated with them. The weighted scores are a weighted average score for the project produced. Through benchmarking successful projects, the best practice shows that a score of 200 or lower results in a higher likelihood of project success (CII, 1999).

Alignment

The alignment model has been established to ensure that all the different project groups can determine a set of common goals to work towards together, rather than side tracking and pulling other team members along with them. The key to this model functioning properly is to establish common goals from which commitment is based off of. Each group or individual must establish a common goal and commit to the completion of that goal in order to have long term project success (CII, 1999). CII research showed that there is a common misalignment of the groups or individuals to the goals established for the project, which leads to improper communication and disagreement throughout the life of the project.

Alignment refers to bringing differing priorities and requirements from the diverse groups of project participants into a uniform set of objectives that will meet the business needs of the facility being constructed.

The typical pre-project team should consist of a number of individuals representing a wide range of the industry, so that every aspect of the project can be properly assessed and pertinent information extracted from the limited information that is available. In drainage construction for example, a project would include owner representatives, designers that specialize in hydraulics, structures, geotechnical, environmental, etc., contractors and subcontractors, suppliers and procurement specialists and many others. Alignment is a necessary process that will pull all participants in the same direction so that everyone is collectively focused on meeting the project objectives (CII, 1997). Commitment from all of the members of the project team must be achieved in order for accountability to be realized for the project's goals.

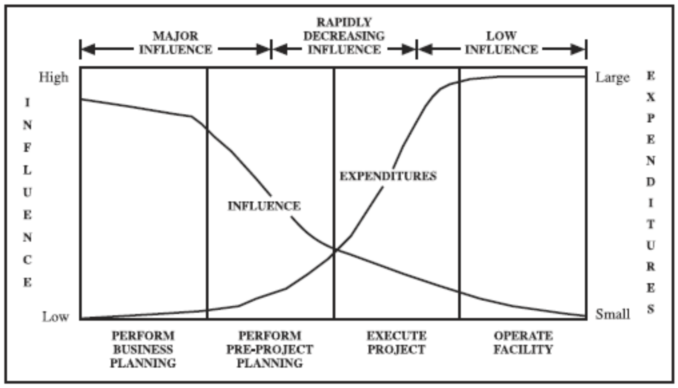

Figure 2: Alignment influence vs. expenditure (CII, 1997)

The alignment model developed 3 dimensions of alignment within a project. The first dimension is a top to bottom alignment in the organization from executives to role playing individuals. The second dimension is the cross organizational alignment from project managers to overhead staff. The third dimension is the project life cycle alignment where pre-project planning and operation are aligned and goals are set (CII, 1997).

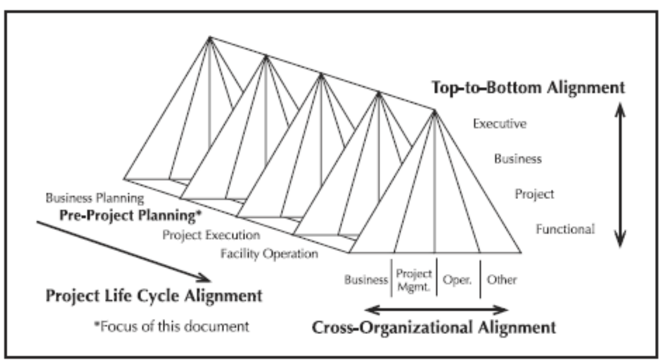

Figure 3: Organizational alignment (CII, 1997)

Alignment in the pre-project planning stage identified 5 categories of importance. First is the execution process, such as processes and procedures that exist. Second is company culture, such as the values and the working environment that the company has created. Third is information that is used to define the scope of the project. Fourth is whether any barriers exist to prohibit alignment. Fifth is the tools and software that are used to manage projects (CII, 1997).

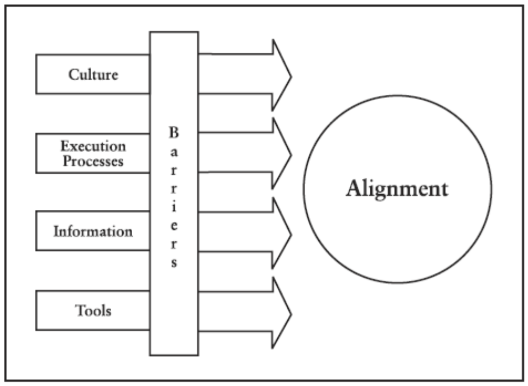

Figure 4: Barrier to alignment (CII, 1997)

CII validated the above alignment critical issues in the form of an alignment effort, and measured this against the success index.

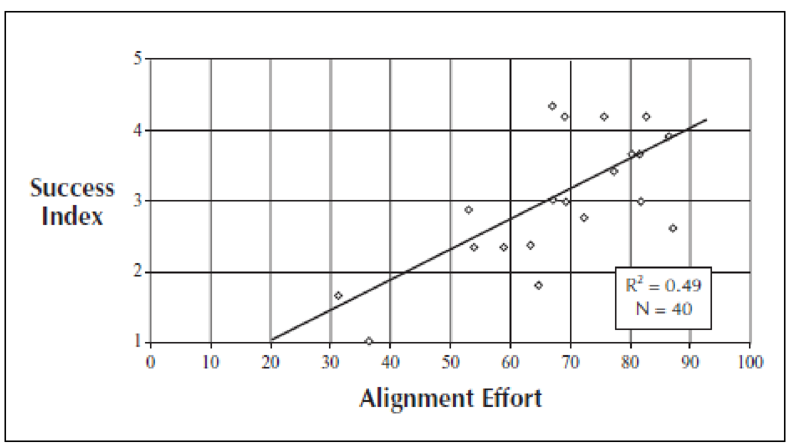

Figure 5: Alignment effort vs. success index (CII, 1997)

This shows that the higher the alignment effort that is put in to the project, the more successful the project will be (CII, 1997).

[redacted] Project development rating index (PDRI)

The Project Development Rating Index (PDRI) is an indicator that summarizes the aggregate values of 70 indicators grouped into 15 categories, which are further grouped into 3 main sections for clarity and ease of use. Those indicators were determined by CII to impact the development of a project as it transitions from one stage of its life cycle to another. For example, as the project completes a concept design, the scores on its 70 indicators will result in a PDRI value that reflects whether the project is ready to move to a preliminary design stage or not. A weighting system was put in place such that the indicators that would seriously alter the project's performance were weighted higher than elements that wouldn't. This was completed throughout the course of 2 workshops with 54 industry experienced individuals that were each asked to weight the elements based on their own personal experience (CII, 1997).

Validation of the PDRI scoring system was conducted to eliminate any error from biased responses from the weighting system. This was done by selecting a sample size of 40 projects and each was given a PDRI score. This scoring was given after all of the projects were completed to ensure knowledge of how successful the project was. The PDRI score was then related to the success index that has previously been developed by CII. The success index is scored from 1-5 and is composed of 4 categories that look at cost performance, schedule performance, 6 month percent design capacity attained, and plant utilization at 6 months. It has been shown through extensive research that a success index score of 3 or higher will indicate that the project has met or exceeded expectations in the 4 above-mentioned categories (CII, 1997).

The 40 projects showed a relationship of the PDRI score against the success score, such that a lower PDRI score indicates a higher success index score. It was shown that a PDRI score of 200 gave a success index score of 3; as mentioned above, this score exceeded expectations in the 4 key project performance indicators. Projects that achieved a PDRI score of 200 or greater showed a higher rate of success than projects with a PDRI score below 200 (CII, 1999).

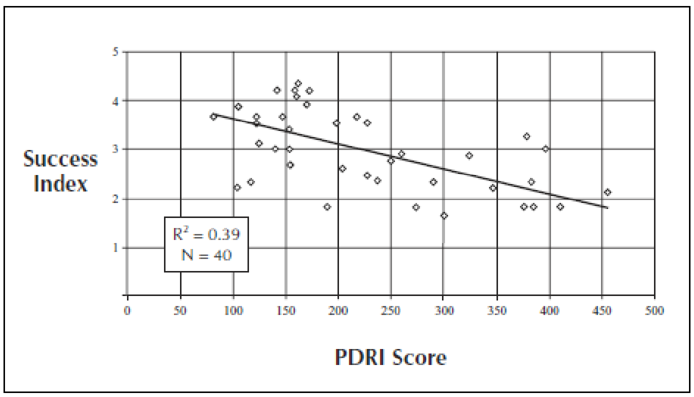

Figure 6: Success index vs. PDRI score (CII, 1997)

Overall, the PDRI provides both owners and contractors with a tool that will highlight key areas of the project's scope that are lagging and requiring additional attention and definition.

[redacted] Applicability of the project alignment to the demonstration subject - DDC

CII defined 10 critical alignment issues which were ranked in terms of their importance level, as given in Column 1 of Table 1. In reviewing these alignment issues, I propose to attempt to incorporate them into the execution of drainage projects using existing processes by simply appending the required issue to the process as it is encountered. For example, Value Engineering (VE), Risk Analysis, Constructability Reviews and Partnering are processes used during project execution. These well-established processes can easily incorporate the requirements for alignment with minimal additional effort. Table 1 summarizes the critical CII alignment issues in Column 1 and shows how they can be incorporated into the existing processes in Column 2.

Table 1: Alignment issues and how they can be applied to a drainage project

CII alignment issue	**Incorporating the alignment issue in drainage projects**
Stakeholders are appropriately represented on the project team.	The VE process generally includes representatives of all stakeholders on the project. Those participating in the VE workshop can assess and subsequently ensure that all stakeholders are appropriately represented on the project team. Facility functions, project goals and alternatives are generally formulated and evaluated during the

	VE exercise. I simply recommend adding the assessment of the suitability of the project team by those participating and recommending enhancement as warranted.
Project leadership is defined, effective, and accountable.	When a project is set up, PMI recommends appointing a clear project leader with authority and accountability to execute the project. While this is simply a management and company culture matter for drainage owners/designers/contractors, a number of checks can be made during key project gates to assess the project leadership. Although such leadership is not easy to directly measure, it can be assessed through a surrogate through the PDRI rating (to be discussed later). Poor PDRI ratings could point to a number of problems on the project including leadership. Furthermore, if the project is implementing formal partnering approach to the job, this can be used as a vehicle to identify leadership issues and correct them.
The priority between cost, schedule, and	The VE process at its core establishes criteria to assess project alternatives. The schedule is generally part of the criteria (if not it can simply

required project features is clear.	be added). Project features compose the balance of the criteria, which are important to the owner, while cost is the denominator in the value equation (Value of all criteria/Cost –yields the best alternative). To incorporate this criteria for alignment I simply recommend that during the VE process, project participants establish the priority (as it would be evident by then) in a formal manner. Since project features are represented by other criteria, and the schedule is represented and all have been given weights for evaluation of design alternative purposes then the only aspect not rated directly is cost (as it is paramount in VE). To resolve this, project participants then define the ranking and weighting of cost along with the other criteria as an addendum to the VE process. Then provide direction to the project leader so that he/she can guide the implementation of alignment with those priorities in mind.
Communication within the team and with	Communication is part of the project management process and is generally mature in various organizations. The approach to its execution varies

stakeholders is open and effective.	widely and is subject to interpretation. The critical thing is to execute it effectively and to reach all stakeholders as required. The communication plan can be spelled out in the project execution plan. Its effectiveness can be reviewed during risk analysis reviews as poor communications is normally one of the risks most companies define for their projects. Therefore, if the communication plan is properly spelled out in the PEP and if the project is reviewing the risks in a formal manner at regular points in time, this can be assessed and corrections made as required.
Team meetings are timely and productive.	A significant body of knowledge on the management of project meetings exists. This issue can be easily addressed by management requirements and training.
The team culture fosters trust, honesty, and shared values.	This requires that the owner and its participants agree to a "team culture fostering trust and honesty, etc.). Given that most drainage projects are based on the traditional competitive contractual process which limits one's ability to achieve the required goals from a team culture of trust/honesty, etc., I can

	simply recommend the project partnering process to shore up this issue. Partnering is all about creating win-win situations, common goals and shared values. It can promote a culture of honesty and trust and includes "health checks" to ensure that the project does not stray from its established path.
The pre-project planning process includes sufficient funding, schedule, and scope to meet objectives.	Generally, this would require the owner recognizing that alignment will benefit the project and that he is willing to pay for it. The VE process, for example, has shown that project savings as a result of completing a VE exceeds the costs of undertaking it. The other processes are generally in place so the owner needs to promote the requirements for proper pre-planning activities and be willing to provide the funding and schedule for it.
The reward and recognition system promotes meeting project objectives.	This is an internal management issue that may be constrained in large organizations.

Teamwork and team building programs are effective.	This can best be achieved through formal partnering activities for the project at hand.
Planning tools, such as simulations, checklists, and work flow diagrams, are used effectively.	Chapter 4 discusses a tool developed for this purpose, where simulation is deployed as a service to facilitate more effective planning.

The summary in Table 1 shows that the proven criteria and issues that CII deemed essential for alignment can be applied through a combination of management decisions, existing processes, and deployment of new processes. A summary of each of the processes of Value Engineering, Risk Analysis, Constructability and Partnering as they are applied in the industry can be found in Appendix 1. It is quite evident that VE and constructability promote wider participation of all stakeholders. By their nature they require multi-disciplinary teams that have stakes in the project. The processes followed in VE are structured and therefore lend themselves further to defining project priorities of cost, schedule and quality and in defining the key objectives that everyone needs to aim for. Constructability emphasises the optimization of the three project management anchors of time, cost and quality, as well as optimizing project designs to achieve more efficiency in construction execution. The partnering process, when used in a formal manner, can promote alignment of the team especially in creating a cooperating win-win culture and in measuring project heath along the way to keep everyone aligned towards project goals.

[redacted] Applicability of PDRI concepts to the demonstration subject - DDC

In reviewing the varying aspects of the PDRI as a front end planning measure from CII, it was determined that this would be a highly applicable tool to use for drainage projects and particularly to the demonstration subject, the City of Edmonton's Drainage Design and Construction branch (DDC). Currently, there is no such measure used for the drainage industry to understand and measure the level of project development or the health of a project at any stage of the life cycle. This determination was made by the author through informal interviews with project managers from the drainage industry.

For the demonstration subject the author examined, it can be noted that projects come to DDC from the Drainage Planning Section (DP). There is no standard measure to indicate the current state of the project's health when it is passed from DP to DDC, nor is there a measure that DDC uses internally as the project completes its design stages.

In order to apply the PDRI to drainage projects, three aspects of the PDRI need to be redesigned or altered to suit the nature of drainage work:

1. Redefinition of the key indicators provided in the PDRI to be applicable to the type of work that DDC performs. This requires eliminating criteria that do not apply, modifying ones that are not suited for drainage work, and adding any missing criteria.

2. Development of a weighting system that accurately reflects the importance of certain key indicators over others. While the weighting system is generic, it is very much inclined towards industrial projects.
3. Development of a benchmarking system that will be able to score the project's current status against a known reference point to indicate the level of success that this project may have.

Due to the limitations of this study, there will not be enough time to establish a weighting system for the key indicators; as shown in the CII research, this is completed over the course of several workshops which require a significant investment of money that is not available for this research. In this demonstration, I will simply accept the weighting system produced by the CII. In the future, once this weighting system has been established, the benchmarking process can be completed on finished projects. This benchmarking should be completed on projects with a wide variety of success levels to establish an appropriate distribution to measure future projects against. Previous projects can be scored "after the fact" to establish a more defined distribution following the same process described in the CII best practice.

When applied to the demonstration project, DDC receives information about prospective drainage projects from DP, as previously indicated. The information that is supplied to DDC is then measured and designed for against current as-built drawings of the existing infrastructure. Internally DDC doesn't measure the level of completed design work or other aspects, such as stakeholder involvement, before proceeding with the construction of the project at hand. This process can be broken down into 4 key areas during the course of the project, as shown in Figure 7 (CII, 1995).

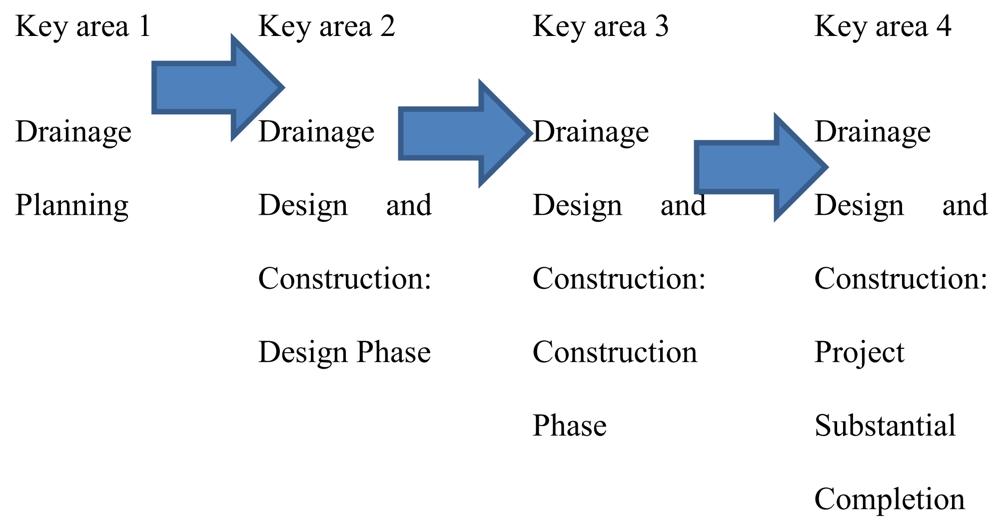

Figure 7: Project life cycle

Figure 7 shows that there are 3 areas (shown with arrows) where the project experiences noteworthy transitions. These 3 areas are where the PDRI should be conducted to give an indication of the project's health (CII, 1995). The PDRI will establish 2 key aspects of the project. First the PDRI will act as a checklist, thus indicating what areas of the project need most attention, as opposed to the areas that are in good standing. Second, the PDRI completion will indicate a project score that, through the use of established weighting and benchmarking, will indicate whether the project should be passed on to the next project area, or if further development in the current area is needed (CII, 1997). Benchmarking will help to establish scores that are shown along a distribution for the 3 transition areas that will have to be met or exceeded to be passed on to the next key area. A distribution will be created to match with a project success factor for the PDRI's performed.

The first transition area's PDRI score will be higher (less defined) than the second or last, as the project becomes more clearly defined and unknowns become know and corrected due to the previous PDRI results (CII, 1995). It is important to note that after each PDRI scoring, the 70 key indicators and their respective categories will also become populated with scores indicating the health of certain aspects of the project. The areas with higher scores should then be developed further in the current key area to improve its score for the subsequent PDRI scoring (CII, 1999).

The application of front end planning, according to CII, could potentially allow an average cost savings for projects ranged from 6–25% and an average schedule reduction of 6–39% (CII, 1997). An average Tunnel Boring Machine (TBM) excavated project is around $13,000,000, and takes roughly 3 years to complete, which translates into 650 working days.

Table 2: Average DDC project cost and schedule savings

Cost Savings	
	$ 13,000,000.00
6%	$ 780,000.00
25%	$ 3,250,000.00

Schedule Savings	
	650 days
6%	39
39%	253.5

As shown in Table 2, the potential of simply implementing this form of front end planning can show a cost savings between $780,000 and $3,250,000 on an average project with a cost of $13,000,000. The schedule savings is between 39 days to 254 days on an average project schedule that is 650 days. DDC currently spends countless engineering, drafting and project management hours producing drawings and reports that show the site layout, utility locations, eco plan, procurement plan, mobilization plan, and permits. The issue is, there may be an aspect of the project that wasn't thoroughly investigated, which could stop the project and alter its plan in such a way that causes everything that was previously produced to need to be redone.

■ The criteria that applies to drainage projects

Through informal interviews with DDC personnel, SMA Consulting project managers, and the knowledge of the author, the PDRI criteria were analyzed and those that applied to drainage projects were selected. The resulting table of criteria is given below.

Table 3: Reformatted PDRI to a drainage tunnel

SECTION I - BASIS OF PROJECT DECISION	
CATEGORY Element	Comments
A. MANUFACTURING OBJECTIVES CRITERIA	
A1. Reliability of subcontractors and consultants	
A2. Maintenance availability	
A3. Operating philosophy	
B. BUSINESS OBJECTIVES	
B1. Knowledge and partnering with construction planning branch	

B2. SSSF funding strategy	SSSF strategy is critical for DDC as it spells out the long term strategic plan for drainage.
B3. Project execution strategy	
B4. Affordability/feasibility of budget	
B5. Capacities to commence/continue project	
B6. Future expansion considerations (stubs)	A stub is essential when a tunnel will be extended in the future. If it is not included the project will be deficient.
B7. Expected project life cycle	
B8. Social issues and stake holder involvement	
C. BASIC DATA RESEARCH & DEVELOPMENT	
C1. Technology (foaming unit, ground radar)	Ground conditioning elements based on the soil layers to be excavated.

C2. Legal entitlement check for the proposed alignment	To determine that the above ground area within the tunnel alignment is accessible for laydown.
D. PROJECT SCOPE	
D1. Project objectives statement	
D2. Project design criteria	
D3. Site characteristics available vs. required	Is the land in the right of way or do I have to ask permission for access?
D4. Dismantling and removal requirements for TBM	Can I remove the TBM during regular hours or outside regular hours?
D5. Lead/discipline scope of work	
D6. Project schedule detail	
E. VALUE ENGINEERING	
E1. Process simplification	
E2. Design & material alternatives considered/rejected	

E3. Design for constructability analysis	Has the design had a constructability workshop performed for feasibility?

SECTION II - BASIS OF DESIGN	
CATEGORY Element	Comments
F. SITE INFORMATION	
F1. Site location	
F2. Surveys & soil tests	
F3. Environmental assessment (ECO plan, ESC)	
F4. Permit requirements (first call, OSCAM)	
F5. Utility sources with supply conditions	
F6. Fire protection & safety considerations	
G. PROCESS/MECHANICAL	
G1. Mobilization plan	
G2. Procurement plan	
G3. Laydown drawings	
G4. Safety management plan	

G5. Utility plan	
G6. TBM specifications, e.g., teeth, foam unit, doors.	Preparation of the TBM based on the geo-technical report.
G7. Tunnel requirements	Is a steep or shallow grade required? Is the tunnel requiring precast segments or rib and lagging?
G8. Geotechnical information	
G9. Mechanical equipment list	
G10. Staging requirements	
G11. Connection knowledge	
G12. Specialty equipment requirements (segments, etc.)	Verify the segments have the correct pressure specific-actions for the depth of tunnel.
G13. Commissioning knowledge	
H. EQUIPMENT SCOPE	
H1. Equipment status	
H2. Equipment location drawings	
H3. Equipment utility requirements	
I. CIVIL, STRUCTURAL, & ARCHITECTURAL	

I1. Civil/structural requirements	
I2. Architectural requirements (pump house or above ground structure)	
J. INFRASTRUCTURE	
J1. Existing infrastructure requirements	
J2. Loading/unload/storage space requirements	
J3. Transportation requirements (TBM, Drill Rig)	What type of truck and trailer is required to deliver the heavy excavation equipment?
K. INSTRUMENT & ELECTRICAL	
K1. Temporary/permanent electrical availability	
K2. Mole cable and structure storage	How much TBM cable is required on site and what are the storage methods being used?
K3. Electrical area classifications	
K4. Power sources identified	
K5. Transformer and gantry plan	
K6. Instrument & electrical specifications	

SECTION III - EXECUTION APPROACH	
CATEGORY Element	Comments
L. PROCUREMENT STRATEGY	
L1. Identify long lead/critical equipment & materials	
L2. Procurement procedures plan/tender document	
L3. Procurement responsibility	
M. DELIVERABLES	
M1. Overall tunnel requirements	
M2. Deliverables defined	
M3. Distribution/monitoring	
N. PROJECT CONTROL	
N1. Project control requirements	The use of EVA, MPDM, etc.
N2. Project accounting requirements	
N3. Risk analysis/risk management	
P. PROJECT EXECUTION PLAN	
P1. Owner approval requirements	
P2. Engineering/construction plan & approach	

P3. Shut down/turn-around requirements	
P4. Commissioning and maintenance requirements	
P5. Startup requirements	
P6. Training requirements (crews, TBM operator)	

3 SIMULATION AS A SERVICE IN CONSTRUCTION

[redacted] Introduction

This chapter discusses a novel approach used to provide simulation services within the construction industry. In this application, I investigate the use of concepts of special purpose simulation modeling to facilitate the use of simulation tools in decision support and construction management. In particular, the special purpose simulation tool was deployed for utility tunnel construction. Background to the state of the art and the construction problem is first provided, followed by discussion of the simulation strategy used (special purpose modeling), then the service provided to clients using the simulation tools, and a more detailed explanation of the input modeling aspects of the problem is given, as they are found to be critical in providing reliable solutions. The main contributions relate to identifying and demonstrating the key ingredients that are essential in order for simulation to provide a relevant service to construction practitioners.

[redacted] State of the art: simulation applications in tunnel construction

Computer simulation is sometimes applied in the construction industry to support the decision-making process for different operations. Simulation enables construction practitioners to analyze complex construction processes, evaluate different scenarios, and therefore optimize time and resources for projects. Although simulation has advantages for the construction industry, the challenge is to make simulation accessible to users by presenting it in a simple and more graphical context. In 1973, Halpin introduced CYCLONE, which simplified simulation modeling for construction practitioners through the use of graphical representation in modeling (Halpin, 1977). CYCLONE models processes based on discrete event simulation. A typical CYCLONE simulation model is given in Figure 8.

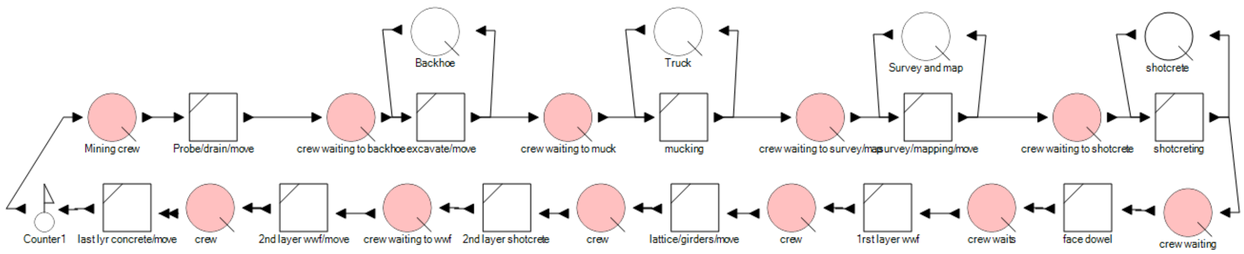

Figure 8: CYCLONE model for a tunnel construction with SEM (AbouRizk, unpublished report, 2011)

CYCLONE is known for its simplicity and ease of use as it only uses few modeling elements to enable a complete model of a construction operation. The box models a task while the queue models a resource in waiting to be processed at the task. The production counter is the golf flag that signals completion of a particular cycle.

A number of simulation systems have been developed based on CYCLONE, including RESQUE (Chang and Carr, 1987) and Stroboscope (Martinez and Ioannou, 1994). These are all general purpose simulation (GPS) tools that can model any process, but a user must have an understanding of simulation techniques to use them effectively. This makes it difficult for industry personnel to use these tools.

Other advancements include 4D modeling methods and Construction Synthetic Environment (COSYE) (AbouRizk and Hague, 2009). Additional innovations were presented in Einstein (2004), and Haas and Einstein (2002) (amongst other publications) where an innovative simulation system for tunnel construction simulation named DAT (Decision Aid for Tunneling) is described. Ioannou (1988) also presented a geologic prediction model for tunneling and risk reduction modeling, as well as planning and simulation approaches to augment those predictions.

Over the years, advancements have been made in construction management simulation tools, with applications to tunneling. Researchers introduced special purpose simulation (SPS) to facilitate modeling of specific types of projects, as it can be developed and customized for various users, and has a more user-friendly interface. For example, Simphony (AbouRizk and Hajjar, 1998) is a special purpose simulation tool developed specifically for modeling construction processes.

Simphony is a discrete event simulation system, originally developed by Hajjar and AbouRizk (1999). Simphony supports different modeling constructs to facilitate adoption in various domains; therefore, Simphony at its core was built to facilitate developing modeling templates, which can be developed and customized for various users. The versatility is provided in the form of templates that can be used to create models. Indeed the CYCLONE model given in Figure 9 was actually developed in Simphony using the CYCLONE template. The same model using the general purpose template is shown in Figure 9.

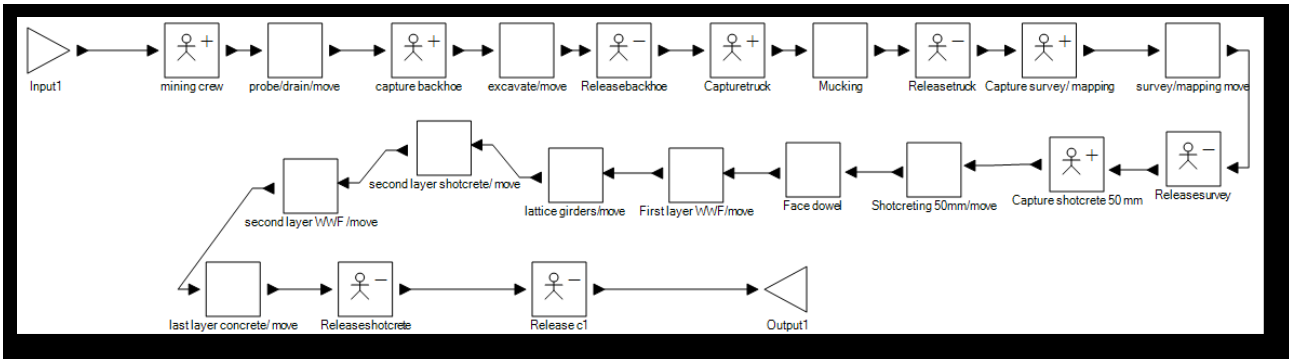

Figure 9: SEM tunnel excavation using general purpose template in Simphony

Of note is the fact that in the GPS template there are significantly more modeling elements and the modeling tends to be more complex than with CYCLONE. Furthermore, writing computer code is often required to produce a workable model. This, however, provides flexibility that gives the modeller the ability to model operations or situations that are more complex.

Simphony also provides an approach called special purpose simulation modeling. “The special purpose simulation (SPS) approach enables a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to easily model a project within that domain using visual modeling tools that have a high degree of resemblance to the actual construction system” (AbouRizk and Hajjar, 1998). Examples of special purpose templates (SPS) previously developed and currently supported in Simphony include a tunneling template, a dewatering template, a program evaluation and review technique (PERT) template, an earthmoving template, a structural steel fabrication template, and a range estimating template. The approach for SPS is basically to use modeling elements that correspond to the real world problem when building a model. The simulation code is encapsulated in these elements. A sample is shown in Figure 10.

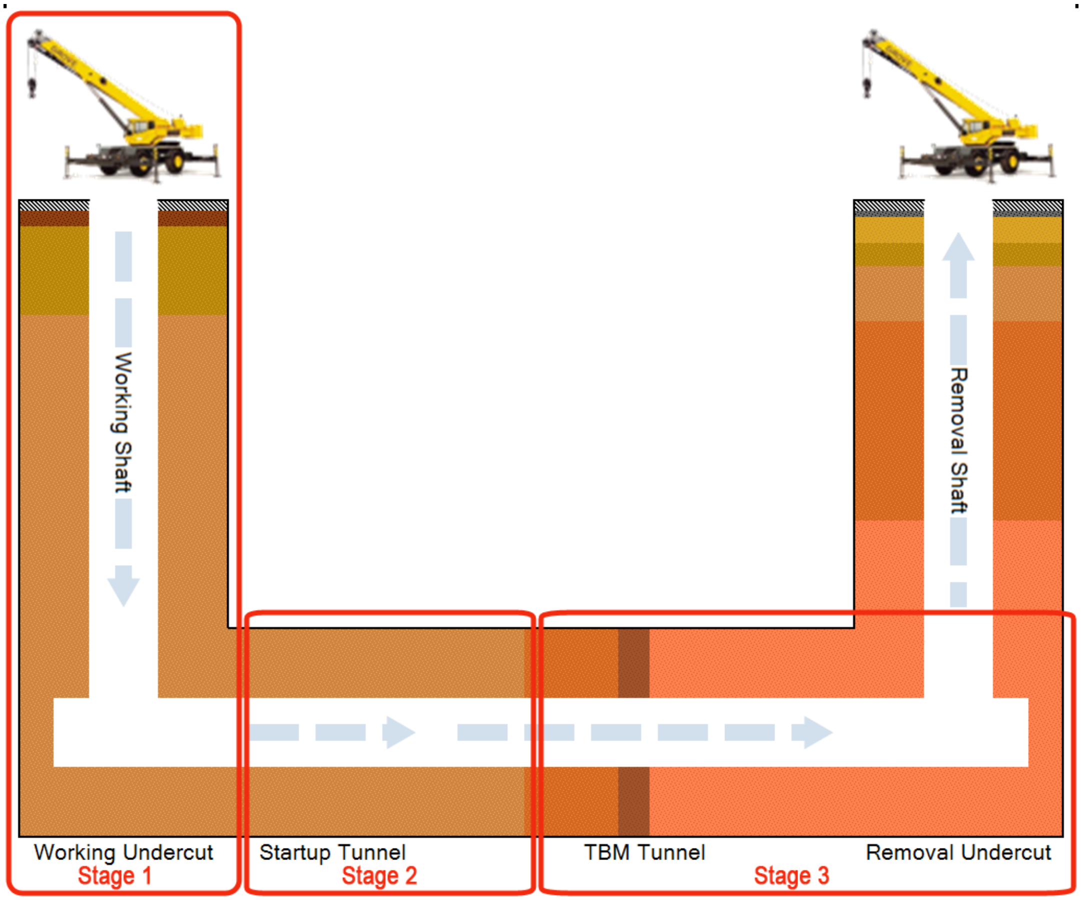

Figure 10: Sample of a SPS tunnel simulation model built with Simphony

I propose to make the simulation approach more useful in construction by building upon the concepts of special purpose simulation modeling to provide a better medium for planning construction projects, yielding more accurate estimates and schedules for the project. The domain I selected for application is utility tunneling. The objective then is to advance the SPS tool in such a manner where the end result:

- Is easy to use without significant knowledge of simulation.

- Provides more accurate results for estimating and scheduling than current systems do.
- Provides information in a ready to use format for estimate preparation and schedule preparation.
- Is efficient to use, not requiring more time than current systems do.
- Provides a medium to enable sensitivity analysis and scenario planning and experimentation.

[redacted] Background to the construction problem

Underground pipe installation typically has two installation methods, trenchless and open cut. The open cut method of installation is suitable (cost effective) to installation depths typically less than 7 meters. Open cut construction requires a large amount of surface area to complete the construction, as a 2:1 slope for a typical open cut angle is required. The surface disruption to road traffic and interference with shallow utilities often make trenchless construction more desirable even though it may have a higher unit cost. Trenchless construction is suitable for many depth applications, but is constrained by the type of ground that is present. Trenchless excavation methods vary between hand excavation and machine excavation. For the purpose of this paper, I will focus on the machine excavation application, and in particular, the tunnel boring machine (TBM) application, but hand excavation is also used to excavate small sections of the tunnel.

The TBM tunnel construction method, as shown in Figure 11, generally starts by laying out the working shaft location, and thus preparing the working site. The working shaft has a predetermined diameter, and is usually excavated with a backhoe and a drilling rig. The backhoe will excavate the first 2 feet and the drilling rig will excavate the remaining depth with hand excavation to aid in expanding the shaft diameter further if necessary.

Figure 11: Rib by rib drill rig assisted excavation of a working shaft

Once at the tunnel alignment depth, the working undercut is constructed, which will start with welding “rib 0” to the shaft wall. Rib 0 is the outline of the working undercut and shows the alignment of the tunnel. The working undercut is hand excavated and is generally a larger diameter than the actual tunnel diameter, as this is where the majority of the TBM assembly will take place. The working undercut is typically 30 meters in length and is lined with a steel rib and wood lagging to support the ground. The first 4 meters of the undercut are much taller and wider ribs to accommodate the TBM being lowered down the shaft. This is also to store some of the TBM cable below ground by hanging it on the walls on a platform of its own as the TBM cable is a very heavy gauge wire and is of a considerable weight. The remaining 26 meters of the undercut is a smaller rib size than the first 4 meters, but is larger than the TBM excavation diameter. The main reasoning for this is to be able to have 2 trains side by side in the undercut. Having 2 trains side by side in the undercut allows for much greater productivity, as when one train is returning from the TBM face full of spoil, the other train that is unloaded can start to travel back to the TBM to begin the excavation process again. The excavation of this portion of each meter of the undercut takes place in 2 stages (benching) whereby the top half is excavated first and supported before the bottom half is completed.

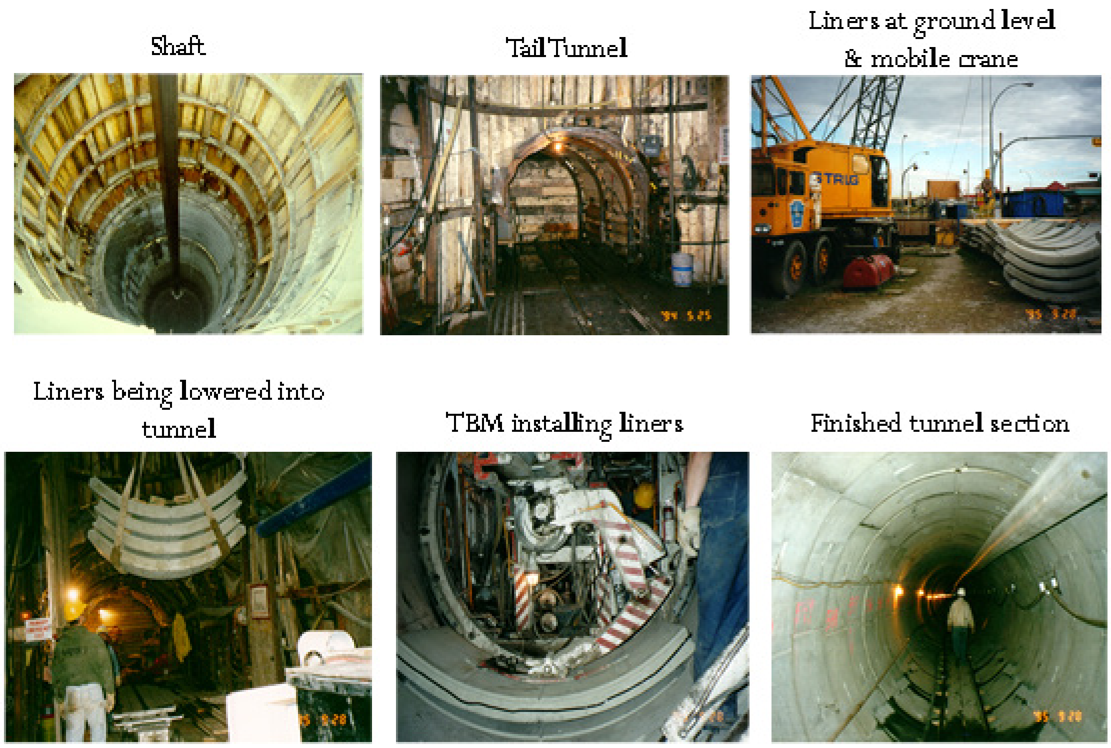

Figure 12: TBM tunnel excavation process

Once the full length of the working undercut is completed, the end of the tunnel (the tunnel face) is supported with wood lagging to prevent collapsing. Next, a metal cradle constructed with heavy I-beams is welded together and concreted into the floor for the entire length of the working undercut to the tunnel face. The working undercut and cradle are important as they make up the main staging area to accept and install the TBM. The TBM is brought to site on a large flatbed truck and trailer, and is lifted, lowered down the working shaft, and placed on the cradle in the working undercut, typically by a 140-ton crane. The TBM is then pulled forward on the cradle with chains to the tunnel face. The TBM is then assembled by heavy duty mechanics over roughly 2 weeks. Electricians then come to site to connect a high-voltage power service that is supplied by to the TBM's power transformers underground, using a very large-gauge power cable (mole cable). A final mechanical check and survey for tunnel alignment is completed before excavation takes place. The face boards are removed and the TBM is launched into the ground carefully to make sure tunnel alignment is not compromised. The TBM excavates the dirt at the face and a single train, with usually 4 dirt cars, accepts the excavated material from the conveyer, travels back to the working shaft, and is taken up the working shaft and dumped by a smaller-sized crane (usually 75 ton). This section of the TBM tunnel is called the 50-meter start up tunnel, as the TBM will excavate until the 50-meter mark and stop. From here, the remaining conveyer sections are installed and the power transformers are placed on top of a gantry that is dragged behind the TBM by chains. The dirt train and cars all fit underneath the gantry, which accepts the dirt from the extended conveyer unit. The working undercut is now outfitted with a wooden platform on which the train tracks are placed. A switch is installed to allow 2 trains with 5 cars to sit in the working undercut at the same time. Now, as one train exits the tunnel loaded with dirt from the TBM and passes the switch, the other train can enter the tunnel and begin being loaded by the TBM. The other train is unloaded by the crane simultaneously, so as to not hinder production of the TBM. During the time that the train is traveling back to the working undercut, the TBM is installing its concrete segmental liner around the outside of the tunnel diameter to support and finish the tunnel excavation. Once the switch is installed and the wood platform is completed in the working undercut, the main TBM tunnel excavation commences.

Prior to the completion of the TBM tunnel, the removal shaft and removal undercut has to be completed to accept the TBM and eventually disassemble and remove it. These components are completed in the same manner as the working shaft and working undercut, with the exception of the removal undercut being shorter in length than the working undercut, as it is usually only 9 meters in length. Once the TBM is removed from the removal shaft by the 140-ton crane, usually, hand excavated connection tunnels need to be excavated to connect an existing tunnel structure to accept flow in to the new tunnel and then connect again at the opposite end of the tunnel to release flow. These hand tunnels range anywhere from a few meters in length to upwards of 20 meters in length. The connection tunnel is usually of a smaller diameter than the main TBM tunnel and is excavated 1 meter length at a time and lined with metal rib and lagging. Once the existing pipe structure is reached and exposed, the hand tunnel needs to be finished typically with cast-in-place formed concrete. Once the concrete is cured, the entire length of the tunnel is inspected, and any variances are patched with concrete. The working undercut now has the concrete segments banded together in a circle and hand installed for the entire 30-meter length working undercut back to the working shaft location. The bottoms of both shafts are finished with cast-in-place concrete to finish the tunnel and seal the hand connection tunnels to the TBM tunnel. Once this is completed, the existing pipe is cut out (breaking out) at the downstream end first, then at the upstream end to accept flow into the new tunnel for the first time. Manhole barrels are now placed on top of the undercut structures and are stacked up to the ground surface where a manhole cover is placed on top. Fillcrete is poured around the outside of the manhole barrels to seal the gap between the inside of the removal shaft and the manhole. The tunnel is now complete.

Simulation of TBM tunnel construction

The tunneling simulation model follows the same process that was explained in the previous section. The model is generally driven by historical data collected for similar tunneling situations. The special purpose simulation model for this problem is illustrated in Figure 13, which shows the major components of the tunnel construction. In special purpose simulation, discrete modeling elements such as work-tasks are added inside these components to accurately reflect how the previously described construction process takes place. The process is therefore flexible to enable a user to make changes to processes taking place for specific projects. These discrete tasks are fitted with durations using standard statistical distributions. The discrete tasks also have labour, equipment, material, and other cost data added to each of them. By providing such information to the tunnel objects, a project estimate can then be produced in standard construction form. Simple processes such as building the shaft liners can generally be modeled with deterministic duration as they do not vary much, while critical path tasks such as the TBM excavation use a fitted distribution, as many factors affect its value for a particular iteration. A statistical distribution, carefully collected from historical data, provides a reasonable approximation for such tasks.

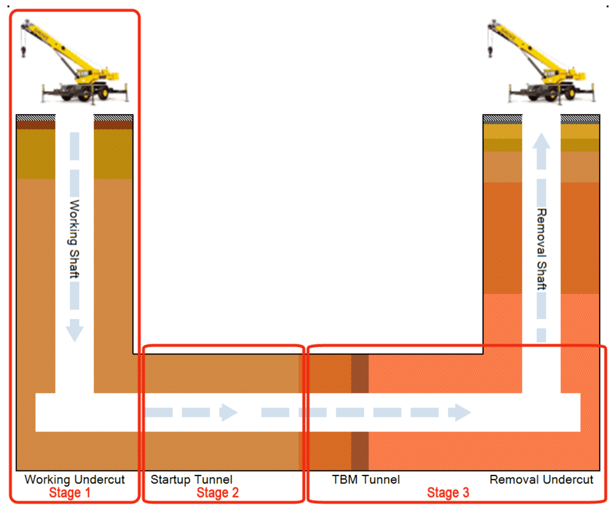

Figure 13: Trenchless TBM tunnel components and initial stages of tunnel excavation

[redacted] Tunneling special purpose template modeling

The tunneling template is a special purpose template developed in Simphony to simplify planning and analysis of tunnel construction projects (AbouRizk, 2013). The template is comprised of modeling elements, most of which represent the different physical components and resources that exist within a typical tunneling project, for example: a shaft element, tunnel element, crane (site) element and TBM element. The template is made up of modeling elements developed in Visual Studio.NET using Simphony services. The elements resemble the real-life items they represent, making template building easier for users not familiar with simulation. The modeling elements model the process of tunneling operation by capturing resources, scheduling events and releasing resources, collecting statistics or controlling work and non-work times. The template uses a hierarchical approach for design and implementation to match the complex nature of the process.

The templates have two parent-level modeling elements and eleven child-level elements. To model, the user can drag and drop the modeling elements, then align them in a pattern that represents the actual tunnel construction sequence (see Figure 13 for a typical model layout).

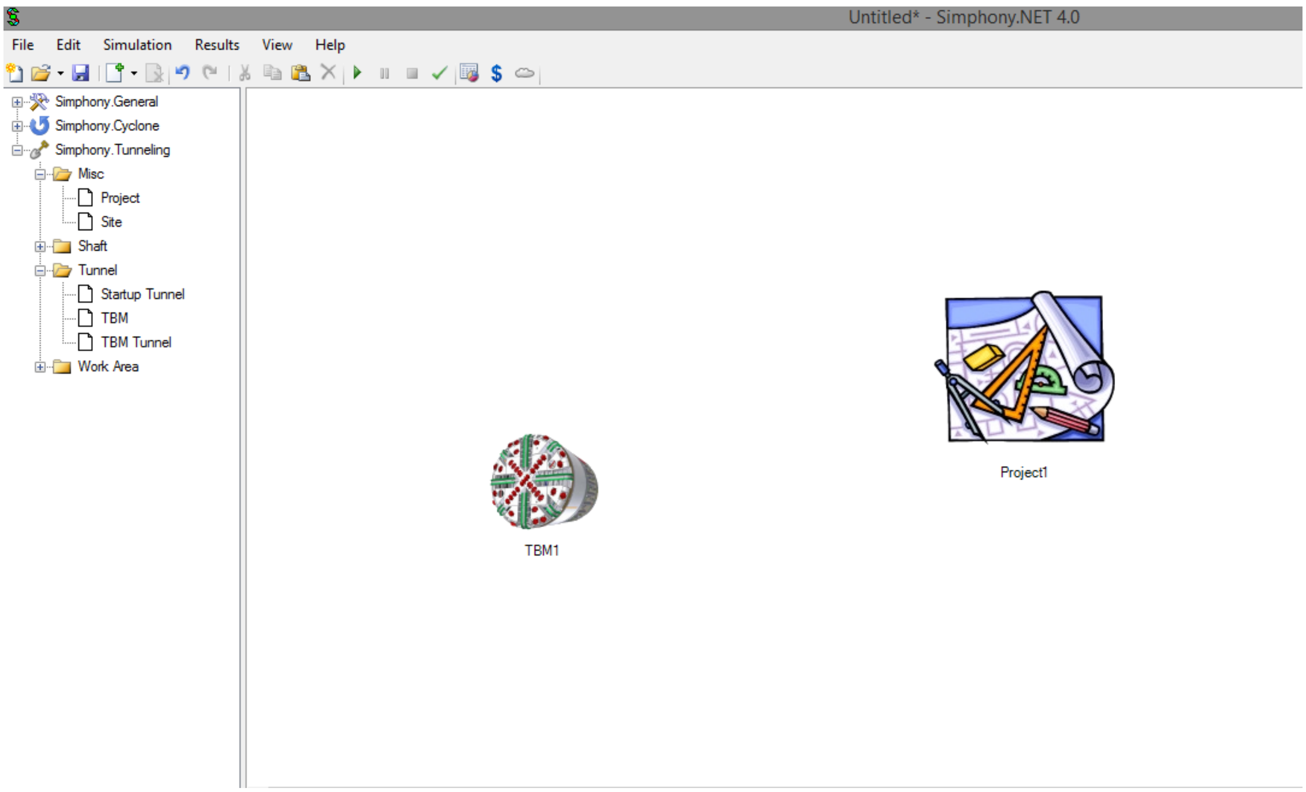

Figure 14: The highest level of the tunneling template

The 2 parent elements, project and TBM elements, are dragged from the side column and dropped on the work area as shown in Figure 14. From here you can define the TBM specifications by single-clicking the TBM element and defining the specifications on the right-side column. By double-clicking the TBM element, you can add any delays/interruption to the TBM. The user can specify their chosen distribution and frequency of interruptions by entering this information in the delay and time to occurrence properties and pressing ok to accept.

By single-clicking on the project element you can now give a name to the project in the right-side column, specify a project start date, and enter any project indirect costs as either a lump sum or a percentage of the total project cost. By double-clicking on the project element, you then get a new work area where you will assemble the project elements that represent the overall project alignment. For any typical tunnel, you will have a working shaft site and a removal shaft site that are added to the work area from the "Misc" heading in the left- side column. In the right-side column, you can then define the name of the site and a specific start date for that site and enter any delays/interruptions that might impact this site. Typically, you would enter any weather delay information that would impact the above-ground site elements.

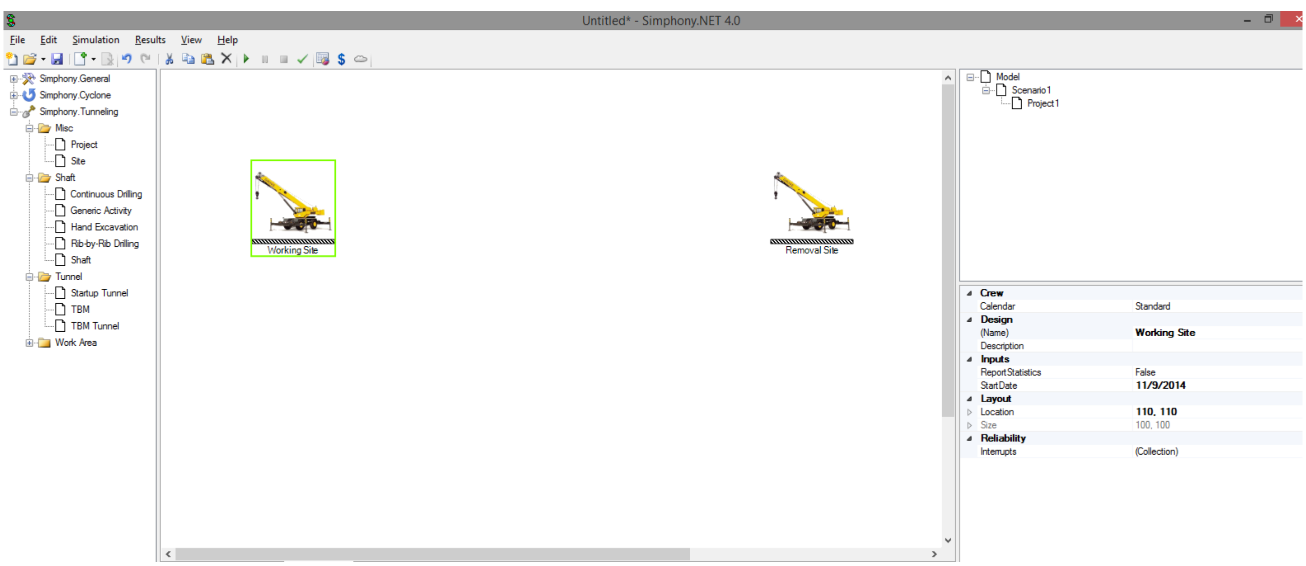

Figure 15: The second level of the tunneling template displaying working sites

The modeller can then drag the shaft element on to the work area for both sites. You can then name the shafts in the right side column, as well as specify the shape of the shaft (rectangular or circular), the diameter of the shaft in meters, and the geotechnical soil layer information. The soil layers are a very key part of the shaft excavation as the soil swell factors greatly affect productivity from layer to layer. The depth in Figure 16 refers to the maximum depth that this layer goes down to. The swell factors are typically referenced from the geotechnical investigation that would have taken place for the project.

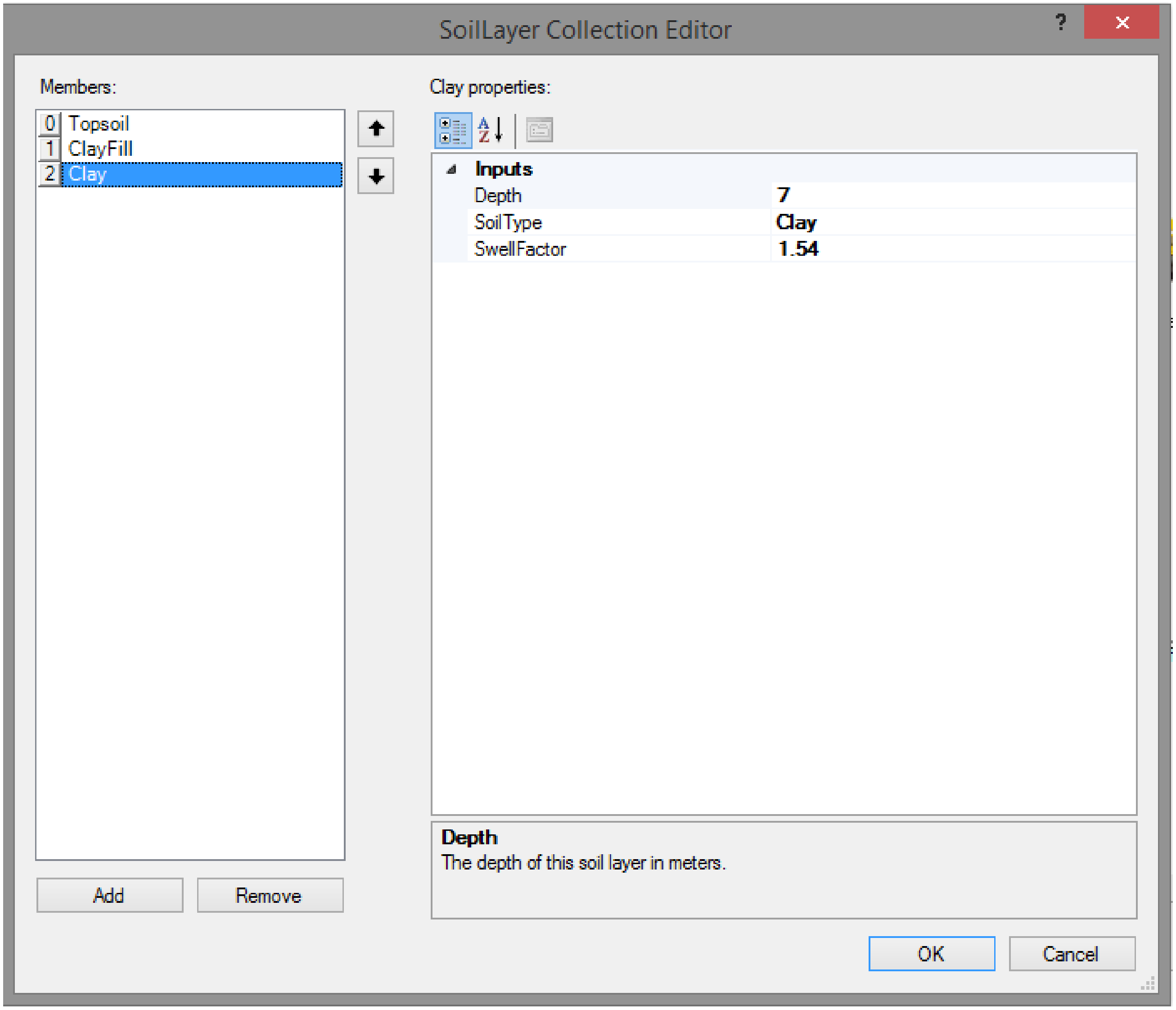

Figure 16: The shaft elements soil layer property editor

After the shaft has been designed for its specifications, double-clicking the shaft element will bring us to the lowest level of the simulation process. Now by only using the shaft column on the left side of the screen you can drag and drop the elements on to the work area to resemble the sequencing of how the work actually takes place as the simulation model will simulate the shaft construction in this order. As seen in Figure 17 you can also set tasks to take place at the same time as each other by splitting the activities and allowing them to take place in parallel.

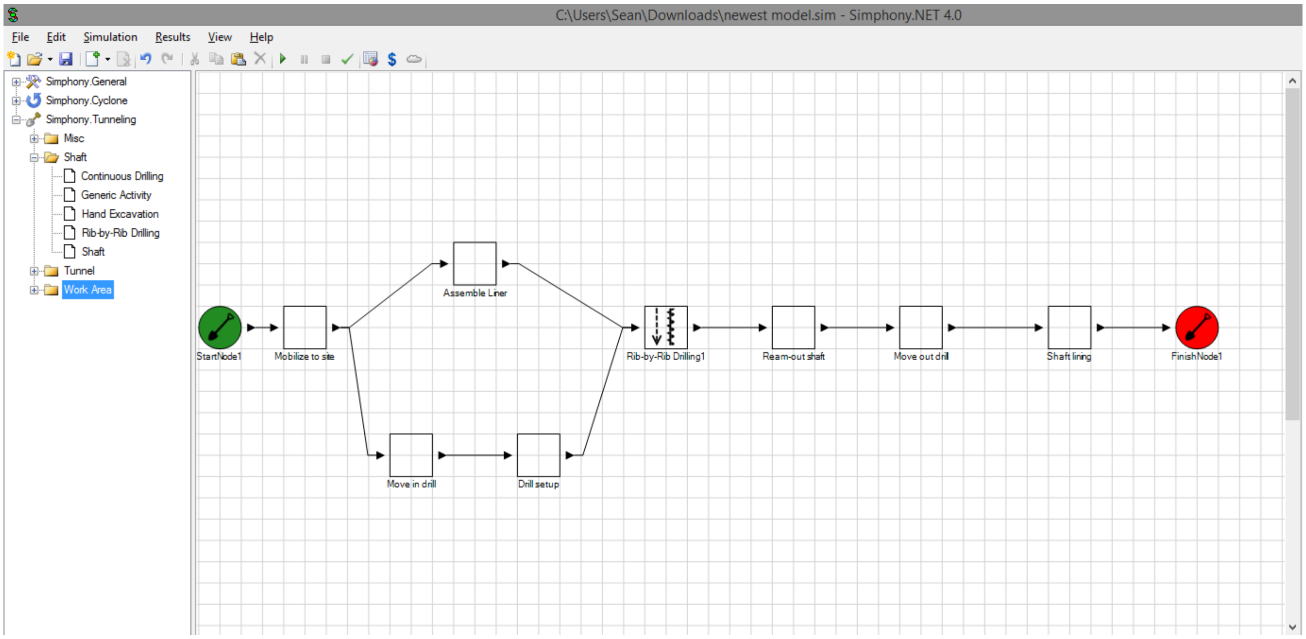

Figure 17: The lowest level of the tunneling template displaying the tasks inside the working shaft element

Inputting data into the generic task elements is done by single-clicking on the element and using the right-side column. Here the details about the crew can be entered, such as what calendar the crew for this element will work and the various components of the crew. This is where the SMARTEST database plays an important role as the estimation of the direct costs of the project is produced from here. By clicking and opening, for example, the labor table editor, you can add the specific position of a worker, the quantity for the task, and their regular and overtime rate. For ease of use if an estimating database already exists, the user can right-click on the element and select the "import from SMARTEST" menu. This will allow the user to select predefined crews for the task rather than entering each member and their rates individually. This is a generic data entry for virtually all of the tasks in the simulation, as the only variance will be the individual tasks crew requirements.

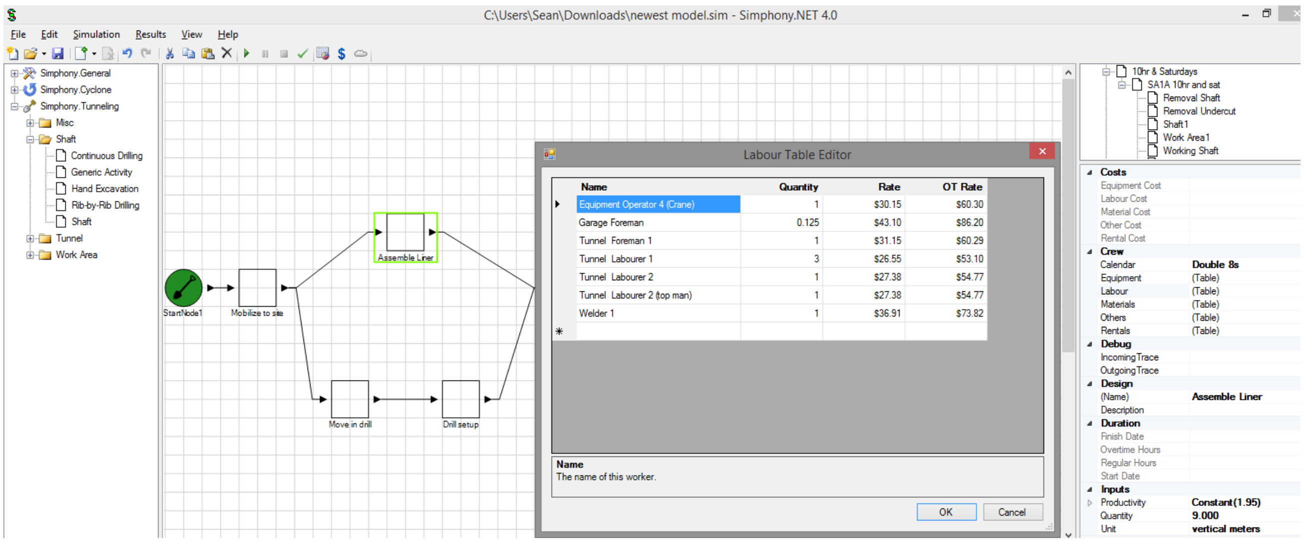

Figure 18: The tunneling templates inputting of estimation data for each task

After inputting the crew data to be estimated you now return to the second level of the interface. You now need to input the working undercut below the shaft, as this is completed by dragging the work area element from the left-side work area column and connecting it to the bottom of the shaft element. By single-clicking on the work areas, which will now be referred to as undercuts, you can input the geometries of the excavation that is required in the right-side column. A soil type and its swell factor can be selected according to the geotechnical investigation. Under the geometry column there is a left side and right side. For the purpose of the working undercut, the left side might be a tail tunnel or a connection tunnel, while the right side is the main working undercut where the TBM will be placed.

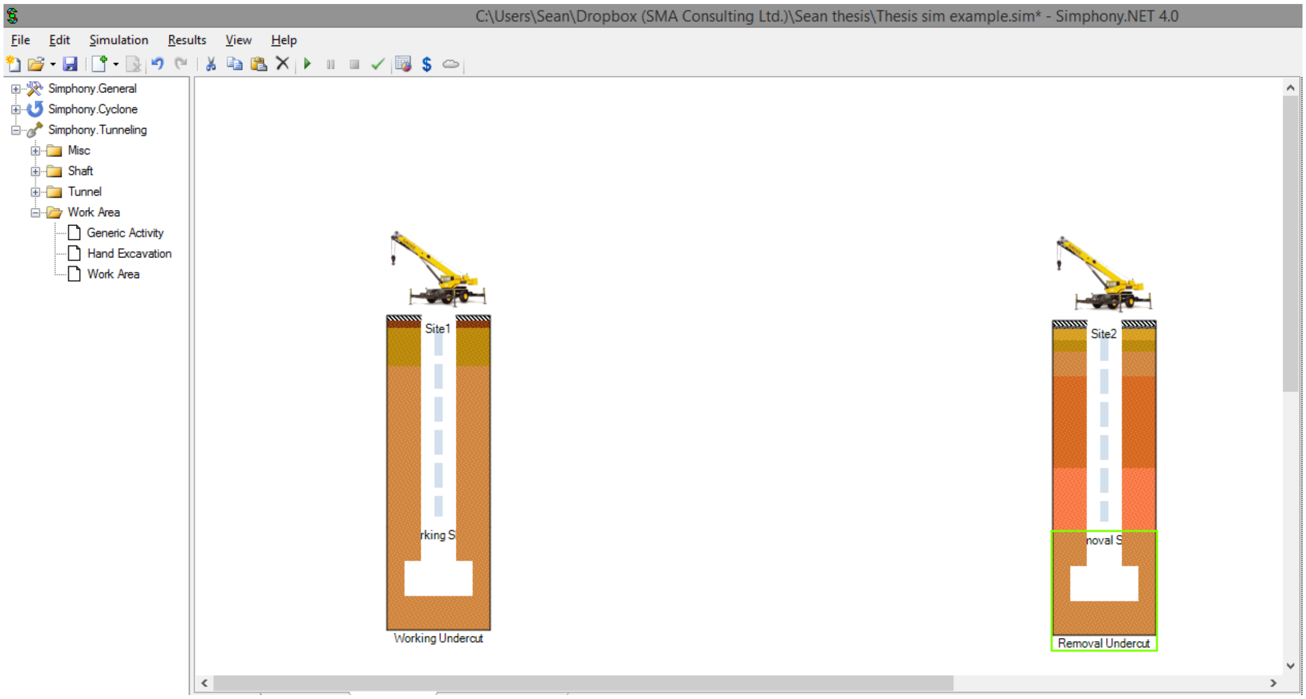

Figure 19: The addition of the shafts with their respective undercuts in the tunneling template

By clicking on the right side configurator, you then open up the undercut geometry editor where you can enter the designed detail for the undercut dimensions. The working undercut will typically have a larger section at the working shaft to accommodate the TBM being placed down the shaft by the crane, cable storage for the TBM, and to have 2 trains side by side. By clicking the add button in the lower left-hand-corner, multiple undercut geometries can be added with varying sizes, where the order of excavation is indicated by the tabs on the top of the editor. By clicking ok, the editor exits and you can now enter in the train logistics for the excavation in the right-side column. Any collected delays that pertain to the undercut or trains themselves can be entered into the interrupts column with their distributions. You can now define the characteristics for a left side and right side train switch installation. For the application of the working shaft undercut there will not be a left side switch, so this can be given values of 0. The right side switch can be defined now based on its installation chainage, or how far in meters from the working shaft the model would like excavation to stop for the switch to be installed. This is key as the excavation will only run a single train until the switch is installed, which will limit production, while after the switch is installed, a double train can be run. The TBM has to be substantially buried with its gantry to be able to install the switch in the undercut. The switch installation duration can be set to a distribution or constant amount of time depending on historical data collected. The unload duration is the time that is required to unload each individual muck car, which can also be set to a distribution or a constant amount of time.

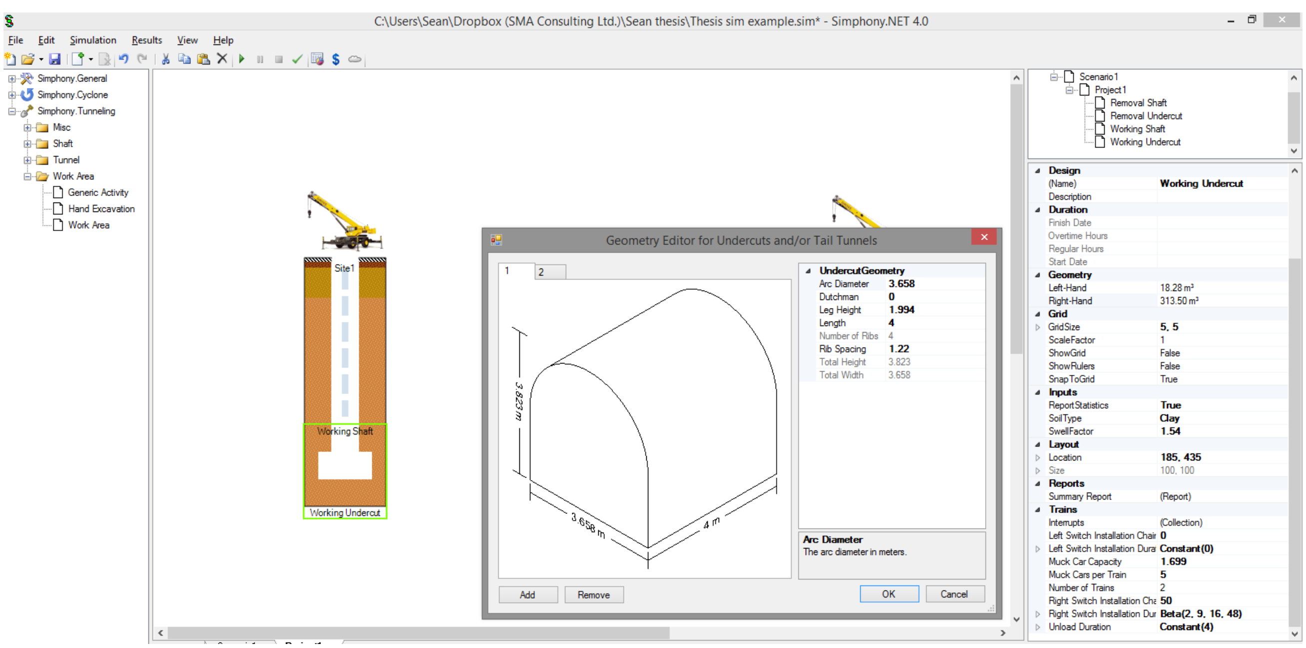

Figure 20: The tunneling template's undercut geometry editor

The modeller can now double-click on the undercut element to access the lowest level of the simulation modeling environment as shown in Figure 20. The generic activity tasks can once again be placed into the work area in the sequence that they will take place, as Simphony will simulate them in that order. The hand excavation tasks have unique properties to the undercut in that they can be set up to excavate the left undercut, the right undercut, and each undercut geometry that the modeller specified. These inputs are completed in the right-side column where the excavation direction is selected as right or left. The excavation production rate is specified as a constant or distribution and the rib installation duration is also specified as a constant or distribution. These two rates will vary greatly depending upon the undercut number, which will also be specified in the right column. Each hand excavation task will represent each undercut direction and geometry that had been specified by the modeller.

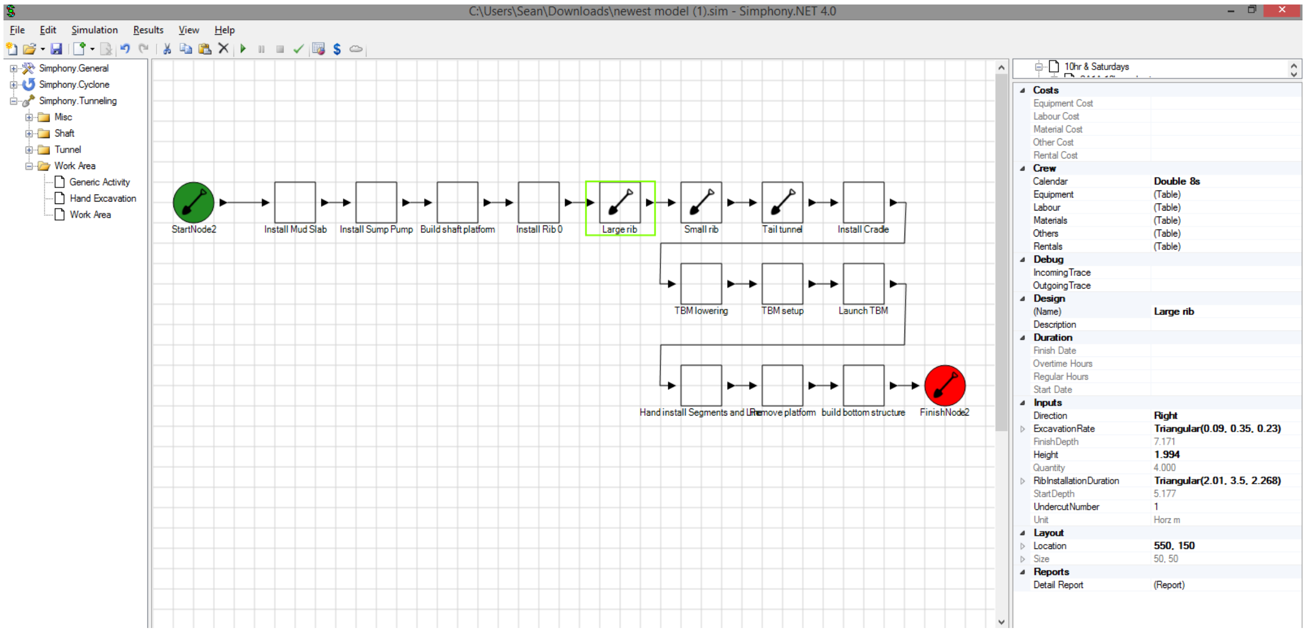

Figure 21: Inputting detail into the excavation task inside the undercut elements

The model can now go back to the second level of Simphony and input the startup tunnel to the work area from the left-side column under the tunnel heading. As shown in Figure 21, you can single-click on the startup tunnel element and input the data for this section in the right-side column. In the inputs heading, you first need to indicate the tunneling direction as either left to right, or right to left. This is added to give the modeller the flexibility of two-way tunneling out each side of the undercut as some tunneling applications limit the above ground footprint by only using one shaft in the middle of the tunnel alignment.

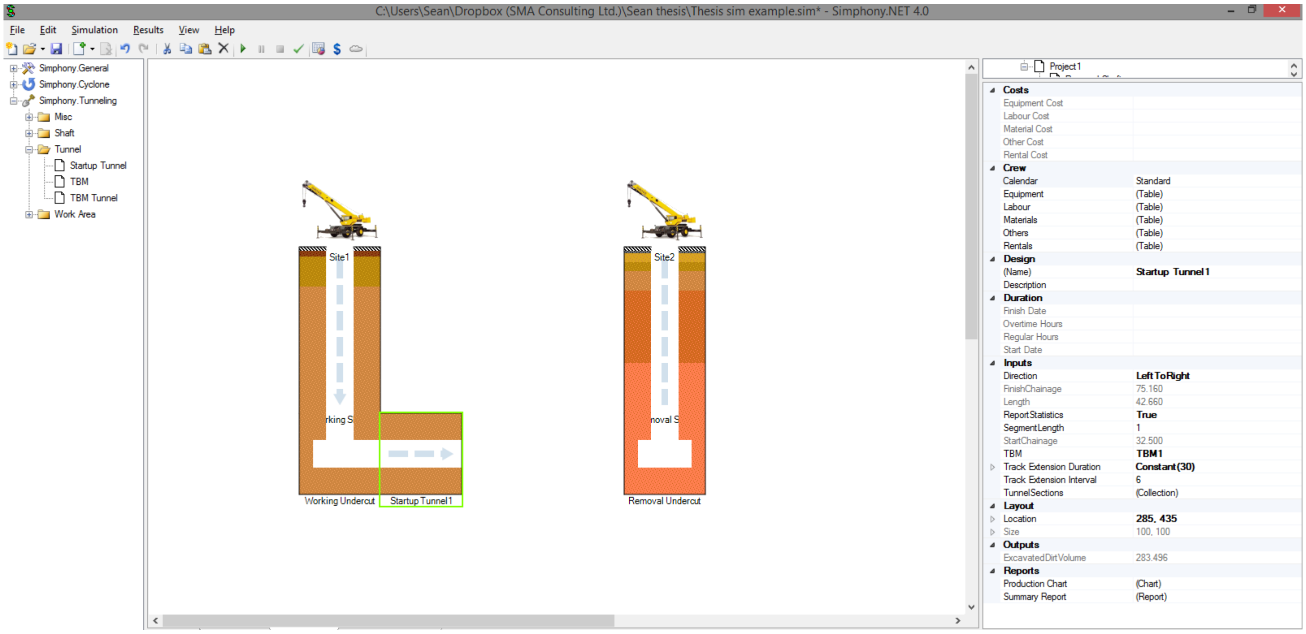

Figure 22: Adding and detailing the startup tunnels properties.

By double-clicking on the startup tunnel element you will move to the startup tunnel editor. The left-side column is where the soil layers will be added, while the right-side column is where the properties for each entered soil layer will be displayed. The inputs for the empty train speed and excavation rates can be added here as either constants or distributions. The length represents how long this soil layer is, in linear meters, with the tunnel chainage displayed above. The lining duration refers to the installation time of each segment ring or whatever type of liner that is to be installed in the tunnel followed by the loaded train speed. The Surveying columns are unique to the tunnel excavation elements, where the user can specify the duration between tunnel surveying events in meters, which will delay the tunnel excavation productivity for the specified surveying duration in minutes. By selecting ok, the modeller can move on to specifying the remaining TBM tunnel.

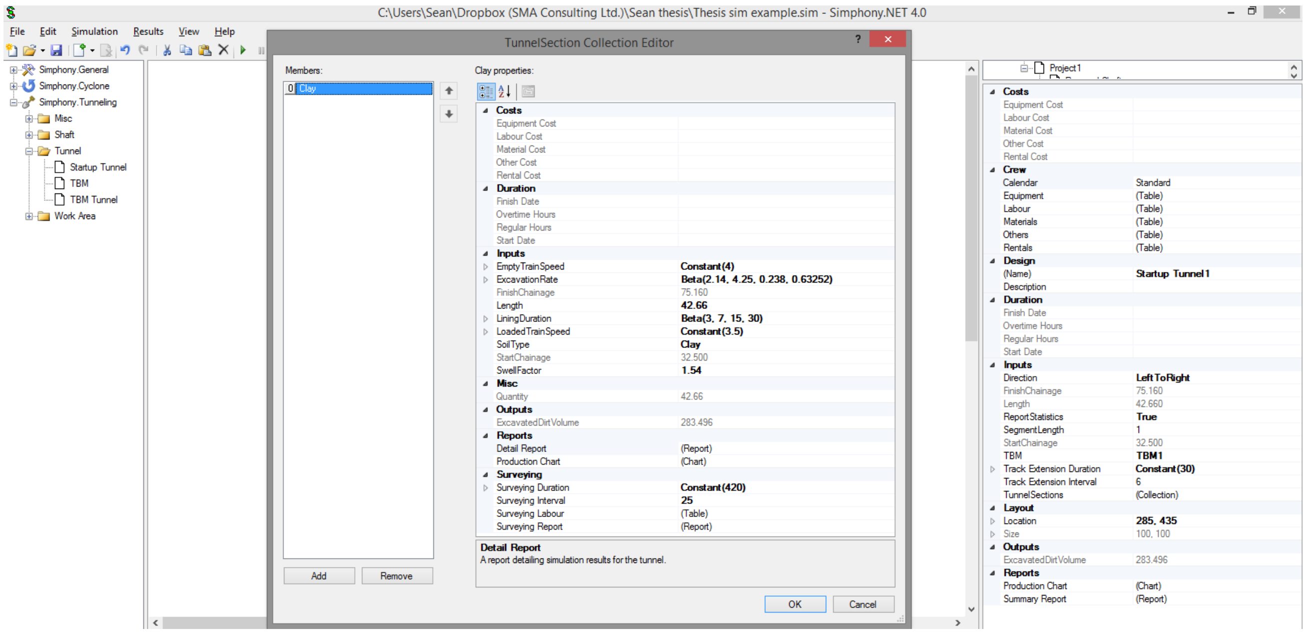

Figure 23: Soil layer advanced property inputting for the startup tunnel excavation element

The TBM tunnel element can be dragged on to the work area from the tunnel heading in the left-side column. The modeller can then input the direction of excavation. This was added for the purpose of being able to model two-way tunneling. The segment length allows the user to configure the liner length in linear meters. TBM refers to which TBM is has been specified to excavate this length of tunnel, as there might be more than one TBM's excavating in a two-way tunnel situation, or throughout the rest of the tunnel alignment. The track extension duration and interval refer to the distance in excavated meters that the train tracks would have to be added to and the time in minutes to install the new tracks.

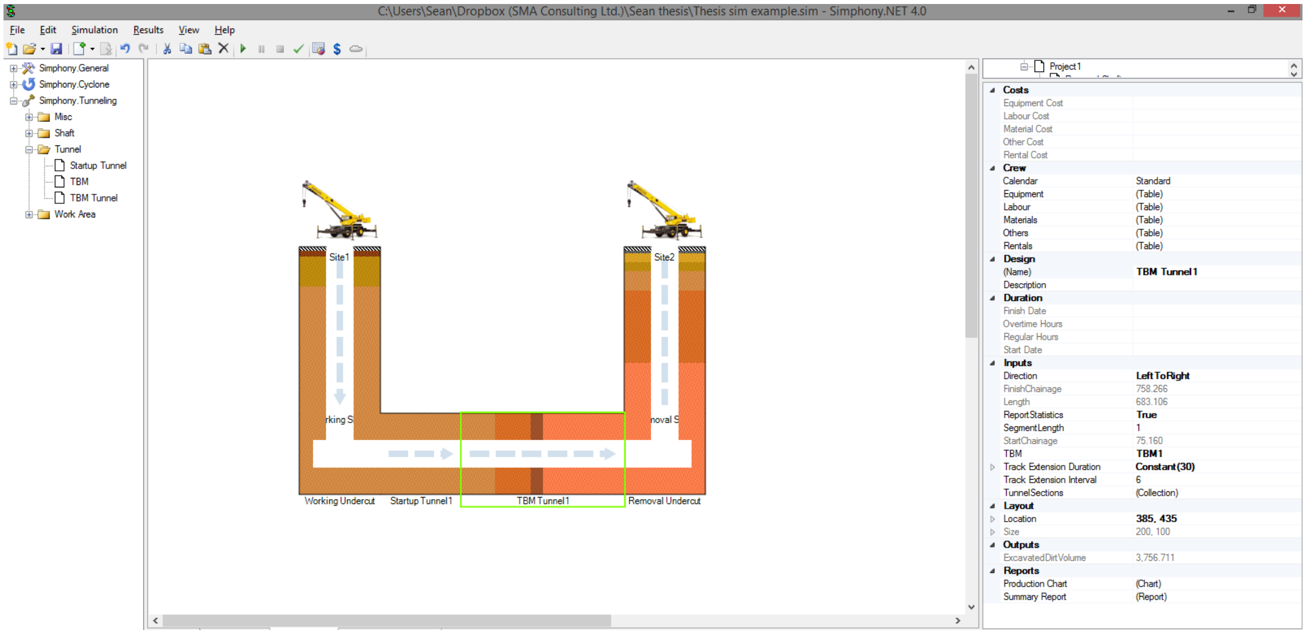

Figure 24: TBM excavation elements initial right side column properties

As shown in Figure 24, by clicking the tunnel sections collection you can then specify each soil layer type for the full duration of the TBM excavation. The soil layers are added in the left-side column and their properties are input in the right-side column. The input for each soil layer allows the modeller to specify the train speeds (loaded and empty) for travel distance calculations. The excavation rate allows the modeller to add a constant or distributed productivity rate for each individual soil layer. This customizes the individual soil layer to whatever excavation machine is being used, as certain machines will perform differently in varying soil conditions. The length specifies the total length in meters that the soil layer occupies, with the soil layers finished chainage displayed above. The lining duration specifies the time it takes for the installation of the liner in minutes, which can be constant or a distribution. The soil type and the corresponding swell factor can be defined. The surveying column again is unique to the TBM excavation tasks as the surveying duration in minutes and interval between survey occurrences in meters is configured to meet the survey requirements of each individual soil layer. Each survey occurrence will stop the TBM excavation for the duration of the survey. This allows the modeller to also determine exact productivity of the finished tunnel, which becomes very useful if the tunnel alignment has one or more curves in it, as more frequent survey intervals are required. The modeller can than accept these properties and be taken back to the second level.

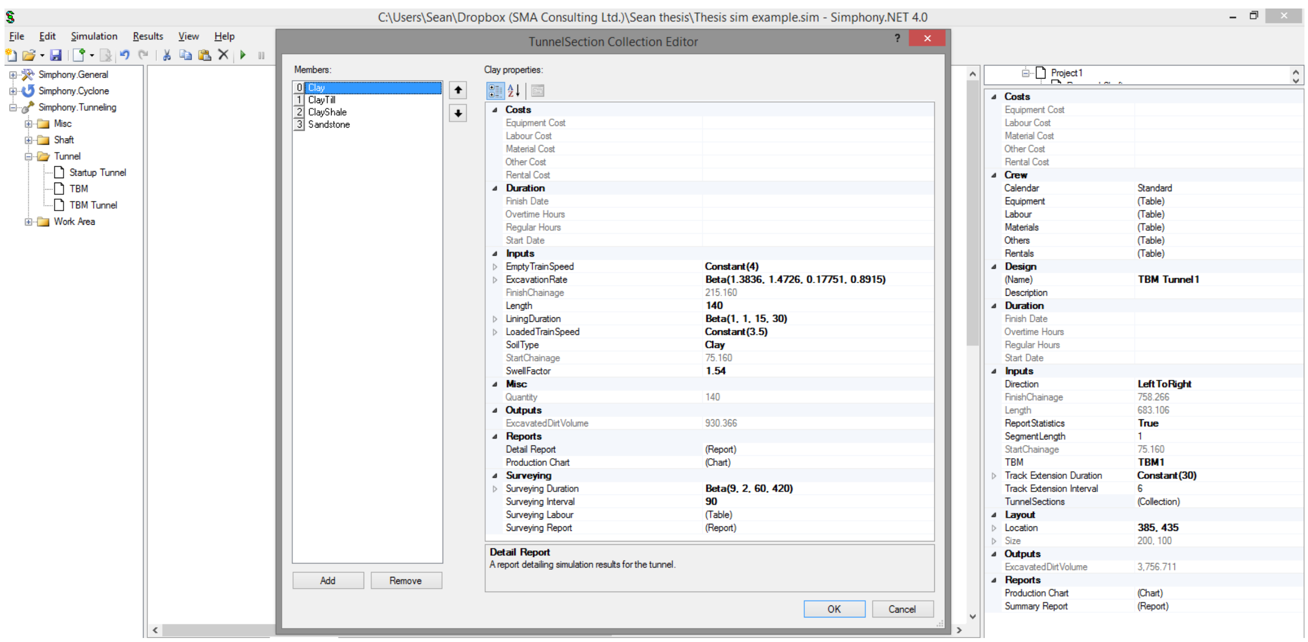

Figure 25: Soil layer advanced property inputting for the tunnel excavation element

The modeller will then repeat the same steps described above for the working shaft and working undercut, for the removal shaft and removal undercut. The modeller can then return to the first level and configure the simulation settings by clicking on the blank work area to access these settings in the right-side column. The enabled property should show true to run the model with the maximum time selected as infinity so that the model will simulate to tunnel completion. The run count can be set for a single run or multiple runs to account for many different scenarios. The modeller can now select the play icon at the top of the Simphony screen to run the model. After the simulation completes the modeller can access the summary report for the simulation by right-clicking on the project icon and selecting summary report.

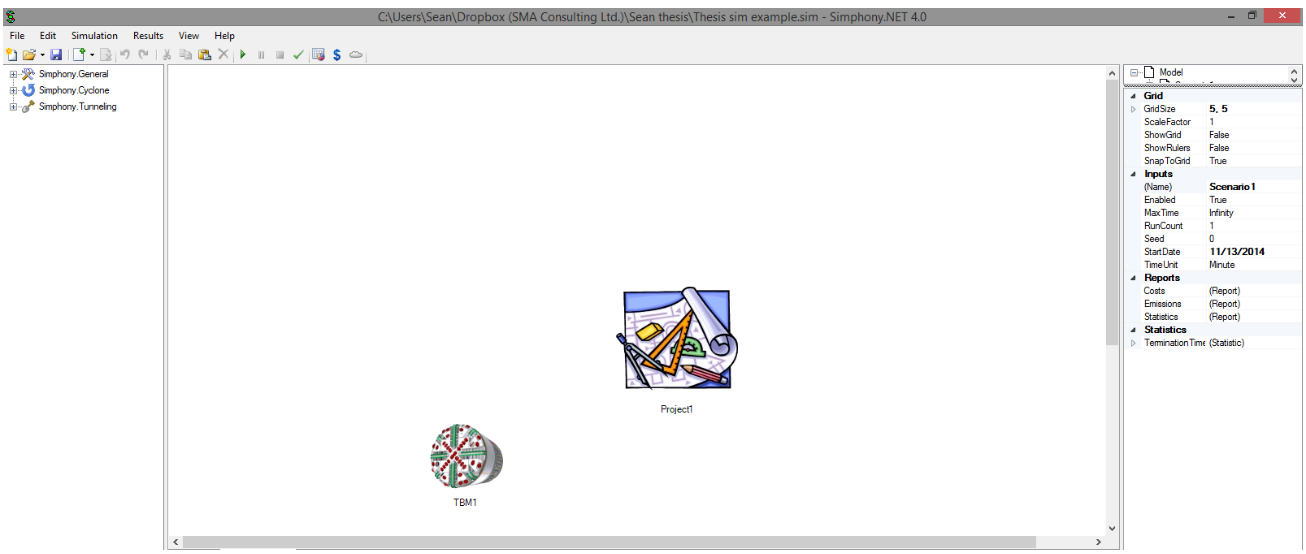

Figure 26: Displaying how to run the model in Simphony

[redacted] Deficiencies in the current approach

The SPS template described above worked reasonably well when the author applied it to a project called W13. W13 is a 973 meters TBM-excavated tunnel that is composed of 2 shafts, 2 hand tunnels sequentially excavated, 2 connections to existing infrastructure, and 1 TBM excavated length. This tunnel was constructed to upgrade the existing W13 sanitary tunnel so that the additional demand on the system could be met without backing up and flooding houses. The main deficiencies were observed to be the following:

- Simplifications and rigidity in key sub-process models: There are assumptions made in the simulation process that are generally too simplistic and greatly influence the validity of the results. Therefore, while the SPS models are reasonable, flexibility in making changes to the underlying process of construction is needed to reflect the unique cases encountered in a given project. For example, the undercut may be more complex than stipulated in the template. The shaft may use different methods than assumed, etc.
- Producing estimates that have critical ingredients of crews, equipment and material: The models produces good information related to production but lack the essential ingredients required for producing an estimate. It generally takes another 80 hours or more to produce the detailed estimate for the tunnel with all required crews and equipment, which are generally required for decision support.
- Producing schedules that can integrate with overall project schedule: The project schedule, which includes other elements not included in the simulation, is also critical for decision making and generally not readily available from the simulation.
- Input modeling: A critical element in tunnel construction relates to delays arising from equipment breakdowns. Those need to be based on accurate historical data and customized to the equipment used for the project of

interest. For TBM tunneling, given the linear and repetitive nature of the work, errors in the input models could easily produce incorrect results.

[redacted] Enhancements to the tunneling template to address the identified deficiencies

3.7.1 Flexibility in modeling key processes

Working with the simulation team, I extended the modeling approach to provide flexibility for building models with required capabilities. The following areas were included:

The simulation model needed the capability of adding predefined crews from a database to allow the modeller to easily input the crews without having to re-enter all the data continuously line item by line item. As shown in Figure 27, the SMARTEST database allows for the entire task to be entered as a crew so that the labour, materials, equipment, and rental costs are completed much faster. By simply selecting ok on the desired crew in the left-side column, all of the tabs shown in the right column of Figure 27 will be added to the task, and thus, be estimated for in the project simulation. The modeller can manipulate these entries once they are inside the task to add additional customization.

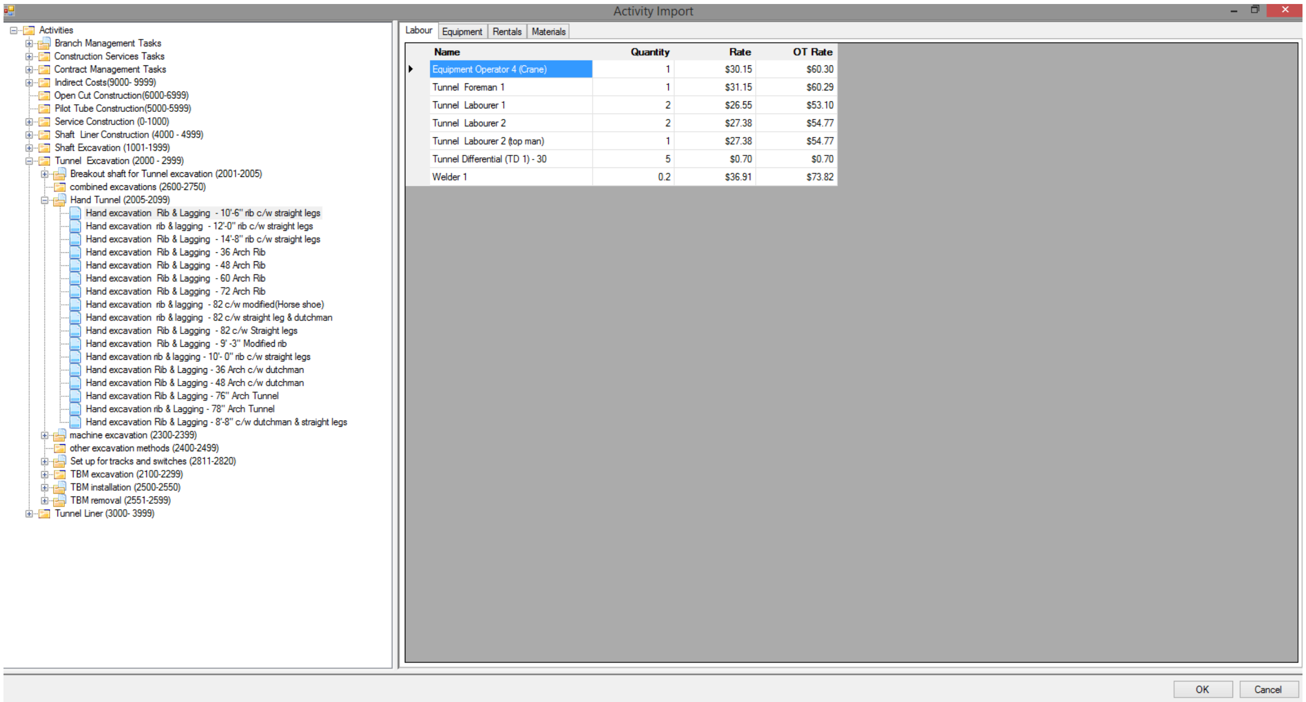

Figure 27: SmartEST estimation database inside the tunneling template

The simulation model required some way of including the indirect cost estimation to the simulation process. The indirect costs, instead of being included in the direct costs, were implemented by right-clicking on the project element and selecting indirect costs. Here, the table editor allows the modeller to input any indirect cost and associate either a fixed lump sum cost for that indirect cost, or a percentage of the overall direct costs that results from each simulation run. While some indirect costs are a fixed amount, others, such as drafting, are best calculated as a percentage as the amount of work will vary with the project size.

Modeling of interruptions/delays has been included in several different elements throughout the simulation model. The interruptions were added to the TBM, working site, and undercut elements to allow the modeller to add historical delay events as constants or distributions to more accurately reflect real world scenarios that would occur. The TBM delays would include only delays that would result in the TBM breaking down, and wouldn't impact the simulation process if the TBM was not at site. The working site delays would include weather and above-ground equipment-related delays. The undercut delays would typically include undercut hand excavation delays or delays regarding the trains.

The addition of surveying checks to each of the TBM excavation elements gives the modeller the ability to simulate a realistic surveying delay to the excavation process. The modeller will input the surveying interval and duration that the survey requires as either constants or distributions for each soil layer in the tunnel alignment. The modeller can then enter the surveying crew and cost for the crew to be able to more accurately estimate their required hours and cost for the project. The surveying cost is usually treated as an indirect cost, but adding this feature to the TBM excavation tasks allows for more accurate estimation. Since the productivity is halted like it would be in an actual tunnel surveying event, the TBM excavation accuracy is improved. This feature becomes even more effective when modeling the TBM having to excavate through a curved section, as curved sections require a full surveying laser move (8 hours) at much shorter intervals (10 meters). This would mean the TBM excavation would be stopped for 8 hours at intervals of approximately 2 days apart (these figures would typically be given distributions from historical data).

The undercut was given the ability of having a left and right geometry to allow the modeller to incorporate the tail tunnel with the working undercut. This feature also gives the modeller the flexibility to have a two-way tunneling operation out of a single undercut and single working shaft. For added clarification, the light blue arrows in the center show the modeller which direction excavation is taking place. This allows for further ability to simulate a broader range of tunneling scenarios.

The ability to add multiple TBMs to excavate the same project was added as a result of the above feature to allow multiple TBM excavations, from the same undercut and shaft, at either the same or differing times. The modeller can specify the TBM that they would want to excavate in the TBM excavation elements in the right-side column under the TBM heading as shown in Figure 28. The modeller would first have to create the specifications for the two TBM's in the first level of the simulation model.

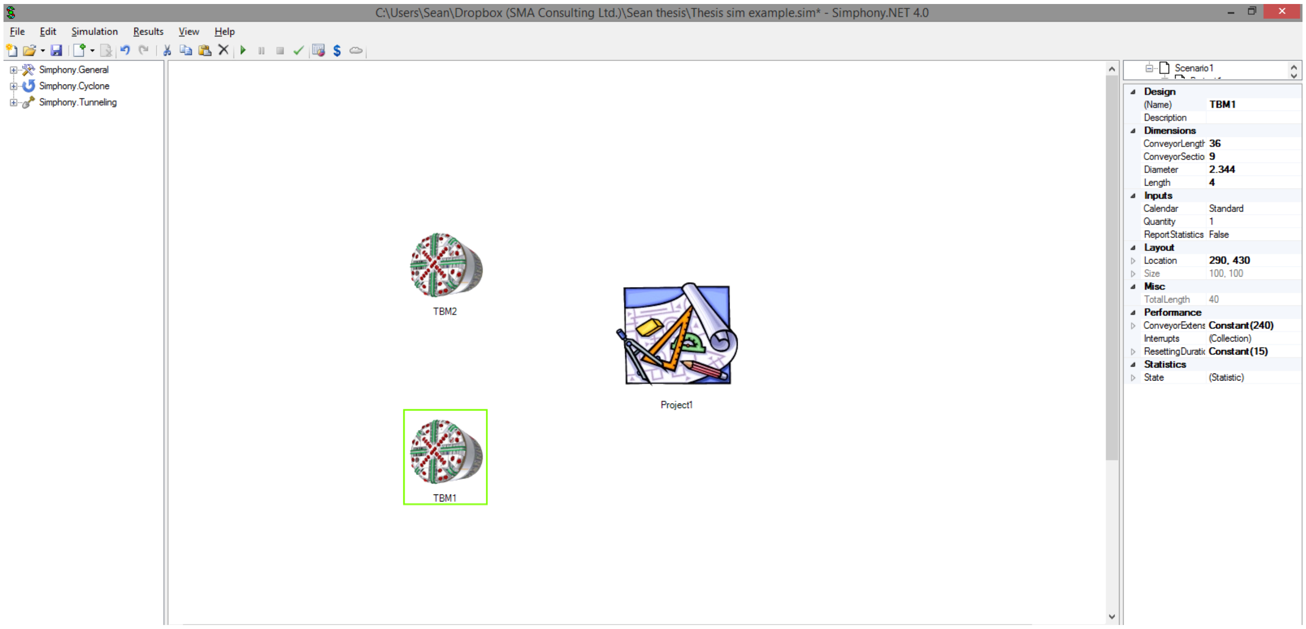

Figure 28: Displaying the ability to add multiple TBM's and configure their properties separately

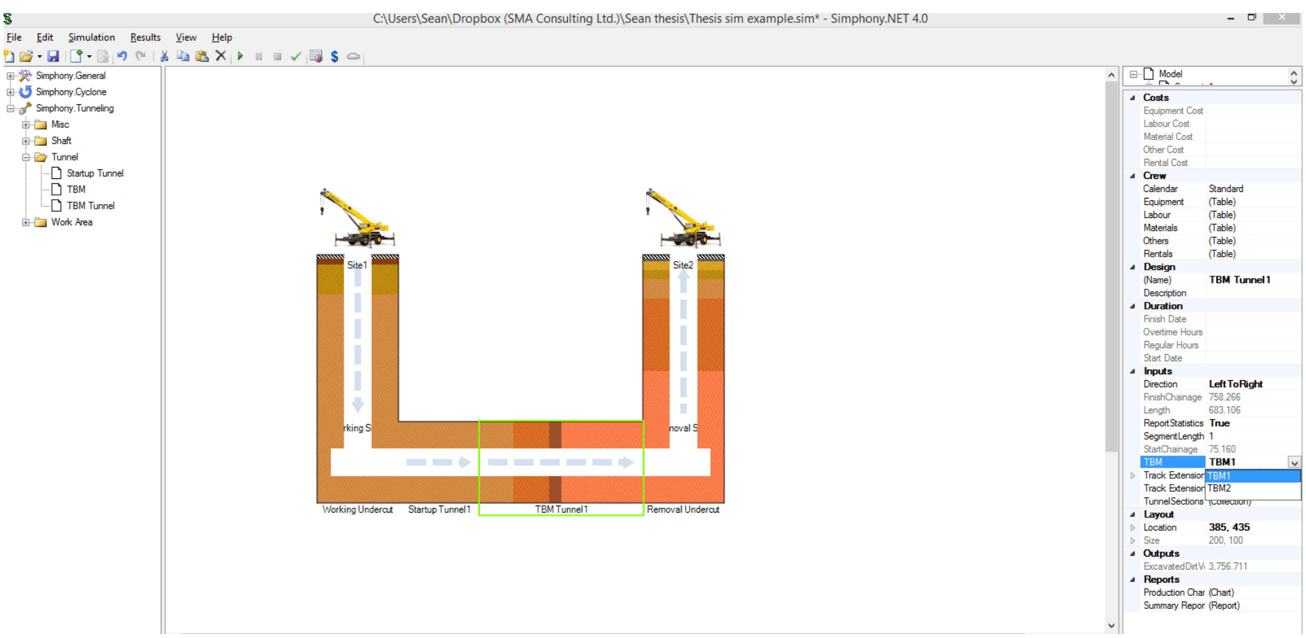

Figure 29: Displaying the ability to select which TBM the modeller wants to excavate the selected tunnel excavation element

[redacted] Estimate enhancements

Working with the simulation team, I built off the integration between SMARTEST and SPS to provide the means by which an estimate can be produced from the simulation. The critical part of this is to use the database of crews and equipment from SMARTEST and assign it to various components of the SPS work packages. At the end of the simulation, those work packages will use the production results from the simulation, the unit rates of crews and equipment, and the various assignments to produce an estimate similar to the ones SMARTEST produces.

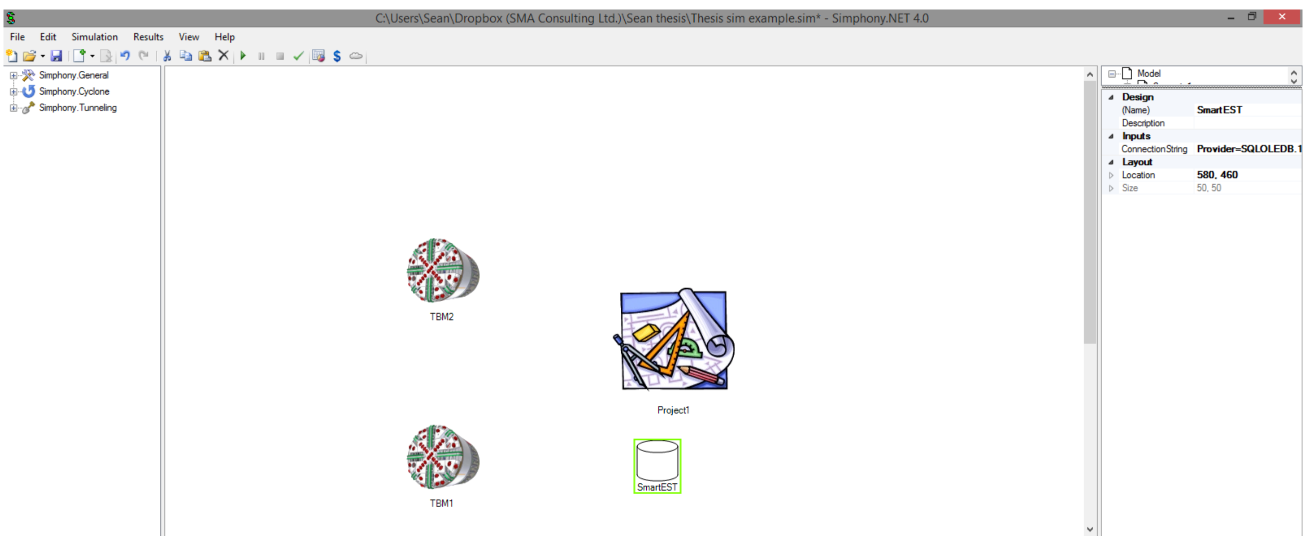

Figure 30: The addition of the SmartEST database to Simphony's highest level and its properties

The SPS provides very easy-to-use features that incorporate estimation into the simulation environment through unit rates. As shown in Figure 31, with the use of the SMARTEST database, crews are stored with their unit rates. A regular time and overtime rate is provided and will automatically be used according to the type of calendar specified in the scenario. This provides us with the added flexibility to also manually adjust the unit rates or add resources to the table with their corresponding unit rate. By looking at the client's actual charges from a past project, I can update these unit rates within SMARTEST to provide accurate year-to-year estimation that is not impacted by inflation. I have revisited and reset proper unit rates to all of the indirect charges associated with the tunneling projects. The TBM estimation is done using a unique method from all the rest of the estimation for the project and from the industry. Typically equipment is estimated on an hour basis, but the TBM for these projects is given a per-meter of installed tunnel unit rate. There is also a lump sum TBM overhaul charge applied to the project that covers its maintenance between projects. This in combination with the per-meter rate will allow the full amount of the TBM to be recovered for the project regardless what happens during the project.

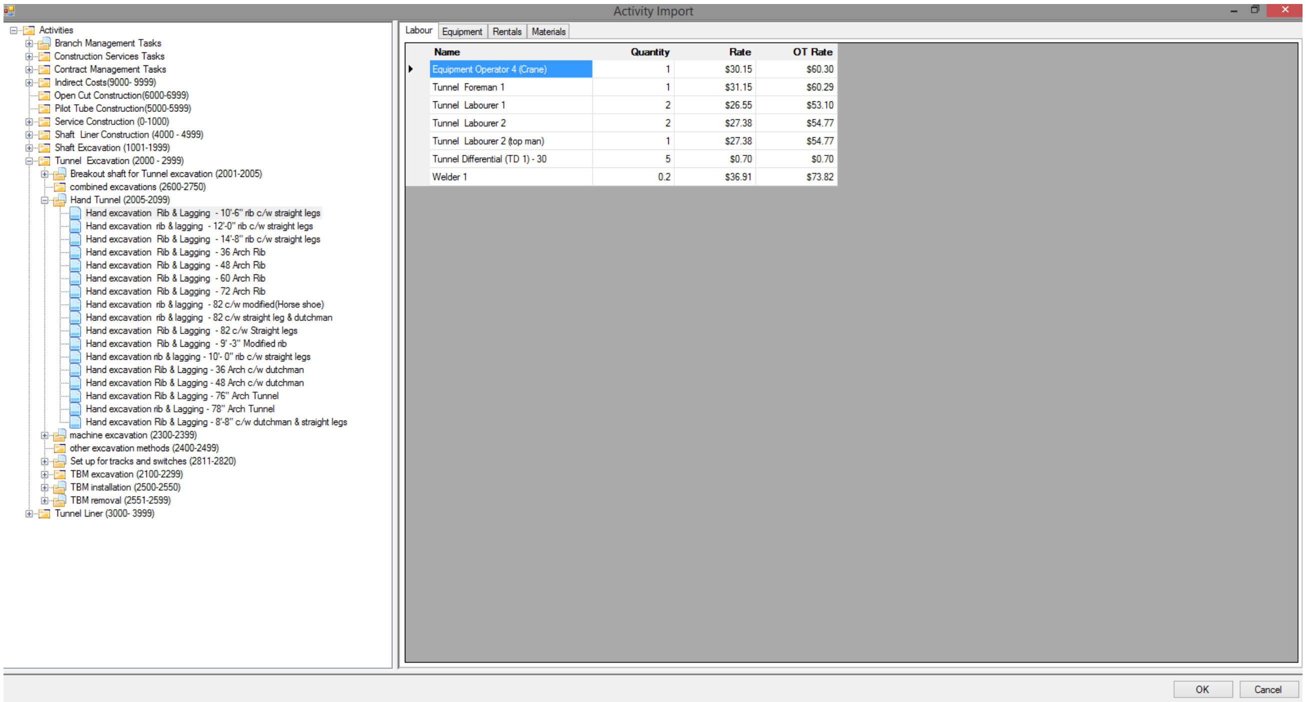

Figure 31: Simplicity of the estimation database being able to add crews to the tunneling template

Indirect charges for the project appear in the high-level project icon. These are also added through SMARTEST, but can be manually entered. By checking the percentage box, this means that the particular indirect cost will be estimated using the percentage entered in the value column. If the percentage column is not checked, then the value entered in the value column will be a fixed dollar value added to the project.

Common areas of concern for estimating projects can be easily reconfigured in the SPS. These work packages can be given new unit rates that reflect actual performance based on past projects. Overall, the estimate will be a much more accurate representation of how the project will materialize as the simulation models the delays previously mentioned and adjusts the estimate accordingly. An example of a full summary report has been provided in Appendix 1. This will demonstrate the effectiveness of the estimation component as it provides a minimum, mean, maximum, and standard deviation amongst all the simulation runs.

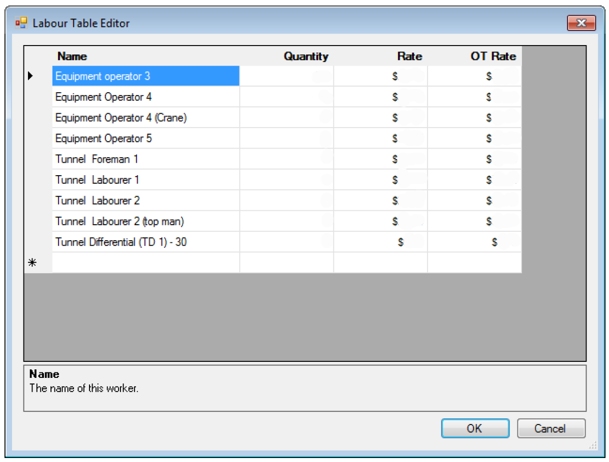

Figure 32: Crew estimation table inside every element of the tunneling template

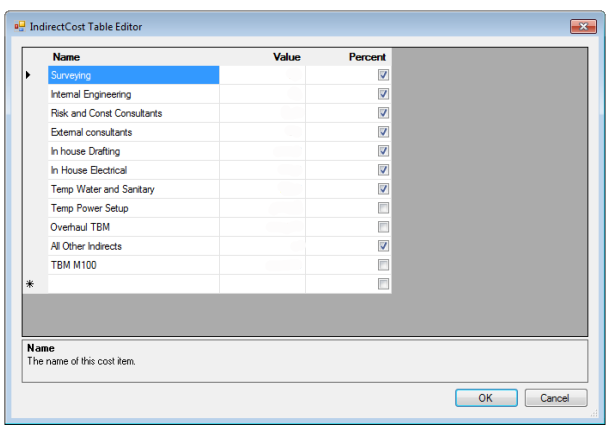

Figure 33: The indirect cost editor table

3.8.1 Schedule production

The production of information for the schedule is simple if the WBS of the tunnel is done in a manner that is equivalent to the WBS of the project. As shown in Appendix 1, the tunneling template's WBS is shown in the direct cost activities shown on the left side of the page. The resulting schedule for the project then adds the lower level tasks that are inside each of these elements in the simulation model. In this case, the work packages will coincide and all the modeler would have to do is simply catch the start and finish times from the simulation for each component and then produce it in the final reports.

[redacted] **Breakdowns/interruptions**

For this application, the critical tasks were evaluated through a Method Productivity Delay Model (Adrain and Boyer, 1976) (MPDM) for which a project's delays/breakdowns are categorized and analyzed. The following shows the strategy I used to achieve this (as this approach is not exactly what the MPDM was created for).

The data is collected on a daily basis, very much like a standard productivity reporting sheet. The difference is that I then categorize a delay into 9 delay types. The total delay hours are placed in the right column and the percentage of the delay is placed in the given category. The hours for each delay are then calculated and totaled and are placed in the total time added row of the delay information table.

Table 4: Daily data collection sheet

Production (m)	*Shift Duration (Hrs)*	*TBM*	*Cleaning TBM*	*TBM Elect*	*TBM Water System*	*Crane*	*Surveying*	*Weather*	*Rocks*	*others*	*Total Delay (hrs)*
1	5	100%									3
0	8	100%									6
1	8										0
1	8	100%									5
0	8	100%									6
0	8	50%								50%	8
1	8										0
1	8							100%			2
4	8										0
4	8									100%	1.5
1	9			100%							5
0	9	100%									9

0	8	100%									8
1	8										0
2	8										0
3	9.5					100%					3
2	9		100%								3.5
3	8									100%	2.5
3	9										0
2	6										0
0	8									100%	8
0	8									100%	8
0	8	50%	50%								8
0	9	50%	50%								9
0	9										0
3	9										0
3	9										0
3	9										0

5	9										0
2	8										0
1	10										0
2	10										0
0	10		50%						50%		10
2	10								100%		5
3	10										0

The non-delay production cycles and the overall production cycles have been separated. Each working day is used as a single cycle within the total production.

Table 5: Production summary table

	Production Time	*Total Number of Cycles*	*Total Production*	*Mean Cycle Time*	*Average Production*
Non-Delayed Production Cycle	899.0	89.0	490.0	10.10	0.55
Overall Production Cycle	2 171.5	218.0	879.0	9.96	0.40

Table 6: Delay information table

Time Variance	*TBM*	*Cleaning TBM*	*TBM Elect*	*TBM Water System*	*Crane*	*Surveying*	*weather*	*Rocks*	*others*
No. of occurrences	49	12	14	2	6	3	8	47	19
Total added time	218.56	49.50	42.52	5.40	36.50	11.25	35.00	167.33	98.68
Probability of occurrence	0.21	0.05	0.06	0.01	0.03	0.01	0.03	0.20	0.08
Relative severity	0.45	0.41	0.31	0.27	0.61	0.38	0.44	0.36	0.52
Expected percentage of delay	9.35%	2.12%	1.82%	0.23%	1.56%	0.48%	1.50%	7.16%	4.22%

Ideal Productivity= 5.56701 m/shift

Total Down time= 32.8%

Method

Productivity=	3.98386	m/shift

The results of the MPDM analysis were fitted to distributions to show the overall delay time, ideal, and method productivities. The ideal productivity is the non-delay productivity that would have been realized if all the delays that occurred were removed. The method productivity is simply the ideal productivity with the delay categories reapplied to it. Each delay category can then be applied in the model as a breakdown element that governs the ideal productivity rate of the excavation.

I have fitted distributions to data representing breakdowns in the process referred to as "interruptions" in the model. I have split the interruptions into two categories: minor interruption and major interruption. A minor interruption is one that lasted between 0.5 and 3.5 hours (less than half a shift) prior to the process resuming its operation, while a major interruption is one that lasted between 4 and 10 hours (half to a full shift). Using statistical analysis, I determined the mean delay time for a minor and major interruption, as well as the mean time between minor and major interruptions. These results were each fitted to a distribution for use in the simulation model. The fitting process used @RISK to select the data and then determine the best fitting distribution. This was completed by producing a cumulative ascending graph for which the distribution was visually selected. The minor breakdowns for the example shown above had a beta distribution fit with shape parameters of 2.0 and 2.0, and range parameters of 1.0 and 4.0, as shown in Figure 34.

The distribution for the time between the occurrences of minor breakdowns is an exponential distribution with a mean of 26.591 hours. The major breakdowns had a beta distribution fit with shape parameters of 2.0 and 5.0, and range parameters of 5.0 and 10.0, as shown in Figure 35.

The distribution for the time between the occurrences of major breakdowns is an exponential distribution with a mean of 41.189 hours. These distributions were placed into Simphony, inside the TBM element, as this is the excavation method and always lies on the critical path.

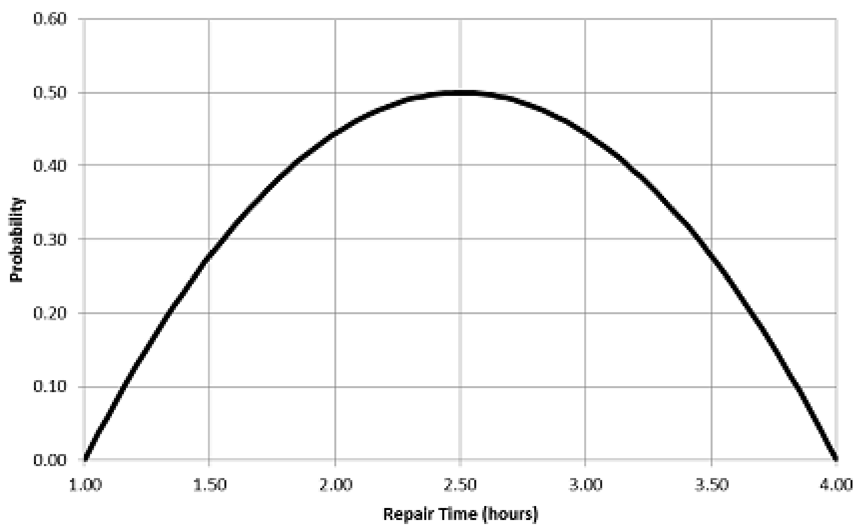

Figure 34: Minor breakdown distribution

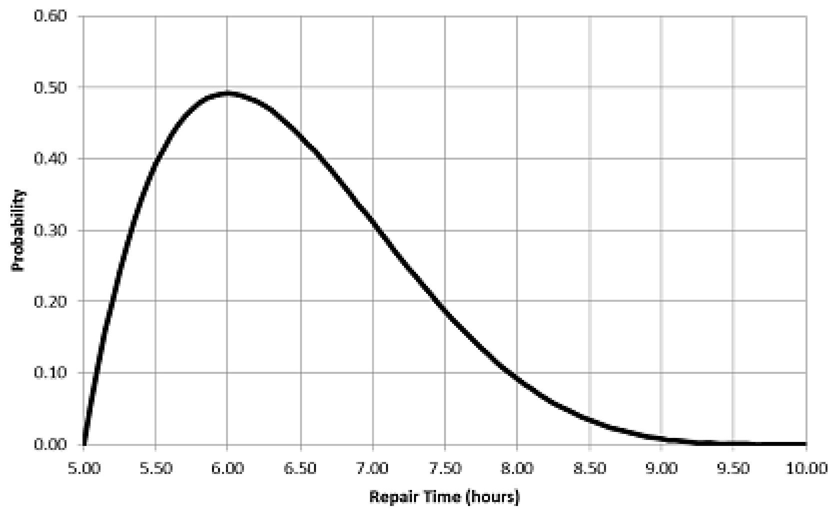

Figure 35: Major breakdown distribution

3.9.1 TBM penetration rates

Penetration rates for each ground condition have been sampled from the Method Productivity Delay Models (MPDM) studies conducted on various projects. The MPDM studies collect every delay that has occurred on a particular project and categorize it. These categories are then compared, in hours of delay, to the overall project working hours to obtain a percent delay time. The ideal productivities for similar ground types were used as the penetration rates. The ideal productivity is the productivity that would have been achieved if no interruptions had been realized. Adding this was essential for not double counting for interruptions when simulating.

TBM penetration rates have been governed by surveying intervals to accurately reflect productivity and cost. Surveying has been broken down into 2 categories, laser calibration and moving the laser forward. The surveying duration is beta distributed with shape parameters of 9 and 2, and a range of 60 to 420 (measured in minutes). This distribution will be sampled every 60 meters of excavated common earth. When excavating in material that is predominantly sand, the distribution will be sampled every 15 meters, as there is a higher probability the installed segment liner that the laser is fixed to will settle, causing the laser itself to be misaligned. There is also a higher probability that the TBM creates a void in the ground either above or below the excavation face, which will shift the excavating alignment of the TBM. A curve in the tunnel alignment will drastically alter the surveying intervals. Curved sections will have a laser movement interval every 6 meters, which will constantly take 420 minutes or 7 hours to complete. Soil swell factors also have been accounted for in the special purpose tunneling model. This will affect the rate at which the TBM fills the dirt car trains as bank ground measurement is converted into loose ground measurement. A higher swell material will mean less ground penetration by the TBM and more frequent train travel as the dirt cars fill up faster. The amount of excavated dirt volume and swell factors are displayed for each tunnel ground type. This will also mean that the TBM will sit idle for longer as it is waiting for the train to return.

[redacted] Simulation as a service

This section describes an innovative approach for applying simulation as a service. In this research, simulation is designed specifically for application to a utility tunnel construction project and customized to meet client output needs, using a special purpose simulation approach. The model outputs the information required by the client in a format that is usable for them. This provides the client with decision support information to make their operations more efficient and effective. Additionally, tools such as value engineering and constructability reviews help the client to obtain more accurate estimates and schedules in the project planning stage.

In general terms, simulation tools are effective in modeling tunnel construction, especially because such processes are linear in nature and are composed of repetitive sub-processes. The challenge is to have the decision maker justify the investment in time, resources and costs associated with building a simulation model for smaller tunnel projects (those that are less than $50 million in cost). For larger projects, the capital investment is significant and the planning time is long, thus providing ample opportunities for deploying simulation in planning the project.

Typically, construction planners rely on two elements once a preliminary design has been produced: the construction costs and the schedule associated with a particular option. Those two elements guide them in selecting the final construction alternative for the project. The simulation in itself is therefore not an end result for a construction planner. It could simply be the means to produce costs and schedule information for decision support. More specifically, schedules are expected to be in a CPM format, and costs in a work-package model, consistent with the models the company uses.

I adopted the simulation tools to produce the costs and schedule for clients. First, simulation modeling normally generates more accurate production information, which is the essence of cost and schedule. Second, if special purpose simulation is used, the development time and the consistency by which estimates and schedules can be produced to reflect varying alternative tunnel plans can be significantly reduced, as compared to developing estimates using standard software or schedules using CPM software. Furthermore, since the base model is the same, the estimate and schedule are based on the same foundation, whereas in practice, they are generally developed by different people on different bases.

The consulting firm where I work has applied the above strategy to the modeling of tunnel construction by adopting a special purpose simulation model. The SPS model provides a quick turnaround time, and is a cost effective service to the client, and at the same time, takes advantage of what simulation has to offer in its accuracy of predictions. SPS provides the flexibility to integrate its simulation environment with a basic service that the client may require, such as estimating, scheduling, pre-project planning, or a constructability review. With the SPS, we custom link the simulation of any project with these tools while building the project schedule and estimate in Microsoft Project and SMARTEST, respectively. The model is built around the work breakdown structure (WBS) of the project and provides detailed information about each work package. After the WBS is defined, the modeling elements are placed inside their work packages, as shown in Figure 36.

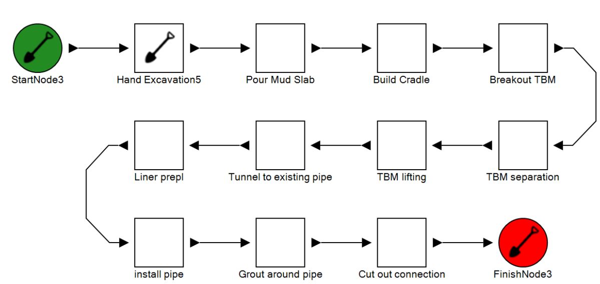

Figure 36: Modeling elements inside the removal shaft work package

Each of these modeling elements inside the work packages has its own unique scheduled durations and crew costs. These modeling elements together create their work packages' cost and schedule duration. This is summarized in a summary report that will show the client the start and finish date of each element, the hours needed to complete the element, its resulting daily productivity, and the estimated cost. It should be noted that this summary sheet is particularly unique for this single simulation.

After the client has selected its preferred level of risk, the cost and duration of this work package is added to the overall project. The client can then take these results to a value engineering or constructability session, to provide key decision support to the project team. The project team will then be able to better create different scenarios to construct the project. The scenarios can then be added to the original model to provide further decision support to the project team. Further scenarios can be run to alter the type of shift that the project team needs to hit any certain cost or schedule constraints. The shift change scenarios will be able to show the client any cost/schedule trade-offs that may exist to further provide added value.

The model output provides a schedule (start/finish dates) and cost for each phase of the project as a distribution.

[redacted] Application to demonstrate the revised SPS template

Note: all numbers presented in this case study were scaled and names were removed for confidentiality.

[redacted] Project background

The Project X TBM tunnel project is a 630 meter tunnel that is part of the Project A line. The tunnel is to be constructed using the M100 TBM. The tunnel is located along a road, where the working shaft is placed in a parking lot and the removal shaft is located near the pump station at an intersection. A hand excavated connection tunnel will be constructed to connect to the pump station.

Figure 37: Project location

[redacted] Objectives and approach

The objective of this analysis is to establish production targets, assess feasibility of the project schedule and budget, and establish a base plan for the construction phase of the project. To achieve those objectives, construction process simulation models were developed, required information was collected and an analysis carried out.

[redacted] Simulation model

The TBM tunnel model is composed of 10 major work packages, each with their own properties and parameters that have been derived based on information presented in the geotechnical reports, from historic data, or from expert opinion. These include: working shaft, working undercut, startup tunnel, tunnel excavation, removal shaft, removal undercut and connection tunnel.

[redacted] Assumptions within the simulation model

The simulation models assume the following:

- Double shifts for every task during construction.
- All drawings are completed 1 month in advance to constructing the element.
- The working undercut is two-way hand tunneling.
- The tail tunnel working undercut is half completed under the previous hand tunnel and not part of the TBM tunnel scope.
- Mixed faces are to be encountered between tunneling layers.
- The removal shaft and undercut start during TBM excavation.
- The M100 TBM is charged out at a rate of $298/meter excavated.
- The unit rate for the precast segments is $1,008.00/linear meter.
- The connection tunnel and hand installing working shaft segments happen at the same time.
- Building up the manholes, one shaft after another, occurs after opening up the tunnel, assuming all other components are completed prior to finishing the TBM component.

- Most construction risks have been incorporated in the model except for catastrophic events, and contingency.

A number of simulation scenarios were run. All scenarios were run multiple times as is the standard in Monte Carlo simulation techniques.

[redacted] Base scenario

The base scenario is composed of a single 8-hour shift that has 2 trains operating with a switch. Under this scenario, the entire project is expected to finish within 2 years, with a total mean cost of approximately $7,914,347.

The individual work package schedules are as follows. The working shaft would be complete in 20 working days. The working undercut takes 91 working days to complete. The simulation estimated an average of 0.340 meters per shift per tunnel, which includes delays, break downs, etc. This is justified as the undercut sections are usually split in to digging the top section and installing the ribs and lagging, then the bottom section with lagging and spreader.

The TBM in clay takes 33 working days to complete. The average productivity is 0.92973 meters per shift. Layer 1 clay takes 41 working days to complete. The average productivity is 2.4786 meters per shift. Layer 2 clay till takes 40 days to complete. The average productivity is 2.71278 meters per shift. Layer 3 clay takes 14 working days to complete. The average productivity is 2.5000 meters per shift. Layer 4 sandstone takes 89 working days to complete. The average productivity is 2.6337 meters per shift.

The removal shaft takes 20 days to complete excavation. The removal undercut takes 72 working days to complete. The undercut excavation productivity is 0.4259 meters per shift. TBM removal will take 13 days to complete. The connection tunnel takes 47 days to complete. The productivity for the excavation is 0.7994 meters per shift. Building up the man holes for both the working and removal shafts takes 14 working days.

Throughout the tunnel excavation, the TBM was idle for 4.5% of the total work hours. A summary of the TBM tunnel work package productivity by layer is given in Table 7.

Upon presenting the base scenario to the client, the director of construction asked to have the models run so that the construction of the project meets the promised requirements. The following scenarios were produced as summarized in the section below. Two scenarios were run, the first with two 8-hour shifts and the second with two 10-hour shifts. Both had two trains operating with a switch in the working shaft area.

Table 7: Single 8-hour shift TBM productivities by soil layer

Work Pack-age	Section	Length (m)	m per shift	Advance per day	Days Required
Tunnel	Start-up (clay)	36.26	0.9297	0.9297	33
	Clay	119	2.4792	2.4791	41
	Clay till	128	2.7128	2.7127	40
	Clay shale	43	2.5000	2.4999	14
	Sand stone	292	2.6337	2.6336	94
				Days 223	

4 CASE STUDY: APPLYING FRONT END PLANNING TO THE DEMONSTRATION SUBJECT – DDC

This TBM tunnel is one segment of the South Edmonton Sanitary Sewer (SESS) overall strategy, connecting the SW1 pump station at Ellerslie Road and Parsons Road to Stages SA1B&C. This segment will allow the SESS flow to bypass the South Edmonton Rich Treatment (SERTS) line. The alignment runs 746 meters north from the intersection of Parsons Road and Ellerslie Road and is to be constructed using an M100 TBM. The tunnel is composed of a working and removal shaft. An additional pump station connection shaft will relieve the force main tunnel from dumping its flow into the SERTS line, and will divert the flow into this tunnel. The TBM tunnel is composed of mainly clay material but has a 300-meter section of sandstone close to the removal shaft. At the removal shaft a 12 meter hand tunnel will connect this tunnel with an existing bottom structure stub under a busy live intersection. The working shaft will be connected to by an external contractor who is also going to remove their TBM from the working shaft.

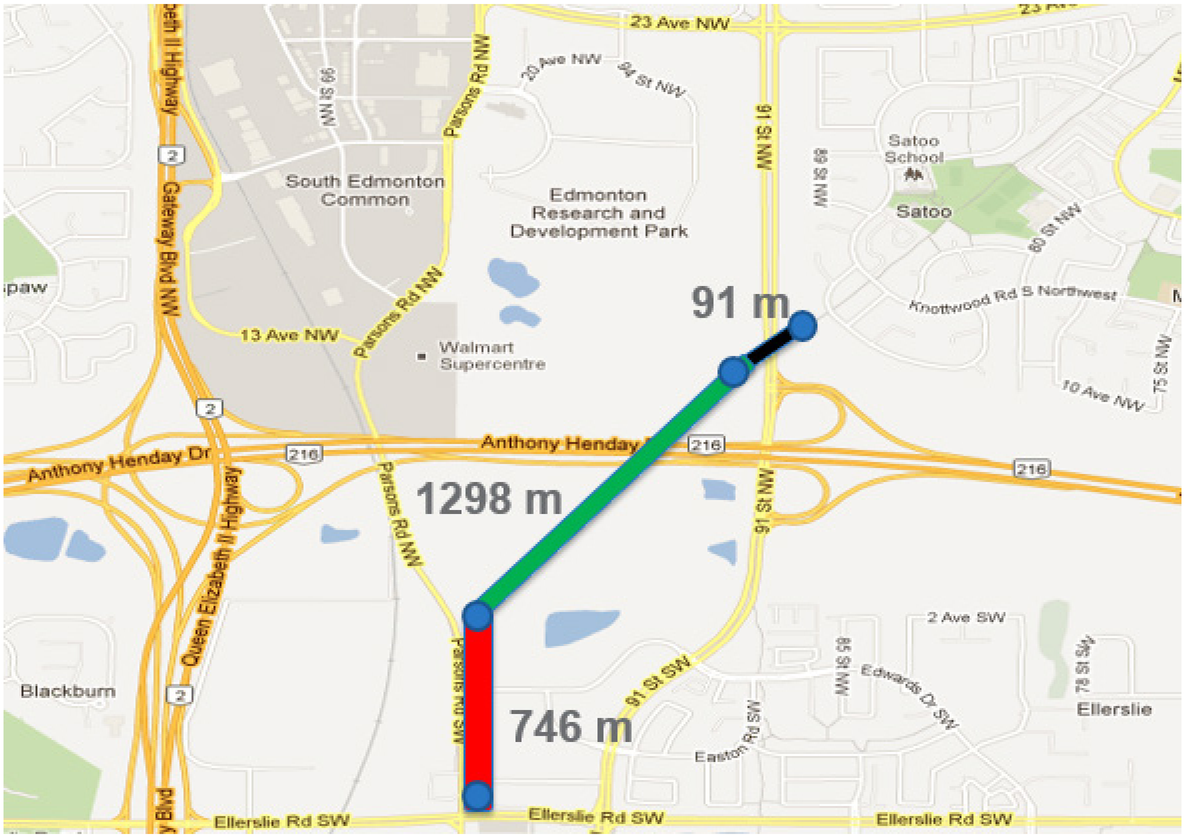

Figure 38: Complete project alignment, red and black highlighted areas are the in-house tunnel while the green is being completed by an external contractor

Figure 39: Project location map

Application of front end planning alignment

Table 8: Alignment application to the drainage project

	CII alignment issue	Incorporating the alignment issue in Drainage projects
1.	Stakeholders are appropriately represented on the project team.	The VE process generally includes representatives of all stakeholders on the project. The stake holder that is directly in front of the working shaft location was communicated with and their permission was

		requested to proceed with construction. A vacant commercial lot beside the working site had permission asked to use their lot for segmental liner storage. Commercial parking lot tenants were asked if temporary construction traffic could use their entrance to gain access to the site trailer until a separate access road was constructed.
	Project leadership is defined, effective, and accountable.	When a project is set up, PMI recommends clear project leader with authority and accountability to execute the project. This need was addressed in the concept planning stage of the project and has not changed to date.
	The priority between cost, schedule, and required project features is clear.	A clear time cost trade off exists in most every project. It was decided that the schedule is a priority on this project as a separate external contractor is connecting with this tunnel. The tunnel also needs to achieve a deadline date to connect to live existing tunnels and con only be completed in the low flow season that exists before spring.
	Communication within the team and with	Communication is part of the project management process and is generally mature in

	stakeholders is open and effective.	various organizations. A weekly project update meeting exists where weekly issues are address with the entire project team. There is also a monthly management review meeting where the project overview is looked at and issues are addressed from a much higher level of management.
	Team meetings are timely and productive.	The weekly and monthly project meetings are significant enough to align the project team with the projects goals.
	The team culture fosters trust, honesty, and shared values.	This requires that the owner and its participants agree to a “team culture fostering trust and honesty etc.). The goals and achievements of this project were laid out for everyone to achieve equally.
	The pre-project planning process includes sufficient funding, schedule, and scope to meet objectives.	Several project start up meetings to establish the project scope funding and schedule time line. Value engineering sessions took place to finalize all of these requirements. A project execution plan (PEP) was created to make sure that everyone is clear on the scope and goals of the project with the budget and schedule included.

	The reward and recognition system promotes meeting project objectives.	The monthly management meeting is in place to ensure that proper recognition of issues are addressed in a timely manner, the weekly project meeting addresses schedule and productivity goals and accomplishments.
	Teamwork and team building programs are effective	…
	Planning tools, such as simulations, checklists, and work flow diagrams, are used effectively.	The (PEP) is constantly referred to for tasks and decisions throughout the life of the project. The simulation models and their results were baselined, and have been updated as the construction process continues. The PDRI has been adapted as a checklist as well as a project health indicator. Constructability reviews have taken place to effectively check the design against its constructability.

■ **Simulation modeling**

The objective of this analysis is to establish production targets, assess feasibility of the project schedule and budget, and establish a base plan for the construction phase of SA1A. To achieve those objectives, construction process simulation models were developed, required information was collected and an analysis carried out. The following tasks were completed during the course of this exercise:

- Information including recorded data from related projects was collected, analyzed and synthesized.
- Key individuals involved in the project were interviewed.
- Existing documents and design reports related to the project were reviewed.
- Workshops, and follow up meetings were carried out.
- Simulation models for production process were developed.
- Analyses of simulation runs were completed to derive production rates, estimates and schedules.
- Meetings were held with design and construction team to review the results.
- Models were adjusted as required.
- Final simulation results were produced and recommendations prepared.

[redacted] Scope of the models

The models were scoped to be limited to the production process that takes place during the construction phase. The schedules, milestones and estimates do not account for design processes including permitting, drafting/shop drawings, approvals, and any other preconstruction design related work packages as per the proposal for this phase of the work. Furthermore, the scope was limited to the tunnel component that would be constructed by internal resources and did not include the open cut component, the trenchless section under the highway and various connections. It is expected that the above excluded work packages will be looked after by the owner's project manager for the project in a separate exercise that integrates the results from this report with other information to produce an overall project plan.

The simulation model was designed and constructed using information as presented in the geotechnical report, as no design drawings were available at the time of model preparation. The model also assumes that the horizontal and vertical alignment of the tunnel will not change. The construction start date is fixed to October 7, 2013 for all model scenarios as per consultation with the construction manager. The cost estimates in this report represent the cost before any additional risk allowance and contingency have been added.

[redacted] Simulation model

The TBM tunnel model is composed of 10 major work packages, each with their own properties and parameters that have been derived based on information presented in the geotechnical reports, from historic data, or from expert opinion. A summary is given in this section:

- Working shaft: The working shaft is composed of 3 soil layers: topsoil, clay fill, and clay. The working shaft is approximately 8 meters deep and has been assumed to be completed as a rib by rib drill assisted excavation.
- Working undercut: The working undercut is situated in a clay soil layer. The working undercut was assumed to be excavated in a two-way hand tunnel excavation method such that both directions of hand tunneling are conducted at the same time. The tail tunnel portion of the undercut is 25

meters in length while the TBM undercut portion is 12 meters in length, both situated in a clay layer.

- Startup tunnel: The first 50 meters start up TBM tunnel is composed strictly of clay material. Here the productivity has been greatly reduced to accommodate for launching the TBM and initializing and setting up the TBM with all of its components, and the switch. The clay material will pose difficult for the TBM to launch in as increased face pressure will result from pushing into the dense material.
- Tunnel excavation: The TBM tunnel excavation has been broken down into its soil layers to give more accurate customized production results.
    - Layer 1: Clay. This layer stretches for 140 meters and will be challenging to excavate in. The use of the foaming agent used on the W13 project is strongly recommended.
    - Layer 2: Clay till. This layer will be 150 meters and will have 20 meters of a mixed face towards the end of clay shale.
    - Layer 3: Clay shale. This layer is the shortest at 50 meters and will get hard towards the end as the tunnel progresses into sandstone.
    - Layer 4: Sandstone. This layer is the longest at 343.13 meters and will be present until breaking through the removal undercut. The use of the foaming agent used on the W13 project is strongly recommended.
- Removal shaft: The removal shaft is 12.8 meters in total depth and has the following soil layers: asphalt, gravel fill, clay fill, clay, clay till, and

sandstone. The first 8 meters of the shaft have been assumed to be excavated continuously by the drill rig, the remaining 4.8 meters have been assumed to be excavated as rib by rib drill assisted excavation.

- Removal undercut: The removal undercut is present in a sandstone layer. The removal undercut will be hand excavated 8 meters in length. The removal undercut has been assumed to have a 16 meter connection to existing tunnel associated with it.
- Connection tunnel: The connection tunnel has been assumed to be 12 meters in length and connects to an existing line. This will be hand excavated, lined with HOBAS pipe, and fillcreted around the pipe.

[redacted] Input to the simulation

Specifying the values for parameters driving the simulation model is critical for deriving accurate forecasts for production from the simulation runs. Data is generally collected from past projects, judgments are made to reflect the unique properties of the project under consideration and statistical distributions are fitted to represent input parameters that are uncertain. For this project I have taken data from several TBM projects and have fitted distributions to this data using standard techniques. I customized the scenarios in the simulation model to reflect the previous recorded productivity studies for the actual TBM that will be used for future projects. This gives a more accurate representation of how the TBM will perform once excavation has started. The following represent the main inputs to the models and the basis of the assumptions made:

- Breakdown/interruptions: I have fitted distributions to data representing breakdowns in the process referred to as "interruptions" in the model. I have split the interruptions into two categories; minor interruption and major interruption. A minor interruption is considered to have lasted between 0.5 to 3.5 hours of duration (less than half a shift) prior to the process resuming its operation, while a major interruption was considered to have lasted between 4 to 10 hours (half to a full shift). Using statistical analysis I determined the mean delay time for a minor and major interruption, as well as the mean time between minor and major interruptions. These results were each fitted to a distribution for use in the simulation model.
- TBM penetration rates: Penetration rates for each ground condition have been sampled from the MPDM studies conducted on various projects. The ideal productivity for similar ground types were used as the penetration rates. The ideal productivity is the productivity that would have been achieved if no interruptions had been realized. Adding this was essential for not double counting for interruptions when simulating.
- Unit rates for estimates: Certain areas were requiring an adjustment to the estimating scheme that has been used on past projects. I have revisited and reset proper unit rates to all of the indirect charges associated with the tunneling projects. Common areas of concern have been the surveying, internal engineering, and drafting. These work packages have been given new unit rates that have reflected performance based on several past projects. Several other unit rates have been adjusted ranging from the sump

pump, to the 360 ton crane. Overall the estimate will be a much more accurate representation of how the project will materialize as the simulation models the delays previously mentioned and adjusts the estimate accordingly.

[redacted] Assumptions within the simulation model

The simulation models assume the following:

- Double shifts for every task during construction.
- All drawings are completed one month in advance to constructing the element.
- The working undercut is two-way hand tunneling.
- The tail tunnel working undercut is half completed under the previous hand tunnel and not part of the TBM tunnel scope.
- Mixed faces are to be encountered between tunneling layers.
- The removal shaft and undercut start during TBM excavation.
- The M100 TBM is charged out at a rate of $350/meter excavated.
- The unit rate for the precast segments is $1,185.00/linear meter.
- The connection tunnel and hand installing working shaft segments happen at the same time.
- Building up the manholes, one shaft after another, occurs after opening up the tunnel. Assuming all other tunnel components are completed prior to finishing the TBM component.

- Most construction risks have been incorporated in the model except for catastrophic events and contingency.
- The construction start date is October 7, 2013.

A number of simulation scenarios were run. All scenarios were run multiple times as is the standard in Monte Carlo simulation techniques. This means that the tunnel for each scenario will be constructed 30 completely independent times. This will allow for various situations and delays within the simulation model to occur, thus enabling us to see all possible outcomes and therefore make decisions in light of the given uncertainty. The 30 runs for each scenario will then produce an output distribution for the estimate and schedule which will provide the estimates represented in the following sections.

[redacted] Base scenario

The base scenario is composed of a single 8 hour shift that has two trains operating with a switch. Under this scenario, the entire project is expected to finish by September 2, 2015, with a total mean cost of approximately $9,324,751.80. For this scenario the project start date was set at October 7, 2013 with preconstruction design related activities happening before this date. The individual work packages schedules are as follows:

- The working shaft would complete in 24 working days finishing on November 7, 2013.
- The working undercut start November 8, 2013 and takes 107 working days to complete on April 23, 2014. The simulation estimated an average of

0.401 meters per shift per tunnel which includes delays, break downs, etc. This is justified as the undercut sections are usually split into digging the top section and installing the ribs and lagging, then the bottom section with lagging and spreader.

- The TBM first 50 meters (clay) starts April 24, 2014 and takes 39 working days to complete by June 17, 2014. The average productivity is 1.0938 meters per shift.
- Layer 1 clay starting June 18, 2014 and taking 48 working days to complete on August 22, 2014. The average productivity is 2.916 meters per shift.
- Layer 2 clay till starts August 25, 2014 and takes 47 days to complete by October 28, 2014. The average productivity is 3.1915 meters per shift.
- Layer 3 clay shale starts October 29, 2014 and takes 17 working days to complete on November 20, 2014. The average productivity is 2.9412 meter per shift.
- Layer 4 sandstone starts November 21, 2014 and takes 105 working days to complete by May 4, 2015. The average productivity is 3.0985 meters per shift.
- The removal shaft needs to start construction November 18, 2014 and will take 23 days complete excavation. The shaft will finish January 7, 2015
- The removal undercut starts construction January 7, 2015 and takes 85 working days to complete by May 4, 2015. The undercut excavation productivity is 0.501 meters per shift.

- TBM removal will commence May 5, 2015 and take 15 days to complete by May 25, 2015.
- The connection tunnel starts May 26, 2015 and takes 55 days to complete by August 10, 2015. The productivity for the excavation is 0.9405 meters per shift.
- Building up the man holes for both the working and removal shaft starts August 11, 2015 and will take 17 working days to complete the project by September 2, 2015. Throughout the tunnel excavation, the TBM was idle for 5.3% of total work hours.

A summary of the TBM tunnel work package productivity by layer is given in Table 9.

Table 9: Single 8-hour shift TBM productivities by soil layer

1x8 hrs shift									
	Workpackage	Section	Length (m)	m/shift	Shifts per day	Advance per day	Hrs/shift	Days required	
	Tunnel	Startup (clay)	42.66	1.0938	1	1.0938	8	39.0	
		Clay	140	2.9167	1	2.9166	8	48.0	
		Clay till	150	3.1915	1	3.1914	8	47.0	
		Clay shale	50	2.9412	1	2.9411	8	17.0	

		Sandstone	343.13	3.0985	1	3.0984	8	110.0	
								Days	261.8

Upon presenting the base scenario to the owner, the director of construction asked to have the models run so that the construction of the project meets promised deadline requirement of March 2015. The following scenarios were produced as summarized in the section below. Two scenarios were run, the first with two 8-hour shifts and the second two 10-hour shifts. Both had two trains operating with a switch in the working shaft area.

[redacted] Scenario 1 - two 8-hour shifts

The first scenario is composed of a double 8-hour shift that has two trains operating with a switch. Under this scenario the entire project is expected to finish February 4, 2015, with a total cost of approximately $9,366,828.21. For this scenario the project start date was set at October 7, 2013 with preconstruction design related activities completing prior to this date. The individual work packages have the following schedule and productivity values:

- The working shaft would complete in 11 working days finishing on October 21, 2013.
- The working undercut starts October 22, 2013 and takes 94 working days to complete on April 7, 2014. The simulation estimated an average of 0.505 meters per shift per tunnel which includes delays, breakdowns, etc. This is

justified as the undercut sections are usually split into digging the top section and installing the ribs and lagging, then the bottom section with lagging and spreader.

- The TBM first 50 meters (clay) starts April 7, 2014 and takes 25 working days to complete on May 9, 2014. The average productivity is 1.1 meters per shift for a daily advancement of 2.3 meters per day.
- Layer 1 clay starting May 12, 2014 and taking 21 working days to complete by June 10, 2014. The average productivity is 3.2 meters per shift for a daily advancement of 6.4 meters per day.
- Layer 2 clay till starts June 11, 2014 and takes 26 days to complete on July 16, 2014. The average productivity is 2.9 meters per shift for a daily advancement of 5.8 meters per day.
- Layer 3 clay shale starts July 17, 2014 and takes 9 working days to complete by July 29, 2014. The average productivity is 2.8 meter per shift for a daily advancement of 5.6 meters per day.
- Layer 4 sandstone starts July 30, 2014 and takes 58 working days to complete on October 17, 2014. The average productivity is 2.9 meters per shift for a daily advancement of 5.9 meters per day.
- Throughout the tunnel excavation the TBM was idling for 3.2% of total work hours.
- The removal shaft needs to start construction August 11, 2014 and will take 11 days to complete excavation. The shaft will finish August 26, 2014.

- The removal undercut starts construction August 26, 2014 and takes 39 working days to complete by October 17, 2014. The undercut excavation productivity is 0.501 meters per shift for an advancement per day of 1.002 meters.
- TBM removal starts October 20, 2014 and completes October 29, 2014.
- The connection tunnel starts November 13, 2014 and takes 38 days to complete on January 21, 2015. The productivity for the excavation is 0.94 meters per shift for an advancement rate per day of 1.9 meters per day.
- Building up the manholes for both the working and removal shaft will start January 22, 2014 and take 6 days to complete by January 29, 2014. Site restoration will then take 4 days and the project will be completed by February 4, 2015.

The production rates for the tunnel work package are summarized in Table 10.

Table 10: Double 8-hour shift TBM productivities by soil layer

2x8 hrs shift								
Work package	Section	Length (m)	m/shift	Shifts per day	Advance per day	Hrs/shift	Days required	
Tunnel	Start-up (clay)	42.66	1.12	2	2.25	8	19.0	38

	Clay	140	3.18	2	6.36	8	22.0	44
	Clay till	150	2.88	2	5.77	8	26.0	52
	Clay shale	50	2.78	2	5.56	8	9.0	18
	Sandstone	343.13	2.96	2	5.92	8	58.0	116
							Days	134

Scenario 2 - two 10-hour shifts

The second scenario is composed of a double 10-hour shift that has two trains operating with a switch. Under this scenario the entire project is expected to finish October 29, 2014, with a total cost of approximately $9,567,580 (estimated at the 90th percentile). For this scenario the project start date was set at October 7, 2013 with preconstruction design related activities completing before this date. The following are the schedules and productivities for individual work packages for this scenario:

- The working shaft would complete in 10 working days finishing on October 18, 2013.

- The working undercut start October 21, 2013 and takes 84 working days to complete on March 6, 2014. The simulation estimated an average of 0.85 meters per shift per tunnel which includes delays, break downs, etc. This is justified as the undercut sections are usually split into digging the top section and installing the ribs and lagging, then the bottom section with lagging and spreader.
- The TBM first 50 meters (clay) starts March 6, 2014 and takes 18 working days to complete on March 31, 2014. The average productivity is 1.3 meters per shift for an advancement of 2.6 meters per day.
- Layer 1 clay starting April 1, 2014 and taking 17 working days to complete by April 23, 2014. The average productivity is 4.1 meters per shift for an advancement of 8.2 meters per day.
- Layer 2 clay till starts April 24, 2014 and takes 18 days to complete by May 19, 2014. The average productivity is 4.2 meters per shift for an advancement of 8.3 meters per day.
- Layer 3 clay shale starts May 20, 2014 and takes 8 working days to complete on May 29, 2014. The average productivity is 3.1 meter per shift for an advancement of 6.3 meters per day.
- Layer 4 sandstone starts May 30, 2014 and takes 45 working days to complete July 31, 2014. The average productivity is 4.2 meters per shift for an advancement of 8.4 meters per day.
- Throughout the tunnel excavation the TBM was idling for 3.4% of total work hours.

- The removal shaft needs to start construction June 9, 2014 and will take 9 days to complete excavation. The shaft will finish June 20, 2014
- The removal undercut starts construction June 20, 2014 and takes 30 working days to complete by July 31, 2014. The undercut excavation productivity is 0.55 meters per shift for advancement per day of 1.1 meters.
- TBM removal starts August 1, 2014 and completes August 12, 2014.
- The connection tunnel starts August 27, 2014 and takes 35 days to complete by October 14, 2014. The productivity for the excavation is 1.13 meters per shift for an advancement of 2.27 meters per day. The finish date is dependent on the connection to existing, as this is an excellent time to connect due to this being a low flow period.

Building up the manholes for both the working and removal shaft will start October 15, 2014 and take 6 days to complete by October 22, 2014.

Table 11: Double 10-hour shift TBM productivities by soil layer

2x10 hrs shift								
Work package	Section	Length (m)	m/shift	Shifts per day	Advance per day	Hrs/shift	Days required	
Tunnel	Startup (clay)	42.66	1.33	2	2.67	10	16.0	32
	Clay	140	4.12	2	8.24	10	17.0	34

	Clay till	150	4.17	2	8.33	10	18.0	36
	Clay shale	50	3.13	2	6.25	10	8.0	16
	Sandstone	343.13	4.18	2	8.37	10	41.0	82
							Days	100

[redacted] Recommendations

- It was recommended to start the project with a double 10-hour shift with targets as per Scenario 2 maintained to complete the project by the required delivery date. During project execution, and after confirming that the established targets are being achieved or exceeded, the construction manager can switch the operation to run at double 8-hour shifts, which would save costs. This call can be made after review of the results when layer 1 (clay) is completed, for example, actual observations collected, and simulations re-run to confirm feasibility of completing the schedule by its due date.
- The reasoning for this is due to the flexibility of the schedule later in the project. It is better for the project to advance to a point that is deemed acceptably comfortable to relax the shift durations. This will allow the project to possibly get ahead of schedule should a larger catastrophic risk materialize that would not be accounted for in the model. It is better to advance ahead of schedule than to be chasing a deadline that is unattainable and impractical. Starting with the double 10-hour shift is most preferred to

prevent a rushed atmosphere that would accompany falling behind schedule early in the project.
There is also some concern associated with the existing pump tie in for the entire tunnel. This is another reason why maintaining a double 10-hour shift would be beneficial to help mitigate any uncertainty associated with possible pump delays towards the end of the project.

- All construction drawings need to be completed one month prior to work requiring them and as per the schedule reflected in the scenarios above. The need to have all of the construction drawings at least one month prior to performing the work package is extremely critical for this project to not run over schedule. The main drawings that seem to delay previous projects are the connection to existing infrastructure, the working and removal cradle drawings, and both working and removal shaft bottom structure drawings.
- This will mean that drawings such as the connection to existing tunnel will have to be produced based off of existing design material. Standard drawings would have to be used for the working and removal cradle drawings while using the dimensions of the projects as-builts. In the case of the removal shaft retro fitting the heights of the cradle will have to be performed on site after the TBM has broken through the undercut.
- Budget targets summary:

The following summary tables include base costs and the risks associated with the simulation results. These costs do not include contingency and the remaining risk values.

Table 12: Summary of cost by work package

Work package	Cost
Working Shaft	$ 451,646.44
Working Undercut	$ 1,505,145.37
TBM Tunnel first 50m	$ 307,833.17
TBM Tunnel Excavation (Remaining)	$ 2,156,165.09
Removal Shaft	$ 381,153.58
Removal Undercut	$ 355,460.60
TBM Removal	$ 72,708.35
Connection Tunnel	$ 362,509.42
Project Budget	$ 9,047,568.49

Table 13: Schedule and productivity targets for the drainage project

Work package	Start date	Finish date	Productivity Target
Working Shaft	Oct 7 2013	Oct 18 2013	1.4m/day
Working Undercut	Oct 21 2013	March 6 2014	0.85m/shift/tunnel direction
TBM Tunnel first 50m	March 6 2014	March 31 2014	2.6m.day
Clay Layer	April 1 2014	April 23 2014	8.2m/day
Clay till layer	April 24 2014	May 19 2014	8.3m/day

Clay shale layer	May 20 2014	May 29 2014	6.3m/day
Sandstone layer	May 30 2014	July 31 2014	8.4m/day
Removal Shaft	June 9 2014	June 20 2014	1.2m/day
Removal Undercut	June 20 2014	June 31 2014	1.1m/day
TBM Removal	August 1 2014	August 12 2014	9% removal /day
Connection Tunnel	August 27 2014	October 14 2014	2.27m/day
Hand Install Segments	August 28 2014	September 17 2014	2.5 rings/day
Build Manhole	October 15 2014	October 22 2014	3 day completion each shaft
Project Completion		October 29 2014	

[redacted] Project construction cost estimate

Table 14: Project cost estimate from the tunneling template

Direct Costs				
	Minimum	Mean	Maximum	Std Dev
Working Shaft				
Labour	$86,946.77	$91,057.06	$97,821.28	$4,324.44
Equipment	$166,565.73	$171,518.54	$179,669.29	$5,210.86
Rental	$0.00	$0.00	$0.00	$0.00
Material	$259,892.71	$259,892.71	$259,892.71	$0.00
Other	$3,571.43	$3,571.43	$3,571.43	$0.00
Total	$516,976.64	$526,039.75	$540,954.71	$9,535.30
Working Undercut				
Labour	$412,081.58	$426,928.71	$443,759.79	$12,163.45
Equipment	$495,764.04	$515,136.61	$534,974.01	$14,432.91
Rental	$56,598.00	$57,524.61	$59,810.78	$1,036.63
Material	$502,863.50	$502,863.50	$502,863.50	$0.00

Other	$0.00	$0.00	$0.00	$0.00
Total	$1,467,932.08	$1,502,453.44	$1,540,016.47	$26,955.15
Removal Shaft				
Labour	$46,656.02	$46,656.02	$46,656.02	$0.00
Equipment	$67,307.84	$67,307.84	$67,307.84	$0.00
Rental	$34,974.44	$34,974.44	$34,974.44	$0.00
Material	$222,477.03	$222,477.03	$222,477.03	$0.00
Other	$3,571.43	$3,571.43	$3,571.43	$0.00
Total	$374,986.75	$374,986.75	$374,986.75	$0.00
Removal Undercut				
Labour	$259,471.11	$263,951.76	$267,683.05	$2,798.13
Equipment	$361,342.71	$372,088.89	$381,013.98	$6,711.10
Rental	$49,888.75	$49,888.75	$49,888.75	$0.00
Material	$48,482.96	$48,482.96	$48,482.96	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$719,185.54	$734,412.37	$747,068.75	$9,509.22

Startup Tunnel				
Labour	$133,552.96	$153,974.87	$169,845.26	$13,293.36
Equipment	$103,520.53	$119,350.07	$131,651.65	$10,304.04
Rental	$0.00	$0.00	$0.00	$0.00
Material	$47,047.93	$47,047.93	$47,047.93	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$284,121.42	$320,372.87	$348,544.84	$23,597.40
TBM Tunnel				
Labour	$988,221.08	$1,017,722.09	$1,087,836.96	$32,964.34
Equipment	$1,125,523.23	$1,159,123.06	$1,238,979.60	$37,544.36
Rental	$11,448.21	$11,789.97	$12,602.22	$381.88
Material	$791,191.37	$791,191.37	$791,191.37	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$2,916,383.89	$2,979,826.48	$3,130,610.15	$70,890.58
Overall				
Labour	$2,107,768.99	$2,147,738.80	$2,240,340.62	$41,993.25

Equipment	$2,626,630.88	$2,672,513.27	$2,778,920.71	$47,259.89
Rentals	$183,329.60	$184,466.29	$187,564.71	$1,333.28
Materials	$2,110,558.20	$2,110,558.20	$2,110,558.20	$0.00
Other	$10,714.29	$10,714.29	$10,714.29	$0.00
Total	$7,041,053.10	$7,125,990.85	$7,328,098.52	$89,672.00
Total Costs				
Item	Minimum	Mean	Maximum	Std Dev
Surveying	$239,395.80	$242,283.69	$249,155.35	$3,048.85
Internal Engineering	$521,037.93	$527,323.32	$542,279.29	$6,635.73
Risk and Const Consultants	$197,149.49	$199,527.74	$205,186.76	$2,510.82
External consultants	$295,724.23	$299,291.62	$307,780.13	$3,766.22
In house Drafting	$141,243.53	$142,947.38	$147,001.66	$1,798.82
In House Electrical	$125,049.11	$126,557.60	$130,147.03	$1,592.57
Temp Water and Sanitary	$74,283.11	$75,179.21	$77,311.44	$946.04
Temp Power Setup	$205,357.14	$205,357.14	$205,357.14	$0.00

Overhaul TBM	$302,678.57	$302,678.57	$302,678.57	$0.00
All Other Indirects	$171,801.70	$173,874.18	$178,805.61	$2,188.00
TBM M100	$231,250.00	$231,250.00	$231,250.00	$0.00
Total	$2,504,970.60	$2,526,270.44	$2,576,952.98	$22,487.05
Total Costs				
Item	Minimum	Mean	Maximum	Std Dev
Direct Costs	$7,041,053.10	$7,125,990.85	$7,328,098.52	$89,672.00
Indirect Costs	$2,504,970.60	$2,526,270.44	$2,576,952.98	$22,487.05
Total	$9,546,023.70	$9,652,261.29	$9,905,051.50	$112,159.05

[redacted] Validation

The tunnel that the tunneling template has been demonstrated and tested on has currently 94/714 meters installed of the "Excavate tunnel by mole" task shown below.

Table 15: Actual vs. estimated expenditure on the project currently

	Actual to Date	*Completion %*	*Estimate*
In-house Tunnel			
Design	$ 229,487.43	47%	$ 490,654.38
Design Consultants	$ -	0%	$ 164,879.71
Geotechnical Consulting	$ 43,234.85	115%	$ 37,465.42
Construction Management Services	$ 98,421.02	49%	$ 200,477.68
Value engineering	$ 42,707.61	100%	$ 42,707.61
Simulation Analysis	$ 45,123.96	100%	$ 45,123.96
Construction	$ 2,647,323.62	31%	$ 8,556,914.12
Indirects - Engineering and related	$ 221,256.41	35%	$ 632,988.10
Internal Engineering	$ 150,720.90	30%	$ 497,991.91

In-house Drafting	$ 70,535.51	52%	$ 134,996.19
Indirects - Others	$ 514,843.96	48%	$ 1,074,821.95
In House Electrical Power services	$ 66,099.04	55%	$ 119,518.05
Temporary water and sanitary setup	$ -	0%	$ 70,997.49
Power supply	$ 5,680.96		$ 230,000.00
Temporary power setup	$ 68,781.25	33%	$ 205,357.14
Survey	$ 42,126.37	18%	$ 228,807.09
Overhauling of mole	$ 323,477.90	107%	$ 302,678.57
CCTV of Parsons Rd. Sewers-Insitucan	$ 8,678.43		$ -
All other indirects (site tools, meetings, supervision, material delivery, etc.)	$ -	0%	$ 147,463.60
Directs - Construction and Material	$ 1,911,223.26	28%	$ 6,849,104.07
Tunnel segments	$ 15,839.57	2%	$ 823,151.79
Working shaft construction	$ 330,609.63	73%	$ 451,646.45
Excavation of undercut and tail tunnel	$ 630,644.29	42%	$ 1,505,145.38
Mole installation	$ 307,944.34	92%	$ 334,799.64

Excavate First (50m)	$ 276,060.22	90%	$ 307,833.18
Excavate tunnel by mole (714m)	$ 350,125.21	16%	$ 2,156,165.10
Patching and Cleaning	$ -	0%	$ 98,530.56
Removal shaft construction	$ -	0%	$ 381,153.59
Removal Undercut	$ -	0%	$ 355,460.61
Mole removal	$ -	0%	$ 72,708.36
Hand tunnel for 1500mm pipe connection	$ -	0%	$ 362,509.43
SUB-TOTAL	$ 2,876,811.05	32%	$ 9,047,568.49

The tunnel project is currently slightly behind schedule, but is projecting to be under budget. The construction tasks that have been completed to date are the mole installation, and excavation of the first (50 m) tasks. These tasks have completed 10% under budget. The tasks that have had work completed on them, but are waiting until the end of the project to complete, are the working shaft construction, excavation of undercut and tail tunnel, and excavate tunnel by mole (714 m) tasks. These tasks are all projecting to be completed within budget. The working shaft needs to have the manhole barrels placed inside it and backfill around the outside with fillcrete, which is projecting to take the remainder of the budget. Excavation of undercut and tail tunnel tasks need to have the equipment and platform removed from it before hand-installing segmental liner in it and a bottom structure built where the shaft is located and backfilling with fillcrete. Currently, the excavate tunnel by mole task is being constructed and is hitting all of the productivity targets necessary.

[redacted] Application of the PDRI

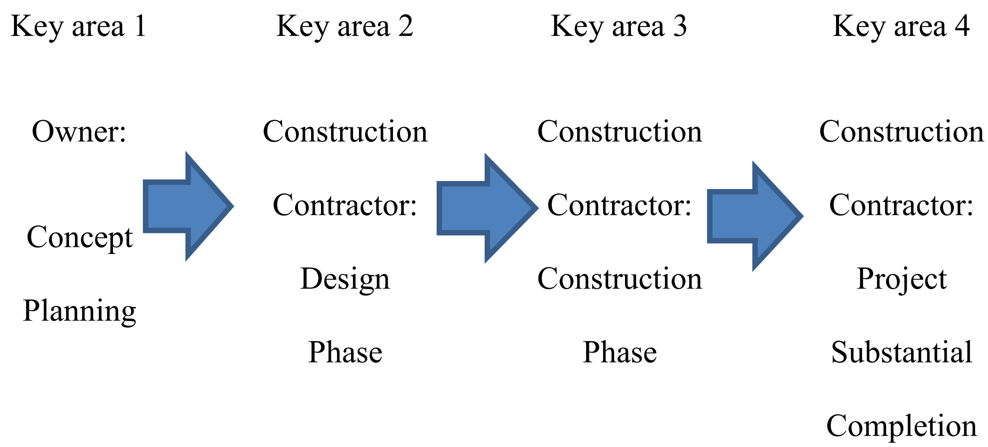

Figure 40: PDRI application areas

The figure above shows that there are 3 areas (shown with arrows) where the project experiences noteworthy transitions. These 3 areas are where the PDRI should be conducted to give an indication of the project's health (CII, 1995). The PDRI helped establish 2 key aspects of the project. First the PDRI acted as a checklist, thus indicating what areas of the project need most attention, as opposed to the areas that are in good standing. Second, the PDRI completion indicated a project score that, through the use of established weighting and benchmarking, will indicate whether the project should be passed on to the next project area, or if further development in the current area is needed (CII, 1997). Benchmarking will help to establish scores that are shown along a distribution for the 3 transition areas that will have to be met or exceeded to be passed on to the next key area. A distribution will be created to match with a project success factor for the PDRI's performed.

The first transition area's PDRI score will be higher (less defined) than the second or last, as the project becomes more clearly defined and unknowns become know and are corrected due to the previous PDRI results (CII, 1995). It is important to note that after each PDRI scoring, the 70 key indicators and their respective categories will also become populated with scores indicating the health of certain aspects of the project. The areas with higher scores should then be developed further in the current key area to improve its score for the subsequent PDRI scoring (CII, 1999).

For the current project's scoring, the first PDRI workshop indicated that the project had a healthy score of 195, which is below the healthy indicator score that CII established (the lower the score the better). The PDRI score card displays all of the key area section scores, as well as each individual category within the sections scores. The right side of the score card displays the section scores for each PDRI rating. Here the differences between the key area section scores are displayed to indicate the areas most and least improved. The results of the first PDRI workshop showed that the section noted to be lacking and needing further improvements to improve the projects quality was section 2, which showed on the PDRI score card as having a higher percentage (the percent of the score to the highest possible section score). In this section the categories H, I, J, and K all need improvement as these indicators add higher scores to this section and the overall PDRI scoring. These indicators pertained exclusively to the site laydown equipment locations and the requirement for utility setup drawings to be completed. There also was a need to further explore and identify the connection points to the existing infrastructure around the removal shaft, as well as further coordinate the connection with the external contractor coming into the working shaft. The project team was then tasked to bring these items to a higher definition in order to maintain a higher success level for the project. Following this, the second PDRI was performed before the project went into the construction phase. The PDRI score card shows the first and second key area scores for all the sections. On the right side of the score card is the detail regarding the scores obtained from the two workshops. To the right of the key area scores is the lowest and highest possible score for each section. The difference row shows the difference between the key area scores for each section to indicate the most and least improved sections. It was previously mentioned that section 2 had the highest score and thus the project team was tasked to bring this score down by defining the individual indicators better. Based on the second PDRI workshop, the second section was defined the most as indicated by the highest difference percentage being obtained. This indicates that the effort made to define this section from the first PDRI workshop was successful.

Table 16: Scoring 1 section 1

SECTION I - BASIS OF PROJECT DECISION								
CATEGORY Element	Definition Level 0	1	2	3	4	5	Score	Comments
A. MANUFACTURING OBJECTIVES CRITERIA							9	
A1. Reliability of subcontractors and consultants					x		4	Electrical consultant
A2. Maintenance availability			x				2	Shop minor issues
A3. Operating philosophy				x			3	Roles and respon-sibilities not clearly laid out
B. BUSINESS OBJECTIVES							18	
B1. Knowledge and partnering with construction planning branch					x		4	Unclear required completion
B2. SSSF funding strategy		x					1	Funds available

B3. Project execution strategy			x				2	PEP defined but working improve-ments
B4. Affordability/feasibility of budget				x			3	Tunnel budget
B5. Capacities to commence/continue project				x			3	Issues with double shifting and OT
B6. Future expansion considerations (stubs)	x						0	This is the final structure in the overall tunnel line
B7. Expected project life cycle		x					1	
B8. Social issues and stake holder involvement					x		4	Working site stakeholder delays

C. BASIC DATA RESEARCH & DEVELOPMENT							3	
C1. Technology (foaming unit, automated total station surveying)			x				2	
C2. Legal entitlement check for the proposed alignment		x					1	
D. PROJECT SCOPE							14	
D1. Project objectives statement					x		4	Needs to be checked whether its conveyance and/or storage
D2. Project design criteria			x				2	Grade of tunnel
D3. Site characteristics available vs. required		x					1	
D4. Installation and removal requirements for TBM					x		4	Details of installation need to be further reviewed with the

								working site stake holders
D5. Lead/discipline scope of work			x				2	As-builts for the connection tunnels to the existing
D6. Project schedule detail		x					1	
E. VALUE ENGINEERING							6	
E1. Process simplification		x					1	
E2. Design & material alternatives Considered/rejected			x				2	Alternatives discussed
E3. Design for constructability analysis				x			3	Segment design check
						Total score	50	

Table 17: Scoring 1 section 2

SECTION II - BASIS OF DESIGN								
CATEGORY Element	Definition Level 0	1	2	3	4	5	Score	Comments
F. SITE INFORMATION							17	
F1. Site location					x		4	
F2. Surveys & soil tests				x			3	
F3. Environmental assessment (ECO plan, ESC)			x				2	
F4. Permit requirements (first call, OSCAM)			x				2	
F5. Utility sources with supply conditions					x		4	
F6. Fire protection & safety considerations			x				2	
G. PROCESS/MECHANICAL							39	
G1. Mobilization plan			x				2	
G2. Procurement plan			x				2	
G3. Laydown drawings					x		4	
G4. Safety management plan		x					1	
G5. Utility plan			x				2	
G6. TBM specifications for e.g. teeth, foam unit, doors				x			3	

G7. Tunnel requirements (segments, track)					x		4	
G8. Geotechnical information				x			3	
G9. Mechanical equipment list			x				2	
G10. Staging requirements				x			3	
G11. Connection knowledge and as-builts						x	5	
G12. Specialty equipment requirements (segments, etc.)				x			3	
G13. Commissioning knowledge						x	5	
H. EQUIPMENT SCOPE							10	
H1. Equipment status				x			3	
H2. Equipment location drawings					x		4	
H3. Equipment utility requirements				x			3	
I. CIVIL, STRUCTURAL, & ARCHITECTURAL							4	
I1. Civil/structural requirements for entire project					x		4	
I2. Architectural requirements (pump house or above ground structure)	x						0	

J. INFRASTRUCTURE							11	
J1. Existing infrastructure requirements (existing pump house)					x		4	
J2. Loading/unloading/storage space requirements					x		4	
J3. Transportation requirements (TBM, drill rig)				x			3	
K. INSTRUMENT & ELECTRICAL							22	
K1. Temporary/permanent electrical availability					x		4	
K2. Mole cable and structure storage				x			3	
K3. Electrical area classifications					x		4	
K4. Power sources identified				x			3	
K5. Transformer and gantry plan					x		4	
K6. Instrument & electrical specifications (500KV transformer)					x		4	

Total score 103

Table 18: Scoring 1 section 3

SECTION III - EXECUTION APPROACH								
CATEGORY	Definition Level							Comments
Element	0	1	2	3	4	5	Score	
L. PROCUREMENT STRATEGY							6	
L1. Identify long lead/critical equipment & materials			x				2	
L2. Procurement procedures plan/tender documents			x				2	
L3. Procurement responsibility			x				2	
M. DELIVERABLES							11	
M1. Overall tunnel construction requirements				x			3	
M2. Deliverables defined (tunnel objectives)				x			3	
M3. Distribution/monitoring of flow						x	5	
N. PROJECT CONTROL							9	
N1. Project control requirements				x			3	
N2. Project accounting requirements					x		4	
N3. Risk analysis			x				2	

P. PROJECT EXECUTION PLAN							16	
P1. Owner approval requirements			x				2	
P2. Engineering/construction plan & approach			x				2	
P3. Shut down/turn-around requirements					x		4	
P4. Commissioning and maintenance requirements					x		4	
P5. Startup requirements		x					1	
P6. Training requirements (crews, TBM operator)				x			3	
						Total score	42	

Table 19: PDRI score card

SECTION IV - Score Card							
CATEGORY							
Element					Scoring 1	Scoring 2	Scoring 3
SECTION I - BASIS OF PROJECT DECISION							
A. MANUFACTURING OBJECTIVES CRITERIA					9	6	0
B. BUSINESS OBJECTIVES					18	13	0
C. BASIC DATA RESEARCH & DEVELOPMENT					3	4	0
D. PROJECT SCOPE					14	9	0

	Scoring 1	Scoring 2	Scoring 3	Section	
OVERALL	50	39	0	Low	High
Percent difference	45%	35% 10%	0%	22	110

E. VALUE ENGINEERING					6	7	0
SECTION II - BASIS OF DESIGN							
F. SITE INFORMATION					17	10	0
G. PROCESS/MECHANICAL					39	27	0
H. EQUIPMENT SCOPE					10	5	0
I. CIVIL, STRUCTURAL, & ARCHITECTURAL					4	3	0
J. INFRASTRUCTURE					11	9	0

OVERALL	103	63	0	Low	High
Percent	64%	39%	0%	32	160
difference		25%			

K. INSTRUMENT & ELECTRICAL					22	9	0	

SECTION III - EXECUTION APPROACH									OVERALL	42	32	0	Low	High
L. PROCUREMENT STRATEGY					6	3	0		Percent	56%	43%	0%	15	75
									difference		13%	43%		
M. DELIVERABLES					11	7	0							
N. PROJECT CONTROL					9	6	0							
P. PROJECT EXECUTION PLAN					16	16	0							

					Low	High
PDRI Score		195	134	0	69	345

5 CONCLUSION

The front end planning study has shown that an increased effort to include front end planning early in the pre-project phase led to a greater chance of achieving higher project success. Of those projects that included front end planning, the average cost savings ranged from 6-25%, and the average reduction of schedule was 6-39%. A PDRI score of 200 or lower resulted in a higher likelihood of project success (CII, 1999). Alignment is most successful at influencing the project's success when adapted to the project at the earliest point. Alignment is three-dimensional when looked at across an organization and the organization should ensure that the proper culture, execution process, information and tools exist, so as not to inhibit alignment from taking place. A list of 10 critical alignment issues makes up the alignment effort score that has been shown to lead to project success. The application of the alignment allowed the project team to recognize and commit to the overall project goals, as well as their own teams' goals. The application of a modified PDRI to both of these branches increased the communication within the project team. The PDRI application also allowed the key indicators of the project to be recognized, included in the project planning, and successfully mitigated prior to the project's construction phase. The PDRI also allowed the project team to focus on the key indicators that were not adequately defined, and thus, showed improved scoring in subsequent PDRI workshops. Finally the PDRI gave the project team a health score shown as the PDRI final score, which allowed the project team to justify transferring the project into the next key area. These collected scores on this project are now being benchmarked to provide future projects with both the CII score of 200 and this project's score at all three transfers between the key areas.

The simulation analysis initially was created to establish production targets, assess feasibility of the project schedule and budget, and establish a base plan for the construction phase of the tunneling project. To achieve those objectives, construction process simulation models were developed, required information was collected and an analysis carried out. The tunneling template makes it possible for simulation to provide a value-adding estimate and schedule solution to the construction industry as a whole. This provides the client with decision support information to make basic client services more efficient and effective. Services such as value engineering and constructability reviews can have multiple project scenarios created for them to allow the client to get more accurate estimates and schedules in the project planning stage. The simulation analysis provided by the tunneling template allowed the project team to make fast, accurate decisions in the early stages of the project. In the concept stage of the project, many different options can be and were explored, from making large adjustments to the tunnel alignment, or as simple as changing the shift that the crews would work. This allowed the project team to select an option that fit the project's budget and scheduled completion date. The tunneling template also has the ability to be updated as the project progresses to forecast completion dates, productivities, and cost. Proper background work is needed from past benchmarked projects to act as verification and validation of the model to its intended application.

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7 APPENDIX 1: SUMMARY REPORT FOR THESIS EXAMPLE

Schedule				
	Minimum	Mean	Maximum	Std Dev
Working Shaft				
Start Date	2013-10-07	2013-10-07	2013-10-07	0.000 days
Finish Date	2013-11-19	2013-11-19	2013-11-25	1.647 days
Regular Hours	466.478	497.733	528.749	19.591
Overtime Hours	0.000	0.000	0.000	0.000
Working Undercut				
Start Date	2013-11-19	2013-11-19	2013-11-25	1.647 days
Finish Date	2014-06-27	2014-06-28	2014-07-18	5.894 days
Regular Hours	2,152.749	2,270.436	2,398.875	63.699
Overtime Hours	0.000	0.000	0.000	0.000
Removal Shaft				
Start Date	2014-03-10	2014-03-10	2014-03-10	0.000 days
Finish Date	2014-04-03	2014-04-03	2014-04-03	0.000 days
Regular Hours	163.940	163.940	163.940	0.000
Overtime Hours	62.257	62.257	62.257	0.000
Shaft1				
Start Date	2014-03-10	2014-03-10	2014-03-10	0.000 days
Finish Date	2014-04-08	2014-04-08	2014-04-08	0.000 days
Regular Hours	206.190	206.190	206.190	0.000

Overtime Hours	80.000	80.000	80.000	0.000
Removal Undercut				
Start Date	2014-04-03	2014-04-03	2014-04-03	0.000 days
Finish Date	2014-07-16	2014-07-16	2014-07-22	2.059 days
Regular Hours	1,183.783	1,218.186	1,246.478	17.901
Overtime Hours	0.000	0.000	0.000	0.000
Work Area1				
Start Date	2014-04-08	2014-04-08	2014-04-08	0.000 days
Finish Date	2014-05-19	2014-05-19	2014-05-23	1.139 days
Regular Hours	459.647	475.948	521.460	17.782
Overtime Hours	0.000	0.000	0.000	0.000
Startup Tunnel				
Start Date	2014-06-27	2014-06-28	2014-07-18	5.894 days
Finish Date	2014-08-06	2014-08-07	2014-08-26	6.448 days
Regular Hours	196.688	216.778	236.216	11.011
Overtime Hours	89.000	98.282	108.000	5.922
TBM Tunnel				
Start Date	2014-08-06	2014-08-07	2014-08-26	6.448 days
Finish Date	2015-05-11	2015-05-12	2015-06-18	9.946 days
Regular Hours	1,480.000	1,572.663	1,634.146	47.270
Overtime Hours	666.106	704.164	730.000	21.018
Overall				

Start Date	2013-10-07	2013-10-07	2013-10-07	0.000 days
Finish Date	2015-05-11	2015-05-12	2015-06-18	9.946 days
Regular Hours	6,429.816	6,621.875	6,773.147	87.706
Overtime Hours	900.257	944.703	975.257	22.848

Direct Costs				
	Minimum	Mean	Maximum	Std Dev
Working Shaft				
Labour	$94,150.66	$100,377.20	$106,555.96	$3,902.86
Equipment	$182,661.84	$190,164.71	$197,610.01	$4,702.88
Rental	$0.00	$0.00	$0.00	$0.00
Material	$291,079.84	$291,079.84	$291,079.84	$0.00
Other	$4,000.00	$4,000.00	$4,000.00	$0.00
Total	$571,892.34	$585,621.74	$599,245.81	$8,605.74
Working Undercut				
Labour	$654,589.61	$696,426.50	$750,055.48	$24,187.43
Equipment	$846,788.39	$900,642.26	$942,323.91	$27,647.55
Rental	$62,989.36	$64,146.04	$65,883.24	$968.82
Material	$578,171.92	$578,171.92	$578,171.92	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$2,144,022.48	$2,239,386.72	$2,336,434.55	$50,294.13
Removal Shaft				
Labour	$66,783.75	$66,783.75	$66,783.75	$0.00

Equipment	$74,564.78	$74,564.78	$74,564.78	$0.00
Rental	$39,171.37	$39,171.37	$39,171.37	$0.00
Material	$249,174.27	$249,174.27	$249,174.27	$0.00
Other	$4,000.00	$4,000.00	$4,000.00	$0.00
Total	$433,694.17	$433,694.17	$433,694.17	$0.00
Shaft1				
Labour	$71,530.14	$71,530.14	$71,530.14	$0.00
Equipment	$117,283.09	$117,283.09	$117,283.09	$0.00
Rental	$0.00	$0.00	$0.00	$0.00
Material	$225,208.84	$225,208.84	$225,208.84	$0.00
Other	$4,000.00	$4,000.00	$4,000.00	$0.00
Total	$418,022.07	$418,022.07	$418,022.07	$0.00
Removal Undercut				
Labour	$309,814.38	$316,930.53	$322,828.91	$3,689.15
Equipment	$450,672.29	$467,696.83	$481,764.38	$8,838.48
Rental	$55,875.40	$55,875.40	$55,875.40	$0.00
Material	$54,300.92	$54,300.92	$54,300.92	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$870,662.99	$894,803.68	$914,769.61	$12,527.58
Work Area1				
Labour	$105,487.67	$108,748.65	$117,853.10	$3,557.27
Equipment	$169,965.17	$177,871.16	$199,944.15	$8,624.31

Rental	$33,923.15	$33,923.15	$33,923.15	$0.00
Material	$42,026.18	$42,026.18	$42,026.18	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$351,402.17	$362,569.13	$393,746.58	$12,181.59
Startup Tunnel				
Labour	$183,983.50	$202,928.00	$221,842.10	$10,759.86
Equipment	$127,631.12	$140,753.20	$153,778.50	$7,383.09
Rental	$0.00	$0.00	$0.00	$0.00
Material	$52,693.68	$52,693.68	$52,693.68	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$364,308.30	$396,374.88	$428,314.28	$18,140.21
TBM Tunnel				
Labour	$1,455,959.11	$1,544,041.78	$1,602,978.14	$46,168.32
Equipment	$1,476,949.96	$1,566,912.22	$1,627,005.12	$46,888.41
Rental	$15,022.75	$15,937.79	$16,549.02	$476.92
Material	$886,134.33	$886,134.33	$886,134.33	$0.00
Other	$0.00	$0.00	$0.00	$0.00
Total	$3,834,066.15	$4,013,026.13	$4,132,666.61	$93,532.24
Overall				
Labour	$2,979,740.47	$3,107,766.54	$3,186,845.59	$56,064.39
Equipment	$3,506,167.15	$3,635,888.24	$3,723,871.64	$54,549.82
Rentals	$207,469.67	$209,053.75	$210,918.96	$1,236.65

Materials	$2,378,789.98	$2,378,789.98	$2,378,789.98	$0.00
Other	$12,000.00	$12,000.00	$12,000.00	$0.00
Total	$9,084,823.08	$9,343,498.51	$9,511,090.48	$110,665.42

Surveying				
	Minimum	Mean	Maximum	Std Dev
Startup Tunnel				
Regular Hours	4.491	5.812	7.000	0.857
Overtime Hours	0.000	1.423	4.857	1.361
Labour	$0.00	$0.00	$0.00	$0.00
TBM Tunnel				
Regular Hours	33.818	45.483	73.986	11.515
Overtime Hours	9.461	17.061	23.699	4.003
Labour	$0.00	$0.00	$0.00	$0.00
Overall				
Regular Hours	38.981	51.296	78.986	11.534
Overtime Hours	10.498	18.484	23.811	3.981
Labour	$0.00	$0.00	$0.00	$0.00

Other Indirect Costs				
Item	Minimum	Mean	Maximum	Std Dev
Surveying	$308,883.98	$317,678.95	$323,377.08	$3,762.62
Internal Engineering	$672,276.91	$691,418.89	$703,820.70	$8,189.24
Risk and Const Consultants	$254,375.05	$261,617.96	$266,310.53	$3,098.63

External consultants	$381,562.57	$392,426.94	$399,465.80	$4,647.95
In house Drafting	$182,241.55	$187,430.58	$190,792.48	$2,219.95
In House Electrical	$161,346.46	$165,940.53	$168,916.97	$1,965.42
Temp Water and Sanitary	$95,844.88	$98,573.91	$100,342.00	$1,167.52
Temp Power Setup	$230,000.00	$230,000.00	$230,000.00	$0.00
Overhaul TBM	$339,000.00	$339,000.00	$339,000.00	$0.00
All Other Indirects	$221,669.68	$227,981.36	$232,070.61	$2,700.24
TBM M100	$259,000.00	$259,000.00	$259,000.00	$0.00
Total	$3,106,201.08	$3,171,069.12	$3,213,096.16	$27,751.57

Total Costs				
Item	Minimum	Mean	Maximum	Std Dev
Direct Costs	$9,084,823.08	$9,343,498.51	$9,511,090.48	$110,665.42
Survey Costs	$0.00	$0.00	$0.00	$0.00
Other Indirect Costs	$3,106,201.08	$3,171,069.12	$3,213,096.16	$27,751.57
Total	$12,191,024.16	$12,514,567.64	$12,724,186.64	$138,416.99

8 APPENDIX 2: TUNNELING PROJECT SCHEDULE

Insert the SA1A schedule here.