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Dynamic Safety and Risk Assessment of Tunnel Construction: Leveraging Systems Engineering through Sigma Modeling

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Tunnel construction appears to be a challenging task that requires extensive design, detailed pre-planning, and geological input while encompassing dynamic and comprehensive safety and risk assessments to ensure project success and protect stakeholders. By leveraging the power of systems engineering, the modeling of a tunnel project can be accomplished, which will offer a comprehensive understanding of all subsystems, ensuring that complex relationships between all the components are well comprehended and controlled. This study investigates the applicability and compatibility of utilizing Sigma modeling language and WordLabTM Workshop modeling environment to model a tunnel project from the systems engineering point of view, demonstrating the ability to integrate multiple activities in a single cohesive model. With its graphical user interface, the WorldLab™ Workshop enables the easy execution of compilation and simulation tasks, which serves as a virtual laboratory for performing interactive and stochastic simulations. The use of systems engineering facilitates the visualization and analysis of the complex interrelationships among various project components, hence enabling the identification of possible risks and operational safety issues. In addition, complex scenarios can be tested through modeling of this kind, allowing project managers to assess the effects of different factors and, consequently, create an interactive knowledge-based system that clearly defines a framework for collaboration and risk mitigation throughout the project. The outcome of simulations implicates that safety and risk management can be addressed proactively by leveraging the combination of system dynamics and Sigma modeling, which will lead to better operational performance. Thus, the study implies a novel perspective on safety management in tunnel engineering, providing practitioners with unprecedented insights.

Keywords: Systems Engineering, Tunnel Project, Safety and Risk Management, Sigma, Construction Safety, Predictive Analytics, Dynamic Modeling

1. Introduction

The construction of tunnels is a complicated and concentrated engineering challenge with unique difficulties *(Shelake et al., 2022)*. For instance, tunnel projects encounter more variables regarding subsurface conditions such as geology, groundwater, underground rock condition, and soil stability *(Deng, 2018)*. All the above pose considerable threats that have implications for the safety of construction workers and the reliability of structural integrity. Therefore, any tunneling work activity must ensure efficiency in safety and risk management. Tunneling, however, includes extremely complex and correlated risks that do not respond as well to traditional risk assessment models as previously believed *(Sousa & Einstein, 2012)*. Such an approach is typically risk-based, and these conventional approaches tend to evaluate risks independently, which may neglect significant inter-linkages across project components. For instance, geological factors may affect structural integrity, which eventually influences the safety of workers on the project and

its timeliness *(Li et al., 2024)*. Hence, this kind of complex project demands an integrated and dynamic approach to address the risk and safety management in this sector *(Zhou et al., 2020)*.

Hence, this study proposes an investigative approach by developing a metaphorical model of a tunnel construction project using a systems engineering approach with the Sigma modeling language and the WorldLab™ Workshop environment *(Rauzy, 2023)*. A systems engineering approach provides a framework to explore the relationship among project components, understand interdependencies, determine areas of risk, and provide for safety in the physical world of the project *(Sterman, 2002)*. Supported by the WorldLab™ Workshop, Sigma modeling facilitates this integration, allowing modeling of the many activities and factors influencing a tunnel project. This modeling environment uses a graphical interface, which makes simulation and visualization of complex scenarios for projects easy and thus aids the project manager in decision-making *(Solheim et al., 2023)*.

2. Background Study

Numerous environmental and engineering difficulties arise during tunnel construction. These massive projects deal with various geological circumstances, including soil types, groundwater depth, and rock strength; each of these factors affects the stability of the structures and can present serious concerns *(Lv et al., 2020)*. Moreover, these conditions can cause extensive environmental, social, and other issues surrounding the project and would again require constant monitoring and changes in the construction plans. However, tunneling demands intensive coordination among many interdependent subsystems, from its excavation and support systems to its ventilation and emergency safety protocols. Failing one subsystem might disintegrate the entire project, emphasizing the significance of a unified approach in safety and risk assessments *(Li et al., 2013)*.

Existing tunnel construction risk management approaches are quite diverse in nature, and different studies have focused on various aspects of tunnel safety. For instance, Wu et al. (2015) proposed a Bayesian network-based investigation to address the safety issue in tunnel construction, where feed-forward, concurrent, and back-forward analyses are performed to develop a decision support system. However, Wang et al. (2020) carried out an approach where they developed a real-time tunnel collapse risk assessment system using subjective and objective weight-based statistical and analytical methods. On the other hand, Liu et al. (2016) presented a microseismic method of warning rockburst for risk assessment and management of rockburst in the drill-and-blast method of tunnel construction. Furthermore, Zhen et al. (2023) introduced a static and dynamic method for the collapse risk of mountain tunnels using fuzzy logic. Moreover, Jianxiu et al. (2021) developed a fuzzy evaluation matrix of the construction risk for double-arch tunnel construction. Although these methodologies help discover specific risks, they generally lack a way to describe the interdependencies and cascade of effects across risks in tunnel construction. With projects becoming more complex, it has become increasingly apparent that traditional approaches may struggle to capture these complex interactions. The existing practices are also limited by their static nature and cannot respond to dynamic changes in project conditions in real-time.

To address this issue, systems engineering has shown promise in treating large-scale constructions as networks of interrelated subsystems for managing complexity *(Zhang et al., 2009)*. This approach allows projects to be viewed both holistically and as collections of constituent parts that influence one another. Thus, systems engineering provides a structured method for project management, enhancing safety and dependability through these interrelationships *(Arayici et al., 2006)*. It has proven effective in industries requiring the coordination of multiple complex systems, such as aerospace and defense, and has the potential to address safety and risk management challenges in construction as well.

Hence, the Sigma modeling language is an initiative with a strong emphasis on supporting the modeling of systems with their complex interactions *(Rauzy, 2024)*. The Sigma modeling platform, with its graphical interface and modular design, enables users to create and visualize the complex interactions among subsystems. Data-driven models defined in Sigma support dynamic simulators that can auto-adjust to underlying conditions *(Robert, 2024)*. The platform provides a

visual representation of subsystem interactions, allowing real-time analysis of how changes affect overall project outcomes *(Schruben, 1992)*.

In this study, the WorldLab™ Workshop is introduced as a modeling environment that complements Sigma modeling, providing an interactive simulation and analysis platform. Its virtual laboratory interface enables users to run deterministic and stochastic simulations, allowing them to test different assumptions and determine potential safety outcomes and risks. Running "what-if" scenarios enables the simulation of various decisions and changes in conditions that can impact overall project results.

Systems engineering has been broadly and successfully applied in various high-risk and complex industries but has seen limited use in construction, particularly tunneling. Traditional models commonly used in construction often fail to account for the dynamic, interdependent nature of tunnel projects. This study presents an innovative application of the Sigma modeling language and the WorldLab™ Workshop for safety and risk assessment, using systems engineering principles to overcome the limitations of conventional modeling paradigms.

This research aims to bridge this gap by developing a dynamic and metaphorical risk assessment model specifically designed for tunnel construction, advancing both theoretical understanding and practical applications in this field.

3. Method

This paper presents the use of a Sigma model in the WorldLab™ Workshop environment to establish a systematic top-down systems engineering-based framework for construction accident risk management and assessment. Models are functional tools, not ideals to which the system must adhere. A model is a useful and practical demonstration that it is feasible to plan, create, and run a system with certain predetermined characteristics. Hence, this approach depicts the way of breaking down the tunnel construction projects into a sequence of specific stages and the corresponding activities, which provides a basis for a detailed analysis of how each stage is associated with different accident occurrences. It includes parameters such as resource availability, accident probabilities, and conditional triggers, enabling project managers to run dynamic safety simulations for progressive assessments.

3.1. *Physical Architecture*

The metaphorical model of the tunnel construction project implies representing the physical components as follows:

- Personnel: This subsystem represents the workforce, including the availability of engineers, architects, human resource managers, safety managers, and workers. It tracks resource availability and includes a counter for the number of accidents that may occur during each activity phase.
- Equipment: This subsystem monitors the availability of necessary equipment, which is necessary to start and finish operations.
- Documents: Before certain phases start, this subsystem makes sure that all required documents are ready and accessible.
- Site: This subsystem stands for the actual construction site and is only designated as ready upon completion of site preparation.
- Tunnel Stage: From initial design to completion, the system state moves step-by-step through each construction stage.

```
system RiskData

    parameter float accidentRateSitePreparation(unit = "month-1") = 0.01;
    parameter float accidentRateExcavation(unit= "month-1") = 0.02;
    parameter float accidentRateLining(unit = "month-1") = 0.005;
    parameter float accidentRateSupports(unit= "month-1") = 0.003;
    parameter float accidentRateWaterproofing(unit = "month-1") = 0.001;
    parameter float accidentRateElectrical(unit = "month-1") = 0.002;
    parameter float accidentRateVentilation(unit = "month-1") = 0.001;
    parameter float accidentRateDrainage(unit = "month-1") = 0.001;
    parameter float accidentRateSafety(unit = "month-1") = 0.001;

end
```

Fig. 1. Simulation parameters considered for accident risk in each stage of construction

- Risk Data: The parameters for accident rates related to each activity stage are contained in this subsystem. Because these rates are represented as probabilities, the model can replicate potential accident scenarios at every level (Fig.1).

3.2 *Functional Architecture*

The tunnel construction project is treated as a cohesive system in the Sigma modeling environment with several interdependent subsystems. They are defined by distinct

construction lifecycle stages, such as design, planning, site preparation, excavation, lining, support installation, waterproofing, electrical installation, ventilation installation, drainage installation, and safety installation (Fig. 2).

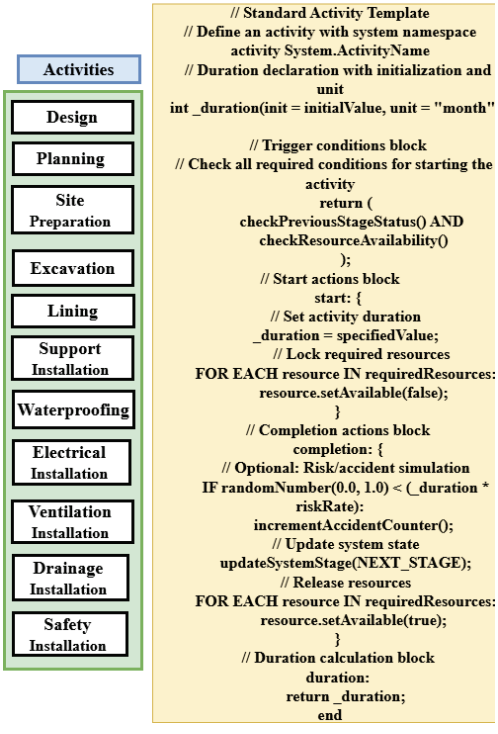

Fig. 2 Tunnel construction activities and corresponding pseudo-code for sigma modeling

Each activity has a defined duration and trigger, start, and completion conditions, ensuring that each task progresses only when specific conditions are met, such as the availability of people, equipment, or documents. The model uses boolean triggers to ensure that each phase follows a logical sequence. For example: design activity requires that engineers and architects should be available, while the planning activity requires the availability of engineers and a human resource manager. Each stage updates the system state upon completion, advancing the tunnel stage through the project lifecycle.

3.3 *Accident Risk Simulation*

The Sigma model integrates accident risks through predefined accident rates associated with each stage of construction, which are encapsulated within the 'Risk Data'. These parameters determine how likely an accident is to occur at each stage of the work process, given the specific hazards of individual activities. Accident frequencies are given for activities (e.g., excavation, lining, support installation, waterproofing, electrical installation, ventilation installation, drainage, and safety installation) as "month^{-1}" units, indicating the monthly probability of an accident. Excavation, for example, has a 0.02 per month accident rate, revealing a corresponding risk in that phase and the nature of the work underground, which can be risky and hazardous.

Thus, for every activity, the model uses a probability equation to see if an accident happens or not, based on the risk rate and activity time duration. For example, if there remains a 0.01 accident risk while site preparation is ongoing, and the stage takes one month; an accident will happen when a random incident occurs which is lower than 0.01. This model outputs the total number of accidents and the accident counter is incremented in the 'Personnel' system when an accident occurs, hence giving the project some quantitative measure of safety performance. It returns some key metrics like the number of accidents, completion time for each phase, and the entire project time. Such metrics are critical in assessing the success of risk mitigation efforts and guiding decisions to reduce accidents and delays.

For instance, the 'Number of Accidents' indicator reflects the safety performance, helping to identify high-risk stages that may require additional mitigation strategies. However, the 'Completion Timeline' contributes to the total project time, allowing stakeholders to assess the impact of delays due to resource unavailability or accident occurrences. Through this structured approach, the Sigma model demonstrates how systems engineering principles can enhance risk assessment and safety in tunnel construction. By decomposing the project into distinct stages with associated accident risks, the model provides a robust framework for managing complex construction projects effectively.

4. Results

For the tunnel project, two folds of simulation were considered: (i) Interactive Simulation and (ii) Stochastic Simulation. Interactive simulation is

defined as a user-controlled modeling method that allows users to communicate directly with the simulation environment. While the simulation is going on, users may change inputs, conditions, or parameters and see the results. In contrast, stochastic simulation presents systems with uncertainty and the results are obtained using probability distributions that describe uncertain variables or processes instead of deterministic.

4.1 Interactive Simulation

To perform interactive simulation, the following parameters are considered.

- **Mission Time**: The mission time was set to 1000 units which defines the total duration over which the simulation processes events and calculates results.

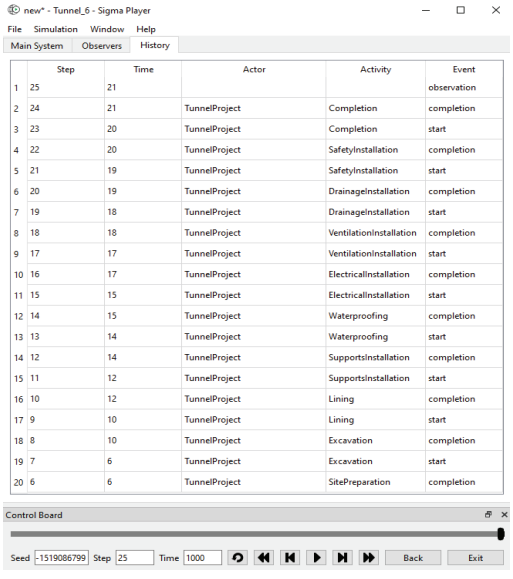

Fig. 3. Demonstration of activities of tunnel project by Sigma player

- **Observation Dates**: The observation was set to start from zero with no additional dates mentioned which depicts data collection started at the inception of the simulation and lasted the entire mission time, and the output data represents the cumulative results from the entire mission period.
- **Random Generator Seed:** A seed of 12345 was utilized which makes the results replicable.

Hence, the Sigma player appears to be an interactive platform in which each of those tasks can be observed by the user when it has started and completed which gives the user detailed insight into the current tunnel construction in a simulated environment. Fig. 3 demonstrates the activities of the tunnel construction by the Sigma player through an interactive simulation.

4.2 Stochastic Simulation

The stochastic simulation is a Monte Carlo simulation that was run 10,000 times. Many executions are performed to ensure that the results are statistically significant, capturing the stochastic variation of accident occurrences from different executions. The key performance indicator (KPI) observed was the 'Number of Accidents', which records the total accidents occurring across all construction phases from site preparation through project completion yielding the following statistical results presented in Table 1.

Table 1. Results of stochastic simulation

Parameters	Value
Mean Accident Count	0.114
Standard Deviation	0.326
Minimum Accidents	0
Maximum Accidents	2
Confidence Range (lower)	0.107
Confidence Range (upper)	0.120

This configuration and setup support a thorough examination of the accident risks across the tunnel construction process, providing insight into both average expectations and the range of possible accident counts (Fig. 4). The high number of runs and the confidence interval suggest a high level of reliability in these results.

5. Discussion

The two-dimensional simulation results of the model provided noteworthy insight into the process of tunnel construction as well as associated accident risks in each of the stages. The key performance indicator, the 'Number of Accidents' enables an in-depth view of the safety risks involved with the tunneling process. The average number of accidents (0.114) indicates that on average less than 1 accident occurred during each simulated project cycle which means that the measures that are put in place during tunnel construction are indeed rather useful at reducing accidents. The low mean value could represent stable safety standards, detailed planning, and

frequent monitoring of risk factors in multiple construction stages.

new* - Tunnel_6 - Sigma Calculator

File Window Help

Results

statistics.csv

1	*Parameters*	[Default Parameters]						
2	*Sigma stochastic simulation*							
3	*System*	*TunnelProject*						
4	*Date*	2025-01-22 14:13:44						
5	*Executions*	10000						
6								
7	*Indicator*	*TunnelProject.NumberOfAccidents*						
8	*Observer*	*TunnelProject.numberOfAccidents*						
9	*Type*	*value*						
10	*Time*	*SampleSize*	*Mean*	*StandardDeviation*	*Minimum*	*Maximum*	*ConfidenceRang...*	*ConfidenceRang...*
11	1000	10000	0.1135	0.325927	0	2	0.106981	0.120019

Fig. 4 Demonstration of results from stochastic simulation

With a standard deviation of 0.326, it implies that the number of accidents is relatively constant between each simulation.

Most of the simulated project cycles resulted in low accident counts, but the minimum number of accidents recorded was zero. On the other hand, the maximum number of accidents recorded was 2, indicating that accidents can occur even with well-controlled risk parameters, especially in more severe or less-than-ideal conditions. Now, while this is rare, it also shows the need to plan for the chance of an accident or for the places that have a higher inherent level of risk. However, the confidence interval (0.107 to 0.120) is tight suggesting that the estimation of the average number of accidents is reasonably precise and that the low accident occurrence observed is likely to be consistent across future simulations or actual construction projects.

As a result, the simulation shows that the model as it is now created suggests a plan to reduce the probability of accidents during construction. Nonetheless, the existence of sporadic high-risk situations indicates that to reduce the likelihood of accidents and raise project safety standards even further, a constant focus on safety improvement is essential, especially during riskier stages of the building process. Hence, this sort of simulation in a virtual laboratory provides the manager of the project with the knowledge of accident possibility in different stages and how different resources can be managed in a construction project so that safety risks are constrained within a narrow margin.

Hence, the simulation results provide valuable knowledge about the risks at different construction phases, show how current safety measures have proved effective, and indicate areas of improvement. Since the general number of accidents in the simulated project cycles is low, this shows the advantages of thorough planning, high safety standards, and risk monitoring over time, but still, sometimes an occurrence of higher-risk situations indicates the area for future improvement and dynamic risk management during critical construction phases.

6. Conclusion

Tunnel construction is a complicated process with many engineering and environmental challenges, and safety and risk management must be given top priority. The complex relationships between subsystems and their dynamic nature can be better understood with the aid of a digital dashboard. Therefore, this study initializes a systems engineering approach using Sigma modeling language and the WorldLab™ Workshop environment to address this safety issue. Principles of system engineering combined with state-of-the-

art simulation tools provide this research with a framework that is both practical and innovative to improve the safety and risk management of tunnel constructions. This model does not only improve the theoretical framework but also brings certain real-time actionable insights to project managers to improve decision-making and allocation of resources. This analysis serves as a valuable tool for project managers and safety officers to further refine risk management strategies and ensure the protection of all personnel involved in the construction. So, the entire study emphasizes the importance of systems engineering in addressing new complexities found in modern projects. The construction industry can be better equipped by adopting dynamic, data-driven risk assessment models and mitigating the possibility of catastrophes while enhancing safety, productivity, and reliability in large-scale infrastructure projects. Future research activities might enhance this framework through the incorporation of other parameters such as economic constraints or environmental impacts to present a broader approach to tunneling construction.

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