Case Study Through the Application of Value Engineering – Tunnel Construction

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Abstract *— Value engineering is an effective approach used by many industries that aims to analyze a product or project to optimize it while reducing costs. VE does not just focus on cost reduction; its purpose is functional cost-effectiveness. This project presents the five phases of the VE process: information, creative, evaluation, development, and report applied to a construction project. A case study was performed on a 5-mile stormwater drainage tunnel where the original design includes two different cross-sections to be excavated using a tunnel boring machine. The alternative was proposed by the contractor, and it resulted in a solution that provides the following advantages: improved schedule, cost savings, add functionality, and simplifies operation and maintenance in the long run. This alternative result in a cost-saving of $1.4 million. VE analysis developed by the builder or the contractor adds significant value or advantages to the project due to its expertise in construction methods.*

Key Terms *— Cost-Effective, Functionality Value Engineering, TBM, Tunnel Construction*

INTRODUCTION

Construction projects bring many benefits to society since the beginning of time; however, one might think that construction is a straightforward operation that is done to satisfy a need, but really, it has been an industry that has constantly been improving in their construction methods (equipment, materials, etc.) and in their management. Construction companies are always looking for ways to reduce costs without compromising quality and functionality, which also translates to improving the schedule [1]. This last statement is referred to as Value Engineering (VE), which originated in the 1940s. Value engineering is defined as "a systematic application of recognized techniques by multi-disciplined team(s) that identifies the function of a service or product, establishes a worth for that function; generates alternatives through the use of creative thinking; and provides the needed functions, reliably, at the lowest overall cost" [2]. It is important to recognize that there is a difference between cost reduction and value engineering. As mentioned before, the construction industry has been improving since the beginning of times, especially in the last century with all the new technologies, therefore reducing the cost of construction was easily done. In contrast, VE does not just focus on cost reduction; its purpose is functional cost-effectiveness. It is not looking for a way to make the construction easier or deliver a cheaper product. It must bring a better value while at the same time bringing financial benefit.

LITERATURE REVIEW

The application of value engineering starts with a Job Plan**,** as shown in Figure 1. The job plan follows a series of phases that are unique to value engineering. As shown in the figure, it consists of five phases: information, creative, evaluation, development**,** and presentation.

In the starting point, the information phase**,** the goal is to collect all requirements, constraints, design of the product**,** and any data available**,** including cost, schedule, historical data of similar projects related to the project case. Following the second step, the creative phase, all the information gathered on the first step is analyzed to identify any problems that could affect the project. Once the potential problems are identified, brainstorming techniques are used to develop potential alternative ideas. Once the new ideas are created, the process continues to the evaluation and analytical phase.

During this phase, all the `ideas from the creative phase are analyzed to determine which one has the most potential in delivering value and cost savings. Once the idea is selected**,** it proceeds to the development phase**,** where the idea is developed in detail**,** including requirements, recommendations**,** and life cycle cost estimates. Lastly, the presentation phase is where the idea is presented to upper management to seek approval and proceed to implementation. During this phase is essential to have a complete written proposal that includes all potential risks.

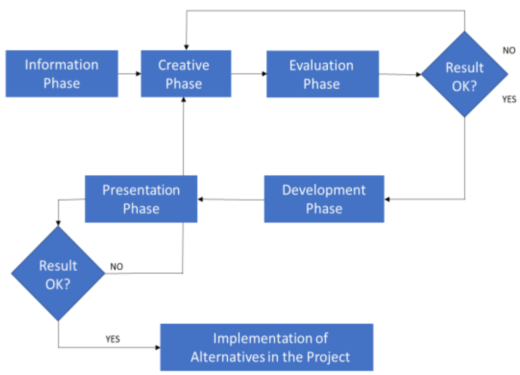

Figure 1
Value Engineering Job Plan

A VE analysis can be performed in the design phase of a project or its construction phase. When VE analysis occurs during the construction phase, it often comes from the contractor, who is the expert and the most crucial participant in the overall process of a construction project. In most cases, the engineer designs without fully understanding construction methods. When VE analysis is performed in the construction phase, but it comes from the owner or the designer, it is hard to develop because the contractor, in most cases, will take the VE opportunity as a change and changes during construction, often represent an expensive solution to the contractor.

If a VE analysis is required during the construction phase is important to have a consummate behavior contractor to avoid or minimize expensive solutions. Consummate behavior refers to a contractor that provides ideas and initiatives in the spirit of adding value to the project [3].

As well as the contractor behavior, VE encounters additional challenges, including lack of knowledge in methodology, lack of experts, lack of teamwork collaboration, unwillingness to dedicate the required time, hesitance to apply resources [4]. Research has proven that teamwork is essential for the application of value engineering. It is highly recommended to have a multidisciplinary team that includes designers, construction engineers, estimators, managers, and highly experienced professionals.

Research Objectives

The main objective of this project is to apply the value engineering job plan to a 5-mile tunnel construction project by evaluating an alternative without compromising the functionality of the deliverable while reducing cost and improving the schedule.

Case Study

Tunnel construction is becoming the preferred method of underground utility construction on heavily urbanized zones due to the lack of space. Utilities like water, wastewater, and storm sewer are often required to be replaced with a larger size system due to the city's growth. After several flooding resulting in property damage, injury, and deaths, the city decided to develop a flood relief tunnel design. The five-mile inverted siphon conveyance tunnel will provide 100-year flood protection for many areas, including 2,200 properties on 3,200 acres valued at $4 billion [5].

To apply the value engineering job plan for this tunnel construction, the information phase is started. Technical data, standards, and drawings were collected during this phase. The project was divided into four key elements: intake structures, shaft structures, lateral tunnels, and the primary tunnel. A graphical representation of the costs associated with each element is shown in Figure 2.

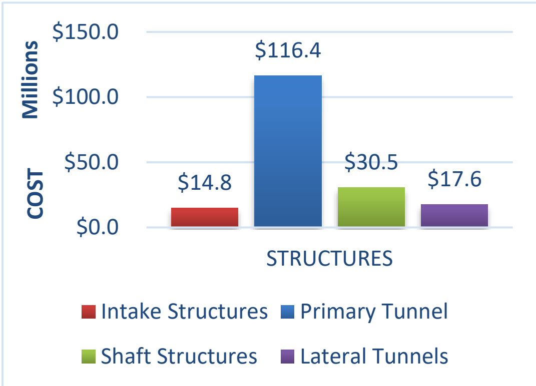

Figure 2
Cost of Key Elements

After compiling all the available information, the creative phase took place. To perform the creative phase, each key element was evaluated based on functionality and cost. The key element that provides more value engineering opportunities is the primary tunnel. This element is the most expensive and is also on the critical path of the overall project schedule. The proposed stormwater drainage relief tunnel was designed with two different cross-sections, a circular cross-section to handle 15,000 ft3/sec (reach #2) and a horseshoe shape cross-section to handle 20,000 ft/sec (reach #1) as shown in Figure 3.

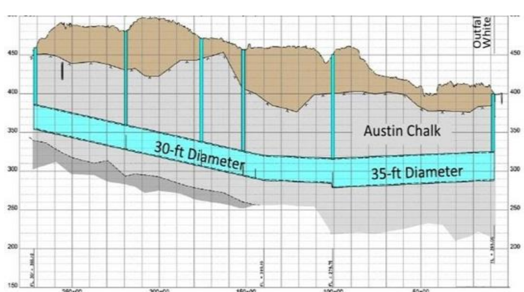

Figure 3
Primary Tunnel Profile

Thus, it is typical to have various tunnel diameters or tunnel cross-sections in a tunnel construction project; tunnel contractors will require to utilize different size Tunnel Boring Machines (TBM) to complete each reach or tunnel runs for a specific cross-section. Typically, each reach will be designed with two vertical shafts; one will be the TBM launching shaft and the receiving shaft. These shafts are aligned with the tunnel centerline; this design feature allows the contactor to retrieve the TBM and replace it with a different size machine. In this case, the challenge relies on that in the cross-section change; the access is not accessible like the typical tunnel construction. Due to easements, the access to this cross-section change is offset from the tunnel centerline alignment. For this reason, the original design proposes a 30'x 35' horseshoe cross-section for reach #1 and a 30'circular cross-section for reach #2, as shown in Figure 4. The horseshoe cross-section will allow the use of the same 30ft diameter TBM and then complete the horseshoe bottom using a roadheader.

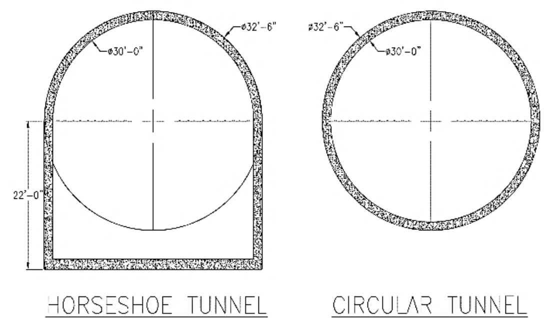

Figure 2
Proposed Cross Sections

To overcome this problem, the proposed alternative consists of providing a similar circular cross-section area that can effectively replace the horseshoe to eliminate the extra cost and time of the bench excavation activity.

Proceeding with the third phase of VE, the design alternative is evaluated. To evaluate the feasibility of the proposed alternative, the first step was to determine the equivalent circular cross-section area that can provide the same capacity as the horseshoe shape. Calculations showed that the equivalent would be a 35ft diameter. After the equivalent diameter was identified, the boring logs were studied. The tunnel will be excavated through hard rock with an unconfined compressive strength of 3,597 psi at depths 110 ft to 170 ft below the surface, as shown in Figure 5. This geotechnical condition allows for an underground TBM diameter conversion which has never been done before. To simplify the comparison, Table 1 shows a summary of the original design and the design alternative.

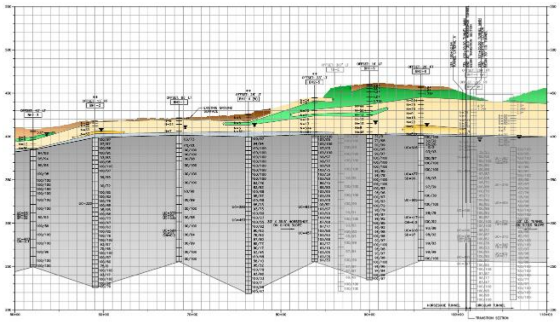

Figure 3
Boring Logs

Table 1
Alternative Comparison

	Original Design		Aletrnative Design	
	Reach #1	Reach #2	Reach #1	Reach #2
Shape	Horseshoe	Circular	Circular	Circular
Excavated Dimensions (ft-in)	38'-9" X 32'-6"	32'-6" Ø	37'-6" Ø	32'-6" Ø
Finish Dimensions (ft-in)	35' X 30'	30' Ø	35' Ø	30' Ø
Concete Liner Thickness (in)	15	15	15	15

Since there is no historical data or experience of another case that can compare to this one, consultations with the TBM manufacturer took place to confirm feasibility. The TBM manufacturer developed a hard rock gripper TBM with the features and technology of reducing the excavation diameter from 37’-6” to 32’-6”, as shown in Figure 6. This modern marvel allows for the use of one TBM.

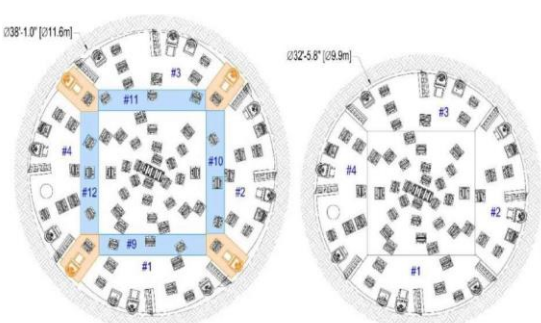

Figure 6
TBM Design Alternative

Once determined the alternative proposed for reach #1 excavation is feasible, the development and recommendation phase begin. In this phase, an in-depth analysis of the life cycle cost estimations and drawings were prepared. Original design costs (shown in Figure 2) are now broken down for the primary tunnel of reach #1, which is the alternative in evaluation. Table 2 shows a cost comparison for the original design and the alternative.

Table 2
Reach #1 Cost Comparison

Cost	Horseshoe Cross-Section	Circular Cross-Section
Equipment	$3.7 M	$3.5 M
Materials	$47.7 M	$48.6 M
Labor	$7.5 M	$5.1 M
Design	$0.0 M	$0.3 M
Total	$58.9 M	$57.5 M
Total Savings	$1.4 M	

The breakdown is considering the typical cost aspects of construction, which are equipment, material, labor, and design. The additional cost of the diameter convertible machine was considered; however, the original design exceeded this cost because it requires a piece of special equipment (roadheader) to efficiently excavate the horseshoe tunnel’s invert. The cost of this special equipment represents a saving on the equipment cost of the alternative design. The circular cross-section is a larger diameter tunnel; thus, it will require additional material to support the excavation at the crown of the tunnel.

To forecast the total costs of equipment and labor, it was necessary to develop a linear schedule for each alternative. As shown in Figure 7, the original design requires a total of 500 working days (WD) to complete reach #1; 38% of this time frame belongs to the bench excavation. The bench excavation process is very conventional, and opportunities for improvement are limited and, in some cases, they are not cost-effective. Also, installing the concrete liner for this design will consume more time due to its shape; a formwork system that can allow the cast of the entire cross-section in one placement will be expensive.

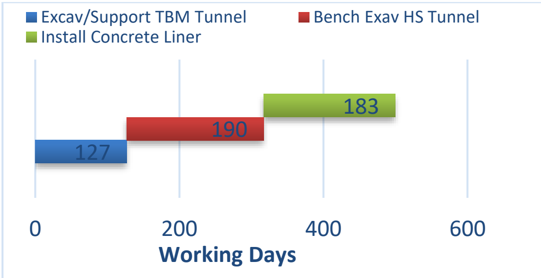

Figure 7
Original Design Schedule

The developed schedule for the alternative design shows clear schedule improvement. Although the TBM excavation will consume more time than the original design, the alternative design will require 339 WD to complete reach #1 as shown in Figure 8; this represents an effective reduction in the schedule of 161 WD. Compared to the original design, the installation of the concrete liner offers savings in time due to its shape. In tunnel construction is typical to cast concrete on a fully round cross-section.

As shown in Table 2, the schedule reduction represents savings in the labor of $2.4M. However, the alternative design's total savings are reduced due to the higher cost of material and the design cost. The potential cost-saving that this alternative can provide is estimated at $1.4M. The primary tunnel is in the critical path of the overall project schedule; the schedule reduction offered by the alternative design can be used as contingency days in the schedule for any unforeseen issue that the project may encounter that caused delays. Also, this improvement can potentially offer savings in overhead costs.

The functional improvement of this job plan is focused on the operation and maintenance of the tunnel. This tunnel is equipped with a dewatering station; this station will drain the entire tunnel as needed to allow maintenance and inspection. Stormwater systems carry debris and sediments. Looking at the tunnel profile (Figure 3), inverted siphon conveyance tunnel, we can expect that due to its geometry, it will collect and accumulate all the debris and sediments of its drainage basin in reach #1. Evaluating both cross-sections, the original design, and the alternative design, it is expected that the horseshoe shape will allow for more sediment accumulation due to its geometry. Circular cross-sections are expected to self-clean because it does not contain corners where sediment will likely accumulate. The circular shape will provide a reduction in operation and maintenance costs to the owner.

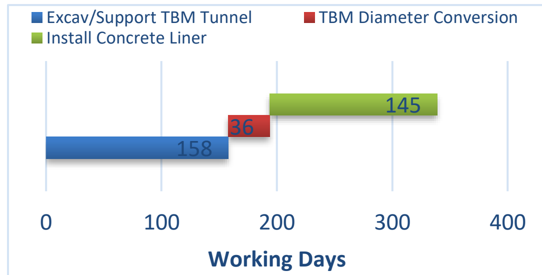

Figure 8
Alternative Design Schedule

After the development phase is completed, the final phase of reporting takes place. Since the project has already begun and the alternative presented is on the critical path, implementing this alternative is time sensitive. The designer of the alternative and TBM manufacturer needs to work simultaneously to expedite details, requirements, and recommendations. These details include the excavation diameter 37'-7", the concrete liner thickness 15" as shown in Figure 9.

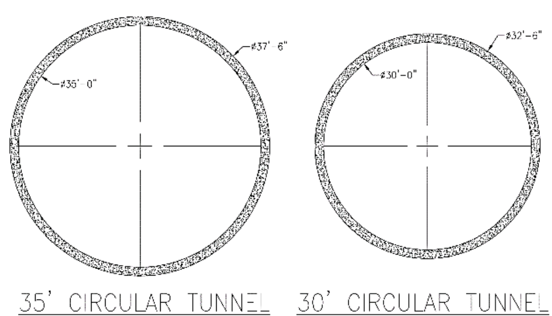

Figure 9
Alternative Design Schedule

This alternative is being proposed by the contractor, and approval is needed from the owner. To gain approval from the owner, a formal oral and written presentation is prepared to the owner mentioning all the above analysis, advantages and disadvantages, design criteria, and specifications.

CONCLUSION

The value engineering methodology is an effective way to improve a project. VE can be applied to infrastructure and construction projects. These projects are very costly and have exceptionally long design processes. When studied in detail, there are always alternative solutions to consider that add functionality. However, in this industry, there is resistance towards VE.

This industry has different entities involved, one is the builder, and the other is the designer. Engineers spend years designing and developing plans and specifications without really understanding construction methods. A VE analysis developed by the builder or the contractor adds significant value or advantages to the project due to its expertise in construction methods.

In this case study, the solution or alternative was proposed by the contractor, and it resulted in an alternative that provides the following advantages: improved schedule, cost savings, add functionality and simplifies operation and maintenance in the long run. This alternative result in a cost-saving of $1.4 million.

The diameter conversion of a TBM inside the tunnel has never been done before; this can represent a disadvantage of the alternative; unforeseen issues can arise that can potentially impact the schedule and cost. For this reason, it is important to evaluate the total savings after the process is completed before sharing savings. It is expected that in a lump sum price contract, the owner will want to have some of the savings.

Tunnel design and construction are becoming more popular nowadays because cities are fully developed and there is a lack of space for new utility construction, and it is suggested that Value Engineering analyses and practices are conducted, especially in large-scale projects since every project will provide different VE opportunity.

REFERENCES

[1] N. L. Rane, "Application of Value Engineering Techniques in Building Construction Projects," *International Journal of Engineering Sciences and Research Technology,* pp. 857-863, 2016.

[2] P. Mahajan, M. Chamarthi, V. Bangar and P. S. Patel, "A Case Study Analysis Through The Implementation Of Value Engineering," *International Research Journal of Engineering and Technology (IRJET),* pp. 2472-2477, 2019.

[3] J. Liu, Z. Wang, M. Skitmore and a. L. Yan, "How Contractor Behavior Affects Engineering Project Value-Added Performance," *Journal of Management in Engineering,* pp. 04019012-1-11, 2019.

[4] N. Naderpajouh and A. Afshar, "A case-based reasoning approach to application oof value engineering methodology in the construction industry," *Construction Management and Economics,* no. 26, pp. 363-372, 2008.

[5] P. J. Smith , J. M. Brooks, Q. D. Tran and E. Silva, "Utilizing “Big Tex” for the Dallas Mill Creek Drainage Relief Tunnel," in *Rapid Excavation and Tunneling and Tunneling Conference*, Las Vegas, NV, 2021.

[6] T.-H. Kim, M. Hyun Woo Lee and a. S.-W. Hong, "Value Engineering for Roadway Expansion Project over Deep Thick Soft Soils," *Journal of Construction Engineering and Management,* vol. 142, no. 2, pp. 05015014-1-9, 2016.

[7] A. Pingbo Tang and M. and Robert B. Bittner, "Use of Value Engineering to Develop Creative Design Solutions for Marine Construction Projects," *Practice Periodical on Structural Design and Construction,* vol. 19, no. 1, pp. 129-136, 2014.

[8] WVDOT, West Virginia Department of Transportation, "Value Enigineering Manual," WVDOT, Charleston, WV, 2004.