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Applying Decision Analysis in a Civil Engineering Project

Adam Hebert and Brandon Thompson

Department of Systems Engineering
United States Military Academy, West Point, NY

Corresponding Author: adam.hebert@westpoint.edu

Author Note: Cadet Adam Hebert is a senior at the United States Military Academy (USMA) majoring in Operations Research. As part of an interdisciplinary capstone project, Cadet Hebert joined five seniors studying Civil Engineering to form Steel Team 7, a team that competed in the 2020 Student Steel Bridge Competition hosted by the American Institute of Steel Construction. Cadet Hebert assisted Steel Team 7 in applying systems engineering concepts as they designed and fabricated a bridge for the competition. Upon graduation, Cadet Hebert will commission as a Field Artillery officer and serve in the 17th Field Artillery Brigade based in Joint Base Lewis-McChord. Brandon Thompson, a Lieutenant Colonel in the United States Army currently serving as an Assistant Professor in the USMA's Department of Systems Engineering, was the advisor for Cadet Hebert in this project.

Abstract: The 2020 USMA Steel Bridge Team, Steel Team 7, applied decision analysis to select the bridge design to use in the Student Steel Bridge Competition. The key dimensions of the Team's application of decision analysis were the decision dimension, the decision maker and stakeholder interaction dimension, the value and time preference dimension and the uncertainty and risk preference dimension. In carrying out the value and time preference dimension, the Team created a decision matrix to quantitatively measure the expected performance of each bridge design relative to the performance measures outlined in the *Student Steel Bridge Competition* (SSBC) *2020 Rulebook*. In executing the uncertainty and risk preference dimension, the Team identified risks based on guidelines outlined in the *SSBC 2020 Rulebook* and conducted several sensitivity analyses to evaluate the risks associated with each bridge design. The decision analysis that the Team conducted maximized their potential to be competitive in the competition.

Keywords: Decision Analysis, Student Steel Bridge Competition, Civil Engineering

1. Introduction

The Student Steel Bridge Competition (SSBC) is an annual intercollegiate competition that challenges undergraduate Civil Engineering students to design and construct a 1:10 scale model of a steel bridge that solves a real-world problem (SSBC 2020 Rulebook, 2019). The 2020 SSBC challenged teams to construct a bridge to replace an unnavigable portion of Katy Trail State Park that was damaged as a result of flooding in the spring and summer of 2019 (SSBC 2020 Rulebook, 2019). Teams were required to design and construct a skew steel bridge. USMA formed Steel Team 7 to compete in the 2020 Steel Bridge Competition, a team composed of five seniors majoring in civil engineering and one senior majoring in operations research.

Each competing team was required to bring fabricated bridge members and connections and construct its bridge on site. Once constructed, the bridges were subjected to two key tests: 1) the lateral load test and 2) the vertical load test (SSBC 2020 Rulebook, 2019). In the lateral load test, a 50-pound lateral load was applied, and sway was measured. In the vertical load test, 1400 pounds and 900 pounds were placed in two locations on the bridge, known as D1 and D2, and vertical deflection was measured (SSBC 2020 Rulebook, 2019).

1.1 Competition Categories

Once constructed and tested, there were seven different competition categories that competing bridges were rated on: aesthetics, construction speed, lightness, stiffness, construction economy, structural efficiency, and overall performance (SSBC 2020 Rulebook, 2019). The aesthetics category was assessed based on the appearance of a bridge and the quality of the poster accompanying the bridge (SSBC 2020 Rulebook, 2019). Construction speed and lightness categories were won by achieving the lowest total time and total weight respectively (SSBC 2020 Rulebook, 2019). The SSBC defined total time and total weight as the time required for bridge construction modified by construction penalties and the sum of a bridge's measured weight and weight penalties respectively (penalties are discussed in further detail in section 1.2 of this report) (SSBC 2020 Rulebook, 2019). The stiffness category was won by the bridge with the lowest aggregate deflection, with aggregate deflection being a sum of the vertical deflections taking place at two points on the bridge, D1 and D2 (SSBC 2020 Rulebook, 2019). The construction economy category was won by the Team that minimized the value produced by Equation 1, displayed below (SSBC 2020 Rulebook, 2019).

Construction cost (\$) = Construction time (minutes) x Number of builders (persons)
x 70,000 (\$/person-minute) + (Total time - Construction time) (1)
x 240,000 (\$/minute) + Load test penalties (\$).

Similarly, the structural efficiency category was won by minimizing one of the three formulas displayed below, depending on the weight of the competing bridge (SSBC 2020 Rulebook, 2019). Bridges weighing 175 pounds or less utilized Equation 2, bridges weighing more than 175 pounds but less than 300 pounds utilized Equation 3, and bridges weighing more than 300 pounds utilized Equation 4 (SSBC 2020 Rulebook, 2019).

Structural Cost (\$) = (Total weight – Measured weight) (pounds) x 5,000 (\$/pound)
+ Aggregate deflection (inches) x 3,150,000 (\$/inch) (2)
+ Load test penalties (\$).

Structural Cost (\$) = (Measured weight – 175) (pounds) x 8,000 (\$/pound)
+ (Total weight – Measured weight) (pounds) x 5,000 (\$/pound) (3)
+ Aggregate deflection (inches) x 3,150,000 (\$/inch)
+ Load test penalties (\$).

Structural Cost (\$) = (Measured weight – 237.5) (pounds) x 16,000 (\$/pound)
+ (Total weight – Measured weight) (pounds) x 5,000 (\$/pound) (4)
+ Aggregate deflection (inches) x 3,150,000 (\$/inch)
+ Load test penalties (\$).

Finally, the overall performance category was won by minimizing the value produced by Equation 5 (SSBC 2020 Rulebook, 2019).

Overall Performance (\$) = Construction Cost (\$) + Structural Cost (\$) (5)

1.2 Guidelines and Penalties

In addition to attempting to optimize bridge performance in these competition categories, competitors had to ensure their bridge met certain guidelines. Failure to do so would lead to disqualification in all competition categories except aesthetics. Violating less stringent guidelines resulted in penalties being assessed in competition categories rather than disqualification. Meeting any of the following criteria resulted in disqualification from the competition in all categories but aesthetics: construction time exceeded 45 minutes, sway on the lateral load test exceeded one inch, and any measured deflection exceeded 3 inches downwards (SSBC 2020 Rulebook, 2019). While not disqualifying, meeting one of the following criteria resulted in significant penalties that would make it extremely difficult to place well in the competition (penalties are listed in parentheses): construction time exceeded 30 minutes (construction time counted as 180 minutes), any measured deflection exceeded two inches (add penalties of \$4,000,000 to construction economy and \$10,000,000 to structural efficiency) (SSBC 2020 Rulebook, 2019).

2. Applying Decision Analysis

At the start of the project Steel Team 7 split itself into two design teams, each of which created their own bridge design. The design teams were named Bags and the Boys, and Cosme and the Kings. Once the two design teams completed their designs, the Team needed to decide which bridge design would maximize the team's chances of performing well in the competition. To make this decision, the Team conducted decision analysis. Decision analysis is an operations research technique used to analyze complex decisions with multiple objectives and uncertainty (Parnell, 2019). There were four dimensions of decision analysis: the decision dimension, the decision maker and stakeholder interaction dimension, the value and time preference dimension, and the uncertainty and risk preference dimension (Parnell, 2019).

2.1 The Decision Dimension

The decision dimension included three key distinctions: the type of alternatives, the number of alternatives, and the decision level of the alternatives (Parnell, 2019). In the context of the Steel Bridge Competition, the type of alternatives was separate bridge designs, the number of alternatives was two due to the two design teams, and the decision level of the alternatives was at Steel Team 7's level. Figure 1 shows the two bridge designs that Steel Team 7 had to select from. The left bridge was the Bags and the Boys bridge design, and the right bridge was the Cosme and the Kings bridge design.

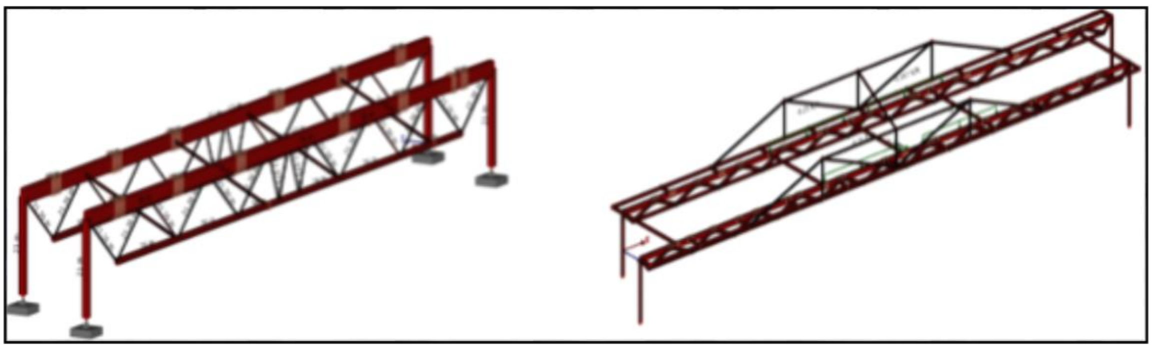

Figure 1. Bridge Designs: Bags and the Boys (left) and Cosme and the Kings (right)

2.2 The Decision Maker and Stakeholder Interaction Dimension

The decision maker and stakeholder interaction dimension is made up of two important distinctions: the number of decision makers and the level of interaction with decision makers and stakeholders (Parnell, 2019). Consisting of six team members, the Steel Team 7 had six decision makers who, beyond clarifying the rules of the competition, lacked any interaction with the SSBC committee, the primary stakeholder.

2.3 The Value and Time Preference Dimension

The value and time preference dimension captures three distinctions: time preference, value modeling, and preference weighting (Parnell, 2019). The Team was unable to take into account time preference during their decision-making process as the Team was unable to assess the amount of time each bridge would take to finish fabricating. Despite the many competition categories in the SSBC, Steel Team 7 determined that their priority was to win the overall performance category. Thus, the Team based its preference weighting on the formula used for calculated overall performance in the competition, which is given as Equation 5 in Section 1.1 of this report. The Team then created a decision matrix to calculate the expected overall performance cost of each bridge design. The Team's value measures in the decision matrix were the three factors which impact overall performance cost: weight, vertical deflection, and construction time. Table 1 contains bridge design metrics which impact the expected performance of a bridge in the three aforementioned value measures, as well as how each bridge design performed in each of these bridge design metrics. These design metrics were used to calculate the value measure costs that the Team used to select their bridge design for the competition. Equations 1 and 4 were used to calculate the value measure costs for each bridge, and Equation 5 was used to calculate the overall performance cost for each bridge. Table 2 displays the resulting value measure costs and overall performance costs for each bridge design.

Table 1. Steel Bridge Performance Metrics

	Teams	
Metrics	Bags and the Boys	Cosme and the Kings
Pieces	79 Units	39 Units
Bolts	57 Units	90 Units
D1	0.29 Inches	0.80 Inches
D2	0.28 Inches	0.90 Inches
Vertical Deflection	0.57 Inches	1.70 Inches
Horizontal Deflection	0.24 Inches	0.17 Inches
Total Bolt Weight	14 lbs.	20 lbs.
Non-Bolt Weight	298 lbs.	430 lbs.
Total Weight	312 lbs.	450 lbs.
Builders	4 Personnel	4 Personnel
Construction time	17.1 Minutes	19.4 Minutes

Table 2. Decision Matrix

	Teams	
Value Measures	Bags and the Boys	Cosme and the Kings
Weight	$1,192,000	$3,400,000
Vertical Deflection	$1,792,500	$5,355,000
Construction Time	$4,796,050	$5,442,150
Overall Performance	**$7,783,550**	**$14,197,150**

In the context of the competition, low values were better in each of the value measures, as the bridge with the lowest overall performance cost wins the competition. Based on Steel Team 7's decision matrix, the Bags and the Boys design had a better expected overall performance than the Cosme and the Kings Bridge design.

2.4 The Uncertainty and Risk Preference Dimension

The final dimension of decision analysis is uncertainty and risk preference, which consists of two major distinctions: uncertainty and risk (Parnell, 2019). In the context of the competition, the guidelines listed in Section 1.2 of this report were considered risks, as violating them resulted in severe penalties or disqualification. Steel Team 7 elected to be extremely risk averse, as USMA's Steel Bridge Team in the 2019 competition was disqualified for the sway on their bridge exceeding one inch during the lateral load test (Hill & Nelson, 2019).

After identifying violating the competitions guidelines as risks, the Team conducted risk analysis by examining the expected performance of each bridge design in qualities that are pertinent the five guidelines above. These qualities were construction time, sway on the lateral load test (horizontal deflection) and vertical deflection measured at D1 and D2. While the Team had predictions for how each design would perform in relation to each of these qualities, these predictions were filled with uncertainty as each bridge design could perform significantly better or worse on each of the above criteria. However, the Team did feel confident that their predictions were within 50% of actual bridge performance. Thus, the Team conducted a sensitivity analysis for both bridge designs in which each of the aforementioned qualities was worsened by 50%. Table 3 shows the results of the Team's sensitivity analysis. Notably, worsening each bridge design's expected performance by 50% did not lead to any of the guidelines listed in Section 1.2 being violated, indicating that neither design carried significant risk.

Another risk that the Team identified was selecting the inferior of the two bridge designs. To address this risk, the Team conducted a sensitivity analysis in which they improved the performance of the Cosme and the Kings bridge design (the bridge design that had a lower expected performance) by 50% in terms of construction time, vertical deflection, and weight. These changes were done one value measure at a time, rather than all three value measures at once. Figure 2 shows the results of this sensitivity analysis.

Table 3. Sensitivity Analysis: Abiding by Guidelines

	Predicted Performance Worsened by 50%		
Bridge Design Metrics	Bags and the Boys	Cosme and the Kings	Guidelines Violated
D1	0.425 Inches	1.20 Inches	None
D2	0.420 Inches	1.35 Inches	None
Horizontal Deflection	0.360 Inches	0.17 Inches	None
Construction Time	25.65 Minutes	29.10 Minutes	None

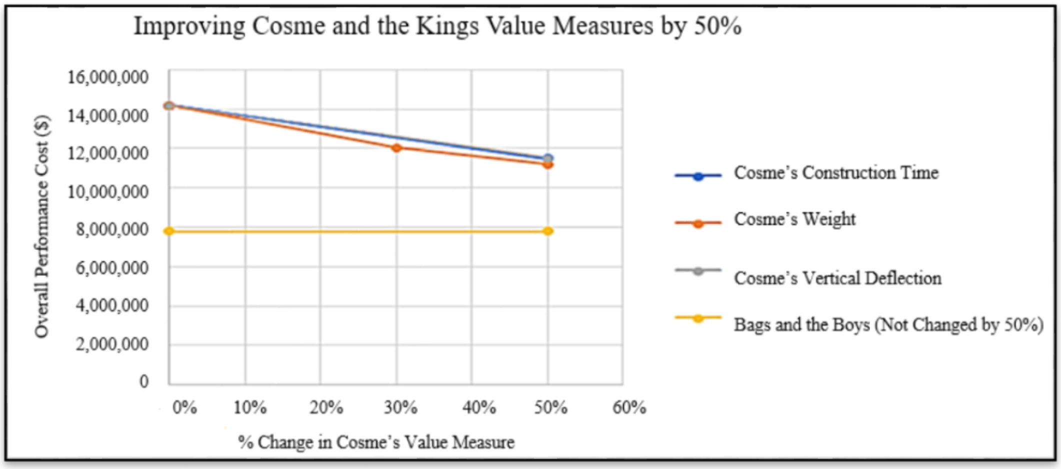

Figure 2. Sensitivity Analysis: Improving Cosme and the Kings by 50%

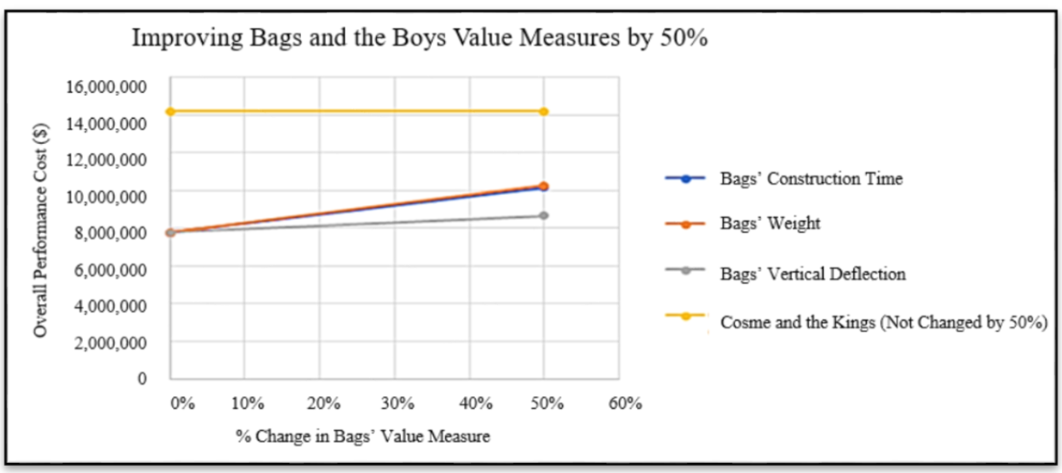

Figure 3. Sensitivity Analysis: Worsening Bags and the Boys by 50%

The Team also conducted a sensitivity analysis in the performance of the Bags and the Boys bridge where the design was decreased by 50% in construction time, vertical deflection, and weight (these changes were done one value measure at a time as well). None of these changes resulted in the Cosme and the Kings bridge design outperforming the Bags and the Boys bridge design. Conducting this sensitivity analysis also allowed the Team to see that weight is the factor that the overall performance of the Bags and the Boys bridge design is most sensitive to due to it having the steepest slope when adjusted by 50%. Figure 3 shows the results of this sensitivity analysis.

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3. Conclusion

Conducting decision analysis allowed Steel Team 7 to quantitatively decide to use the Bags and the Boys bridge design in the Steel Bridge Competition. USMA's 2019 Steel Bridge Team did not thoroughly conduct decision analysis when deciding on their bridge design and ultimately were disqualified from the competition (Hill & Nelson, 2019). While the results of Steel Team 7's decision remain to be seen, the improved decision analysis that Steel Team 7 conducted maximized their potential to be competitive in the competition. Regardless of the outcome, this is the goal that decision makers seek to achieve when conducting decision analysis.

4. Acknowledgements

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5. References

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