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Engineering and Project Management of Steel Bridge Construction

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Abstract: Annually, the American Institute of Steel Construction (AISC) holds a competition for engineering students to design and construct, for time, a scaled model of a steel bridge. This year's United States Military Academy team was interdisciplinary in nature as it consisted of cadets from the Civil and Mechanical Engineering Department (CME) and the Department of Systems Engineering (DSE). This paper identifies the contributions of Systems Engineering cadets to the Steel Bridge Capstone Team. During the design phase, Multi-Criteria Decision Making (MCDM) modeling methods assisted in final bridge selection. Project management tools, such as the GANNT chart, were used throughout the project life cycle to manage resources and time constraints. Finally, a linear optimization model was created to assess the usefulness of accepting penalties during construction on competition day. This project is ongoing and expects final results after AISC competition day on 22 April.

Keywords: American Institute of Steel Construction (AISC), Multi-Criteria Decision Making (MCDM), Project Management

1. Introduction

1.1 Student Steel Bridge Competition

The Student Steel Bridge Competition (SSBC) is a yearly event held by AISC to test knowledge of students around the United States and provide an avenue for application of undergraduate Civil Engineering education (AISC & ASCE, 2022). The mission of the SSBC is to "[c]hallenge students to extend their classroom knowledge to a practical, hands-on steel design project that grows their interpersonal and professional skills, encourages innovation, and fosters impactful relationships between students and faculty, and students and industry professionals," (AISC & ASCE, 2022). Each year, unique design specifications are put forth for the competition and students are required to design a bridge that meets the specifications and can be disassembled and erected in a time-based scenario on competition day. The final bridge that is presented on competition day is graded in the fields of: stiffness, lightness, construction speed, aesthetics, cost estimation, structural efficiency, and construction economy (AISC & ASCE, 2022). Cost estimation, structural efficiency, and construction economy are calculated values based on measurements obtained on competition day (AISC & ASCE, 2022).

While the specifications and rules associated with the competition are straightforward in nature, the challenge arises in designing and implementing the best possible product in a time-constrained environment. With the rules being released in September, students are allotted roughly 7 months to complete tasks such as: design, select, order, fabricate, construct, test, and paint their respective products.

1.2 Problem Definition

History is full of examples where engineers had great solutions to the wrong problem (Parnell et al., 2011). As a result, the first step of the Systems Decision Process is to correctly define the problem (Parnell et al., 2011). In the context of SSBC, our team sought to redefine the problem regarding the goals and expectations of the collective team. A client-based approach was taken—using the civil engineering cadets as stakeholders—to look holistically at the project and determine the expected outputs of our team. Interviews were conducted by the DSE cadets to first understand which of the requirements laid out in the rules were the most important to each respective stakeholder, and in what order they fell in as an entire group. The results of our interviews were placed into a Findings Conclusions Recommendations (FCR) matrix. Using the FCR, the team created a functional hierarchy for the project, which can be seen in Figure 1 below.

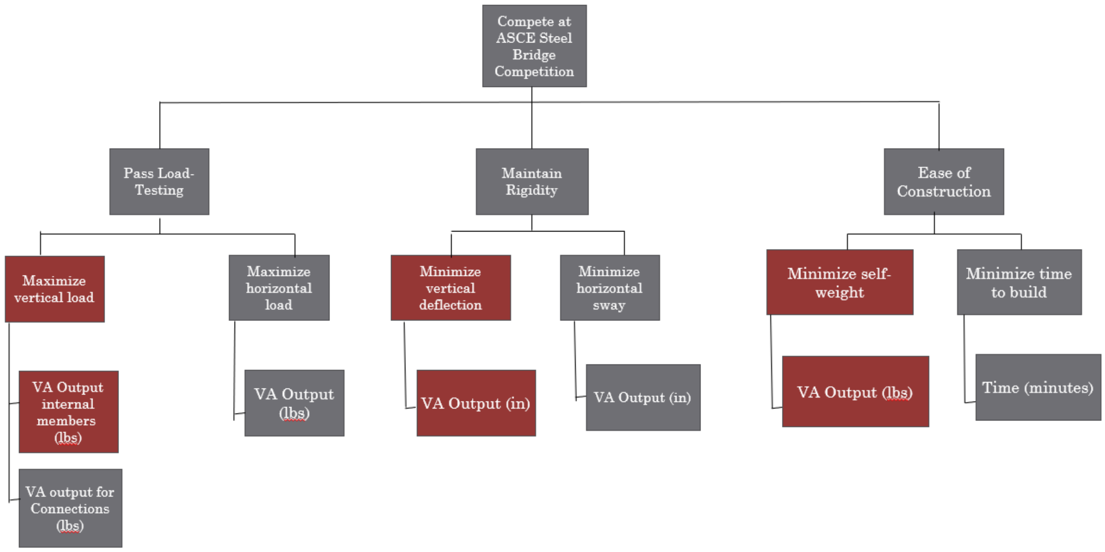

Figure 1. Functional Hierarchy

The functions of the system are to pass load testing, maintain rigidity while under a load, and be easily constructable. Within those functions, there are a total of 6 objectives and 7 value measures. Ideally, one would be capable of having an expected output for each value measure in the design phase. However, due to limitations in the design software used by CME cadets, Visual Analysis (VA), not all value measures are measurable during the design phase. In the Figure 1, the boxes that are red are value measures that we identified were feasible to obtain values for and thus measure options against during design. The boxes in grey represent values we determined to be important enough to measure prior to competing but were unattainable during the design process.

The resulting revised problem statement is: The 2022 Steel Bridge Team, the Steel Magnolias, designs and constructs a steel bridge that meets or exceeds ASCE minimum requirements in stiffness & strength while satisfying the stakeholders' weight expectations in order to compete at and win the 2022 Student Steel Bridge Competition.

2. Quantitative Value Modeling

2.1 What is it?

At the beginning of the design process, cadets from CME split into two teams, each team independently designing a bridge for competition. Given the mutually exclusive nature of this project, a decision between candidate solutions was inevitable. Decisions to complex problems are challenging due to the competing nature of their design criteria. For instance, an increased ability to hold gravity load for a bridge may only be possible by increasing the bridges self-weight. Multi-Criteria Decision Making is a field of study that was implemented dedicated to solving problems such as these.

For the SSBC, it was determined early in the project lifecycle that we would be using the Additive Value Model (AVM) in conjunction with swing weighting, as documented in works by Parnell, Driscoll, and Henderson (2011). For our problem, we identified that the values we could measure were stiffness, strength, and weight. Stakeholder interviews allowed us to determine the relative importance of each of these values, as well as how the value for each of them would change as their performance changed. A points-based system was created to assign weights, a relative measure of importance for each criterion, based on the order of importance identified by each stakeholder. We then determined that stiffness and weight followed a linear trend due to both the rules and the stakeholders identifying a value for a perfect score and a minimum acceptable value. Strength, however, was not linear. The minimal acceptable value for strength was given via competition rules but was not assigned a value of zero as it was still acceptable. It was evident to our team that there was value in creating a bridge capable of holding

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additional weight beyond the competition requirements—but the value diminishes as it increases beyond the required load. A piece-wise function was manually created to capture the change in value as the strength changed and a parabolic function was fit to the result. To visualize, the value function that we developed is shown below in Figure 2. The creation of value functions for all three value measures allowed us to receive a value for any input (*x*) received from VA output.

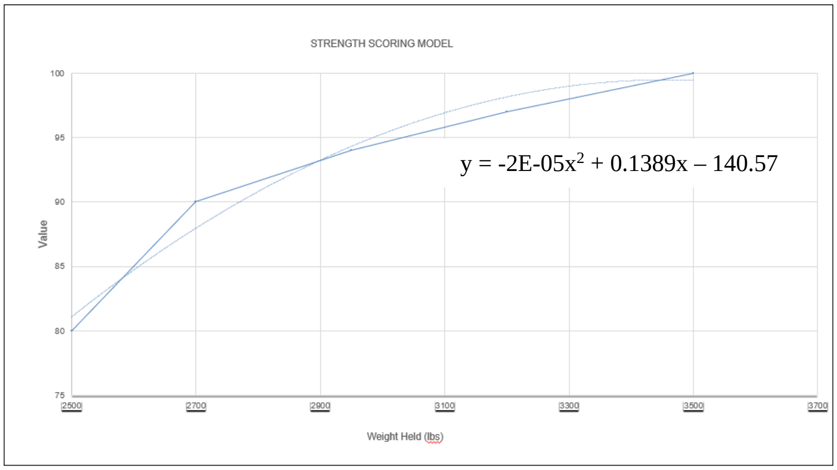

Figure 2. Strength Value Function

Based on the value functions that were created, each design candidate received three scores, one for each measurable value measure. The value obtained from the value functions was multiplied by its respective weight, from the points-based system, and each design received a summed score, per the AVM governing equation (1).

$$v(x) = \sum_{i=1}^{n} w_i \, v_i(x_i) \quad (1)$$

Additional research was conducted into the field of MCDM following the work that we completed on our design selection. Highlights from this research suggest that functions should often be defined as piece-wise functions to most accurately capture the changes in value with changes in raw score (Rezaei, 2018). Secondly, research suggests that the use of one exclusive method for MCDM is not ideal but rather a combination of modeling methods is necessary (Velasquez & Hester, 2013). While this information was not used for our project, it is a known area for improvement.

2.2 Design Selection Using Quantitative Value Modeling

The previously discussed methodologies do not advance the project towards completion unless properly implemented. For MCDM, the overall goal was to determine which bridge design to select after splitting into teams to create candidate solutions. As both bridges were analyzed using the same VA software the values that were determined for stiffness, strength, and weight were scalable and accurate relative to one another. The chart below, Figure 3, is the weighted scoring matrix we created that provided us with the final value score for each bridge.

				Raw Score			Weighted Score		
Value Criteria	**OBJ**	**Value**	**Relative Wt.**	**Team 1**	**Team 2**	**Ideal**	**Team 1**	**Team 2**	**Ideal**
Stiffness	MIN	65	0.33	85.6	89.6	100	28.53	29.87	33.33
Strength	MAX	100	0.51	100	100	100	51.28	51.28	51.28
Weight	MIN	30	0.15	72	32.8	100	11.08	5.05	15.38
Total		195	1.00				90.89	86.19	100.00

Figure 3. Weighted Scoring Matrix

The use of functions such as that displayed previously in Figure 2 allowed us to determine the raw scores displayed on the chart, which were then multiplied by the corresponding number in the Relative Weight column as per equation (1). The results from these charts gave us total scores for each criterion as well as an overall score for the candidate solution—with a max of 100 as shown in the ideal column. Based on the results of our swing weight matrix we determined that the solution produced by stakeholders in Team 1 was more optimal, with the largest advantage resulting from the self-weight criteria. As a result the team decided to move forward with Team 1's design.

3. Optimization

As the steel bridge project advanced beyond the design phase, we as systems engineers began to take a deeper look at how we could improve the team's performance at the SSBC. Through analysis of the rules, it was noted that there are actions in which time penalties are assessed during the construction of the bridge. A natural question followed for us: is there a scenario in which deliberately taking a penalty would benefit, rather than hinder, our performance? Equation (2) below is given by AISC as the calculation for construction economy at the competition, the metric that determines overall placement.

$$C_c = (Construction\ Time)\ x\ (\#\ of\ builders) x\ 70{,}000 + (Total\ Time - Construction\ Time)\ x\ 240{,}000 + load\ test\ penalties \qquad (2)$$

Of the variables within equation (2), we assessed that the number of builders and Total Time—the addition of construction time and additional time from penalties—are subject to manual manipulation and worth further assessment. However, all team members expressed a strong desire to compete on competition day. Therefore, we established the number of builders would be six. As a result, Total Time is the only variable subject to manipulation. We determined that the creation of a linear optimization model may provide us an answer to our question—in which the increase in Total Time by incurring penalties may be outweighed by the resulting decrease in construction time. Equation (3) serves as the objective function for the optimization model.

$$max \sum_{i}^{n} B_i x_i - P_i x_i \qquad (3)$$

In the above equation B_i represents the benefit or time saved of incurring the i^{th} penalty, where P_i is the time added to the score when the penalty is assessed for the i^{th} penalty. Given by the rules there were 11 penalties identified however 4 of these could be eliminated without further analysis as they were cost and weight penalties, in which it would never positively impact total time. Of the remaining time associated penalties, 3 could be eliminated as the infraction would increase the time to construct as well as incur a penalty—such as dropping a bolt or tool. The final 4 penalties to be analyzed are listed in Figure 4. These 4 penalties have been determined to have a reasonable possibility to provide benefit for the team. To determine the coefficients for B_i numerous time trials were planned to be conducted while intentionally varying penalties taken. Due to time constraints, the coefficients for B_i were estimated. In any scenario where B_i is greater than P_i that penalty would be deliberately taken during the competition to maximize our governing equation. It is understood that equation (3) is constrained by the values of x_i. x_i can never be greater than or equal to zero, as we cannot take negative penalties and x_3 is constrained as it must be less than or equal to 24, as there are a limited number of unconstructed members that could come in contact during contact.

Penalty	**Infraction**	***B_i* (estimated, minutes)**	***P_i* (minutes)**
P_1	Bridge member touches ground outside footings/staging yard	-5	.25
P_2	Unconstructed members contact each other outside the staging yard	-1	.25
P_4	Constructed members touch without connection	-10	2
P_7	Builder touches the highway or beyond the boundary	2	5

Figure 4. Optimization Table

P_4 is the only penalty that is anticipated to have a benefit to our overall time to construct, as noted by the positive value for B_i however this penalty would never be beneficial within the governing equation as it is still less than the penalty that will be assessed by taking this penalty. The negative values for the rest of the penalties result from our perception of their influence on the construction time from our limited time trials, with the values closer to 0 being perceived as more beneficial. Based on our analysis, the penalties from the rules are too penal to ever be beneficial to willingly take during the construction of our bridge.

4. Project Management Methodologies

While we needed to serve as the expert systems engineers on the project, we were additionally required to serve as the project managers for the Civil Engineering cadets. To achieve the goal of being effective project managers, we were required to utilize techniques and strategies that lead to cohesive and effective teamwork and task completion. These techniques include fostering successful teamwork, educated decision making skills, and the creation and utilization of GANTT Charts that map out the entirety of our project's timeline.

Working effectively as part of a team that includes individuals from different engineering disciplines was a challenge from the time the project was incepted. To foster successful interdisciplinary teamwork, we found that we needed to assign a designated leader of the group instead of merely having a collection of individuals with no one designating responsibility. This led to enhanced time to make decisions and better outcomes for the team. We also found that relying on each other to help with the decision-making process led to a more cohesive and effective team as well (Nancarrow, Booth, Ariss, 2013). Humbling oneself to ask the others for help brought a sense of pride to the person helping, allowing buy-in from them even if they weren't directly responsible.

4.1 GANTT Charts

To speed along our process, we utilized a GANTT Chart, a method of scheduling a project that allows for visualization of the project timeline. When creating the GANTT Chart, we looked at each task individually to determine predecessors so we could estimate start and end dates of respective tasks. The chart describes the allocation of resources as well, which we determined to be the team member that was assigned to each respective task. Our initial thought was to create personnel groups as our resources that were required to complete each task; however, as we continued to refine the chart, we realized this was an ineffective way to designate resources as often it was more effective to only select members of each team assigned to a task. The GANTT chart for our project is displayed below in Figure 4.

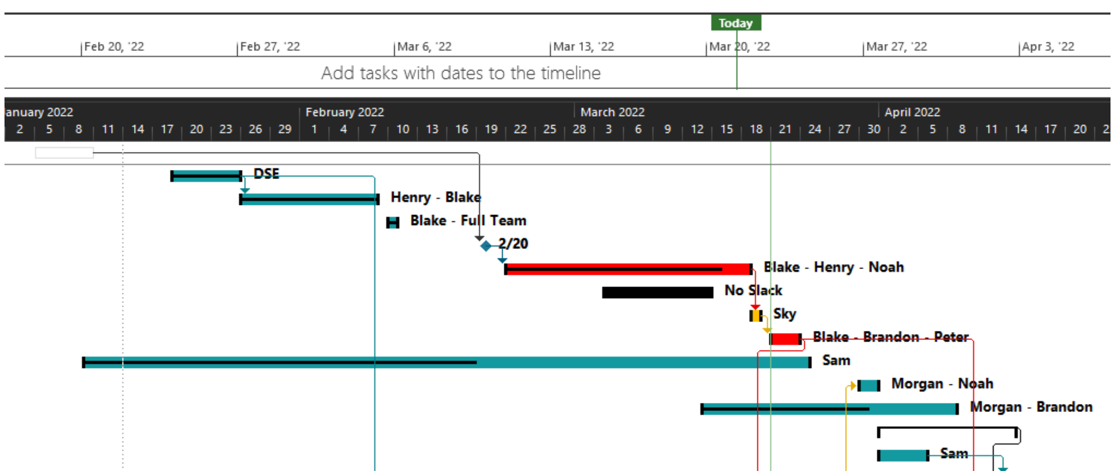

Figure 4. GANTT Chart

While we created multiple GANTT charts at the beginning of our project. However, due to a lack of personal accountability, they were not utilized in an effective way to ensure we were on track. Additionally, lack of accountability in keeping up with the timeline specified by the GANTT led to falling behind schedule. While our overall goal was met, a proper amount of time was not allocated for each task resulting in diminished quality of products. Moving into the second semester, we redesigned out GANTT Chart to define the resources for each task as individuals more specifically. The reason we did this is because it assigned an individual name to each task instead of a separated group. Assigning a name to the task promoted ownership of each task which led to greater efficiency on completing required tasks for the project.

To make our GANTT chart more easily read and ensure a clear understanding of the timeline, we used a color-coding system to separate tasks based on anticipated slack. After consulting the stakeholders, we determined a realistic estimate in total man-hours that each task would take to complete. Using this estimate, we calculated slack which was then identified within the schedule by color-coding those tasks as red. We expanded upon this idea by designating tasks where there would absolutely be no slack by coloring the respective bar black. Lastly, we assigned tasks as orange if they did not fall on our critical path, allowing us the flexibility to move around our schedule so we could remain on time.

Over the course of the project, properly identifying tasks that contained slack as well as tasks that did not became essential. These identifications ensured the completion of all tasks and eventually the construction of the bridge. Due to the volatility of the supply chain in addition to failure of the team, there is a high chance the bridge would not have been completed on time without proper scheduling. Having a backup plan for when tasks went awry became necessary to the success of our project.

5. Analysis & Conclusion

Conducting analysis for the performance of this project, at its current state, is challenging given that the competition does not occur until after this paper has been written. Rather, we can analyze the steps we took as the systems engineers and project managers throughout this project’s life cycle. Using this analysis, we can provide meaningful suggestions on how to improve this project in the years to come. One of our greatest challenges was adequately preparing a schedule with associated task ownership, resulting in a rather consistent failure to meet designated timelines. In future iterations of the project, we suggest the association of each task to a specific team member to improve accountability of task completion—as was implemented later in the project’s life cycle. We also suggest attempting to crash the project schedule to allow for more resources to be allocated to certain tasks. Tasks such as the design, fabrication, as well as ordering of the steel. This can be met by allocating more time from those in charge of these tasks, as well as those helping. Crashing the most time consuming tasks would assist in schedule deconfliction as unforeseen setbacks occur, ultimately giving more flexibility to work around the schedule.

As previously mentioned, additional work could be done to improve the process of design selection through improvement of the MCDM process and modeling techniques used. Our approach relied on linear and parabolic equations, but piecewise functions may have better fit our stakeholders true value assessments. Another recommendation would be to conduct value modeling prior to the rules being released, as we were attempting to conduct stakeholder analysis while the stakeholders had already begun the design phase. Pertaining more to our Civil Engineering teammates, we would recommend relying more on SolidWorks and other useful software to model values in conjunction with VA. Lastly, our project often suffered from failure to check others work. The implementation of an extremely thorough quality control insurance process will assist in preventing projects such as this one from falling behind schedule. While our project is not yet complete, we expect to have competition results as well as completion of a useful linear optimization model for presentation at the capstone conference.

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