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A TAILORED ANALYTICAL APPROACH TO DESIGN SYNTHESIS FROM CONCEPT TO REALITY

Carl Jolma, Robert Minger

GS Engineering, Houghton, MI

ABSTRACT

This paper presents a case study in which tailored analytical models are utilized to improve decision making in the design process. This methodology was leveraged in the design of improvements for the Heavy Assault Scissor Bridge (HASB), which resulted in an optimized end product that added new functionality to the legacy bridge system while reducing weight by 36%. The study demonstrates the importance of adapting the analytical approach to the specific problem at hand, highlighting the iterative and recursive nature of trade studies in navigating complex design challenges. By isolating variables at key decision points, the study shows how trade studies can inform more efficient and effective design choices. Through practical examples and simulations, the paper illustrates how this tailored approach can lead to the development of a robust and reliable control mechanism for a folding bridge.

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1. INTRODUCTION

In an era where the quest for efficiency and performance optimization in engineering has never been more critical, the traditional trial-and-error methods fall short, demanding deliberate application of both technology and strategy to efficiently solve problems. No matter what the design objective is, it is critical to the success of a design effort to find the optimal solution amongst a wide array of possibilities. The solution to this problem is embracing the power of analytical design tools via deliberate use of them throughout the engineering process. Challenging conventions of design, strengthening the connection between disparate analyses, and applying a methodical approach allow engineers to be efficient both in the design process and in their results. By rethinking how engineering challenges are approached, new levels of performance can be unlocked, and innovations that were once deemed impossible can be realized. This combination of technology and methodology can exceed expectations, as demonstrated by this case study. Following is an example of how these analytical tools are harnessed to produce a weight-reduced bridging mechanism that brings significant capabilities enhancement to the scissoring assault bridges in use by our armed forces.

2. BACKGROUND

New mission profiles, and new operational needs often require new solutions, however, procurement costs, timelines, and the need for training can slow or even derail adoption of new technologies. After a half-century in service the Armored Vehicle Launched Bridge (AVLB) began to show its age, unable to carry the weight of modern combat vehicles and their armor [1]. The Heavy Assault Scissor Bridge (HASB) was introduced to replace it. While the updated design improved on the Military Load Class (MLC) of its predecessor [2], much of the same design philosophy was utilized resulting in many of the same limitations. A need was identified to not only reduce the weight of the cable-cylinder system used to unfold the bridge, but to also eliminate the reliance on gravity to refold the bridge during retrieval [1]. Reducing the weight of launching system reduces the baseline load on the bridge structure, which increases the load capacity of vehicles traversing the bridge. The increased (MLC) is necessary to handle today's heavier vehicles and improvements to the mechanism could expand the motion profile and speed of recovery of the bridge. Simple enhancements to major technologies like this can have an outsized force-multiplying effect on the readiness and capability of our fighting force.

Figure 1. Deployment of the HASB

3. APPROACH

As discussed in the previous section, the U.S. Army identified the need for a new bridge launching and retrieval mechanism. GS Engineering successfully developed an optimal solution by integrating several computational tools, engineering expertise, and systems engineering processes into an efficient decision-based design synthesis process. An alternating sequence of design phases and trade studies of increasing detail were used to sequentially narrow the scope of the control design problem until the optimal solution was identified.

GS Engineering's approach rested on two objectives; reduce the complexity of decision by limiting the scope of each decision and capitalize on the strengths of analytical tools to find an optimal design solution.

To address the first objective, the team broke the complex design problem into multiple iterations of design studies and decisions of limited complexity. The first concept selection decision in the project was necessarily wide in scope in order to capture the full gamut of design approaches. Therefore, it was necessary to limit the depth of detail required for this decision As the project progressed, each decision and design study continued to narrow in scope but increase in detail. By taking this approach, each decision and design solved a simple problem. This enabled efficient use of design tools to iterate on solutions, rather than get bogged down on highly complex decision making.

To accomplish the second objective, GS Engineering made deliberate use of multiple design tools, including Creo Parametric and the Altair suite of analysis and optimization tools, to solve specific problems throughout the design process. In each phase of the project, the outputs of the design tools fed information to the decision gate at the end of that phase. Specific analytical tools were selected based on the needs of each decision and each solution concept. In addition, the scope of each design study was limited. Analytical tools tend to be most efficient at solving optimization problems of limited scope. As problems expand in scope and size, the labor required to set up these problems increases exponentially. Additionally, a more complicated response surface increases the risk that a highly efficient global extrema is missed because the tool solves for moderately efficient local extrema. Therefore, every effort was made to minimize the number of variables for each study.

GS Engineering executed this project in 3 phases; design scope realization, detailed concept investigation, and design for manufacturing. The first phase was focused on identifying the total available solution options, then down-selecting to a small number of the most promising solution approaches. The decision-making method in this phase used qualitative judgements to identify a few common solution approaches present in the multiple concepts that were brainstormed. The selected solution approaches were used as inputs to the next phase, Detailed Concept Investigation. In this phase, the focus turned to quantitative methods for design optimization and decision making. Because the number of solution approaches was limited to two, much more time was invested in the optimization of each solution prior to down-select. This is where the power of the computational tools used in this effort stand out. Multi-body dynamics were combined with design of experiments to identify an optimal kinematic arrangement for the linkage-based solution. At the completion of this phase, a single solution approach was selected. The final phase focused on exploring a finer level of detail in the design, Design for Manufacturing. Topology optimization was utilized in this phase to identify an ideal structure prior to selection of a manufacturing method.

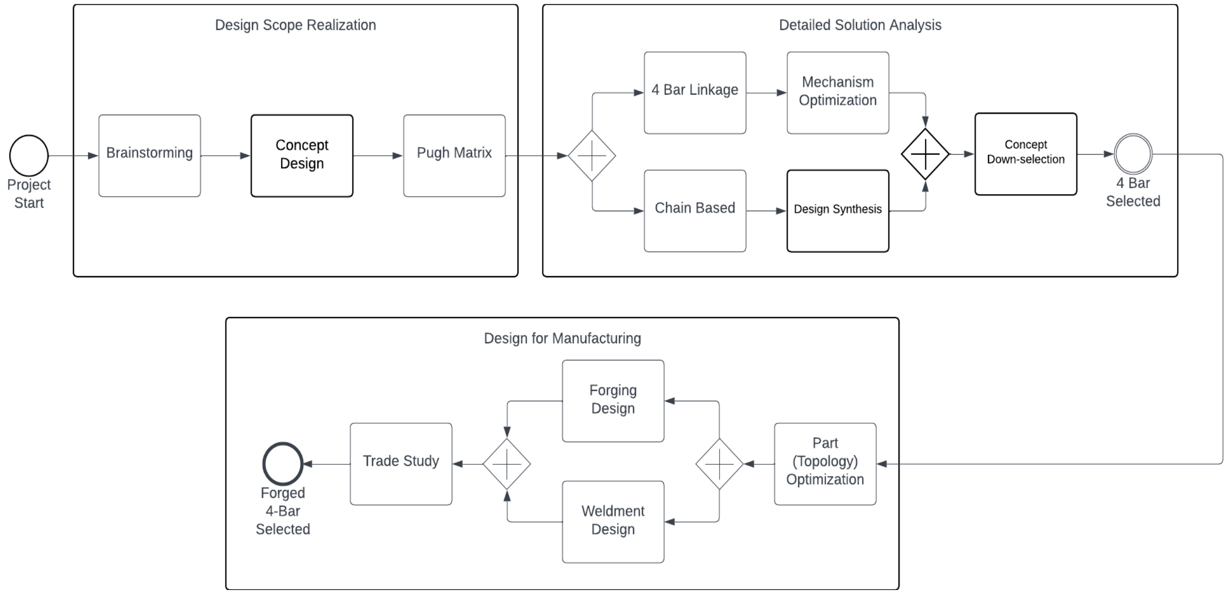


Figure 2. HASB Mechanism Realization Process

4. DESIGN SCOPE REALIZATION

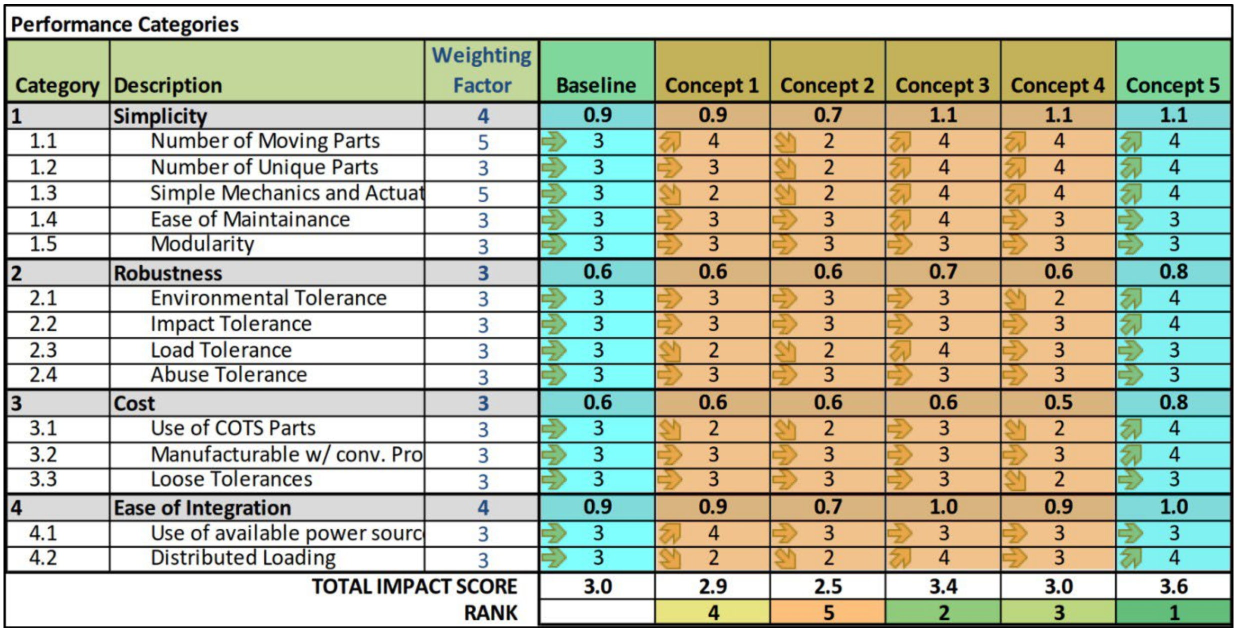
To kick off solution development, GS Engineering initiated a concepting phase. This phase attempted to capture the total available solution space at a high level. Because the scope of this phase was so broad, the decision was set up to limit the depth of understanding needed on each solution concept prior to decision making. This was accomplished with the use of pairwise decision making, and the plan to combine multiple solution concepts into a few common architectural solutions.

GS Engineering initiated the concepting phase by completing several group and individual brainstorming sessions. Following these sessions, each solution concept was nominally developed in CAD and kinematic modeling to capture the essence of that concept. During the synthesis stage, some initial optimization studies were run on the linkage concepts to refine our optimization approach prior to the more detailed optimization studies performed in the next phase. In these initial optimization runs, we established the tool workflows utilizing Altair MotionSolve as the kinematic design tool, and Altair HyperStudy as the design study tool. We also identified the importance of identifying a single optimization parameter in the study. Some of our initial optimization runs utilized multi-parameter optimizations, but we found that this approach was not responsive enough for how we used the tools to make decisions.

Following the synthesis stage, we moved to the decision-making stage. As mentioned previously, our approach for limiting scope depth in this stage relied on two methods, using engineering judgement rather than analytical methods, and condensing the multitude of concepts to the common architectural approaches. To that end, a Pugh matrix was used as the decision-making tool to organize the team's judgements on the viability of each concept.

As can be seen in Table 1, the Pugh matrix consists of 5 components, decision criteria, criteria weighting, baseline solution, concept alternatives, and ranking of each alternative. Once the design criteria and weighting were established, population of the concept performance commenced. To enable pairwise decision making, the baseline design was used as a component of every pairwise decision. The baseline performance against

Table 1. Pugh matrix of HASB launch mechanism concepts.



Performance Categories								
Category	**Description**	**Weighting Factor**	**Baseline**	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
1	**Simplicity**	4	**0.9**	**0.9**	**0.7**	**1.1**	**1.1**	**1.1**
1.1	Number of Moving Parts	5	→ 3	↗ 4	↘ 2	↗ 4	↗ 4	↗ 4
1.2	Number of Unique Parts	3	→ 3	→ 3	↘ 2	↗ 4	↗ 4	↗ 4
1.3	Simple Mechanics and Actuat	5	→ 3	↘ 2	↘ 2	↗ 4	↗ 4	↗ 4
1.4	Ease of Maintainance	3	→ 3	→ 3	→ 3	↗ 4	→ 3	→ 3
1.5	Modularity	3	→ 3	→ 3	→ 3	→ 3	→ 3	→ 3
2	**Robustness**	3	**0.6**	**0.6**	**0.6**	**0.7**	**0.6**	**0.8**
2.1	Environmental Tolerance	3	→ 3	→ 3	→ 3	→ 3	↘ 2	↗ 4
2.2	Impact Tolerance	3	→ 3	→ 3	→ 3	→ 3	→ 3	↗ 4
2.3	Load Tolerance	3	→ 3	↘ 2	↘ 2	↗ 4	→ 3	→ 3
2.4	Abuse Tolerance	3	→ 3	→ 3	→ 3	→ 3	→ 3	→ 3
3	**Cost**	3	**0.6**	**0.6**	**0.6**	**0.6**	**0.5**	**0.8**
3.1	Use of COTS Parts	3	→ 3	↘ 2	↘ 2	→ 3	↘ 2	↗ 4
3.2	Manufacturable w/ conv. Pro	3	→ 3	→ 3	→ 3	→ 3	→ 3	↗ 4
3.3	Loose Tolerances	3	→ 3	→ 3	→ 3	→ 3	↘ 2	→ 3
4	**Ease of Integration**	4	**0.9**	**0.9**	**0.7**	**1.0**	**0.9**	**1.0**
4.1	Use of available power sourc	3	→ 3	↗ 4	→ 3	→ 3	→ 3	→ 3
4.2	Distributed Loading	3	→ 3	↘ 2	↘ 2	↗ 4	→ 3	↗ 4
		TOTAL IMPACT SCORE	**3.0**	**2.9**	**2.5**	**3.4**	**3.0**	**3.6**
		RANK		**4**	**5**	**2**	**3**	**1**

all decision criteria was set to 3 on a 5-point scale. Then, each concept was considered against the baseline, in terms of performance to each decision criterion. The data was accumulated as shown in the figure. As can be seen in the figure, Concept 5 ranked most highly on the matrix, with Concept 3 in second place.

Because this decision was made with such limited information, GS Engineering did not select a single concept to proceed with. Rather, the concepts were grouped by architectural approach. As can be seen in the figure, the blue highlighted concepts are of a loop-based approach, which make use of a chain or cable to provide torque to the center bridge pin. The orange-highlighted concepts are of a linkage-based approach, which utilize a linkage to develop the torque needed to open and close the bridge.

GS Engineering then chose to proceed with the most promising concepts developed for each architectural approach. Therefore, Concept 5 (Improved Baseline) was selected as the loop-based approach, and Concept 3 (Linkage with Linear Actuator) was selected as the linkage-based approach. These concepts were then developed further in the next phase, in order to down-select to a single solution concept.

5. DETAILED SOLUTION ANALYSIS

Following completion of the Concepting phase, GS Engineering proceeded with a detailed investigation of the two solution architectures, to determine the optimal architecture for the HASB. This phase of the design process highlights the use of analytical tools to enable optimization of multiple solution concepts, prior to down-selection of a single concept. This approach was taken so the design team has a very good understanding of the promise of each solution concept prior to making a decision on which concept to proceed with. This approach is enabled by two important activities; reduction in the number of concepts under consideration such that sufficient effort can be dedicated to each candidate in this phase, and the efficient use of analytical tools to solve specific design problems during design synthesis. As discussed in the previous section, the Concepting phase was completed to whittle the number of solution concepts to a manageable number for this type of approach. Now in this phase, the tailored use of analytical tools to enable design synthesis will be discussed.

In order to make full and efficient use of the analytical tools at our disposal, GS Engineering developed a tailored approach to the synthesis of each design concept. Because each concept has its own unique features and challenges, we identified a unique toolset and approach that would add the most realism to each concept in a limited timeframe. In both design concepts, the optimization objective is focused on reducing the weight of the bridge deployment system.

Reducing weight for the Linkage-based concept was achieved by reducing the required input forces to the mechanism, as the hydraulic cylinder that powers the system was by far the heaviest component of the system. By reducing the cylinder force required, we were able to proceed with a smaller cylinder, which led to a very light solution. However, with so many possible combinations of link lengths and pivot point positions which can result in mechanisms with wildly different performance characteristics, the kinematics of the Linkage design was very difficult to optimize. Therefore, the focus of the Linkage design synthesis was focused on developing a kinematically optimized linkage arrangement through analytical methods. The optimization objective for the Linkage-based design was to increase the mechanical advantage of the linkage over its sweep of movement.

The Improved Baseline concept was comparatively simple in kinematic terms. However, this chain-based design was much more complicated than the Linkage design in implementation, due to the need for more components and more complicated interfaces between components. Therefore, design synthesis of the Improved Baseline focused on developing the components and their respective interfaces. Reducing the weight of the Improved Baseline system was accomplished through iterations of design development of the components, and finite element analysis of the design to determine structural integrity of the components.

5.1. Linkage Optimization

As discussed in the previous section, The design synthesis of the Linkage design was focused on optimizing the kinematics of the linkage to increase mechanical advantage across the operating range. This was accomplished by using Altair MotionSolve to define the parameters of a design study, which was then performed in Altair

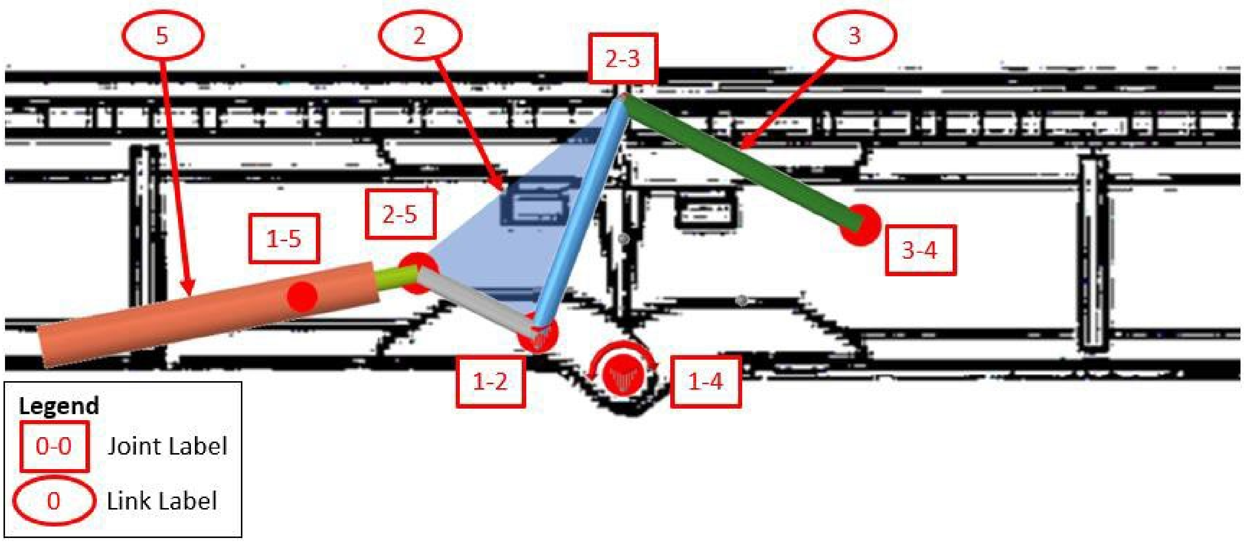


Figure 3. Nominal geometry of the Linkage concept

Table 2. Description of joints in the linkage concept

Variable	Description
IC $1\text{-}5_x$	Placement of Joint 1-5 along the horizontal axis
IC $1\text{-}5_z$	Placement of Joint 1-5 along the vertical axis
IC $1\text{-}2_x$	Placement of Joint 1-2 along the horizontal axis
IC $1\text{-}2_z$	Placement of Joint 1-2 along the vertical axis
Length_{2a}	Length of Link 2a (grey bar shown in the figure)
Length_{2b}	Length of Link 2b (blue bar shown in the figure)
θ_2	Angle between the Links 2a and 2b. This value drives the relative placement of Joints 2-5 and 2-3.
Length_3	Length of Link 3 (green bar)

HyperStudy. A model of the nominal 4-bar linkage concept was developed in MotionSolve, as shown in Figure 3. Note that the linkage is superimposed on a graphics of the bridge itself, to make the integration details of the mechanism clear.

With the model defined, it was time to define the parameters of the study itself. For this specific linkage, 8 input variables were defined. These 8 variables control the configuration of the 4-bar mechanism that comprises the essence of this concept. These variables are described in Table 2.

A nominal value for each of these variables was assigned, which defines the configuration of the graphic in Figure 3. Also, an upper and lower bound for each variable was set to bound the scope of the study to realistic variable values.

Following definition of the variables, the output responses of interest were defined in the study. Five responses were defined, of which 4 are constraints. The first two constraints define the position of the cylinder body to ensure the concept meets a design requirement that the mechanism cannot exceed the bridge boundaries when the bridge is fully extended. The final two constraints ensure that the study doesn't produce a result that is impossible to implement. This occurs if the cylinder force vector aligns with Joint 1-2.

The final output response was the objective of the study, calculated as the minimum mechanical advantage of the linkage across the range of the mechanism's movement. The study seeks to maximize this response, in order to produce a linkage that requires the least amount of input force across the range of motion.

A Genetic Algorithm (GA) was selected as the search algorithm for optimization of the study. This type of algorithm is a global search method that performs iterations of samples. At each iteration, the algorithm ranks the sample population with respect to their fitness. The highest-ranking designs then proceed to the next iteration. This process continues until the terminating conditions for the algorithm are reached, as set in the study parameters. [3].

Once the study model was defined, variables were defined, constraints were set, and objective defined, the study was ready to be conducted. The study was executed in Altair HyperStudy, and it generated the solution shown in the Figure 4. This optimized iteration resulted in a kinematic solution that minimized the input force needed across the range of the mechanism operation.

Multiple iterations of the optimization were performed prior to this final study. These iterations highlighted that this design of experiments not only provides an analytical method for determining the optimal solution in a huge population of kinematic solutions, but it also provides valuable design insight during buildup and execution. Through iterations of the study, we came across

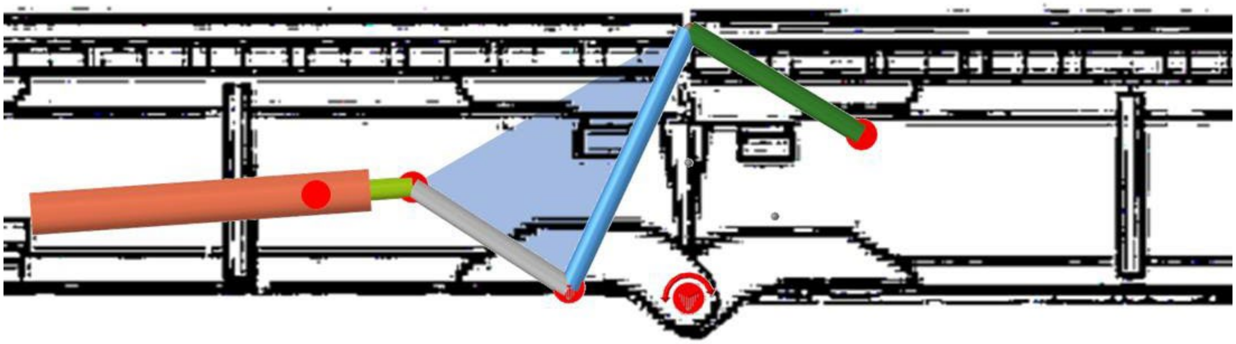


Figure 4. Optimized geometry of Linkage concept

several insights that were not obvious at the outset. Our initial linkage designs utilized an end mounted cylinder. After several initial iterations, it became apparent that end mounting the cylinder limited the angular movement of the cylinder during travel of the linkage, which limited the effective force being applied to the linkage at full cylinder extension. At this insight, an additional degree of freedom was added to the study to permit the cylinder to be mounted anywhere along the length of its body. As can be seen in the optimized iteration, a trunnion mount near the shaft end of the cylinder body provides the most efficient force vector over the linkage sweep. Moving to the trunnion mount cylinder also clarified one of our initial constraints on the mechanism. One initial bounding constraint of the mechanism was that it was contained within the envelope of the bridge at all times. However, most trunnion mount iterations result in the cylinder body exceeding the bridge envelope at some point during the sweep of the linkage. We realized that the envelope constraint only needs to apply when the bridge is fully extended, as this is the only point in time where we need to be concerned about vehicles contacting the mechanism while traversing the bridge itself.

The multiple iterations of the linkage optimization provided two benefits to the design team. First, this analytical method allowed the team to quickly identify an optimal kinematic configuration for the linkage out of an infinite population of possible solutions. By providing wide coverage of the solution population with this analytical approach, we were more likely to discover the globally optimal solution. In addition, performing iterations of the study helped us clarify our constraints and identify non-obvious design solutions.

5.2. Chain-Based Design Synthesis

As mentioned previously, GS Engineering tailored the design synthesis of the two concepts based on their unique challenges and strengths. Due to kinematic simplicity but complexity in implementation, the synthesis of the Improved Baseline design focused on modeling the implementation of the solution in order to iron out the component interface challenges, then subjecting each iteration of the design to simulated input forces within a finite-element analysis tool. Multiple iterations of this approach were completed, with the resulting solution as shown in the figure below.

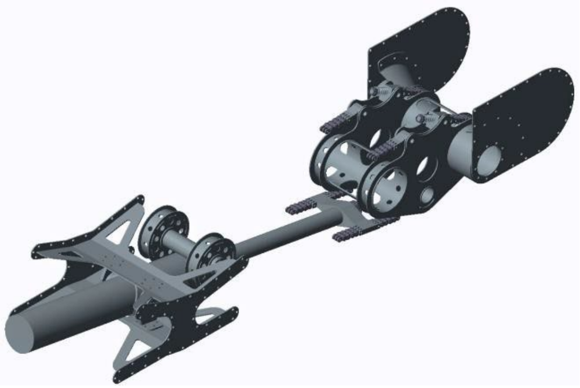


Figure 5. Chain-Based (Improved Baseline) Design

5.3. Down-Selection

Upon completion of design synthesis of both solution concepts, the team then down-selected to the preferred concept. As discussed previously, the stated goal of the project was to reduce weight of the system while adding functionality. Both systems provided the additional capability required, and both solution concepts met the constraints of the design envelope. The remaining deciding factor between the two options was total system weight. As a result, the trade study for down-selection hinged on this single decision criterion. Against this criterion, the linkage design was the better option, so it was selected as the single concept to proceed with.

This phase of the project highlights how analytical tools can be used to efficiently synthesize promising concepts for meeting the stated design goals. In this case, the analytical tools also removed any uncertainty that the concepts could meet the constraints of the design envelope. In addition, the high fidelity of the final iterations of both solution concepts amply demonstrated the promise of each approach. Because this uncertainty was removed from the decision-making process, the down-selection was straightforward.

6. DESIGN FOR MANUFACTURING

Once the linkage-based design was selected as the solution concept, the scope of the project continued to deepen. In this phase of the project, the team considered manufacturing methods for the selected design. Once again, the team made use of analytical tools to identify the optimal design pathway, in order to more efficiently produce the optimal solution.

The design synthesis stage initiated with a topology optimization study of link 2. This study was undertaken to first understand the optimal load path through the link structure. Upon completion of the topology optimization, manufacturable designs were developed to mimic the optimized structure.

Upon completion of the design synthesis stage, down-selection to a single manufacturing method was performed. Once again, due to the use of analytical tools, the manufacturability concepts were well understood. As a result, the decision was fairly straightforward.

6.1. Topology Optimization

A topology optimization exercise was performed to better understand the load inputs to the design and the most efficient structure for meeting those loads. The optimization was performed in Altair OptiStruct.

Prior to optimization, pin loads on each of the Link 2 joints were extracted from the MotionView model created in the last phase. These pin forces are a critical piece of the optimization, as the optimization software uses these input loads to determine the load paths through the part structure.

The optimization software works by removing FE mesh elements to minimize the objective function. Therefore, the available design envelope needs to be meshed prior to optimization. The envelope model was created and mesh, as shown in the figure below. Note the cyan colored mesh. This area of the part is a "non-design" area, meaning the optimization software will not remove material from these areas.

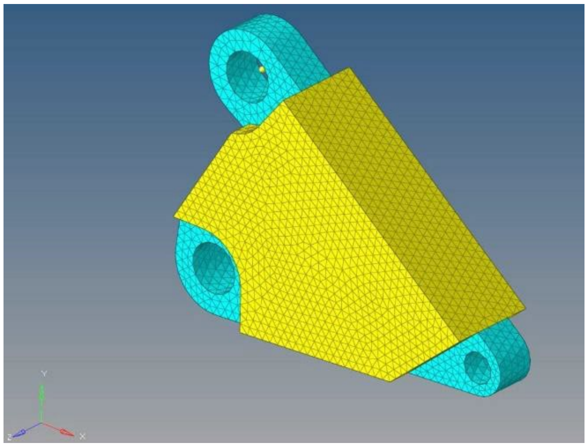


Figure 6. Design envelope for topology optimization

Using these parameters, the optimization study was performed. The resulting structure is shown in the figure below. This structure was used as the basis for the manufacturable concepts that the team developed.

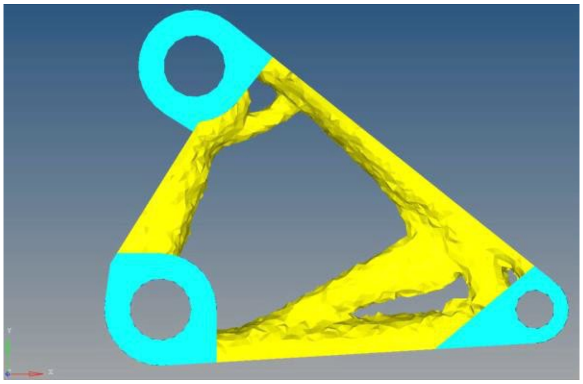


Figure 7. Optimized Structure

The design team used this topology optimization to influence the development of the manufacturable designs. Each manufacturable design sought to mimic the structure defined in the optimization, so that structural efficiency was maximized in the final design.

The team developed two manufacturable concepts, welded steel fabrication and forged aluminum. Each design was developed in CAD, then subjected to structural analysis to ensure the design would withstand the expected pin loads. Several iterations of each design were completed to ensure that the designed concept would meet the loading conditions in operation. The two designs are shown below.

Figure 8. Manufacturability concepts

6.2. Manufacturing Selection

Because analytical tools were used to develop high fidelity in the concepts, uncertainty as to the concept performance was reduced. As a result, the decision on which concept to proceed with was straightforward. The decision was made to proceed with the forged design as this was the lighter design.

7. Conclusions

This case study highlights the use of analytical tools to enable quick and decisive decision-making during the engineering process. In order to use these analytical tools effectively, GS Engineering recommends the following considerations be given to their use:

- Ensure that design problem to be solved is sufficiently narrow in scope to provide a quick and effective analysis. In our case study, this was done by segregating design decisions into separate phases of the project.
- Tailor the use of analytical tools based on the challenges of specific designs or design processes. For example, we chose to use different analytical tools for design synthesis of the chain-based concept and linkage-based concepts, based on the needs of the concepts and the strengths of the tools.
- Do not attempt to solve every problem with an analytical tool. Use engineering judgement and expertise to make decisions that cannot be easily answered by modeling or analysis. In our example, the initial phase of the project relied heavily on engineering judgement due to the broad scope of that phase.

8. REFERENCES

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