Old Main Bell Final Design Report

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Introduction [7, 8, 11]

Back in 2016, when Colorado State University's all new Canvas Stadium was being built, the Old Main Bell found its way back to campus. There, it became an integral part of culture here at CSU, being a massive hit among both students and alumni alike. Despite that, alumni can find it difficult to ring the bell due to its weight and position requiring technique and strength many of them do not possess.

Problem Statement

The following problem statement was created to address the specific points the sponsor of the project wanted addressed and what problems allowed this project to come to light.

"Ringing the Old Main Bell requires a specific set of strength and technique which causes difficulty for many members of the Alumni Association."

Background

The Old Main Bell was commissioned in 1897 and was placed in the belltower of the Old Main building around 1910. There, it became a staple of culture around campus, being rung for ceremonious events or for football games, much like today. That is, until around 1919, when a group of at least 4 men snuck into the tower building under the cover of night and stole the bell, where it went missing for many years. Some thought it had burned up in the fire that destroyed the Old Main building, where others believed it had been melted down to help the war effort during World War 2. But in 2016, these theories were proven wrong when Kristi Bohlender received an anonymous phone call from an attorney regarding the bell. A few days later, it quite literally appeared on her doorstep. Since then, the bell has been installed into Canvas Stadium and has once again become a part of the campus culture for students and alumni alike. That said, the weight and position of the 500-pound bell can make it hard for some alumni to ring, and as such, this project's goal is to make it easier for them and anyone else who wishes to participate in this tradition. [6]

Quality Function Deployment [7, 8, 11]

To best understand the quality function deployment of this project, see the updated house of quality (HOQ) in Appendix A. The HOQ will be explained in further detail in the next few points.

Customers and Requirements

The customers of the Old Main Bell project consist of multiple different entities. The primary customer is the project sponsor, Donna Reiser – Senior Director, Alumni Operations. Beyond Mrs. Reiser, the primary mission of the bell ringing tradition is Colorado State Alumni. Bringing in the next customer of the project, the Alumni of Colorado State are the primary users of the bell. The student population is also a key customer of the project as after a Colorado State football win, a student will ring the bell. However, in recent years the football team has not won many games, leading to the bell having minimal rings at the conclusion of football games. The final customer of the project is the Facilities Management (FM) team of Colorado State University. The FM team will complete the regular maintenance on the bell and also complete repairs to the bell and its components. This team is also critical to the completion of the project due to their role in advising and completing permitting requirements if they are needed. They also must be comfortable with the functionality of the project to ensure that it meets their safety requirements. The following list describes the customers with their corresponding requirements, these requirements were then turned into the performance specifications to correlate target values.

- Donna Reiser & Alumni
    - Lowering the force required to ring the bell.
        - This is the primary objective of this project, 60%.
    - The system needs to look nice and presentable to the public.
        - 10%
    - The action of ringing the bell needs to be accommodating to many people.
        - 10%
    - The set up needs to be easily done by one person.
        - 7.5%
    - The systems to ring the bell must be secure and safe.
        - 7.55%
- Facilities Management
    - Maintenance plan and schedule for regular check ups to ensure proper function.
        - 3%
    - Parts list to know what parts to replace if needed.
        - 2%

Performance Specifications

The following lists the specifications of the Old Main Bell project.

- Pull Force / Energy Application
    - Maximum force of 260-320 pounds, with target of 40-45 pounds.
        - Seen in Appendix B the Ohio Bureau of Labor Compensation and the article written by Jeffrey Lemmer the force offers a wide range of abilities the opportunity to ring the bell [4, 5].
        - Working to find a good balance of pull force and displacement, target subject to change with approval.
        - This performance specification could not be met due to displacement constraints
    - Previous iterations regarding the pulley system proved the decrease in required force could be achieved, however, significant displacement would be required of the rope negating the benefit.

        - To achieve the force required, a pre-load of potential energy into the Bell will require less kinetic energy be supplied by the person ringing the Bell.
- Aesthetically Pleasing
    - Final finishing design reviewed by sponsor and marketing team.
    - This specification is not quantifiable, customer can decide on finish.
    - The primary purpose of the Bell is marketing to the Alumni Association and prospective students to CSU.
    - Better positioning of person ringing the bell for better photos.
        - Position was approved by the marketing team.
- Ergonomics of Ringing the Bell
    - Simple method of ringing.
        - Remove much of the need to have a technique mastered to ring.
            - Previous design iterations proved that a technique is needed to ring the Bell efficiently.
                - To achieve this, simple yet important instructions to ring the Bell will be added
        - Ensure the technique allows for multiple people and is usable in photos
    - Gain input from Alumni who ring the Bell to understand methods to grip the ringing method.
        - Alumni have differing abilities and strengths to how they can move their hands.
- Set-up of Ringing System
    - Bell must be ready to ring at a moment's notice.
        - To meet this, a time of no more than 2 minutes should be taken to set up the system for operation.
        - Must be able to be setup by one person with little to no additional tools
            - Only tool required is a standard 5/8 in socket contained in the tower
- Security of Bell Ringing System
    - Methods to ring bell must be locked and/or inoperable when not in use.
        - Fully enclosed system
        - Locking system
        - Reuse of existing security door
- Operating Manual & Maintenance Schedule
    - Operating Manual to include:
        - Set-up procedures
            - Checks to ensure safe set-up.
        - Safety procedures
        - Operations guide
        - Bill of materials with included links
    - Maintenance Schedule to include:
        - Annual maintenance
            - Procedure of what needs checked.

        - Annual consumable replenishment.
    - Foreseen failures
        - Locations and time
        - Methods to mitigate.
    - Replacement parts
        - Included Bill of Materials with links

Concept Generation & Evaluation

The exploration of design process was used to generate potential concepts. This led to the team finding possible solutions on their own to later convene and discuss the possibility of each of the options. The team also discussed potential concepts with the team advisor. To evaluate each of the possible solutions, the use of the performance specifications was considered to see how each solution met these. The following tables (I-II) go into detail how the final proposed solution was decided with them being the primary specifications the team needed to consider. The scores have been normalized for each concept to a percentage based on the maximum possible score for the criteria and corresponding weight.

In Table I, the methods to reduce the required force to ring the Bell are shown. The winning concept is the ratchet pre-load. This concept outperformed the other concepts primarily in the first three criteria. This is due, in part, to the simplicity of a ratchet mechanism and the low space required of the entirety of the design. Where the other designs would require additional space beyond the existing box to contain all necessary parts, the ratchet is able to be fully contained within the box. Eliminating the need for large parts to be stored elsewhere. Along with the pre-load still allowing for an experience of ringing the Bell that is not hindered by large displacement of the pull rope.

Table I: Reducing Force Morphological Chart

Reducing Force		Lever Pre-Load		Ratchet Pre-Load		Pulley		Spring Assist	
Criteria	Weight	Rating	Total	Rating	Total	Rating	Total	Rating	Total
Complexity (1-high)	3	4	12	5	15	3	9	3	9
Space (1-low space)	2	3	6	5	10	3	6	2	4
Time to deploy (1-large)	4	3	12	5	20	3	12	5	20
Pull Force (1-high)	5	3	15	3	15	4	20	4	20
Maintenance (1-high)	2	4	8	4	8	5	10	3	6
Novelty (1-boring)	4	4	16	4	16	4	16	4	16
Cost of Parts (1-high)	2	4	8	4	8	2	4	1	2
		Total Option A	77	Total Option B	92	Total Option C	77	Total Option D	77
			70.0%		83.6%		70.0%		70.0%

In Table II, the methods to ensure safe, efficient, and secure access to the Bell are shown. The concept that performed best is an internal frame that will be installed within the existing access box. This concept won because of its ease to implement and its ability to be fully locked in the existing access box. The frame is a “drop-in” piece meaning there is no need to cut or drill into the existing structure, allowing for the frame to be easily removed if necessary. The frame also does not need any parts to be attached external to the box on the façade of the Bell tower.

Table II: Security and Setup Morphological Chart

Security & Setup		Permanent		Internal Frame	
Criteria	Weight	Rating	Total	Rating	Total
Ease of Implementation (1-difficult)	3	2	6	4	12
Access to Public (1-open)	4	1	4	4	16
1 Person Setup (1-multiple people)	5	5	25	5	25
Required Equipment (1-additional equipment)	4	4	16	4	16
Cost of Parts (1-high)	2	3	6	3	6
		Total Option A	57	Total Option B	75
			63.3%		83.3%

Comprehensive Design

The proposed solution involves a framework constructed of T-slotted extruded aluminum framing from McMaster Carr. Through the use of double slot rails, the frame was able to support the size of the ratchet mounting locations with minimal changes to the ratchet to mount. The double slot rail also added additional stability when affixed in the box as it did not allow further rotation due to a lever action of force applied at the different points force was applied. Primarily, the frame allows for there to be modularity to the design without the need to permanently change the box. By adding the rotating arm, the rope from the Bell is able to be redirected out of the box while minimizing the contact of the rope with the termination of the pipe it travels in up the Bell tower. This redirection reduces the friction felt by the rope, thus making it easier to pull while, also, increasing the life span of the rope. More detailed drawings are included in the engineering drawings package.

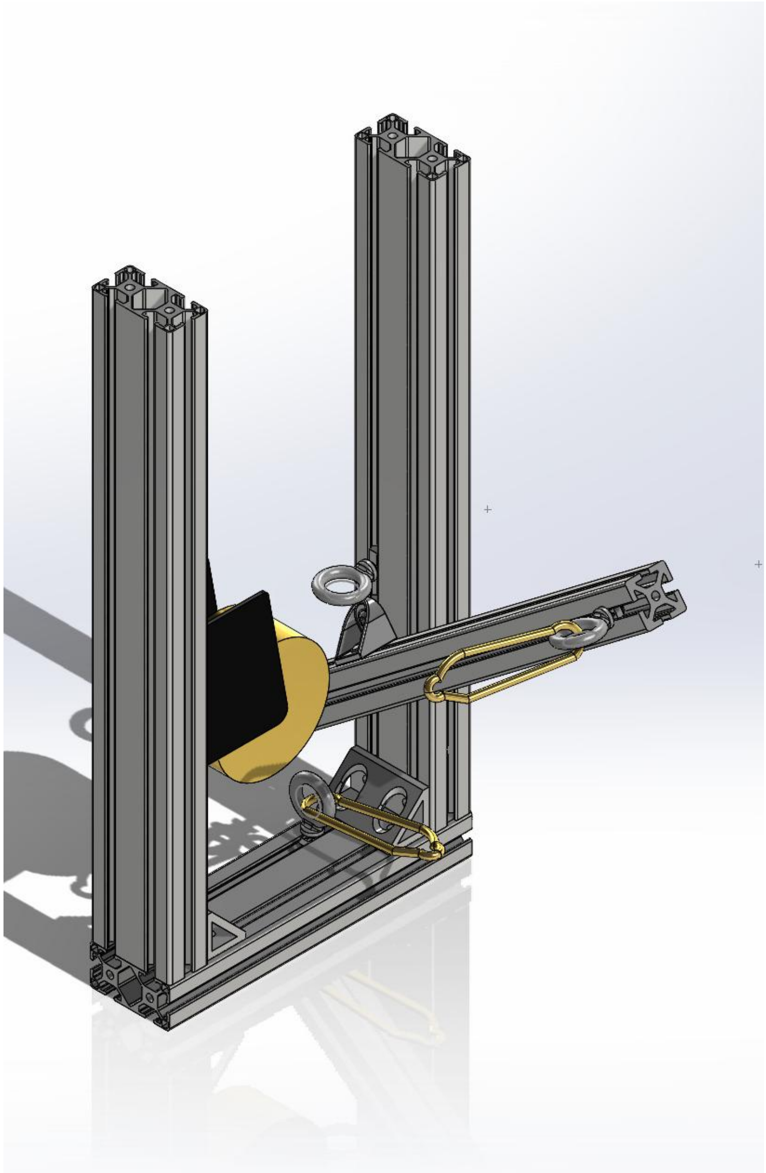

Figure 1: Proposed Solution

Design for X

When going through the concept generation process for the current solution, three main factors were considered as overarching requirements that the solution was based around. These concepts correlated with the performance specifications provided by the project sponsor as well as overall goals for the project. These design factors were designing for ease of use, designing for maintenance, and designing for safety and reliability.

When designing for ease of use, the biggest considerations were pull force, ergonomics, and setup. To achieve this, the use of a potential energy preload system was used. To allow for an easy setup of the system, the ratchet system works to have the box quickly opened, the safety disengaged, and the bell be raised and released by one person. Additionally, the horizontal pull allows for simple access to ringing the bell by alumni without the need to perform uncomfortable movements.

When designing for maintenance, the primary consideration went into the methods of reduction and the materials used. A big focus was put into the method of reduction and instructions for assembly, as it was important that the method used was simple enough for someone with no background in the project to be able to repair or remake the system with little to no issues. In addition, an emphasis was put on using components that were sold by readily available companies to ensure ease of maintenance. Making sure the parts can simply be purchased when it comes time to be replaced, and that minimal work needs to be done to them before implementation ensures that the solution will be easy to repair in the years to come.

When designing for safety and reliability, quality parts are quintessential. To achieve the desired safety levels and reliability, using readily available and proven parts helps achieve this to a high level. As the parts are commercially available only after they have been tested and proven by the manufacturer. The primary source for our frame materials came from McMaster Carr, ensuring availability and ease of ordering for replacement parts. However, the acquired parts are similar enough to many other manufacturers' products and will be able to be interchanged or modified if necessary in the future.

Tradeoffs

When it comes to tradeoffs, Mrs. Reiser did not provide many specifications that would conflict with one another. For this reason, the group is primarily concerned with two areas, that being the space available to implement any solution and the relation to the CSU Alumni Center's social media team.

Regarding the space limitations, the housing box was measured to be recessed into the wall 5 in, with the space itself being 24 in x $10\frac{1}{2}$ in x $7\frac{3}{16}$ in. This is not a lot of space for work to be done and will severely limit what can be done without altering any of the existing infrastructure, something that the CSU facilities team said could theoretically be possible but would require many permits and a lot of money to pull off. This means whatever ends up being implemented must be compact enough to fit into this box or up on top with the bell, while not subtracting from the presentation. This restriction has led to the system being designed to exactly fit into the box to give the frame points to brace against while under load, It also allows for reuse of the existing door and locks, while providing a completely new experience for the people ringing the bell.

Going off that, the second major tradeoff is the involvement with the social media team and the greater alumni center. This boils down to the group having to be consciously always thinking about the presentation of work, as it will end up in view of the public eye and will reflect back on the alumni center or will be posted either on a social media platform or in one of the alumni association's newsletters. The group wants their work to reflect the pride this university holds for the tradition of ringing the bell, and as such, the appearance of the implemented system could not look careless and sloppy, even if it worked. For this among other reasons, the initial prototype's frame was upgraded from wood to aluminum, as it not only functions better but also looks nicer. This also applies to how the alumni center utilizes the bell as a source of publicity, meaning any implemented solution had to also allow for enticing photographs similar to what they are currently putting out, restricting the orientation of the system to primarily horizontal.

Risk Analysis and Mitigation

The implemented design uses a ratchet and pulley system, which is safe when properly used and maintained. In order to achieve the safe use and longevity of the system, there has been an operational manual written for it as well as a maintenance schedule written out. The operational manual will be used to train the Alumni Center Staff who will be responsible for operating the Bell. The maintenance schedule has been shared with Colorado State University's Facilities Management for input into their maintenance management system. This includes a yearly reminder to inspect the Bell system to ensure the system is still in well operating status. They will also be able to do a more in-depth inspection of the rope specifically as the majority of it is housed within a pipe in the tower. This inspection will allow for wear patterns to be noticed before complete failure of the rope unexpectedly. In table 1, the FMEA table is presented to detail each of the critical systems within the pulley system and their associated risk analysis and the mitigation of each.

In addition, a plexiglass screen has been installed over the mechanism, with pinch points clearly labeled to prevent injury. The screen is on hinges so it can be opened for maintenance purposes, as it is safe to interact with the ratchet as long as it is not loaded. In addition, a setup and operations sheet has been attached to the inside of the door to the bell to ensure instructions are easy to reach and clear to operators and participants for an added level of safety.

Table III: FMEA Table

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Carabiner connections	Carabiner failure	Carabiner breaks and rapidly releases energy in system, person falls from pull attempt	10	Improper connection, age	1	Yearly maintenance check, operations manual to check orientation of carabiners	1	10	Make sure the system is checked for wear at least once/year and understanding ops.	Facilities Management and Alumni Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	10	1	1	10
Eye Bolts w/mounts on T-slotted frame	Eye bolt or anchor failure	Rapid release of energy in system, person falls from pull attempt	10	Eye bolt shears, anchors disconnect from frame	2	Yearly maintenance check, operations manual to check status of anchors	1	20	Make sure the system is checked for wear at least once/year and understanding ops.	Facilities Management and Alumni Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	10	2	1	20
Ratchet release	Ratchet does not release and/or binds up with strap inbetween gears	Bell suddenly stops, unable to complete ringing w/o intervention to reset ratchet	10	Improper force applied to release mechanism	4	Instructions to rapidly applied high force to pull ratchet release	5	200	Make sure the operator understands how to release ratchet	Facilities Management and Alumni Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	10	3	4	120
Pulleys	Pulleys open and release rope	Rope disengages from system	6	Pulley connection point left open is opens during operation	2	Yearly maintenance check, operations manual to check status of pulley engagement	1	12	Make sure the system is checked for wear at least once/year and understanding ops.	Facilities Management and Alumni Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	6	2	1	12
Pulleys	Pulley failure	Rapid release of energy in system, person falls from pull attempt	10	Age, improper use/handling	1	Yearly maintenance check, operations manual to check status of pulley engagement	1	10	Make sure the system is checked for wear at least once/year and understanding ops.	Facilities Management and Alumni Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	10	1	1	10
Rope	Rope frays and breaks apart	Rapid release of energy in system, person falls from pull attempt	10	Age, friction	3	Yearly maintenance check of internal rope, operations manual to check status of visible rope	3	90	Make sure the system is checked for wear at least once/year and understanding ops.	Facilities Management and Alumni Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	10	3	3	90
Energy Storage	Person puts hands inside box when the ratchet is engaged	Serious bodily injury	10	Safety guard is not in place	1	Safety shield to block access and stickers marking locations of pinch points	1	10	Make sure safety guards are in place and signified in the operational manual	Alumnu Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	10	1	1	10
T-slot frame fold out arm	Arm disconnects/breaks off from main framework	Rapid release of energy in system, person falls from pull attempt	10	Age	1	Yearly maintenance check of deformation of T-slot connection	1	10	Make sure the system is checked for wear at least once/year and understanding ops.	Facilities Management and Alumni Center staff who op bell	Alumni Center staff trained and given access to op. manual. Facilities recieves maint. Sched	10	1	1	10

Predicted Performance

Pull Force Reduction

In order to achieve sufficient reduction in pull force, the bell is preloaded using the ratchet. This builds up potential energy, and when the ratchet is released, it is converted to kinetic energy and gives the bell momentum. This allows the person ringing to take over and keep the bell's momentum going instead of having to build up the momentum themselves, the part of the process that was found in testing to be the most difficult. In testing, this method allowed the user to exert significantly less effort than the previous method, and the fact that the method does not increase the amount of distance the rope has to travel means it is easier to exert the force required to make the bell ring.

Figure 2: Ratchet System Proof of Concept

Aesthetically Pleasing

In order to satisfy the stated aesthetic requirements without sacrificing function, the constructed frame was designed to fit entirely within the existing box. In order to allow for the desired function of the redirect system, the pulley that needs to be outside of the box was put onto a folding arm that swings out and locks in place to allow the design to be self-contained. This folding arm allows for the rope to come out and easily be pulled in a horizontal motion, a motion commonly used when large groups of people are ringing the bell or posing for photos. In addition, the material chosen was selected due to both its functionality and its aesthetics. T-slotted aluminum framing has a professional style and is visually appealing in the use case.

Ergonomics of Pulling

In order to satisfy the ergonomics requirements, a horizontal pull has been selected to achieve as many requirements as possible. The horizontal pull of an average college student is higher than their vertical pull when taken in the context of ringing the bell, coming in at an average of 71.20 lbs. compared to the vertical's average of 52.35 lbs. In addition, the horizontal pull was requested by Mrs. Reiser, as it provides more people with the opportunity to hold the rope when taking pictures, also satisfying the aesthetic requirements. However, the horizontal pull is slightly more difficult of a position in comparison to the vertical, as in an ideal scenario similar to how we were theorizing the user could put their body weight into the pull. The horizontal pull overall satisfies more of our weighted criteria, and as such was selected for use.

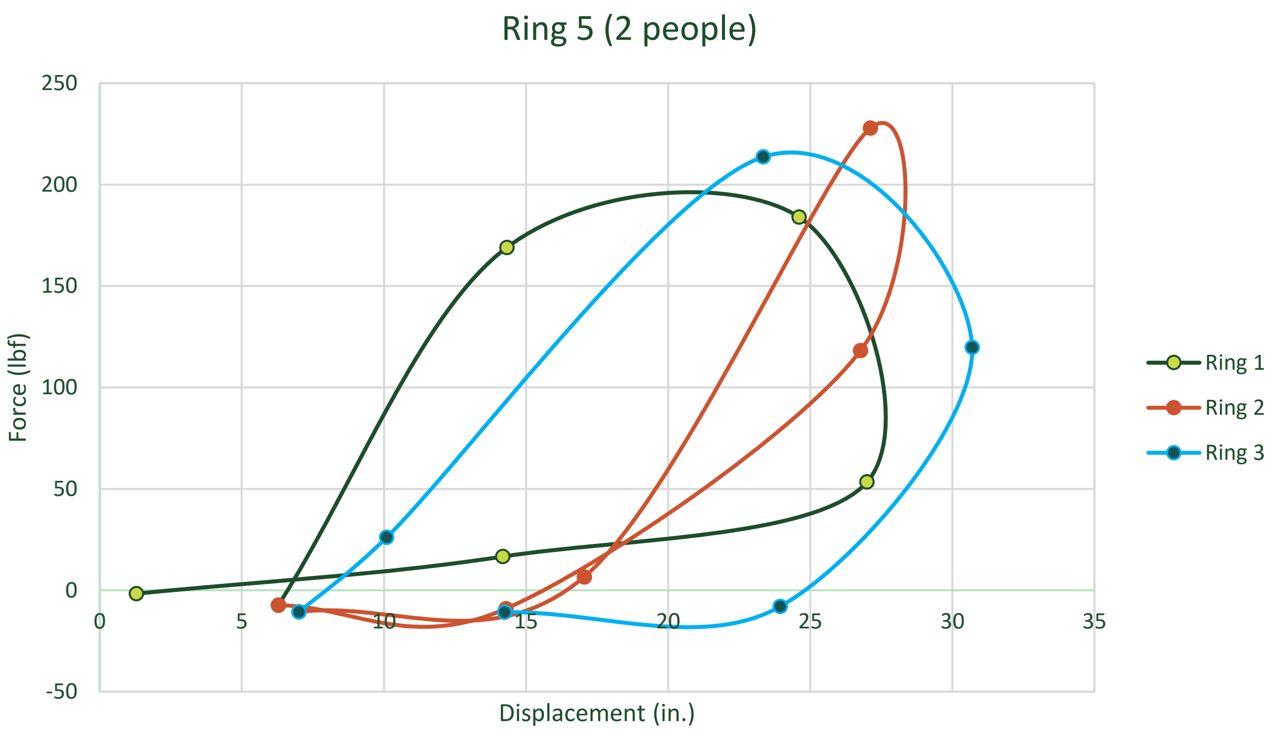

Figure 3: Bell Pull Test Force vs. Displacement Ring 5

Security & Setup

In order to satisfy the security and setup requirements, efforts were made to completely secure the mechanism inside of the existing box. This design allows for the reuse of the existing security infrastructure, while also being entirely self-contained. The folding arm in the design also allows for the desired functionality while being able to be secured entirely within the box. In addition, the method is designed to allow for easy setup for a single person, with setup instructions listed on the inside of the door and minimal actions being required to get the desired functionality. This solution ranked the highest in our evaluation shown in Table II, with it being the most feasible for implementation while also allowing for ease of setup.

Safety & Maintenance Setup

In order to satisfy the safety and maintenance requirements, off-the-shelf parts from McMaster Carr, Harbor Freight, and Petzl were chosen to be implemented. This was done to ensure ease of maintenance by using parts that are readily available and easy to replace if the need arises. The manufacturers, McMaster Carr and Petzel, were selected for their reliable products and plentiful documentation. For the same reason, the ratchet selected is a generic 1200 lb. capacity ratchet from Harbor Freight, meaning it is easy to find and most likely something many of the people working with the bell have seen before. This allows an operator with little to no experience with the system to operate and fix it with minimal issues if using the maintenance instructions provided. As can be seen in Table I, the off-the-shelf parts were better for this scenario in every weighted category, and as such were selected for the project.

Probability of Success

Pre-loading of Bell

To ensure success in pre-loading the Bell, there were multiple prototyping iterations completed to check on the viability of the concept. The first proof of concept test for the ratchet pre-load system was done in the materials lab lifting a weight. This test allowed for the concept to be tested to see if the release of energy from a ratchet would be viable to pursue further. The testing scenario can be seen in figure 4.

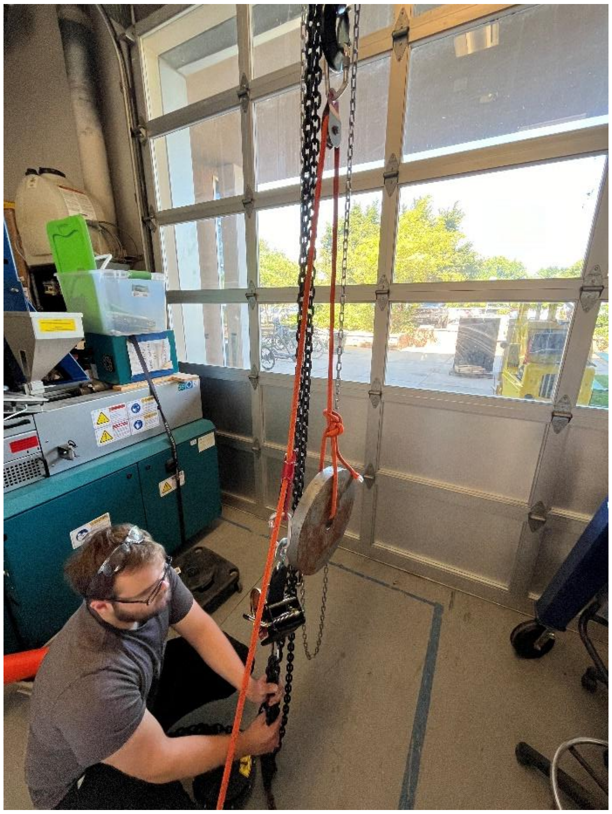

Figure 4: Proof-of-concept Test

The second prototype of the ratchet pre-load system was done with a 2”x6” wood plank placed on the ground outside the box. This prototype was done outside the box to test the system without the need to spend unneeded money and resources on creating a system to fit inside the box. This system can be seen in figure 5.

Figure 5: Ratchet prototype mounted outside of box

To ensure that the rope could be directed out of the box area with minimal contact with the pipe termination and the façade of the Bell tower, the team created a wooden frame to test the feasibility of the positioning of pulleys. The use of wood throughout the testing of the early prototypes was to allow for low-cost prototyping while also being an easier material to work with. Figure 6 depicts the early prototypes of the wooden frame to prove the rope could be redirected out of the box effectively.

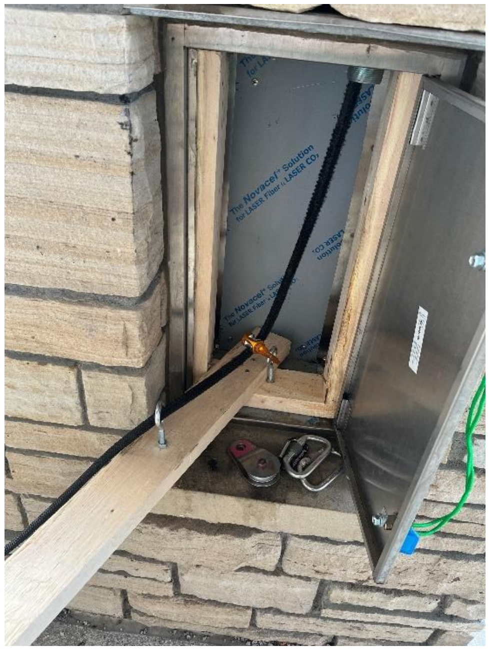

Figure 6: Prototype of rope redirection wooden frame

After the testing of different components of the ratchet pre-load system, the team combined the wooden frame with the ratchet to conduct a test of the full system in its near complete form but out of wood. This test was done to understand if the complete design was feasible in the small space of the box. The wooden frame ratchet prototype can be seen in figure 6 above. The ringing is completed in this testing at a different angle without the arm to redirect the rope so it is not in contact with the ratchet system, as the mounting point on the bottom piece of wood is not the ideal position. This was corrected with the use of the T-slotted framing in the final product. In this stage, the prototype was demonstrated to staff members of the Alumni Association to seek feedback from them on the design, where it was decided that work could continue to the final design.

Figure 7: Completed system installed in box

Upon successful completion of the integrated prototype, the construction of a similar design using T-slotted aluminum framing was completed. This design ultimately became the final product. The aluminum framing was used as it allows for a modular design approach because parts are not permanently affixed to any point on the frame, rather the parts can be repositioned easily without the need to drill new holes. This system can be seen in figures 7 and 8. It was at this point where the team had Dr. Troxell partake in the testing to have him ring the Bell with the ratchet pre-load system. Through this testing, the team was able to observe another person ring the Bell who had prior experience in ringing it in its original state and give feedback of the system. This proved to be greatly helpful in the understanding that the Bell would still ring even if the user could not apply large amount of force to keep the Bell ringing after the ratchet is released.

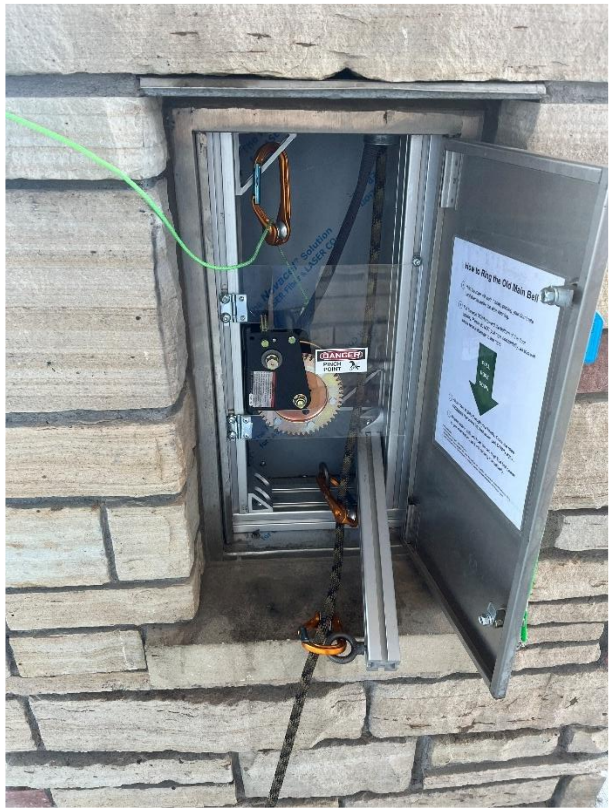

Figure 8: Frame in operational setup

Aesthetically Pleasing

To ensure success in the field of aesthetics, frequent conversations were had with Mrs. Reiser and other members of the Alumni Center. In doing this, all decisions were made with informed approval of what the Alumni Center was looking for, what would look good by their standards, and get suggestions on how the existing design could be improved. The final design was built to fit entirely within the existing infrastructure, with all the parts that protrude from the space folding in for storage. This allows for reuse of the existing door and lock system and does not change from the existing appearance when the door is shut. In addition, the choice of using T-slotted aluminum framing was made not only for structural integrity, but also because the material looks very professional. All of these designs were run by the team at the Alumni association for approval before implementation to ensure the aesthetics were up to their standards.

Ergonomics of Pulling

To satisfy the ergonomics of pulling requirement for the project, a horizontal rope pull was chosen. This was done because of the test data collected in the previous semester of the project where it was determined that the average pull force in the horizontal configuration was 71.20 lbs., surpassing the vertical's 52.35lbs. In addition, after researching the configuration most used when ringing the bell, it was determined that the horizontal pull was better for photos and videos for the Alumni Association's social media page. All this information was relayed to Mrs. Reiser for approval before the design was made. After receiving approval, a re-directional pulley system was implemented using two Rollclip A carabiner pulleys (Part #1) connected to eyebolts (Part #11) on the frame. One of these pulleys is connected to an arm that folds out of the box, and the other is attached to the frame directly under the outlet, as can be seen in Figure 8 These redirects allow for a significant reduction in friction between the rope and the outlet, as well as preventing the rope from rubbing on the stone wall as easily. An additional eyebolt was secured to the frame after the implementation of the ratchet to ensure the rope does not come in contact with any of the gear mechanisms while in use. This system puts the rope in position for an optimal pull every time while also preventing wear so the rope doesn't need to be replaced as often. After testing, members of the Alumni Association staff have confirmed that the improved horizontal pull was an improvement from the previous method in terms of force required.

Security & Setup

To ensure success in the field of security and setup procedures, focus was put towards ensuring the setup is self-contained and simplistic. Similar to the aesthetically pleasing section, much of the validation for this portion came from consultation with Mrs. Reiser. Security has always been a major concern for the project, with the initial designs revolving around being restricted to the existing box, and the previous design implementing a removable enclosure to allow for additional space without sacrificing security. The current design has gone back to being completely contained within the box, with parts folding out to get the functionality the design needs without having to sacrifice the security of the existing box. The team had frequent meetings with Mrs. Reiser to ensure the design was up to her standards, and after they were given the green light implemented the design into the setup. In addition, an emphasis was put toward a single person setup, with all the required materials being placed inside the box along with operating instructions. The current design has minimal moving parts, and the operators main job is to engage the ratchet, load the bell, and release the lock to put the ratchet into free spool.

Safety & Maintenance Setup

To ensure success in the field of safety and maintenance, an emphasis was put on high quality off the shelf materials, specifically the use of pulleys from Petzl and T-slotted extruded aluminum. This emphasis was to ensure the parts would not fail after extensive wear over years of use while also having replacements be easy to find, order, and swap out. The specific reason for using these companies comes down to their product's reliability and documentation. Every piece of equipment sold has extensive documentation, including everything from a basic specifications section on the store page to multiple technical information documents such as notices and declarations of conformity. When it comes to reliability, the component with the lowest working load of our selected components, the ROLLCLIP A (Part #1), has an advertised working load of 900 lbs. (4kN), well above the forces expected to be in the system [10]. In addition, in the case of a breakage these parts are sold at most major climbing and metal retailers, and if something happens to the manufacturer and their equipment is no longer being sold, the parts are generic enough that they can easily be substituted with one from a different manufacturer.

Project Plan

Project planning and management is critical to the successful completion of any project, the Old Main Bell project is no different. The following will explain how the team will accomplish this.

Schedule

The Gantt Chart in Appendix C outlines the critical path flowchart the team used to complete the project. The schedule details this past semester due to changes that occurred following the previous semester. At the beginning of this semester the team was planning out two-three weeks ahead due to the changing design. However, soon after the design was realized, the team was able to create a plan for the remainder of the semester and kept to that schedule to complete the final project.

The factors critical to the achievement of the project was the redesign of the system at the beginning of the semester due to the feedback from the previous semester. From this stage, the critical part of the process was constructing and prototyping multiple iterations of the new design all within one semester. This process was able to be documented well through the flowchart primarily through the different prototyping phases staying on track and parts being ordered and delivered within the windows that were designated on the chart. The refining of the design coincided with the planned phases of prototyping, so there were not delays in the schedule due to unforeseen prototypes that needed to be accomplished.

Resource allocation for the critical path was addressed primarily by the project leader. This occurred throughout the semester through engaging with the team as well as the team sponsor and advisor through the semester.

Budget

The budget of this project is relatively open-ended, with an anticipated amount of $2000 that has been set as the maximum amount. Of this budget, $551.36 was spent. In figure 9, a pie chart depicts the current budget breakdown. Figure 9 depicts the current income of the project, all costs associated with this project are funded by the Alumni Association.

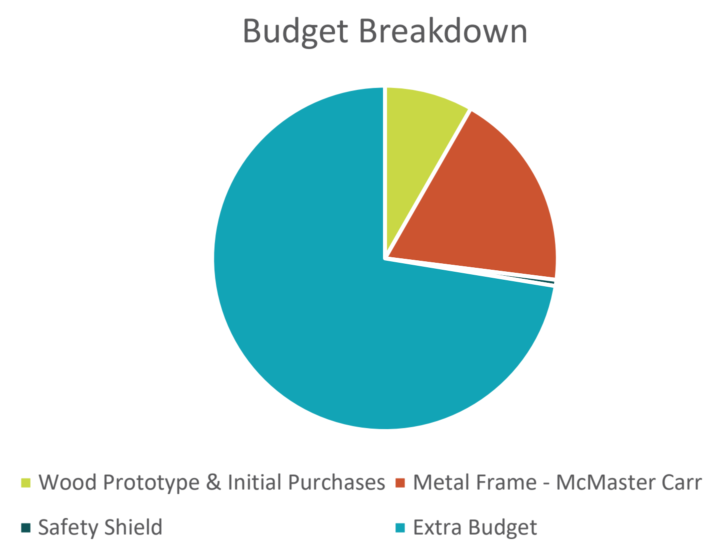

Figure 9: Budget Pie Chart

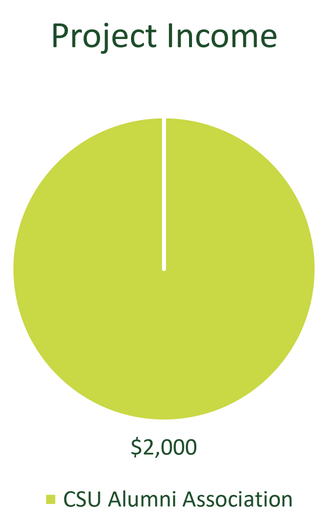

Figure 10: Project Income Pie Chart

The final budget is comprised of solely materials. Due to the completion of initial testing and the aid of the Mechanical Engineering department, it was feasible to reuse existing testing materials all provided by the department for all tests, thus mitigating the need for any budget for testing. The team did not end up using any of the contingency budget as no additional expenses outside of the materials budget was spent. A detailed breakdown of the expenses is provided in Appendix E.

Conclusion

To conclude, this project is integral in helping to preserve the excitement of tradition here at Colorado State University. In fixing the Old Main Bell, the group hopes to allow all the alumni of the university to be able to participate with little to no assistance, while also implementing a routine maintenance schedule to ensure that the bell can be rung for many years to come. By using a ratchet preload system, the required force to ring the bell was decreased significantly. The goal of the project is to have a system that withstands the test of time, lasting many years with little maintenance. The overall budget comprised of funding from the Alumni Association to purchase parts needed. This budget encompasses a total of $2,000, with $551.36 of that budget being spent. Overall, this system aims to bring access to ringing the bell to the overall campus community has been laid out through this report.

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[11] B. Bushlack, J. Toebe, "Old Main Bell Critical Design Report," Colorado State University, May 2024.

Note: Sources [7], [8], and [11] are original works of the author, all of which regard this same project. The Introduction, Quality Function Deployment sections are taken completely from those reports. The remaining parts are primarily new content, with some previous work mixed in.

Appendix A

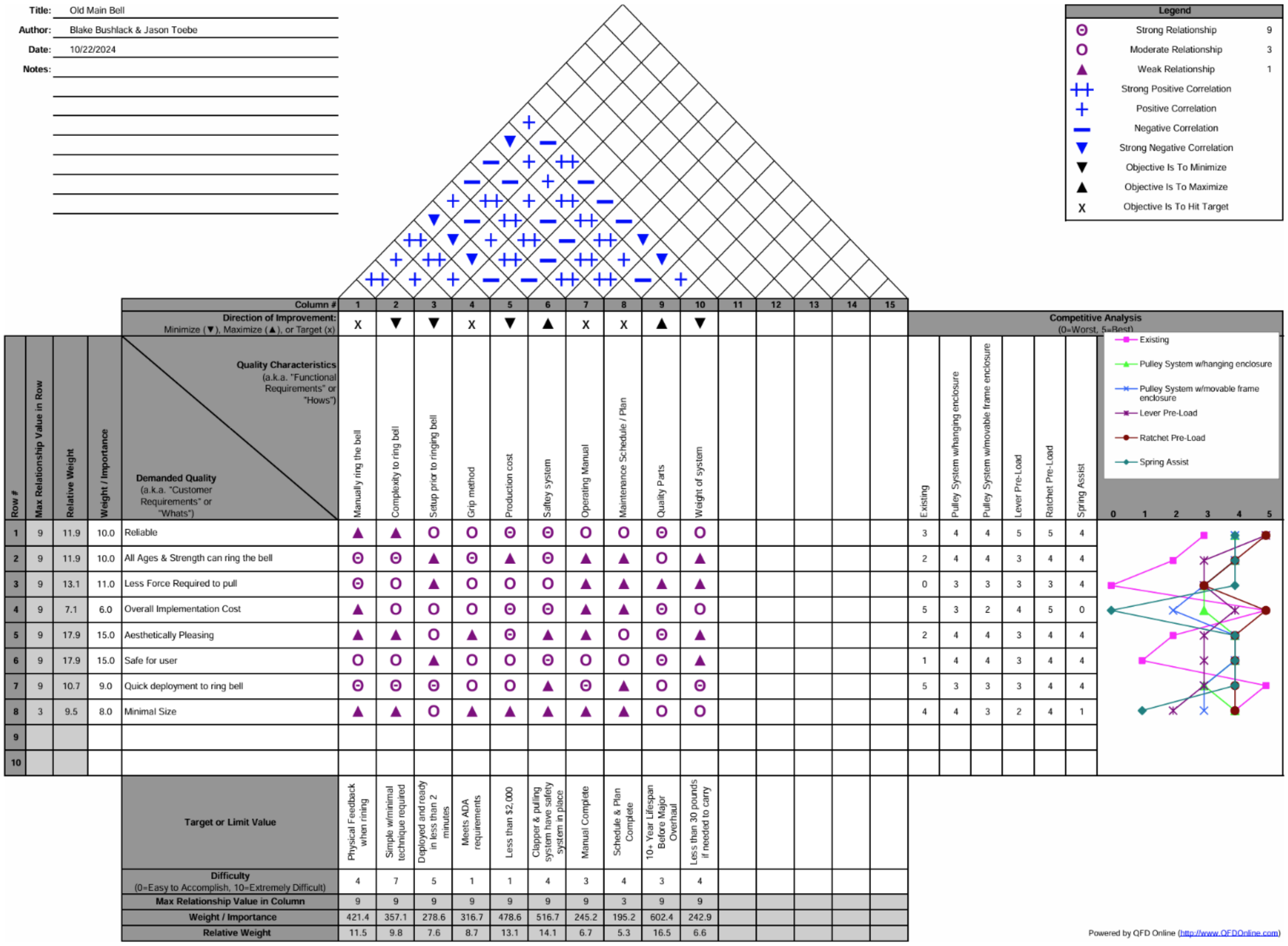

Figure 11: Completed House of Quality

Appendix B

Table IV: 2 hand pull maximum force across various percentages of the population [3]

Action	Hand Height (inches)	Most Protective (Green)	Moderate (Yellow)	Least Protective (Red)
		80+% population protected	*50-80% population protected*	*<50% population protected*
2 Hand Pull	32 inches	41 lbs. or less	42-57 lbs.	58 lbs. or more
	33 inches	44 lbs. or less	43-60 lbs.	61 lbs. or more
	34 inches	47 lbs. or less	48-63 lbs.	64 lbs. or more
	35 inches	50 lbs. or less	51-65 lbs.	66 lbs. or more
	36 inches	52 lbs. or less	53-68 lbs.	69 lbs. or more
	37 inches	55 lbs. or less	56-70 lbs.	71 lbs. or more
	38 inches	58 lbs. or less	59-72 lbs.	73 lbs. or more
	39 inches	60 lbs. or less	61-73 lbs.	74 lbs. or more
	40 inches	62 lbs. or less	63-74 lbs.	75 lbs. or more
	41 inches	64 lbs. or less	65-76 lbs.	77 lbs. or more
	42 inches	66 lbs. or less	67-77 lbs.	78 lbs. or more
	43 inches	67 lbs. or less	68-79 lbs.	80 lbs. or more
	44 inches	69 lbs. or less	70-80 lbs.	81 lbs. or more
	45 inches	70 lbs. or less	71-81 lbs.	82 lbs. or more
	46 inches	71 lbs. or less	72-82 lbs.	83 lbs. or more
	47 inches	72 lbs. or less	73-83 lbs.	84 lbs. or more
	48 inches	73 lbs. or less	74-83 lbs.	84 lbs. or more

Table V: 2 hand pull with turn maximum force across various percentages of the population [3]

Action	Hand Height (inches)	Most Protective (Green)	Moderate (Yellow)	Least Protective (Red)
		80+% population protected	*50-80% population protected*	*<50% population protected*
2 Hand Turn (Push/Pull)	32 inches	60 ft-lbs. or less	61-74 ft-lbs.	75 ft-lbs. or more
	33 inches	62 ft-lbs. or less	63-76 ft-lbs.	77 ft-lbs. or more
	34 inches	64 ft-lbs. or less	65-78 ft-lbs.	79 ft-lbs. or more
	35 inches	65 ft-lbs. or less	66-80 ft-lbs.	81 ft-lbs. or more
	36 inches	67 ft-lbs. or less	68-82 ft-lbs.	83 ft-lbs. or more
	37 inches	69 ft-lbs. or less	70-84 ft-lbs.	85 ft-lbs. or more
	38 inches	70 ft-lbs. or less	71-86 ft-lbs.	87 ft-lbs. or more
	39 inches	72 ft-lbs. or less	73-88 ft-lbs.	89 ft-lbs. or more
	40 inches	73 ft-lbs. or less	74-90 ft-lbs.	91 ft-lbs. or more
	41 inches	74 ft-lbs. or less	75-91 ft-lbs.	92 ft-lbs. or more
	42 inches	75 ft-lbs. or less	76-92 ft-lbs.	93 ft-lbs. or more
	43 inches	76 ft-lbs. or less	77-93 ft-lbs.	94 ft-lbs. or more
	44 inches	77 ft-lbs. or less	78-94 ft-lbs.	95 ft-lbs. or more
	45 inches	78 ft-lbs. or less	79-95 ft-lbs.	96 ft-lbs. or more
	46 inches	78 ft-lbs. or less	79-95 ft-lbs.	96 ft-lbs. or more
	47 inches	79 ft-lbs. or less	80-96 ft-lbs.	97 ft-lbs. or more
	48 inches	80 ft-lbs. or less	81-97 ft-lbs.	98 ft-lbs. or more

If using the online web interface, this torque calculation is performed for the user. However, to calculate turning torque, multiply **maximum hand force (in lbs.) by respective **moment arm (in feet)**. The moment arm will be the distance between the center of the object being turned and the hand dynamometer that is exerting the torque.*

Table VI: Changes in 1 repetition maximum strength across age groups [5]

TABLE 3. Changes in 1 repetition maximum strength by age (mean ± *SE*).

	Young (n = 18)			Older (n = 21)		
	Pre-ST	Post-ST	%Δ	Pre-ST	Post-ST	%Δ
Biceps curl (kg)‡	26.1 ± 3.1	36.8 ± 3.4§	52.3	21.6 ± 1.6	28.0 ± 1.8§	32.9
Chest press (kg)‡*	55.8 ± 5.4	69.7 ± 6.7§	25.6	36.8 ± 2.4	43.3 ± 2.9§	18.1
Lat pulldown (kg)†	57.0 ± 5.8	70.7 ± 6.9§	26.5	40.4 ± 2.6	50.0 ± 3.3§	24.6
Shoulder press (kg)†	46.6 ± 3.8	55.8 ± 5.5§	18.1	32.4 ± 1.9	36.5 ± 2.3§	12.3
Triceps pushdown (kg)‡	64.6 ± 6.3	85.7 ± 8.8§	32.1	42.3 ± 2.8	54.3 ± 3.7§	29.3
Knee extension (kg)*	98.1 ± 7.8	122.8 ± 8.9§	31.6	63.0 ± 4.4	80.9 ± 5.6§	24.1
Leg press (kg)****	578.8 ± 38.5	749.7 ± 45.4§	29.5	447.8 ± 27.6	544.9 ± 27.2§	26.4

* The increase in strength with strength training (ST) was significantly influenced by age ($p < 0.05$).
† The increase in strength with ST was significantly influenced by age ($p < 0.01$).
‡ The increase in strength with ST was significantly influenced by age ($p < 0.001$).
§ The exercise showed a significant increase in 1RM strength with 24 weeks of ST ($p \leq 0.001$).

Table VII: Changes in 1 repetition maximum strength across genders [5]

TABLE 4. Changes in 1 repetition maximum strength by sex (mean ± *SE*).

	Men (n = 21)			Women (n = 18)		
	Pre-ST	Post-ST	%Δ	Pre-ST	Post-ST	%Δ
Biceps curl (kg)	31.2 ± 1.9	40.5 ± 2.2§	31.4	15.0 ± 0.8	22.2 ± 0.9§	54.1
Chest press (kg)†	58.3 ± 4.0	70.9 ± 5.3§	21.2	30.7 ± 1.5	37.5 ± 2.2§	22.0
Lat pulldown (kg)‡	62.0 ± 3.8	76.7 ± 4.6§	24.0	31.7 ± 1.6	39.5 ± 1.8§	27.1
Shoulder press (kg) ‡	47.4 ± 3.1	57.3 ± 4.3§	20.5	29.0 ± 1.2	31.6 ± 1.5§	8.5
Triceps pushdown (kg)‡	65.9 ± 5.0	88.0 ± 6.9§	33.3	37.1 ± 2.3	46.5 ± 2.7§	27.5
Knee extension (kg)*	97.4 ± 6.3	123.4 ± 6.7§	21.7	58.0 ± 4.6	73.2 ± 5.9§	34.3
Leg press (kg)	613.4 ± 24.7	747.4 ± 33.3§	29.0	385.6 ± 24.2	513.5 ± 34.0§	26.9

* The increase in strength with strength training (ST) was significantly influenced by sex ($p < 0.05$).
† The increase in strength with ST was significantly influenced by sex ($p < 0.01$).
‡ The increase in strength with ST was significantly influenced by sex ($p < 0.001$).
§ The exercise showed a significant increase in 1RM strength with 24 weeks of ST ($p \leq 0.001$).

Appendix C

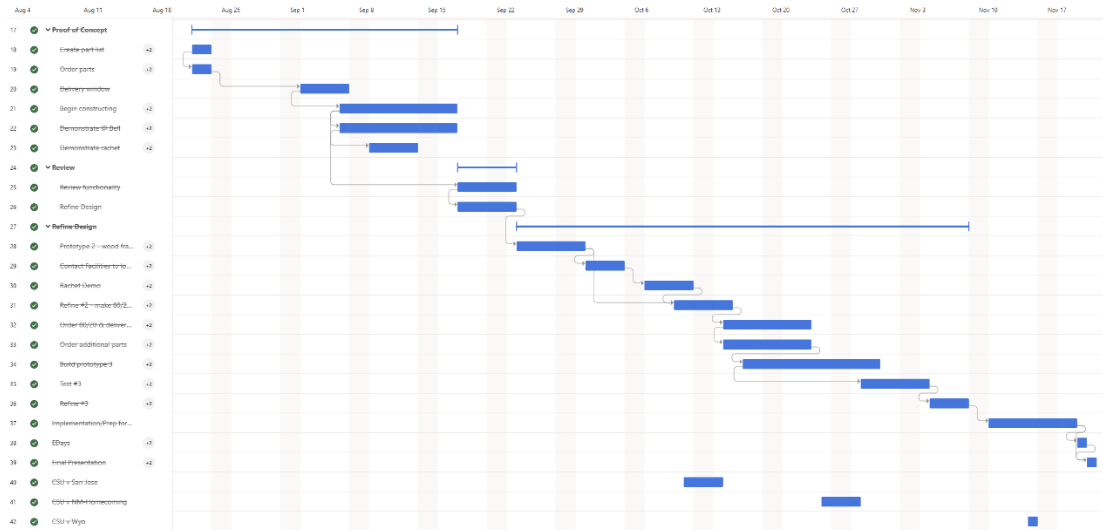

Figure 12: Old Main Bell Project Timeline Gantt Chart

Appendix D

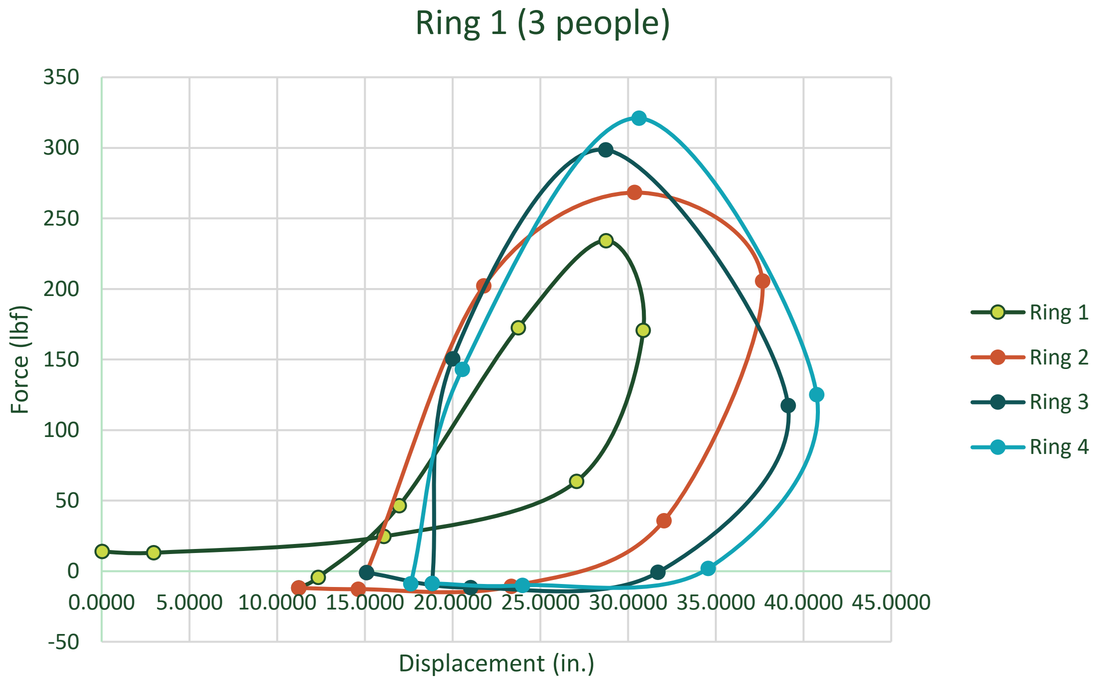

Figure 13: Bell Pull Test Force vs. Displacement Ring 1

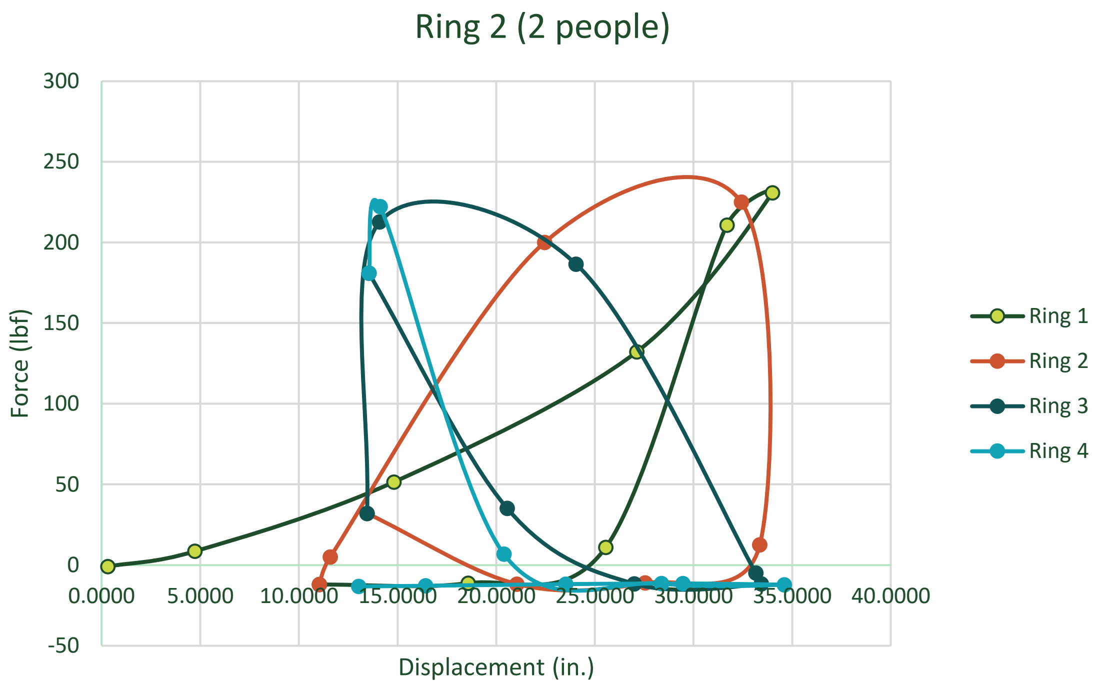

Figure 14: Bell Pull Test Force vs. Displacement Ring 2

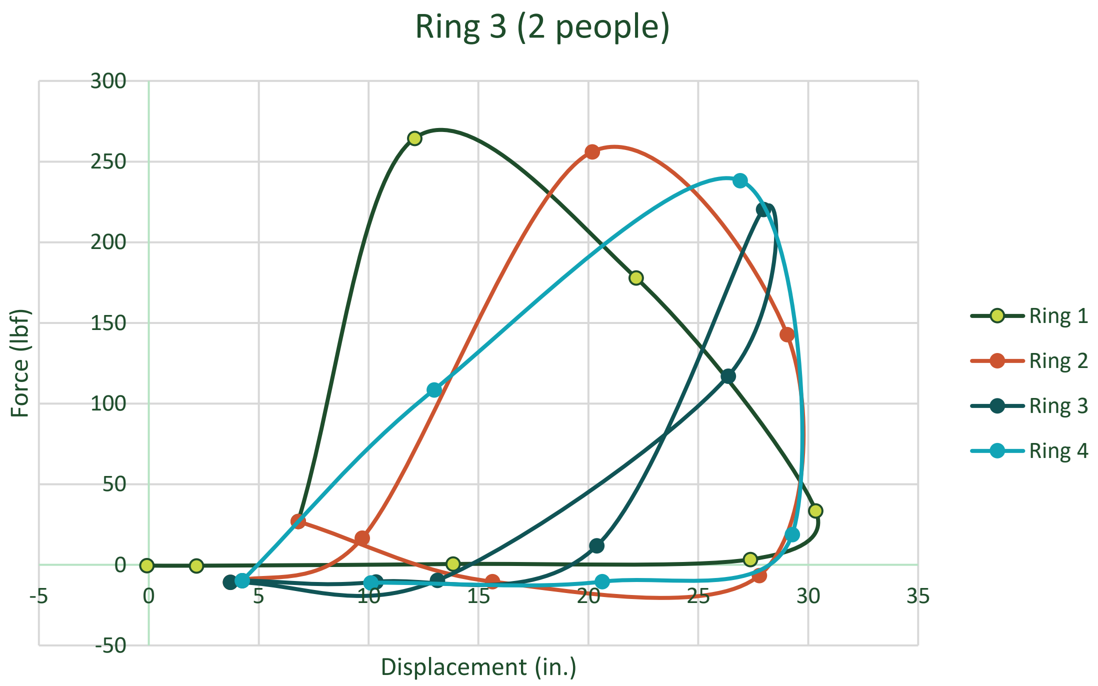

Figure 15: Bell Pull Test Force vs. Displacement Ring 3

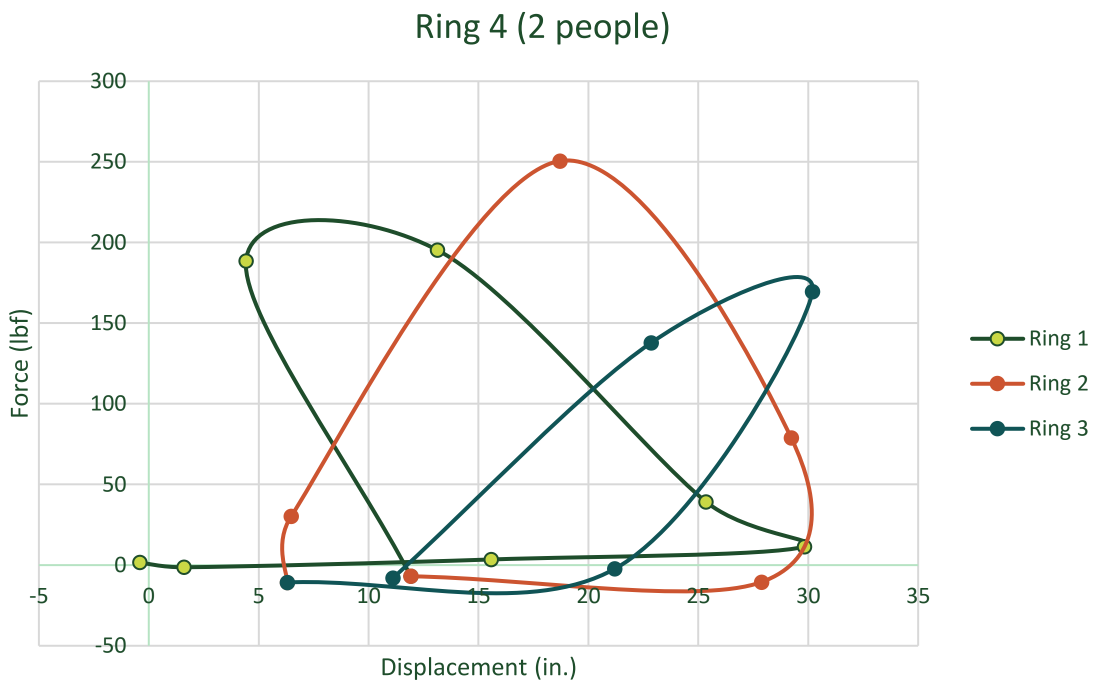

Figure 16: Bell Pull Test Force vs. Displacement Ring 4

Appendix E

Table VIII: Bill of Materials

Item #	Part name	Part number/Catalog number	Description	Purpose	Vendor name	Shop catalog (Yes/No	Website link	Unit price	Quantity	Total cost	Actual Unit Price	Actual Quantity	Actual Total Cost	Link to new part (if needed)
1	ROLLCLIP A	P74	Pulley-carabiner that facilitates installation of th	Redirecting rope from box	Amazon	No	https://www.amazon.com/PL1ZL-P74-ROLLCLIP-A-Pulley-Carabiner/dp/B01CR6FR9S/ref=sr_1_5?crid=2AJ8Y4XW1HVZC&dib=eyJ2IjoiMSJ9.Fn-sLKWedZSvyZE2ThBDcKBX9IY0B7db-	$ 39.95	3	$ 119.85	$ 39.95	3	$ 119.85	
2	3/8in x 2 1/2in I-bolt	204273502	I-bolt to help redirect rope	I-bolt to connect to POC wood fra	Home Depot	Yes	https://www.homedepot.com/p/Everbilt-3-8-in-x-2-1-2-in-Zinc-Plated-Eye-Bolt-with-Nut-807196/204273502	$ 1.38	3	$ 4.14	$ 1.38	3	$ 4.14	
3	3/8in nut	204647890	nut to attach I-bolt	use to attach I-bolt	Home Depot	Yes	https://www.homedepot.com/p/Everbilt-3-8-in-16-Zinc-Plated-Hex-Nut-801756/204647890	$ 0.21	3	$ 0.63	$ 2.98	3	$ 8.94	depot.com/p/DECKMATE-Marine-Grade-Stainless-
4	3/8in washer	204633114	washer to use with nut and I-bolt	use to attach I-bolt	Home Depot	Yes	https://www.homedepot.com/p/Everbilt-3-8-in-Zinc-Flat-Washer-804586/204633114	$ 0.27	3	$ 0.81	$ 0.27	3	$ 0.81	
5	#8 x 3" wood screws	100134103	Wood screws	Wood screws to attach wood fra	Home Depot	Yes	https://www.homedepot.com/p/Grip-Rite-8-x-3-in-2-Phillips-Bugle-Head-Coarse-Thread-Wood-Screws-1-lb-Box-3GS1/100134103	$ 9.58	1	$ 9.58	$ 9.58	1	$ 9.58	
6	2x4	312528776	2x4x8ft wood	POC wood frame	Home Depot	Yes	https://www.homedepot.com/p/2-in-x-4-in-x-8-ft-Prime-Stud-058449/312528776	$ 3.65	1	$ 3.65	$ 3.65	1	$ 3.65	
										$ 138.66			$ 8.99	Shipping HD
													$ 2.57	Tax HD
													$ 6.99	Tax Amazon
													$ 165.52	Total
													$ (26.86)	Overage
7	Single 4-Slot Rail, Silver	5537T102	6' T-Slotted extruded aluminum beam	Frame	McMaster-Carr	Yes	https://www.mcmaster.com/5537T102/	$ 68.89	1	$ 68.89	$ 68.89	1	$ 68.89	
8	T-Slotted Framing, Doub	3136N73	8' T-Slotted extruded double aluminum beam	Frame	McMaster-Carr	Yes	https://www.mcmaster.com/catalog/3136N73	$ 117.82	1	$ 117.82	$ 117.82	1	$ 117.82	
9	Gusset Bracket for 40 m	5537T66	Brackets designed for 8020 aluminum	Attaching frame together	McMaster-Carr	Yes	https://www.mcmaster.com/5537T66/	$ 13.14	2	$ 26.28	$ 13.14	2	$ 26.28	
10	T-Slotted Framing Faste	6000N203	Fasteners designed to be compatible with 8020	Attaching frame together	McMaster-Carr	Yes	https://www.mcmaster.com/catalog/6000N203	$ 6.67	3	$ 20.01	$ 6.67	3	$ 20.01	
11	Steel Eyebolt - for Lifting	3040T13	Eyebolt designed to be compatible with 8020 al	Attaching pulleys to frame	McMaster-Carr	Yes	https://www.mcmaster.com/catalog/3040T13	$ 7.39	3	$ 22.17	$ 7.39	3	$ 22.17	
12	Medium-Strength Class	91280A978	Hex head screw	Attaching ratchet to frame	McMaster-Carr	Yes	https://www.mcmaster.com/catalog/91280A978	$ 11.44	1	$ 11.44	$ 11.44	1	$ 11.44	
13	T-Slotted Framing 360 D	3136N532	360 degree piviot designed to attach two peice	Attaching arm to frame	McMaster-Carr	Yes	https://www.mcmaster.com/catalog/3136N532	$ 16.85	1	$ 16.85	$ 16.85	1	$ 16.85	
14	T-Slotted Framing Silve	5537T665	Brackets designed for 8020 aluminum	Attaching frame together	McMaster-Carr	Yes	https://www.mcmaster.com/catalog/5537T665	$ 16.97	2	$ 33.94	$ 16.97	2	$ 33.94	
										$ 317.40			$ 317.40	
													$ 56.94	Shipping
													$ 374.34	Total
													$ (56.94)	Overage
15	OPTIX .093 in. x 11 in. x	100282591	Sheet of acrylic	Safety sheild	Home Depot	Yes	https://www.homedepot.com/p/OPTIX-093-in-x-11-in-x-14-in-Clear-Acrylic-Sheet-1AU0515A/100282591	$ 8.78	1	$ 8.78	8.78	1	$ 8.78	
16	1-1/2 in. Galvanized Non	314151491	Hinge	Attaching safety sheild to frame	Home Depot	Yes	https://www.homedepot.com/p/Everbilt-1-1-2-in-Zinc-Plated-	$ 3.93	1	$ 3.93	2.72	1	$ 2.72	
													$ 11.50	Total
													$ 551.36	