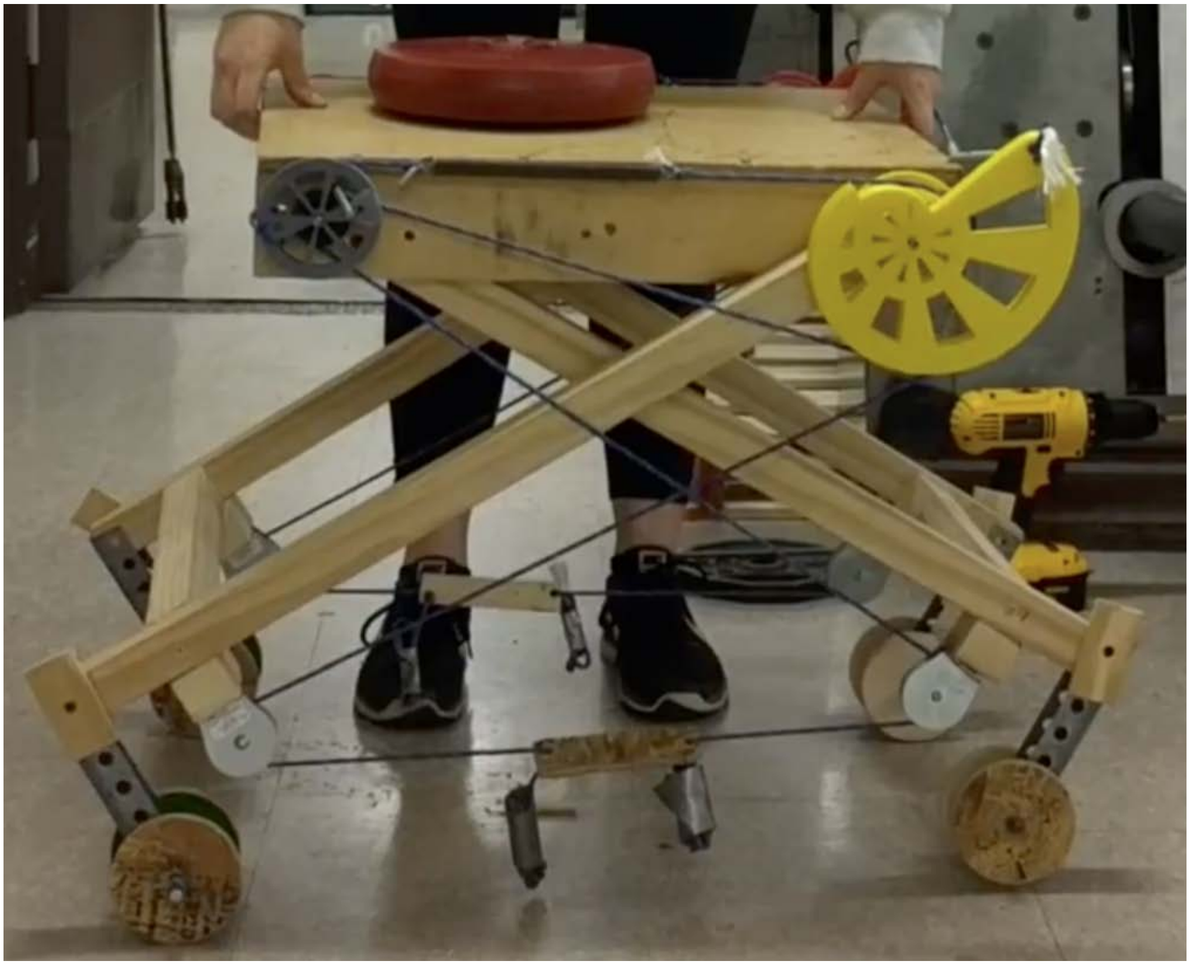
Final Project Report: The Able Table



ME 270

Team ABD - 1

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I. Abstract

Throughout the semester, we developed a prototype of a table, that we called “The Able Table.” The Able Table uses a counterbalance mechanism to balance at a range of heights through the use of a counterbalance mechanism comprised of expansion springs and variable radius pulleys (cams). We then performed a Design of Experiments analysis to determine a combination of cams and springs that would maximize the height range that The Able Table would be balanced at. Finally, we performed Design for Assembly analysis to determine the most efficient and cost effective method to assemble The Able Table for large scale manufacturing.

II. Introduction

Thousands of people across the country suffer injuries that cause back pain. Due to these problems, daily tasks such as bending down and lifting heavy object can become quite cumbersome. The Able Table is a product that would help user to lift objects with minimal effort. This is done by utilizing a spring based counterbalance mechanism. This mechanism and the final prototype of The Able Table can be seen below in Figure 1.

Figure 1. The Able Table final prototype

III. History

Our team developed multiple designs for our product before reaching our final prototype. Our initial idea utilized a crank of sorts to move the table up and down. Additionally, it included sets of wooden sleeves on each leg that connected to a spring that would reside in between. This can be seen in Figure 2. The reason we chose to place the springs in between the legs was because we thought that it would help in keeping the table balanced.

However, it became obvious after testing that this design was inappropriate for the goal that we were trying to accomplish. Several problems were noted: the wooden sleeves frequently became stuck, the crank mechanism was difficult to turn, and the spring never seemed to remain completely horizontal as the table moved from height to height. We felt that a lot of these problems were occurring because of the fact that the friction between the wooden sleeves and the legs was too great. Furthermore, we felt that our crank mechanism was too poorly constructed, so if we were to move forward, we needed to come up with a better, more solid design. This led to the changes that were made for Iteration #2.

Figure 2. The first iteration of The Able Table (arrows denote the wooden sleeves used)

For our second iteration, we replaced the wooden sleeves with metal rails that connected to the spring in the middle by acrylic pieces. With this change, the table was able to make a somewhat smoother transition from height to height, as compared to our first iteration. In addition, we redesigned the crank mechanism to make it easier to turn and more stable. These changes can be seen in Figure 3 and Figure 4.

After making all these changes, we still ran into some very significant problems. The major issue was that, despite being able to move the table up and down with a smaller force than Iteration #1, Iteration #2 still failed to balance. A user could move it from height to height, but, after letting go of the table, it would fall to the ground. This significant issue was the main motivator for the extensive changes that were made to The Able Table prototype for iteration #3.

Figure 3. The second iteration of The Able Table

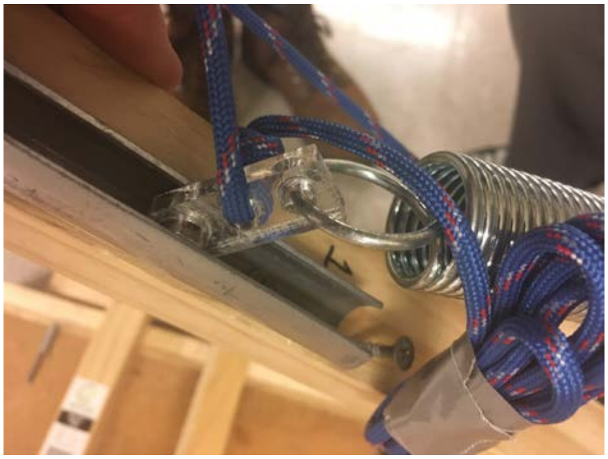

Figure 4. The acrylic piece used to connect the spring to the rails

For our third and final iteration, we scaled down the table significantly so that it would be easier to work with and easier to make balanced. Moreover, we removed the spring from in between the legs because, after studying mechanism extensively, we deduced that it served no real purpose. After these design decisions were made, we continued on to develop a counterbalance mechanism consisting of a varying radius pulley and a spring. This counterbalance mechanism allowed for the table to be balanced at a specific range of heights. A further explanation of the mechanism is provided in Section IV of the report.

After design and testing of the counterbalance mechanism was complete, we went on to add an additional mechanism that could be used to stretch the spring. This additional mechanism allowed the table to hold greater weight because the springs created a greater torque for the counterbalance mechanism. Finally, we added wheels to the bottoms of the legs of The Able Table prototype so that the transition from height to height would be a lot smoother. The completed final prototype can be seen in Figure 5.

Figure 5. The final iteration of The Able Table

IV. How It Works

The most important and unique aspect of The Able Table is the spring and variable radius pulley, or “cam”, mechanism which allows equilibrium to be attained at a range of heights for the table. The cams, which freely rotate, let more or less cable be wrapped around them as the table transitions from height to height. If a user wishes to make the table transition to a lower height, they would apply a downward force on the table, which, in turn, would increase the tension in the cables, and make the cams release cable which would cause the table legs to separate and the tabletop to move to the lower height. Conversely, applying a force upward to lift the table would reduce the tension in the cables. This would cause the cams to rotate to maintain equilibrium and wrap more cable around them in order to reduce the space between the legs and send the tabletop upward.

To reach the final design of these cams, a lot of factors had to be taken into consideration.

The table is able to be balanced by varying the radius of the cam, and hence varying the moment caused by cable tension. Using a spring to counter the torque caused by cable tension, we sought an equation relating the radius of the cam to the angle of rotation, α. The free body diagram used in helping us to find this relation can be seen in Figure 6.

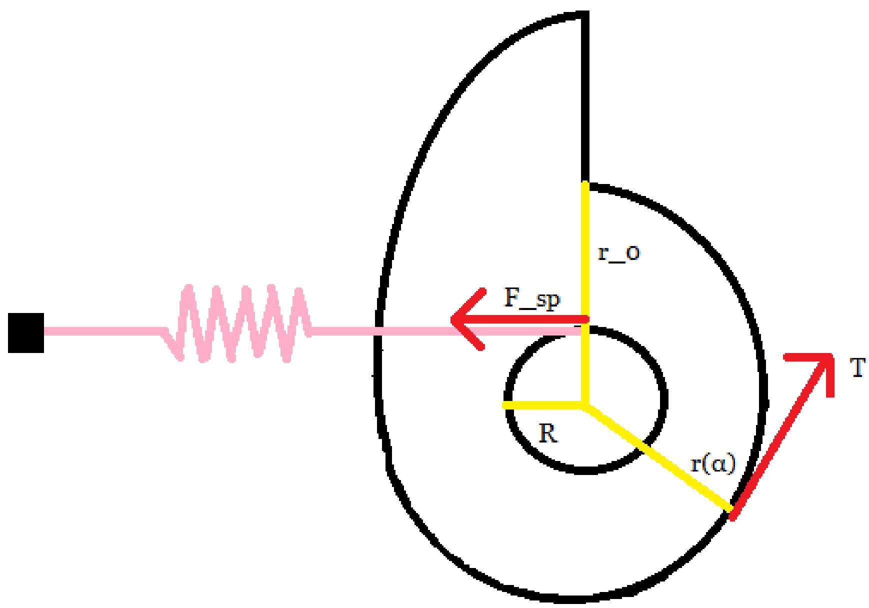

Figure 6. Schematic of a 'cam' or variable radius pulley

The following relation must hold in order for the table to remain balanced:

$$M_{spring} = M_{Tension}$$

After considering this relation and analyzing all factors of equilibrium we obtained the following equation:

$$r(\alpha) = r_0 + \frac{R^2 k}{T}\alpha$$

The cam radius, therefore, linearly increases as the angle increases from zero to 360 degrees. From our table design, however tension, T, turned out to be highly nonlinear, and could not be easily measured. This was determined after observing the movement of the table.

Thus, to find the best cam design we performed multiple Design of Experiment trials. By varying the inner radius of the cam, R, and the spring constant, k, we were able to find the arrangement of spring and cams that maximized the range of heights for which the table would be balanced. Details of these trials can be found in Section V.

For the final cam, we chose the initial radius to be $\sigma_0 = 1$ inch, the final radius to be 4 inches, and the inner radius, R, to be 1.5 inches. The spring that allowed the greatest range in which the table was balanced had a spring of constant 4.8 lb/in. Thus, for these values of k and R, we expect a tension, T, value of approximately 22.6 lb, which imposes a limit on the amount of weight we can put on the table with it still remaining balanced.

Furthermore, The Able Table utilizes an additional mechanism that stretches the spring, allowing the user to place objects of varying weights on it and have it still be balanced at a range of heights. The mechanism is a cylindrical object that is placed on the side of the table with a cable that is attached to the spring connected to it. The user can wrap the cable around the cylinder by turning it with its handle, which stretches the spring, and then can lock the mechanism in place by placing a pin through it. This allows the spring to be "pre-torqued" so that it could create a greater torque for the heavier objects and remain balanced. The mechanism can be seen in Figure 7.

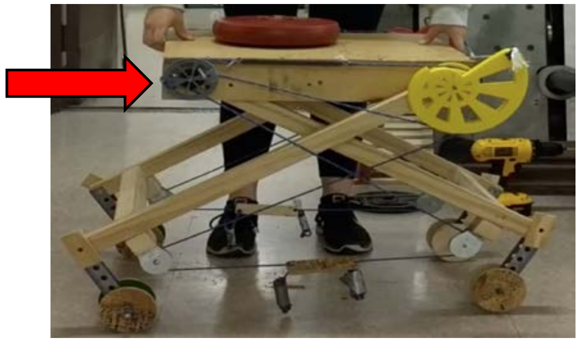

Figure 7. Arrow denote the pre-torque mechanism

V. Design of Experiments

Optimizing the range that the table was able to reach was the most important part of running our Design of Experiments (DOE). As a side optimization, we also measured the force required to pushing the table down to the nearest 3 or 5 pound increments. This was not a precisely measured force, but helped us keep in mind that although a larger range could be reached, it was also important to minimize the additional force needed to push down the table. Measuring this output was relatively simple, we would raise the table to its physical maximum and then slowly lower it until the table held itself and we were able to walk away. We would then push down on the table, assuming it would move without much effort, and continue to move it in small increments until it was impossible to move down any further, or until it would continue to fall without our force on it. If the table was unable to move without a great force, or would move up without an additional weight placed on it, we would add weight until ease of movement was regained, and then took note on the weight necessary. The variables used to test this output were the cam size, with the connection radius ranging from 0.8 in, 1.5 in, and 2.5 in, the spring constant, 4.8 lb/in, 10 lb/in, and 25 lb/in, and the pre-torque stretch length of 0 inches, ¾ inches, and 2 ¼ inches.

Noise:	E1	E2	E3	E12	E13	E23	E123
	0.60	0.06	1.71	-1.74	-0.41	-0.45	-2.25

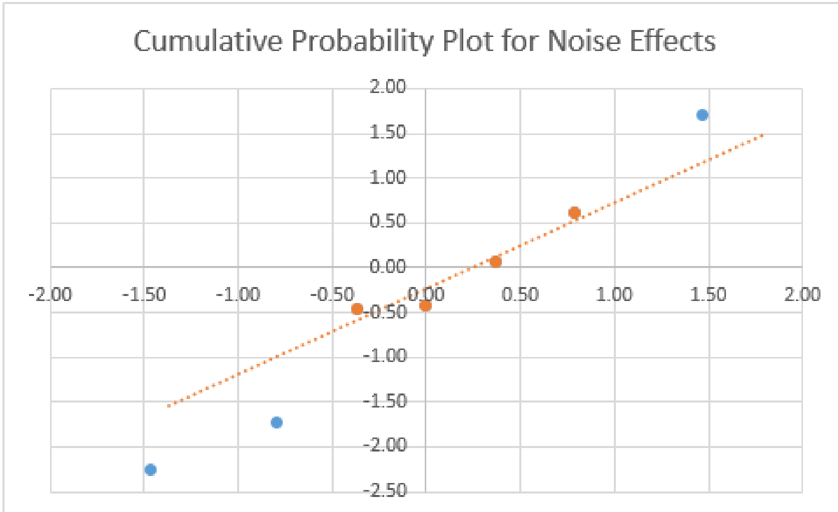

Figure 8. Noise plot for a three-variable system, with E1, E2, and E3 corresponding to cam size, spring constant, and length of pre-torqued spring respectively

Noise:	E1	E2	E12
	0.10	-0.19	-1.99

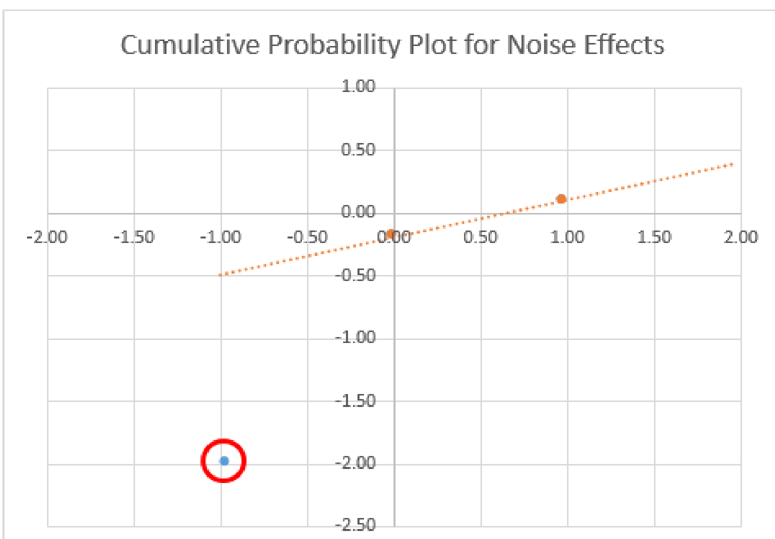

Figure 9. Noise plot for two variable system with E1 and E2 corresponding to cam size and spring constant respectively

As seen in Figure 8, our original test was run with three variables. The third noise element is very significant as well as the combination of all three and the first and the second elements. After analyzing this three-variable system and seeing this noise, we decided to analyze it further. The two variables of spring and pre-torque actually are both ways of changing the torque holding the cam up. Since they were changing the same thing, varying both of them in a test was not giving us proper understanding of which change was actually improving our design.

It was decided that eliminating one of these variables would provide us more accurate data that we could use to move forward. This is seen in Figure 9, where the same two springs and cams were used, but the pre-torque was not changed from experiment to experiment. This would then eliminate the noise caused by E3 on the left side, and we are able to further see that E12 is still significant. The E12 effect of noise was very significant showing that changing both variables at once does not in itself affect the table range. This can be seen further in Figure 10.

Main:	E1	E2	E12
	6.85	-9.85	0.35

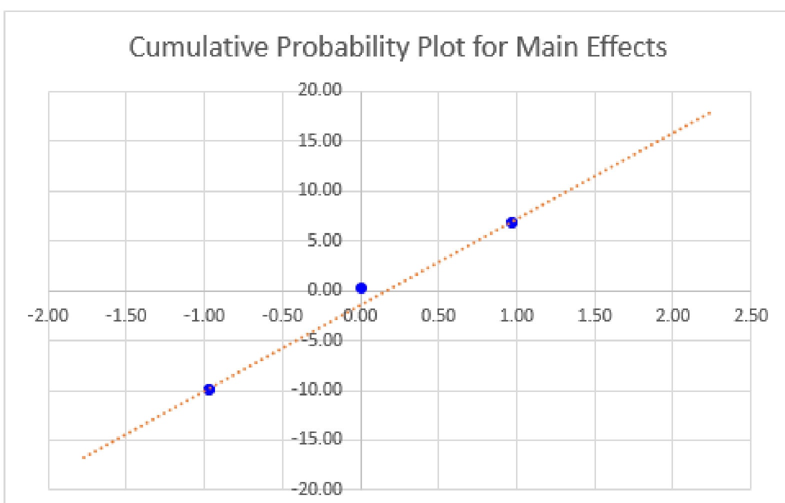

Figure 10. Main effects of the two-variable system with E1 and E2 corresponding to cam size and spring constant respectively

Main:	E1	E2	E3	E12	E13	E23	E123
	15.66	-3.04	4.34	-10.34	-1.96	-16.66	11.04

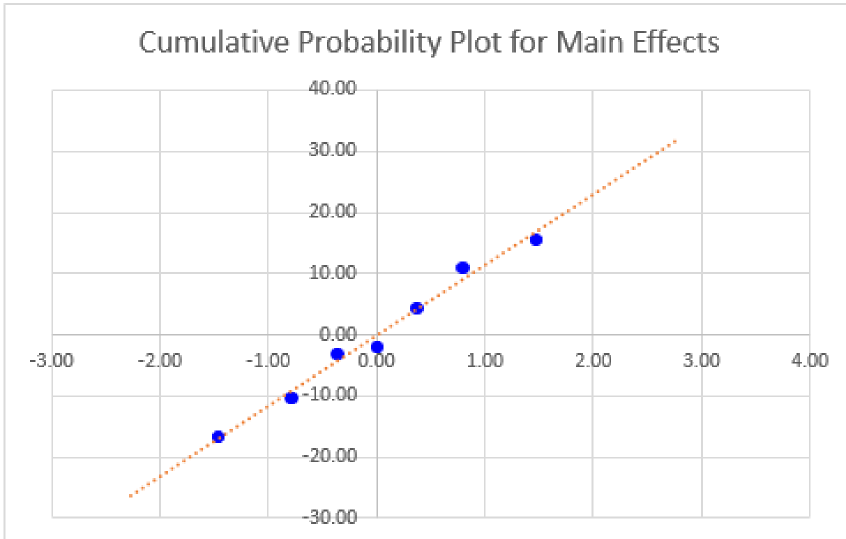

Figure 11. Main effects of a three-variable system, with E1, E2, and E3 corresponding to cam size, spring constant, and length of pre-torqued spring respectively.

Looking mainly at the two-variable simplified DOE in Figure 10, we see that the first effect, the cam size, is better with an increasing cam. This is highlighted in yellow. We then see that at a bigger magnitude, changing the spring constant from 4.8 to 10 lbs/in is not helpful. The effect of them both changing is negligible since it is well below the 2σ value of 1.48, and, as seen previously, has a high noise value. Comparing this to the three-variable DOE in Figure 11, it is confirmed that increasing the spring constant would not help in increasing the range for which our table remained balanced. This was slightly less in magnitude in three variables because it eliminated the positive E3 effect that accounts for the higher spring constant. Thus, from the two-variable DOE our characteristic equation is as follows:

$$y = \bar{y} + \frac{E_1}{2}x_1 + \frac{E_2}{2}x_2 = 7.66 + 3.43x_1 - 4.93x_2$$

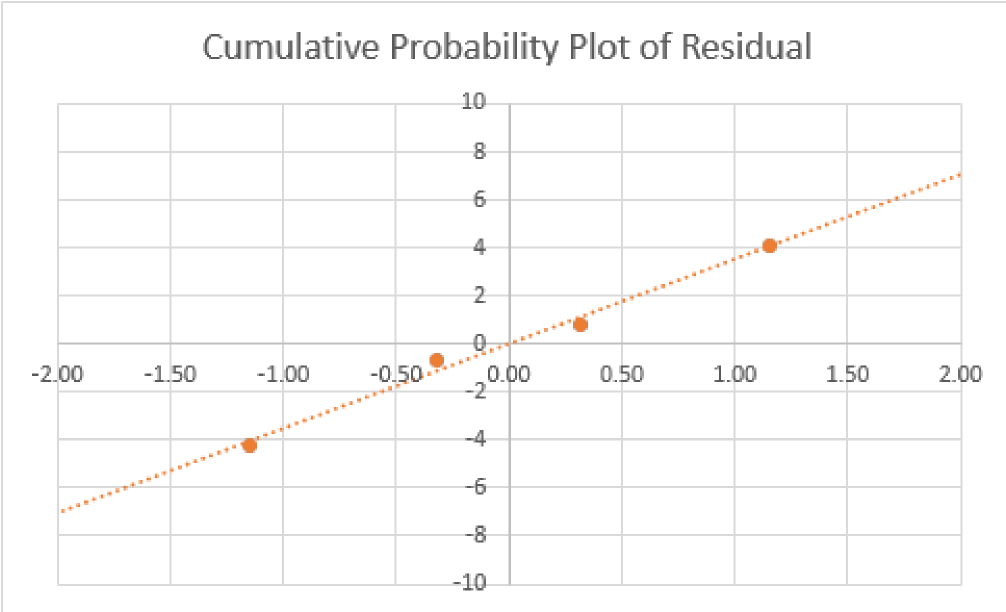

Figure 12. Plot of the residuals based on the two-variable DOE system

Not only did the two-variable DOE provide the least noise, it also provided us with the best residuals as seen in Figure 12. The characteristic equation seen above provided a good prediction of our output, therefore we used this to decide on the larger of the two cams measured and the smaller of the two springs measured. According to the equation, a positive E1 should mean a larger cam would improve our system, while a bigger spring constant would hurt our range. For this reason, we did not go on to test the third spring as its k value was significantly larger than the other springs we tested.

Following this logic, further tests with weaker springs should be carried out in order to find the best range. A larger cam was designed and tested since our characteristic equation implied this would be helpful, but the cam with a radius of 2.5 inches ended up actually worsening the system, most likely because it was too much larger.

VI. Manufacturing

In order to get a better idea of how easy and cost effective it would be to assemble our prototype, we completed a Design for Assembly (DFA) Analysis. We found an approximate time that it would take to fully assembly our prototype by examining the amount of time each part would take to handle, align, insert and secure to the rest of the parts. We followed the given approximated times for DFA presented during the DFA lecture. However, we estimated that the rope in our design would take about sixty seconds to assemble onto the prototype. We made this estimate due to the fact that the rope needs to be placed in a complicated manner that could not be estimated by the ways that were presented in lecture. As seen in Table 1, we found that it would take approximately 253.4 seconds to fully assemble our prototype.

Furthermore, we calculated the DFA efficiency for our prototype, which was 4.73%. This efficiency was calculated after finding that the theoretical number of parts for our prototype was 4. We found that we could combine the tabletop, the table sides, the table legs, and the wheels into one part because they were made of the same material, required the same tolerance, and moved at the same time as one another. Additionally, we could combine the pulleys, the pre-torque cylinders and the cams for the same reasons. Then, we were left with two other parts: the rope and the springs. The efficiency was exceptionally low, which indicates that our prototype contains a lot of unnecessary parts. This makes sense because as we were building our prototype we used several fasteners and other duplicated parts that in theory could become one.

Table 1. DFA tabulation table

Step	Part	α Symmetry	β Symmetry	Handling and Alignment Time (s)	Handling and Alignment Total	Insert and Secure Time (s)	Insert and Secure Total	Number of Parts	Total Time (s)
1	Table Top	180	180	0.5 (fetch) + 1.0 (symmetry) + 0.3 (large) + 0.3 (aspect ratio)	2.6	0	0	1	2.6
2	Table Side	180	180	0.5 (fetch) + 1.0 (symmetry) + 0.3 (large) + 0.3 (aspect ratio)	2.1	0.5 (placement)	0.5	2	5.2
3	Screw	360	0	0.5 (fetch) + 1.0 (symmetry) + 0.1 (aspect ratio)	1.6	0.5 (placement) + 1.0 (turning insertion) + 2.0 (tightening)	3.5	4	20.4
4	Table Leg	360	360	0.5 (fetch) + 2.0 (symmetry) + 0.3 (large) + 0.1 (aspect ratio)	2.9	0.5 (placement) + 0.3 (align to hole) + 0.4 (hold)	1.2	2	8.2
5	Fixed Pulley - on bottom of legs	360	180	0.5(fetch) +1.5(symmetry)	2	0.5 (placement) + 0.6 (align to hole)	1.1	4	12.4
6	Screw	360	0	0.5 (fetch) + 1.0 (symmetry) + 0.1 (aspect ratio)	1.6	0.5 (placement) + 1.0 (turning insertion) + 2.0 (tightening)	3.5	8	40.8
7	Pin	180	0	0.5 (fetch) + 0.5 (symmetry) + 0.1 (aspect ratio)	1.1	0.5 (placement) + 0.2 (align to hole) + 0.4(tight tolerance) + 7 (two sided tightening)	8.1	8	73.6
8	Wheel	180	0	0.5 (fetch) + 0.5 (symmetry)	1	0.5 (placement) + 0.1 (align to pin) + 0.4 (hold)	0.6	8	12.8
9	Fixed Pulley - on table sides	180	0	0.5(fetch) +0.5(symmetry)	1	0.5 (placement) + 0.1 (align to pin)	0.6	2	3.2
10	Cams	360	360	0.5(fetch) +2(symmetry)	2.5	0.5 (placement) + 0.1 (align to pin)	0.6	2	6.2
11	Pre-torque Cylinder	180	0	0.5(fetch) +0.5(symmetry)	1	0.5 (placement) + 0.1 (align to pin)	0.6	2	3.2
12	Spring - on table sides	180	0	0.5(fetch) +0.5(symmetry)	1.4	0.5 (placement) + 0.1 (align to pin)+0.4 (insertion difficulty)	1	2	4.8
13	Rope				30		30	1	60
								Total Time:	253.4

In selecting the manufacturing material used for each component, we focused on finding the least costly but highest quality material that we could. For this reason, we decided to only manufacture three parts: the pre-torque cylinder, the wheels, and the pulleys. These three parts will be made with ABS plastic through the use of plastic molding. The rest of the parts will be purchased from distributors. The main reason of this is that all the pieces will be standardized and buying them in this manner will be cheaper in the long run. After deciding on this and considering an estimation of the labor that it would take to assemble The Able Table, we found that the cost of putting one product together would be $180.41. The details of each expense can be seen in Table 2.

Table 2. Cost Analysis

Parts	Material	Production	Material Cost	Piece Part Cost	Fully Burdened Cost	Total Capital Investments	Quantity	Total Fully Burdened Cost
Wheel	ABS	Plastic Molding	$0.05	$0.13	$0.23	$5,354.82	8	$1.84
Cams	ABS	Plastic Molding	$1.22	$4.55	$4.74	$9,574.01	2	$9.48
Pre-torque Cylinder	ABS	Plastic Molding	$0.20	$1.02	$1.36	$16,950.45	2	$2.72
Miscellaneous	**Material**	**Company**	**Catalog number**	**Quantity**			**Cost per part**	**Total cost**
Pin	12L14 Carbon Steel(36")	MC Master	1327K71	1.5	7*6"(upper shaft)+4*3"(wheels)	54	$20	$30
Fixed Pulley - on bottom of legs	Steel	MC Master	3099T34	2			$7.02	$14.04
Fixed Pulley - on table sides	Acetal Plastic	MC Master	3434T37	2			$2.25	$4.50
Screw	Zinc-Plated Steel(pack of 100)	MC Master	90190A125	12	$3.57	100	$0.04	$0.43
Spring - on table sides	4.80lb/in (pack of 3)	MC Master	9044K383	2	$8.18	3	$2.73	$5.45
Table Top/Sides	1/2 in. x 4 ft. x 4 ft. PureBond Prefinished Maple Project Panel	The Home Depot	3127	1			$38.80	$38.80
Table Leg	Square Tubing	Speedy Metals	1.5" width. 0.065"wall 60"length	7	4*59"(length)+2*42"(width1)+2*37.5"(width2)	395	$10.66	$70.18
Rope	Rope 50ft x 1/8"	The Home Depot	498533	1			$2.97	$2.97
Assembly								
Labor Assenbly								$1.06
							Total cost:	$180.41

VII. Budget and Task Overview

We bought a variety of different materials in order to construct the different iterations of our prototype. The specific cost of each material can be seen in Figure 13.

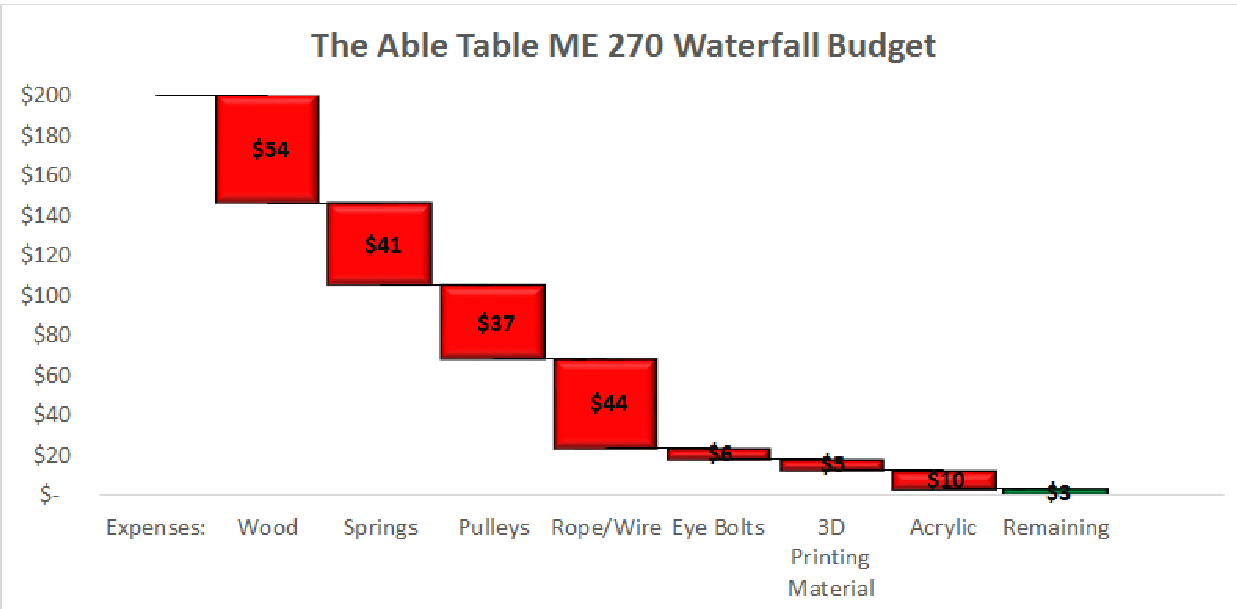

Figure 13. The Able Table Waterfall Budget

The Gantt chart in Figure 14 shows the original plan over the year in green, with the actual time taken in red and the time gained and lost due to it. As seen in the chart, we fell behind within the early stages of our project up until March. At this time, we gained back a lot of lost time because we changed our design from using a gearbox crank to using cams. This made installation time a lot shorter. Additionally, in the last few weeks of work, we were able to make up for lost time and to finish by the Final Presentation deadline.

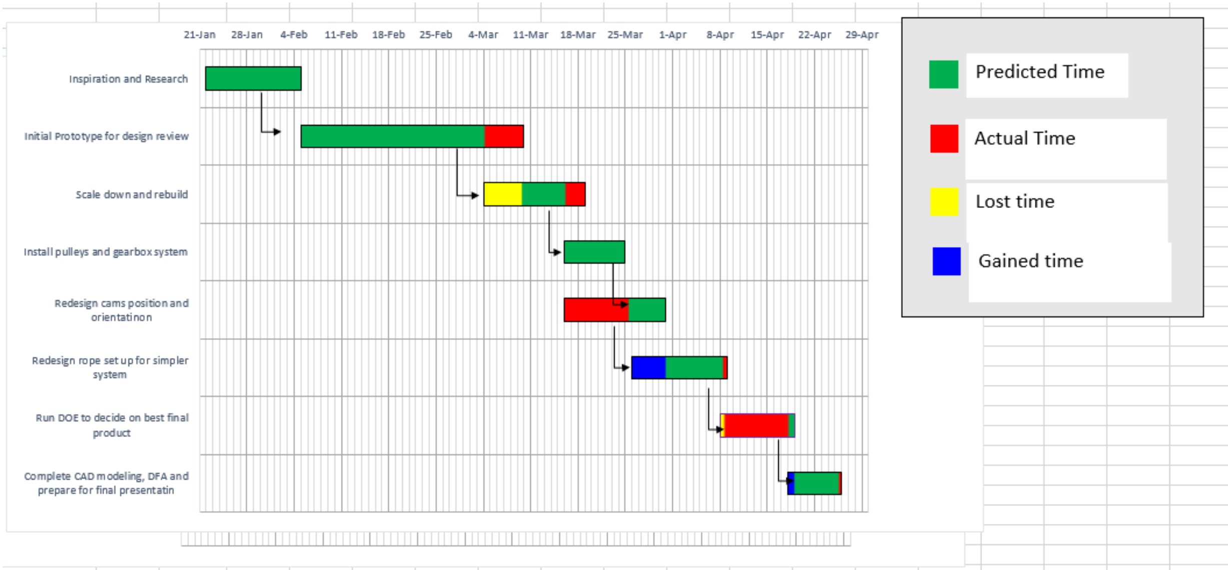

Figure 14. The Able Table Gantt Chart

VIII. Conclusion

Throughout this semester, we have found that the keys to success in working on a project like this is to put in the hard work, be dedicated to the project, and learn from each failure that is encountered. From the beginning of the semester to now, the design of The Able Table has changed dramatically. Our initial thoughts about how each aspect of the table were mostly wrong, but we kept pushing through mental blocks and discovered the current design of our prototype. Thus, this project has taught us to look at design as the iterative process that it should be and never give up on something that you know you could achieve through dedication and hard work.