Eleva: An Affordable and Portable Mechanical Wheelchair Lift

Mechanical Engineering Senior Design Analysis Report

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***Abstract*—Eleva is an affordable and portable mechanical wheelchair lift that enables individuals with mobility impairments to safely ascend and descend staircases while remaining in their wheelchairs. The assistive platform and ratchet design for one user and one caregiver targets hard-to-reach, low-infrastructure environments and enables a dignified and more accessible option to support a user's right to healthcare.**

***Index Terms*—accessibility, wheelchair lift, healthcare.**

I. Introduction

According to the World Health Organization, one billion people across the world have disabilities [1]. With an aging population, this number is set to increase in the following years. Yet, according to the United Nations in 2022, roughly 40% of people around the world who require the use of assistive technologies, such as wheelchairs and hearing aids, cannot obtain them [1]. This figure demonstrates a severe lack of access to healthcare, particularly in low-income countries. In some low-income communities, only about 3% of the population has access to such technologies, depriving people of products that are essential to their quality of life [1]. Talking to health experts, it becomes noticeable that there is limited availability of accessibility technologies for people with mobility impairments to come and go, particularly in residential settings of developing countries [2]. Existing solutions include chair-lifts and ramps, but unfortunately, they are not always appropriate for this portion of the population. Equipment such as elevators and stair-lifts are prohibitively expensive and require heavy infrastructure changes. They also require reliable electricity which is not always available in low-income communities [3]. Ramps are also often times unsuitable due to the amount of infrastructure they require. As a result, individuals tend to rely on relatives and neighbors to carry them, which is extremely dangerous for both and detrimental to the caregiver's health in the long term [2].

Therefore, the purpose of this project was to develop a solution able to fulfill this social demand while meeting design constraints for these populations. Namely, this design is constrained to a low overall cost, minimal infrastructural intervention, independence of electricity, compliance with safety regulations, and being actuated by a reasonable force from an average person. Eleva is a simple, mechanically operated wheelchair lift for individuals with mobility impairments living in hard-to-reach places. Using the technology of a ratcheting mechanism, Eleva can be used in places with challenging topography, low infrastructure, no electricity, and only requires one caregiver to operate. Eleva allows for a safe ascent and descent of a wheelchair on any set of stairs using only a base plate as required infrastructure installation.

II. Important Measurements and Assumptions

Listed below are basic assumptions important to establish prior to discussion of force, safety, strength, and performance analyses conducted for different parts of the Eleva mechanical wheelchair lift. These will be referenced throughout the report. Figure 1 shows a labeled image of the design.

A. Masses of Components

The weight of the wheelchair is assumed to be 18 kg, which corresponds to the weight of the wheelchair used in the prototyping process [19]. The weight of the sled base (not including the ratchet post) is also 18 kg, which was measured experimentally in the Columbia Mechanical Engineering Teaching Lab. The weight of the ratchet post was 4 kg, which was also measured experimentally. The weight of the user is

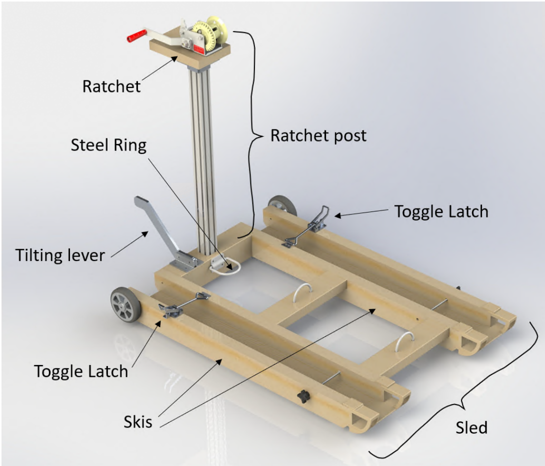

Fig. 1. Labeled Eleva lift

assumed to be 115 kg, which is a typical standard weight capacity for wheelchairs [20].

B. Stairs

The angle of the stairs is assumed to be $45°$, which is the upper limit for standard stairs (OSHA 1910.25 [21]).

C. Friction Measurements

Friction measurements were taken by sliding a sample unit of the ski material across the test staircase chosen and recording its motion at a high frame rate. The piece's kinematics were computationally tracked using the software Tracker [10]. The velocity as a function of time curve was fitted with the equation:

$$x' = g(\sin(\theta) - \mu \cos(\theta))t + A \tag{1}$$

Where A is a constant, θ is the slop of the staircase and g the gravitational acceleration. x coordinates are along the slope of the staircase with x increasing upwards. The result obtained

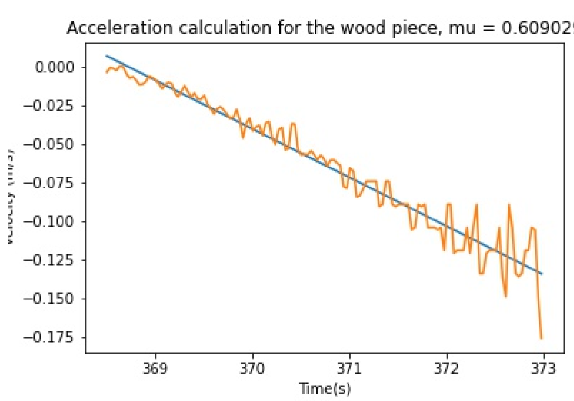

Fig. 2. Graph showing the fit used to obtain the coefficient of friction.

was a coefficient of $\mu \approx 0.61$, which is consistent with literature [6] and was then used to guide or design decisions. The graph shows that there were considerable errors, likely due to a combination of improper contact of the wood with the floor and poor tracking performance. Tracking precision could be improved with more markers and higher resolution cameras.

III. Analysis

To determine the feasibility of Eleva's use in the real world, the model underwent a series of tests to ensure it met certain design criteria. Particular emphasis was placed on ensuring all parts of the system met the necessary factors of safety (Fos) defined by regulations. A variety of methods, ranging from simple analytical calculations to complex finite element analysis (FEA), were utilized to assess the capabilities of each component of the system in order to extract experimental factors of safety.

A. Base Plate / Ground Ring FOS Calculations

As the only element of installed infrastructure and with its function of supporting the entire model, force and strength analysis of the base plate is important to ensure Eleva is safe to operate in the real world. Based on interviews with healthcare workers, the most common type of outdoor flooring surrounding staircases is concrete, which was assumed for calculations [2]. The base plate model selected for Eleva was chosen for its small shape and lie-flat ring design, making it less obtrusive to those using the staircase normally. It is designed and manufactured by 3M and is rated for holding a 141 kgf load in extreme events, including fall restraint. Assuming that the worst-case scenario is restraining free fall and multiplying the capacity by the cosine of the maximum slope of the staircase ($45°$). This requires a factor of safety of at least 2 for the rated load as per OSHA 1910.140, OSHA 1926.502, and ANSI Z359.2. Using the assumed weight of 155 kg for the complete system:

$$F_{os} = 2 \cdot \frac{141\ kg \cdot g \cdot \cos(45°)}{155\ kg \cdot g} \approx 2.57 \tag{2}$$

The calculated factor of safety of 2.57 exceeds the required minimum to be in compliance with OSHA 1910.140, OSHA 1926.502, and ANSI Z359.2. This F_{os} is for the extreme event case of fall restraint. Based on these calculations, the day-to-day operation events of Eleva would yield a higher factor of safety. Additionally, the selected base plate model allows for 1/2" wedge anchors to be installed into concrete, which can each withstand 15.3 kN in shear stress [18]. The factor of safety for the wedge anchors can then be calculated by dividing its rated load ($15.3kN$) by the maximum operating load ($155kg \cdot g$) as shown:

$$F_{os} = \frac{15.3kN}{155\ kg \cdot g} \approx 10 \tag{3}$$

Errors in those estimates could arise from a discrepancy between the manufacturer's provided data and the actual materials' properties. However, both the base plate and its wedge anchors have safety factors above industry standards, showing high confidence in operating under these design parameters safely.

B. Input Force and Gear Ratio

A major constraint for Eleva's design and use is having a 'reasonable' force input by the operator, which makes the estimated input force and required gear ratio essential components of analysis. An average human can apply roughly 220 N while comfortably gripping and rotating a winch [4], as is done with the ratchet when operating Eleva. As previously stated, the base case for this design considers a staircase with a 45° slope and a system mass of 155 kg. Considering a kinetic friction coefficient between wood and concrete of 0.61 (empirically determined), Newton's Second Law (4) is used to find the force on the ratchet when the system is ascending and Equation 5 is then used to determine the gear ratio:

$$\sum F = ma = 0 \rightarrow \; mg[\mu \cdot cos(45°) + sin(45°)] = F_{ratchet}$$
$$\rightarrow F_{ratchet} = 1720N \tag{4}$$

$$\frac{F_{ratchet}}{F_{applied}} = \frac{1720N}{220N} \approx 7.82 \tag{5}$$

Based on these calculations, a gear ratio of 8:1 is adept for this design scenario. In fact, the coefficient of friction between wood and concrete can be larger than 0.61, which would increase the required force. However, there is evidence that an average person can input more than 220 N without major effort [5], especially since the ratcheting mechanism on Eleva allows for the caregiver to safely take breaks during the operation. Additionally, 45° is the upper limit for many standard stairs [7] [21], so this analysis accounts for a worst-case scenario. Thus, the above design parameters seem to be reasonable for this application.

C. Factor of Safety Calculations for Rear Toggle Latches

Toggle latches were chosen to secure the back wheels of a user's wheelchair because of the potential for compatibility with different chair models, common availability, and ease of use. Each latch used in Eleva's design is rated for 300 kgf per manufacturer specification, which is a total rating of 5884 N when summed together. It is assumed that forces are equally distributed between the two latches (one on each side). The modeled scenario uses the combined 155 kg weight of the user and wheelchair and involves the user inadvertently trying to force the latch open by inclining at extreme angles.

$$F = Mg\frac{L_1}{L_2} = Mg\frac{325\ mm}{155\ mm} \approx 3188\ N \tag{6}$$

Where L_2 is the distance between the latch and the pivot point in the skis and L_1 is the maximum horizontal distance between the center of mass of the user and that same pivot point.

$$F_{os} \approx \frac{5884\ N}{3188\ N} \approx 1.85 \tag{7}$$

The resulting factor of safety for the latches, as shown in Equation 7, was calculated to be 1.85. This F_{os} is low compared to existing standards, and could be improved through use of toggle latches made from stronger or thicker material.

The current locking mechanism for the wheels on the front of a user's wheelchair is constructed from steel rods that screw into threads embedded in the interior side wall of each ski. Analysis was not conducted on this safety mechanism because it would likely be altered for large-scale production in order to comply with existing safety regulations.

D. Sled F_{os} calculations

The sled base of Eleva is the primary contact surface between the model and the stairs. For prototype creation, this was constructed from pressurized, construction-grade pine, but in larger-scale manufacturing, it would likely be made from aluminum. Analysis was conducted to determine the ability of the sled to cope with and adjust to maximum forces. To calculate the maximum load, the analysis considered the extreme case of someone being dropped onto the stairs, where the person was falling for 0.5m and the collision time takes 0.1s. It is assumed that the sled is nearly horizontal.

$$mgh = \frac{mv^2}{2} \rightarrow v = \sqrt{2gh} \rightarrow P = m\sqrt{2gh} \tag{8}$$

$$F = \frac{\Delta P}{\Delta t} = \frac{m\sqrt{2gh}}{0.1s} = 4852.3\ N \tag{9}$$

Equation 9 shows the calculation of a maximum possible load force on the entire base to be 4852.3 N or 2426.1 N for each rail.

The calculations were based on the maximum deflection that the skis could take before being unsafe to operate. We used the 2018 National Design Specification (NDS) for Wood Construction [11] to base our design on. According to the NDS [11] the deflection can be calculated as:

$$\delta = \frac{5 \cdot w \cdot L^4}{384 \cdot E \cdot I} \tag{10}$$

Where δ is the ski's deflection, L is the length of the beam that composes the bottom section of the ski, I is the moment of inertia of the cross-sectional area, E is the Young's modulus of the ski's material, w is the estimated uniformly distributed linear load (simplified as total load divided by the length of the skis).

By using the maximum deflect criteria standard of $\delta \leq \frac{L}{360}$ we obtain a factor of safety:

$$F_{os} = \frac{w \cdot L}{F} \approx 4.1 \tag{11}$$

E. Ratchet Post Force Analysis & F_{os} Calculations

To conduct FEA analysis of the ratchet post, the entire assembly had to be simplified and broken down into its individual components with simplified geometry and forces distribution.

The assembly was divided into a main beam, a ratchet and its block, the attachment beam (on the bottom of the assembly

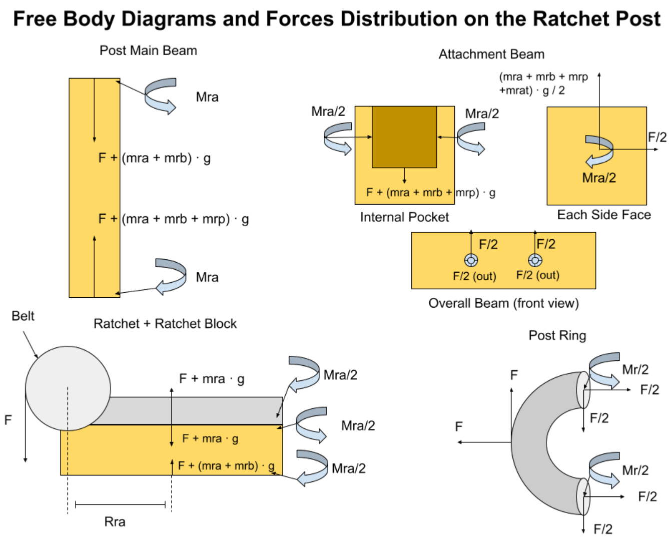

Fig. 3. Free body diagrams with forces distribution across the surfaces of the different components. Blue thick arrows indicate moment applied to a face (indicated by the thin black arrow coming from the blue arrow). Gravitational forces are omitted. Force arrows show the force acting on the surface. Vectors not to scale.

and in which the main beam is inserted) and the ring that turns the ratchet belt 90 degrees to face the horizontal position. In the analysis F is the tension on the ratchet belt, Mra = Mr = F · Rra is the moment caused by the ratchet on the face of the ratchet block, mra is the mass of the ratchet, mrb is the mass of the ratchet block, mrp is the mass of the main beam, mrat is the mass of the attachment beam.

The diagrams and forces were then inserted as boundary conditions into the SolidWorks Finite Element Analysis (FEA) tool to extract the stress distributions of each piece. While the Eleva prototype was primarily built using construction-grade pine wood, FEA was conducted assuming that the main beam, ratchet, block, and attachment were made of 6061-T6 aluminum alloy to reflect anticipated future design decisions for large scale production.

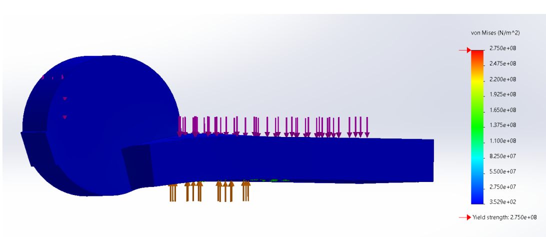

Fig. 4. FEA Analysis of the ratchet

Figures 4 and 5 display the FEA results of stress analysis for the ratchet and ratchet post achieved after different meshing techniques were applied and convergence was apparent. From these results, we can conclude that the post displays a maximum Von Mises stress of $\sigma \approx 70\ MPa$. Using

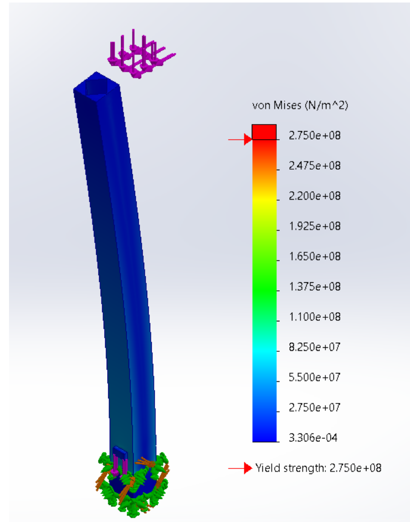

Fig. 5. FEA Analysis of the ratchet post

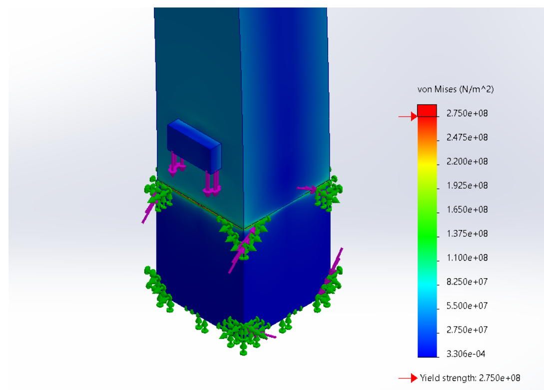

Fig. 6. FEA Analysis of the ratchet post base

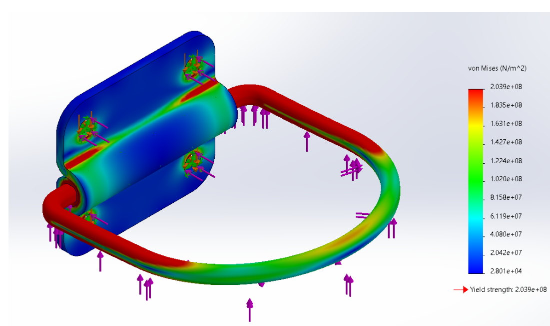

Fig. 7. FEA Analysis of the steel ring

$\sigma_{al} \approx 280\ MPa$ [12], which yields a factor of safety:

$$F_{os} = \frac{\sigma_{al}}{\sigma} \approx 4 \tag{12}$$

Figures 6 through 8 show the results for the following components: ratchet post base, steel ring, and back support for the ratchet post. The factor of safety on the steel ring attached to the post sub-assembly was calculated based on the max stress reading of approximately 204 MPa. We assumed

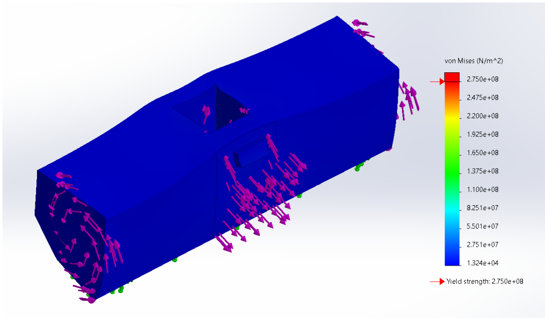

Fig. 8. FEA Analysis of the back support for the ratchet post

galvanized steel with an Ultimate Shear Strength of 450 MPa [13] [14].

$$F_{os} \approx \frac{450\ MPa}{204\ MPa} \approx 2.21 \tag{13}$$

In this analysis, it is important to recognize that areas of force application were approximated and the simplified shape of parts compared to the complexity of the actual model could render the results less accurately. While this error is relevant to exact calculation, results would still likely trend in the same direction.

F. Force Analysis on Back Wheels

The current method of getting over the first steps in the set of stairs involves:

1) Placing the sled as close as possible to the beginning of the stairs.
2) Loading the sled with the wheelchair/patient and securing ratchet post and belt.
3) Stepping on the lever to tilt the sled up to 30° so that the back wheels engage with the ground.
4) Rolling the tilted sled on the back wheels until the front of the sled is over the first 2 or 3 steps.

Plugging into SolidWorks the masses from Section III as well as literature values for the center of mass of humans in a sitting position [22], we were able to obtain the center of mass of the entire assembly, which we will use to calculate the forces on the wheels and shafts during tilting. Note that the pivot around which the assembly rotates changes depending on whether the wheels have engaged or not. At inclinations less than 30°, the wheels have not engaged and the pivot is the axis passing through the lower-back corner of the skis. But when the operator has stepped on the lever to tilt the sled at least 30°, the back wheels engage and become the only components in contact with the floor. At this moment, the wheels carry all of the forces from the weight of the patient and components, as well as the downward force from the caregiver stepping on the lever to tilt the sled.

At this instant, the force on the wheels is maximum, call it $2F_w$ since there are two wheels. To solve for it, however,

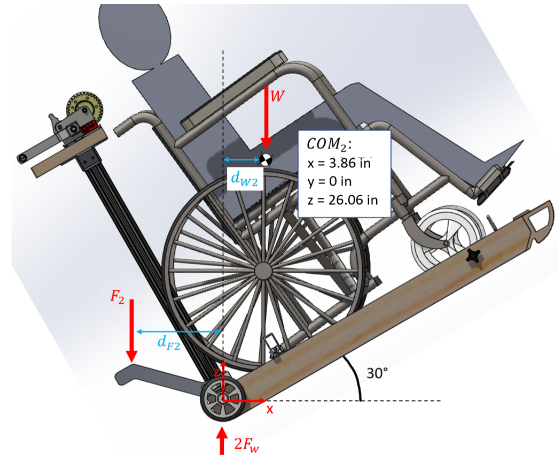

Fig. 9. Center of Mass with wheels as pivot/origin

we first need to compute the stepping force F_2 by doing a moment balance equation about the wheels:

$$\sum M_{wheels} = F_2 d_{F2} - W d_{w2} = 0 \tag{14}$$

$$F_2 d_{F2} = W d_{w2} \implies F_2 = \frac{mg d_{w2}}{d_{F2}} = 827.01N \tag{15}$$

Then, we can do a force balance equation to solve for F_w, the reaction force from the ground on a single wheel.

$$\sum F_z = 2F_w - F_2 - W = 0 \tag{16}$$

$$F_w = \frac{F_2 + mg}{2} = 491.5N \tag{17}$$

Since the wheels used in the sled were rated for 300 lbf = 1334.5 N [23], the factor of safety is $1334.5/491 = 2.72$, which is acceptable. To improve it further, larger wheels or wheels from stronger materials could be used.

The loads on the shaft that connects the wheels to the skis should also be analyzed since the sled experiences a large bending moment as shown below. Assuming the shaft is of negligible weight compared to the loads it carries, the maximum shear stress τ_{max} can be solved from the cantilever beam equations for a circular cross section [25].

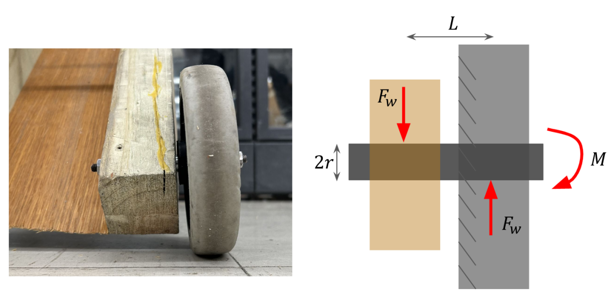

Fig. 10. Shaft as cantilever on "fixed" wheel

$$V_{max} = F_w = 491.5N \tag{18}$$

$$\tau_{max} = \frac{4V_{max}}{\pi r^2} = 10MPa \quad (19)$$

The 0.625" shafts we used in the sled had a tensile strength of $\sigma_s = 125$ ksi = 862 MPa [24], from which we can estimate the shear strength [26]:

$$\tau_s = 0.75 \times \sigma_s = 646.5MPa \quad (20)$$

Therefore, the factor of safety is $646.5/10 = 64.6$, which is extremely good.

G. Cost Analysis and Competitor Evaluation

The cost analysis of the Eleva was conducted to determine the final cost of production per unit. The costs of the individual components are outlined in the Table I below, including assembly, packing, shipping costs.

Component	**Material / Model**	Final Cost ($)
Aluminum 8020	6061 Alloy [31]	9.95
Baseplate	[33]	36
Wood	Timber - Pine [29]	25.64
Ratchet + Cable	[34]	45
Latches	[27]	3
Screws	[28]	3
Tie Down ring	[30]	8.66
Wheels	[32]	3
Assembly		10
Packing		5
Shipping		20
Final production cost		169.25
Units produced		12686
Legal		60000
Operational		60000
R&D		48000
Profit margin		0.05
Final sales cost		191.6

TABLE I

TABLE SHOWING THE ESTIMATED COSTS FOR RUNNING A BUSINESS IN BRAZIL TO SELL THE ELEVA. REDUCED VERSION;. FINAL COSTS INCLUDE SHIPPING AND MACHINING/MANUFACTURING COSTS.

Based on research in Latin America [16], the estimated revenue for the target market is $37.8 billion, with a share of 0.3262195122 coming from Brazil. According to IBGE [17], the lower limb disability population in Brazil is estimated to be 8,132,000, with 38% of them being low-income individuals. This results in an estimated 487,920 potential customers, assuming a 10% penetration rate. Estimating that the equipment lasts for 5 years and that 13% of the population in Brazil lives in favelas, we expect to sell 12,686 units per year. Based on this number, and using the costs from Table I, the final production cost is $169.25 per unit. If we wanted to also consider business expenses, we can add estimated legal, operational, and R&D costs, as well as a 5% profit margin, giving us a final sales cost of $191.6 per unit.

The estimated revenue per year based on this analysis is $12686 \times \$191.6 = \$2,430,638$, with a profit of $121,532.

Current solutions in the market include chairlifts and ramps. The global company Stannah is an industrial engineering firm that manufactures and supplies stairlifts, lifting platforms and residential lifts. Stannah operates in Brazil and has installed over 750,000 chairlifts around the world. As reported on their website, a straight stair-lift average cost is between $3,400 – $5,500. Many customers choose an option in the $4,000-$4,500 range, while others opt for a preowned stair chair lift with a slightly lower price tag. [9]

Other solutions include the construction of ramps done by the government in Brazil. While costs for ramps vary greatly depending on the location, steepness of the steps, and material it is reasonable to assume a price anywhere from $4,000-$12,000 or possibly more. [8] Overall solutions exist in the current market but are significantly expensive to a major part of the population. The consumer targeted by Eleva, person with disability with low-income in hard-to-reach urban areas, is not being tended to by the current players.

DISCUSSIONS & CONCLUSION

Eleva displays satisfactory Factor of Safety values, with a minimum of 1.85 at the locking latches and 2.72 for the wheels. Eleva falls within the standardized safety requirements of all other components, ensuring safe operation.

Practical testing of the product indicates agreement with the analysis results as no failure or principle of failure was found in any component of the final prototype even after extensive real life testing. Quantities that were experimentally measured (such as the friction coefficient) agree with values taken from literature [6].

Future improvements to the safety of the system could focus on the locking mechanisms. The comparatively low Factor of Safety of the locking latches and wheels can be addressed by replacing them with options rated for higher loads.

As an updated, wheelchair-compatible, mechanical stairlift, Eleva is better able to meet the needs of users with mobility impairments who lack electricity, financial resources, or live in areas with low infrastructure or challenging topography. This affordable mechanical solution enables a dignified and more accessible option to ensure a user's right to healthcare.

ACKNOWLEDGMENTS

We would like to thank Dr. Yevgeniy Yesilevskiy and Dr. Kristin Myers for their guidance and mentoring throughout the project. We would also like to thank the Columbia Mechanical Engineering Teaching Lab and the staff for their help. We would also like to acknowledge the Makerspace staff for providing the space and equipment necessary for testing and prototyping Eleva.

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