Full Materials Selection Study

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Summary

This report outlines the methodologies and techniques employed in a Triple-Bottom-Line design approach to guide material selection, ecological assessment, and cost modeling for rocket airbrakes. Design requirements were translated into specific selection objectives, which were addressed using both Microsoft Excel and Granta EduPack. More specifically, the optimal material and manufacturing process were determined using Ashby's selection methodology, Saaty's Pairwise Comparison, and a Weighted Property Index. The selected material and process were then evaluated in terms of cost and environmental impact, relative to the existing material currently in use. Based on environmental considerations highlighted through a Social Life Cycle Assessment (SLCA) and an Eco-Audit, a new composite material was generated using Granta's Synthesizer tool. The analysis process was then reiterated for this proposed solution. Results indicate that the composite's overall performance, cost profile, and environmental footprint make it the most suitable material choice for the given design objectives.

Identification of Design Constraints

Product and Stakeholder

The product under consideration is a set of deployable air brakes designed to slow down amateur high-powered rockets, depicted in Figure 1. The primary stakeholder is Cal Poly Space Systems (CPSS), a student-run rocketry organization at California Polytechnic State University. CPSS requires air brakes capable of decelerating a rocket during ascent to enable finer control over apogee. These air brakes must endure substantial aerodynamic forces without failure, while remaining sufficiently lightweight to minimize impacts on the rocket's projected apogee and center of gravity.

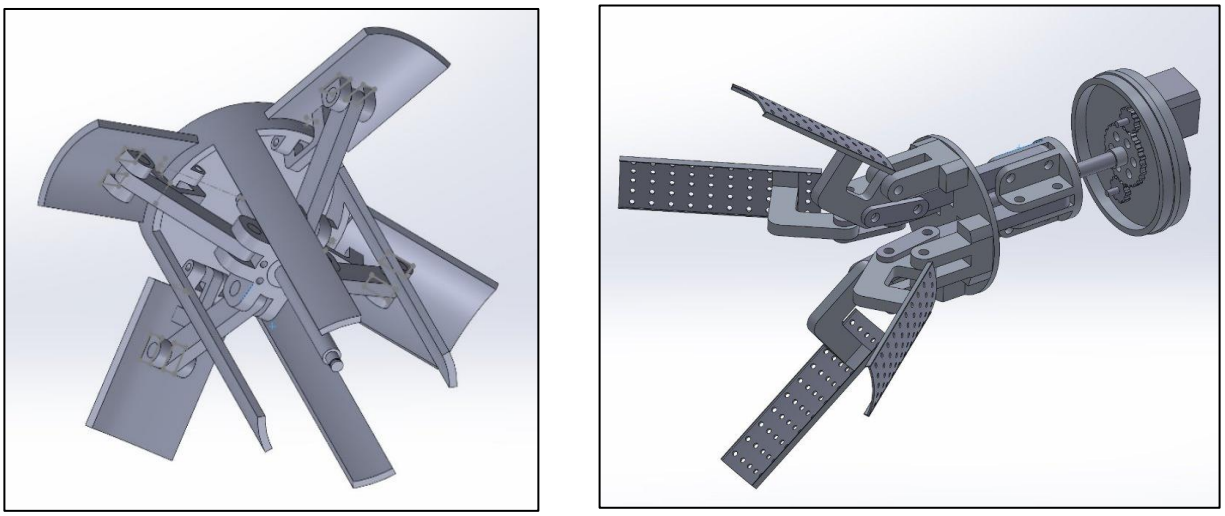


Figure 1. Airbrakes Models

Although maximizing altitude remains a desirable goal, the selected material must primarily be light enough to permit the use of lower-cost, lower-thrust motors while still achieving a target apogee of at least 5,000 feet. Impact resistance is considered a beneficial but non-essential property, as survivability in the event of a ballistic descent is not a primary design driver.

Given the club's limited funding, cost-effectiveness is a critical objective. Environmental impact, in contrast, is of minor concern to CPSS. Materials that are readily available and can be easily sourced are strongly preferred, as are those compatible with the club's in-house manufacturing capabilities.

Needs, Functions, Objectives, and Constraints

CPSS seeks air brakes that are both more affordable and more effective than current alternatives, capable of reliably slowing a subsonic rocket without mechanical failure. Functionally, the air brakes operate as panels loaded in bending. The design is stiffness-limited, and geometric parameters such as length and width are considered fixed; only the thickness may be varied to influence performance.

The primary design objectives are to minimize both mass and cost. Within CPSS, these objectives are inherently linked—lighter materials, despite usually being more expensive, can lead to lower overall mission costs by enabling higher altitudes with less powerful motors. Environmental considerations are secondary and have limited influence on material selection.

Design constraints are focused on ensuring structural and thermal integrity during flight. These include minimum requirements for yield strength, shear modulus, fracture toughness, and heat resistance. Additionally, all candidate materials must be compatible with manufacturing processes available to CPSS members at Cal Poly, as all components are fabricated in-house.

Preliminary Life Cycle Analysis

Cal Poly Space Systems (CPSS) has traditionally fabricated air brakes using 6061-T6 aluminum, employing in-house manufacturing tools such as manual mills, lathes, drills, and water jets. To evaluate the environmental impact of this manufacturing method, both a Streamlined Life Cycle Analysis (SLCA) and an Eco-Audit on Granta EduPack were conducted. These assessments examined the environmental footprint of the air brakes across their entire life cycle, from raw material extraction to end-of-life disposal. Key factors considered included total energy consumption, carbon dioxide emissions, the generation of solid and liquid waste, and the depletion of raw material resources.

Preliminary SLCA

The SLCA evaluates environmental impact across five distinct life stages: pre-manufacture, product manufacture, product delivery, product use, and end-of-life (recycling or disposal). Each stage is rated based on material selection, energy usage, and the production of solid, liquid, and gaseous residues. Scores are assigned on a 0–4 scale, with higher scores

indicating lower environmental impact. These scores are then summed to highlight life stages with the greatest opportunities for ecological improvement.

The SLCA results for the traditionally manufactured aluminum air brakes are summarized in Figure 2. Stages receiving a total score of 12 or lower were flagged as potential areas for improvement. The Pre-Manufacture stage received the lowest score overall, primarily due to uncertainty surrounding the source of the aluminum stock used by CPSS. Although aluminum is highly recyclable, and much of the current U.S. supply comes from recycled sources [1], the environmental footprint of virgin aluminum is significantly higher. Primary aluminum production is highly energy-intensive and generates large quantities of waste, whereas recycled aluminum uses substantially less energy and produces minimal emissions. Thus, due to the lack of specific sourcing information, the Pre-Manufacture stage was conservatively rated with a moderate impact score. Similarly, the Material Choice category was rated lower due to this uncertainty, despite aluminum's favorable end-of-life characteristics.

Traditionally Manufactured Airbrakes						
	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	2	2	2	1	9
Product Manufacture	3	3	2	4	4	16
Product Delivery	4	4	4	4	4	20
Product Use	4	4	4	4	4	20
Recycling, Disposal	4	4	4	4	4	20
Total	17	17	16	18	17	85

Figure 2. SLCA Table for Traditionally Manufactured Airbrakes

The remaining life stages scored well. In the Product Manufacture stage, aluminum's inertness and compatibility with low-energy, low-waste fabrication techniques contributed to a high environmental score. Product Delivery received maximum points, as the air brakes are produced and used internally by CPSS, eliminating the environmental cost of shipping and packaging. Product Use also achieved a perfect score, as the air brakes require no energy input or maintenance and generate no emissions during use. Finally, the Recycling/Disposal stage scored highly due to aluminum's full recyclability, single-material construction, and the low energy required for remelting and repurposing.

Overall, the SLCA results indicate that the traditional aluminum air brake design is environmentally favorable, particularly in its use, delivery, and end-of-life stages. The primary area for ecological improvement lies in the sourcing of raw materials, where greater use of certified recycled aluminum could significantly reduce the environmental burden

Preliminary Eco-Audit

An Eco-Audit was conducted using Granta EduPack to evaluate the environmental impact of the traditional airbrake manufacturing process, focusing on energy consumption and CO_2 emissions. The audit considered the material selection, manufacturing, and transportation stages.

The material selected for the analysis was 6016-T6 aluminum, as previously discussed, and was assumed to be of standard industrial grade—comprising a typical blend of virgin and recycled aluminum. For the manufacturing stage, it was assumed that the aluminum stock was produced via an extrusion and rolling process. The secondary shaping process was modeled as a cutting/trimming operation, through which the airbrake components would be cut from the stock material. Based on typical observations from the traditional process, material loss during trimming was estimated at approximately 25%.

For the transportation stage, although the airbrakes themselves are not distributed externally, the transport of raw material was still modeled to account for its ecological impact. It was assumed that the aluminum stock was produced in China and transported 100 km to an airport via a 16–32 ton truck. From there, it would be flown to America on a long-haul aircraft carrying dedicated freight. Upon arrival, a 16–32 ton truck would carry the material 100 km to a regional distributor's warehouse, after which it would be transported roughly 2000 km to Cal Poly on a 7.5–16 ton truck.

The airbrakes were assumed to have a one-year lifespan, consistent with the typical duration of CPSS projects. At the end of their service life, they were assumed to be disposed of in a landfill. No energy use was attributed to the product's operational phase, as the airbrakes themselves do not consume significant energy in use. They are powered by a small battery and operate passively on amateur rockets, resulting in negligible energy demand.

Based on these assumptions, the Eco-Audit produced estimates for energy usage and CO_2 emissions at each life-cycle stage, as summarized in Figure 3 and Figure 4. On their own, these results may not appear especially informative. However, considering the high SLCA score received by the traditional manufacturing process, it can be reasonably inferred that the energy use and emissions are within a broadly acceptable range in terms of environmental impact.

This Eco-Audit will serve as a baseline reference for assessing future manufacturing methods. Ideally, alternative processes will offer a similar or reduced environmental footprint. For the time being, though, the traditional method appears to perform well from an ecological standpoint.

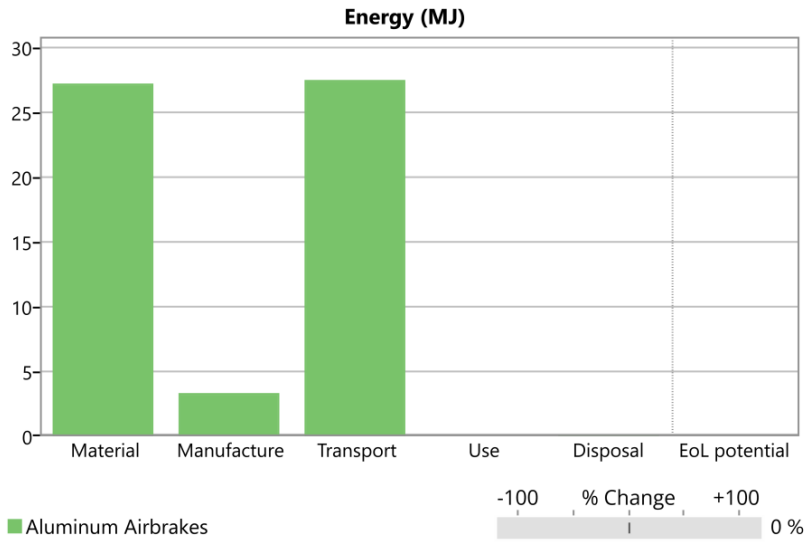


Figure 3. Energy Eco-Audit of Traditionally Manufactured Airbrakes

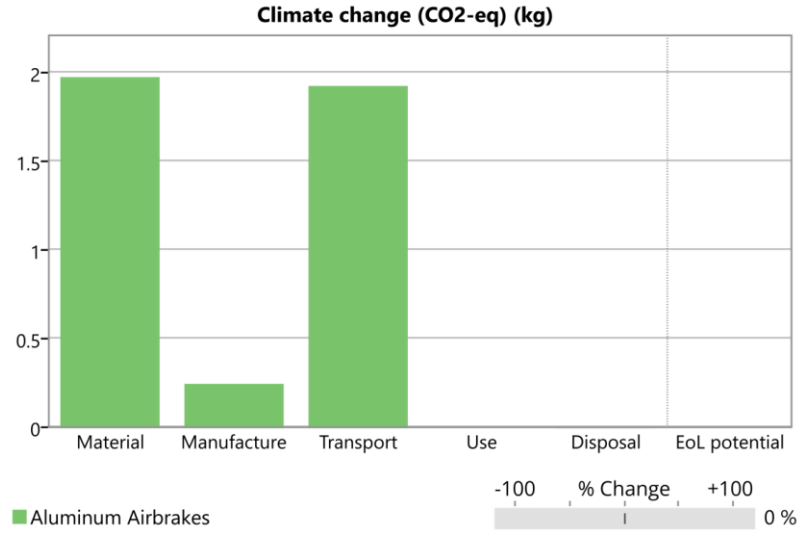


Figure 4. CO_2 Eco-Audit of Traditionally Manufactured Airbrakes

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Material Selection

Ashby Selection

Viable materials were initially screened based on the key performance constraints identified from stakeholder requirements. These constraints included yield strength, maximum

service temperature, fracture toughness, and shear modulus. Yield strength was required to exceed 200 MPa, fracture toughness had to be greater than 20 MPa$\sqrt{m}$, and the shear modulus had to be above 15 GPa. The material also needed to withstand temperatures up to 100 °C, reflecting the extreme thermal conditions during summer desert launches and heating from drag forces. Additionally, only materials compatible with in-house manufacturing methods at Cal Poly were considered. These included fabrication using a manual mill, lathe, water jet, autoclave, and various saws and drills. This ensured that the chosen material would be compatible with CPSS's available infrastructure.

Although environmental impact is not a primary concern for CPSS, results from the SLCA and Eco Audit indicated that the traditional aluminum design was relatively eco-friendly. Therefore, to avoid significantly increasing the ecological burden, a constraint was applied such that the embodied energy and CO_2 emissions of any new candidate material could not exceed three times that of aluminum (348 MJ/kg and 25.26 kg/kg, respectively).

Following this preliminary screening, the remaining materials were evaluated against the two primary design objectives of minimizing mass and cost. As stated previously, the airbrakes were modeled as a panel in bending with fixed length and width and a variable thickness. Under this design model, two key performance indices were established: Mass per Unit of Compressive Stiffness $\left(\frac{\rho}{E_f^{\frac{1}{3}}}\right)$ and Cost per Unit of Compressive Stiffness $\left(\frac{\rho\, C_m}{E_f^{\frac{1}{3}}}\right)$. Since the design is stiffness-limited, these indices provide a more accurate basis for comparison than raw material cost or density alone. Materials with lower values of these indices will require less material to meet performance requirements, thereby minimizing total mass or cost.

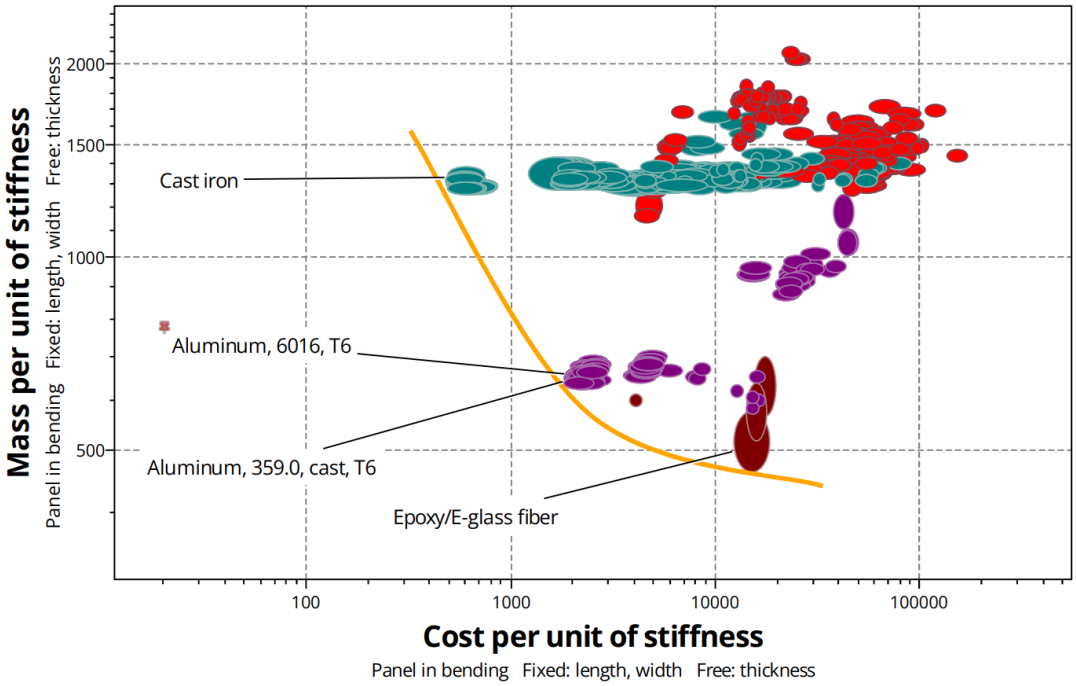


Figure 5. Ashby Material Selection Chart

The Ashby selection process involved plotting all viable materials against these indices. The x-axis represented Cost per Unit Stiffness, and the y-axis represented Mass per Unit Stiffness. A trade-off curve was then drawn, highlighting the materials that offered the best compromise between the two objectives. Materials lying closest to this curve were considered most optimal in terms of balancing performance and affordability. The final candidates identified near this curve were cast iron, Aluminum 359, and a fiberglass composite, as shown in the Ashby Diagram in Figure 5. For comparison, the traditionally used 6061-T6 aluminum is also shown on the same plot.

Weighted Property Index

After identifying promising candidate materials, a Weighted Property Index (WPI) was applied to determine the most suitable option for CPSS's needs. This index considers multiple performance-relevant properties, each weighted according to its relative importance using Saaty's Pairwise Comparison Method.

Although many properties used in the Ashby selection were go/no-go constraints, yield strength was included in the WPI as an optimizable property. Enhancing strength, while not strictly necessary, could improve the reusability and durability of the air brakes. In addition to yield strength, the two performance indices (Mass per Unit of Stiffness and Cost per Unit of Stiffness) were included as core metrics, since they directly align with the primary objectives of minimizing weight and cost. Lastly, corrosion resistance was added, as it affects long-term performance and the effectiveness of surface coatings that may improve aerodynamic or thermal properties.

Among these, Mass per Unit of Stiffness and Cost per Unit of Stiffness received the highest priority, with mass weighted more heavily due to its broader system-level impact. Reducing mass not only improves rocket performance but can also reduce the motor size required, resulting in overall project cost savings. Corrosion resistance received moderate priority, particularly for its contribution to finish quality and potential heat shielding. Yield strength received the lowest priority, since all candidates met the minimum required threshold.

The complete Saaty pairwise comparison matrix is shown in Figure 6, where a value of 1 indicates equal importance and a value of 9 signifies extreme importance of the row property over the column property. Intermediate values reflect varying degrees of relative importance.

	Strength	Cost/Stiffness	Mass/Stiffness	Corrosion
Strength	1.00	0.14	0.14	0.25
Cost/Stiffness	7.00	1.00	0.50	3.00
Mass/Stiffness	7.00	2.00	1.00	3.00
Corrosion	4.00	0.33	0.33	1.00
Total	19.00	3.48	1.98	7.25

Figure 6. Saaty's Pairwise Comparison

Each column was normalized to obtain relative weightings, which were then averaged to produce final weight factors for each property, as shown in Figure 7. As expected, Mass per Unit of Stiffness received the highest weighting, followed by Cost per Unit of Stiffness, confirming the dominance of mass and cost in the design criteria.

	Strength	Cost/Stiffness	Mass/Stiffness	Corrosion	Weights
Strength	.05	.04	.07	.03	0.050124846
Cost/Stiffness	.37	.29	.25	.41	0.330724359
Mass/Stiffness	.37	.58	.51	.41	0.465895180
Corrosion	.21	.1	.17	.14	0.153255615
Total	1	1	1	1	

Figure 7. Normalized Weights from Saaty's Matrix

To compute the final WPI, numerical values for quantifiable properties were taken from Granta EduPack. The exception was corrosion resistance, which lacks a consistent numerical definition across all materials. Instead, materials were rated on a scale of 1 to 5 based on data from research sources, where 5 represents high corrosion resistance. Based on this analysis, fiberglass was rated the highest, cast iron the lowest, and aluminum intermediate [2]. The full Weighted Property Index table is presented in Figure 8, where β represents the computed weighting factors and the percentage columns reflect each material's normalized performance across all metrics.

Materials / **Properties**	**Weighting Factors (β)**	**Fiberglass**	**Cast Iron**	**Aluminum**
Strength (MPa)	0.050122	100	32.85714286	33.28571429
Cost/Stiffness $\frac{\$}{m^3 * MPa}$	0.33072	15000	592	2150
Mass/Stiffness $\frac{kg}{m^3 * MPa}$	0.46590	518	1330	640
Corrosion	0.15326	5	2.75	4
WPI Result		**68.2328**	**61.293**	**60.7437**

Figure 8. Weighted Property Index Results

From the WPI results, fiberglass emerged as the most suitable candidate, slightly outperforming the others. Its dominance stemmed primarily from its very low mass per unit stiffness and high corrosion resistance, despite its higher cost per unit stiffness. Cast iron, while unexpected, proved surprisingly competitive due to its extremely low cost, although its high density makes it impractical for aerodynamic applications. Aluminum 359 maintained a strong balance between cost and mass, closely mirroring the performance of the traditionally used 6061 aluminum.

The strong showing of fiberglass is consistent with its widespread use in aerospace engineering applications, particularly when carbon fiber is not a viable option. The competitiveness of cast iron, however, was unexpected. Although generally unsuitable for aerodynamic structures, its very low cost and acceptable mechanical performance allowed it to remain a candidate under the current weighting scheme.

Ultimately, the WPI reflects a subjective prioritization of properties. Should CPSS shift its emphasis (whether it be toward higher performance, lower cost, or greater durability) the results could change significantly. For instance, increased funding might justify prioritizing mass and corrosion resistance, reinforcing fiberglass as the top candidate. Conversely, tighter budgets might force trade-offs favoring cost, even if that results in a heavier or less optimal material. Thus, the materials selection remains flexible, contingent on evolving project goals, resources, and design requirements.

Sensitivity Analysis

To evaluate the stability of our selection methodology, we conducted a two-stage sensitivity analysis to monitor how changes in WPI weights influence our materials selection. The stages were implemented as follows: distributing the largest weight (mass/stiffness) into the second largest category (cost/stiffness), then iterating by distributing equally into both the second and third largest (corrosion resistance) categories. The rationale for the first round was to quantify the relative importance of mass and cost—a significant optimization problem for a low-capital club building for a rocket. Nonetheless, in our WPI analysis, we placed a significant emphasis on mass, largely because of CPSS's hard requirement of a successful (as much as possible) launch. Moreover, cost was considered to have slight flexibility with varying department support and grant funding. Yet, with significantly different material values for both mass and cost, overall stability is not necessarily expected. The results from the evaluation of the mass-cost relationship are shown in Figure 9.

From Figure 9, it is readily apparent that cast iron benefits doubly from both the reduction in mass relevance and a corresponding increase to the significance of cost. With a crossover point at around 0.42, any notable devaluing of mass as a weighting factor suggests cast iron as the optimal material. For context, our material selection utilized a weighting factor of approximately 0.47. Thus, the stability of the selection is dubious if the club has a particularly

poor financial situation that causes a change in priority.[1] However, the relationship between aluminum and Fiberglass is significant, with Fiberglass demonstrating an advantage over a large mass weight range. Thus, Aluminum appears to be an average, or "compromise material" as any favoring of mass aligns it below Fiberglass, and any heightened emphasis on cost features cast iron with a sizable victory.

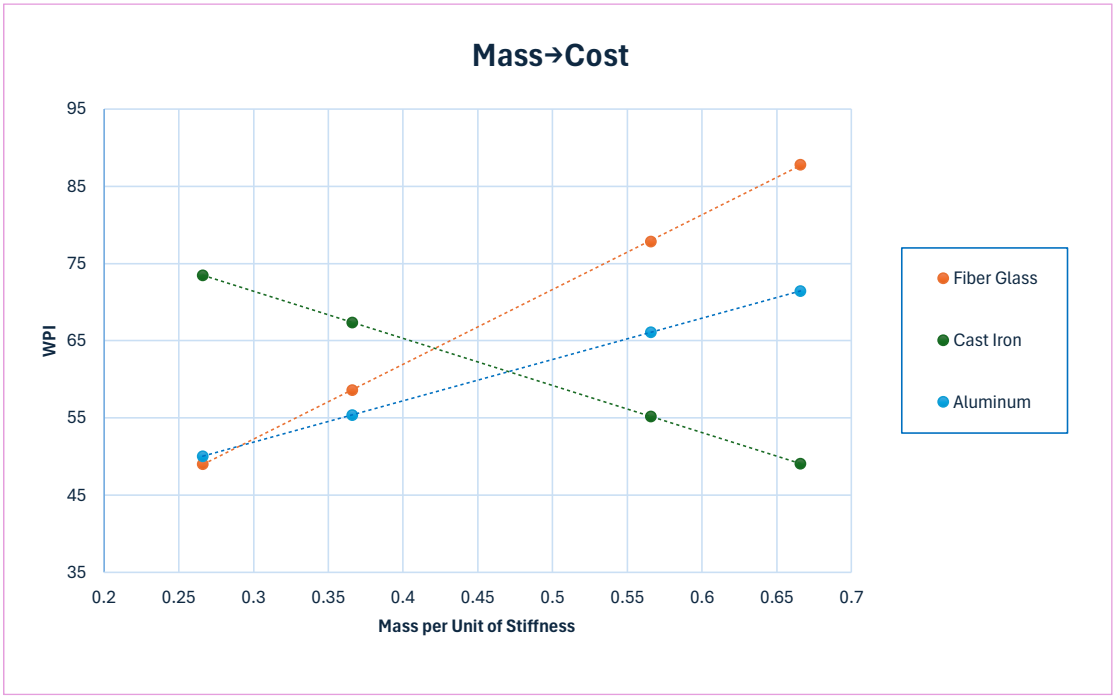


Figure 9: Mass Weights Distributed into Cost

However, the longevity and environmental durability of the air brakes are relevant to any discussion on cost. The club may have an interest in preserving the mechanism for multiple launches, or even years. Thus, it is worthwhile to consider corrosion resistance as well, to determine if collectively framing both longevity and cost against mass leads to any notable variations in the stability results. Moreover, we were discouraged from the strength of cast iron in the WPI results—mostly because its large mass challenges its feasibility as a material for the desired use, despite passing our existing material constraints. To do so, an equal distribution into both corrosion resistance and cost was used. The results are encapsulated in Figure 10.

Similar behavior is observed compared to the previous iteration with some distinguished qualities. The lower relative importance of cost in the rebalancing process effectively delays the crossover point between Fiberglass and Cast Iron to be around 0.39 (.03 smaller than previous). However, from the Saaty Weights, cost per unit stiffness is still held above corrosion resistance.

[1] It is worth noting that a weighting factor difference of 0.05 (calculated by subtracting the crossover point from the reference weight) is within a relatively small tolerance. Thus, it would be feasible for the club to exceed the acceptable domain for Fiberglass.

Therefore, Cast Iron once again demonstrates dominance for mass weights less than the crossover value.

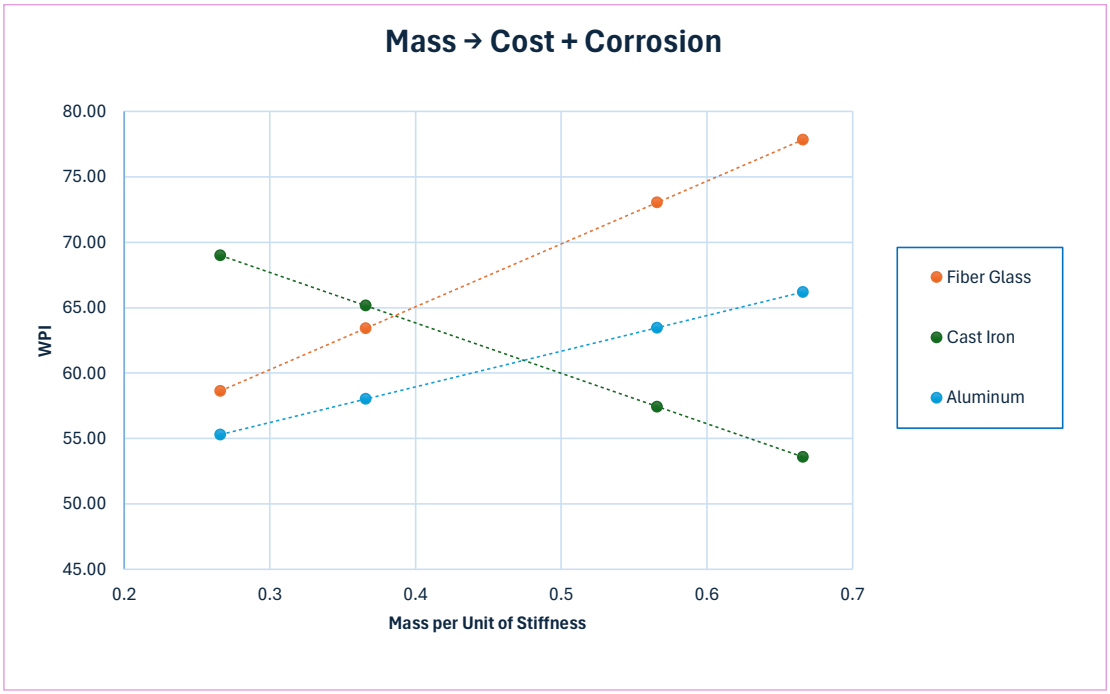


Figure 10: Mass Weights Equally Distributed into Corrosion Resistance and Cost

Aluminum also reasserts its status as a compromise material, as either Cast Iron or Fiberglass has higher WPI values across the mass domain. Because of Cast Iron's relatively poor corrosion value, the gradient of Cast Iron with respect to mass is less severe, contributing to the argument for Fiberglass's stability as a solution. Ultimately, because of the assumption that cost is held secondary to mass, the material selection results shown in Figure 10 are stable, especially if mass was increasingly favored over cost.[2] Conditionally, if the club must prioritize cost, the selection's instability will become apparent, with Cast Iron being the most attractive choice. However, we allotted the Saaty weights with the club's finances in mind, thus, as of this moment, Fiberglass remains the solution, with a WPI advantage of around 7 and a mass weighting factor tolerance of around 0.03. As a result, Fiberglass will be considered.

Process Selection

After determining fiberglass to be the most optimal material for CPSS airbrakes, it became necessary to evaluate viable processing methods. To identify appropriate processes, constraints were applied within Granta EduPack to reflect both the manufacturing capabilities of CPSS and the specific requirements of the product geometry. First, all candidate processes were limited to

[2] While mass is already weighted relatively high at 0.47, there could be situations in the future in which the club has enough funding to justify increasing the weight. However, given the results of the sensitivity analysis, this would do nothing other than cement the selection choice further.

those compatible with fiberglass. Additionally, only processes capable of producing flat sheets were considered, as this form most closely aligns with the geometry of the airbrake design.

These constraints narrowed the list of viable processing methods to four primary and four secondary processes. As fiberglass must first be cured into a flat sheet before being machined to its final dimensions, a minimum of two processing stages is required. The four primary methods identified included hand lay-up, vacuum or pressure bagging, autoclave molding, and continuous laminating, as shown in Figure 11 However, of these, only hand lay-up and autoclave molding are feasible in-house at CPSS. While both autoclave molding and hand lay-ups can achieve relatively tight tolerances, as indicated by Figure 11, historical outcomes at CPSS indicate that autoclave molding consistently produces better results. By contrast, hand lay-ups performed by CPSS members have frequently resulted in warped or structurally inconsistent components due to a lack of experience in composite layup techniques. As a result, hand lay-ups are gradually being phased out of use within the club.

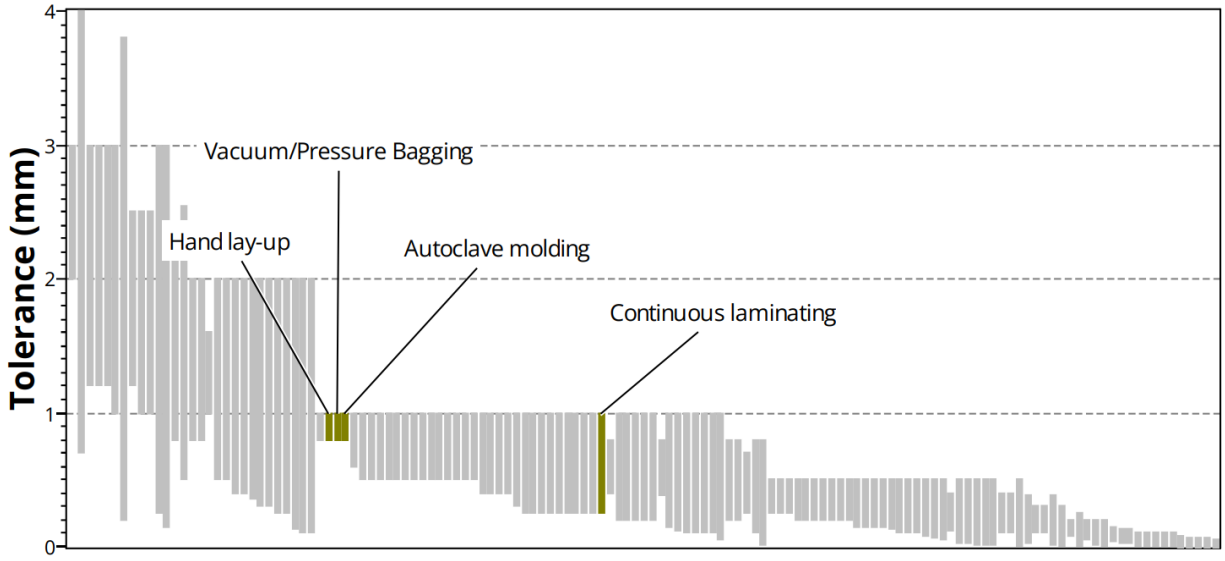


Figure 11. Primary Processing Methods

Thus, given the performance demands of airbrakes—particularly their need for structural soundness and surface smoothness for aerodynamic efficiency—the autoclave was deemed the only acceptable primary processing method. In addition to producing higher-quality parts, autoclave curing reduces the likelihood of material waste resulting from failed layups. Although this method is more resource-intensive, it aligns with the CPSS tendency to prioritize performance over cost.

After determining the primary process, attention turned to identifying a suitable secondary processing method to cut the cured fiberglass sheets to their final shape. The four methods identified were abrasive waterjet cutting, band saw, laser cutting, and conventional waterjet cutting, as shown in Figure 12. Of these, CPSS has access to both the band saw and waterjet cutter. Although Figure 12 indicates that waterjet cutting offers a tighter tolerance, dimensional precision

is not as critical when it comes to trimming the length and width of the airbrakes. Furthermore, dimensional tolerances can be controlled with careful operation using either method.

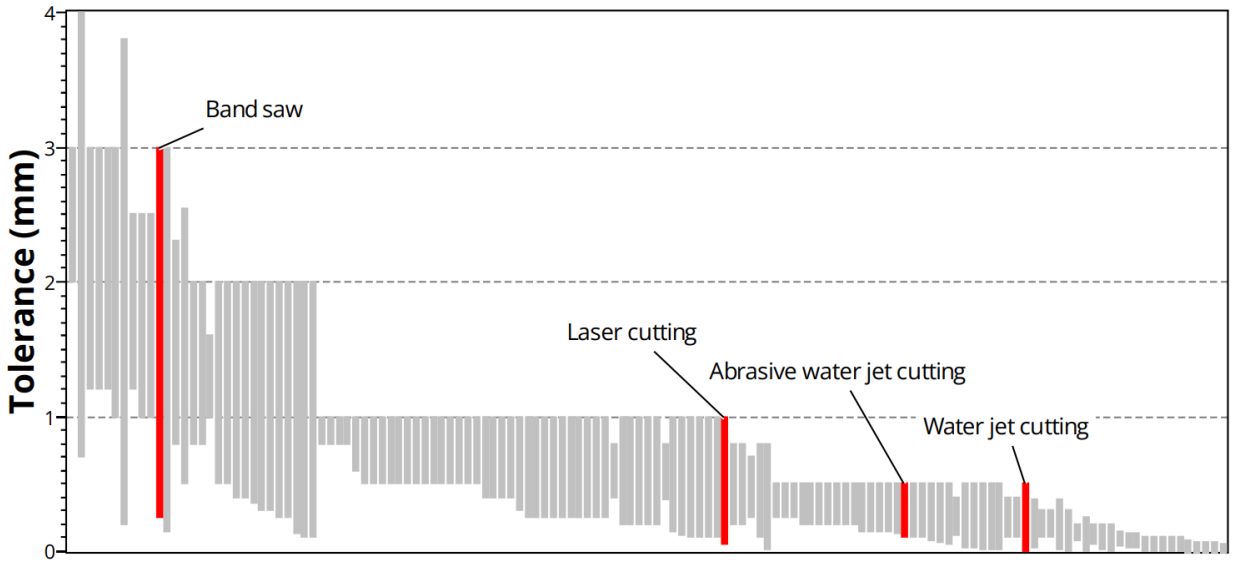


Figure 12. Secondary Processing Methods

As such, both waterjet cutting and band saw usage are acceptable options for shaping the airbrakes following curing. CPSS therefore has two viable manufacturing routes available: fiberglass can be cured using the autoclave and then shaped using either a band saw or a waterjet cutter. The final selection between the two would ultimately depend on cost considerations, as both methods meet performance and tolerance requirements.

Cost Model

A key consideration between manufacturing processes is the overall cost. To provide a holistic cost analysis, all cost parameters must be addressed. Fortunately, they are encapsulated in a digestible form in Equation 1.

$$\underbrace{C}_{\text{Total Cost}} = \underbrace{\left[\frac{mC_m}{U_m}\right]}_{\text{Material Cost}} + \underbrace{\frac{1}{n}[C_t]}_{\text{Tooling Cost}} + \underbrace{\frac{1}{\dot{n}}\left[\dot{C}_{oh} + \frac{C_c}{Lt_{wo}}(1+d)^{t_{wo}}\right]}_{\text{Capital + Overhead Cost}} \quad (1)$$

This equation was then used to model how the overall cost of each material and process combination is subject to fluctuations as a function of batch size n. To do so, data was accumulated

through either Granta Edupack averages (if provided a range) or from Dr. Galos.[3] Our cost model was constructed from the following table, which has some assumptions enumerated below:

	Autoclave Molding	Bandsaw	Waterjet
Material, mCm ($)	0.964744406	0.964744406	0.964744406
Gross Overhead Rate, CL ($/h)	600	600	600
Load factor, L	1	1	1
Capital write-off time, two (y)	87600	87600	87600
Discount rate, d	1	1	1
Material Utilization Fraction	0.875	0.875	0.94
Tooling Cost	9921.5	1000	1000
Capital Cost	509200	7395	64700
Batch Rate	0.525	1	6
Years of Use	10	10	10

Figure 13. Cost Values for Fiberglass

Most notably, it was somewhat difficult to estimate values that are extremely dependent on the type of machine. For example, Water jetting can machine a significant number of parts if the machine is large enough to repeatedly cut parts out of a large section of sheet metal. Thus, the batch rates and tooling costs were estimated [2]. Moreover, for the overhead cost, it was assumed that there are 10 employees working on the parts, and that each part takes the full Cal Poly Hangar shop hours (8 hours per part). Moreover, to manufacture the air brakes, two stages are required: a primary molding process (autoclave molding) and a secondary trimming process (either the bandsaw or the waterjet). Because the autoclave is the only machine to complete the primary molding process, it is effectively consistent between the two secondary processes. Nonetheless, it is included in the cost model for transparency, despite relative cost being the main parameter of interest.[4] Because CPSS only works on one major rocket project per year, only one air brake system is manufactured, which implies a meager batch size of four brakes per year (four brakes per one complete air brake system). As such, the cost analysis differs significantly from most conventional trends, as tooling cost will not decrease the overall cost value much—considering that the tooling cost is a function of the small batch size. A complete cost plot is shown below in Figure 14:

[3] Dr. Galos provided the following: a labor rate of $20 per hour per employee, write off time of 10 years (87,600 hours), and a universal load factor of 1.0.

[4] Taking the Autoclave into consideration, it was regarded as a "fixed cost," akin to paying a contractor. Employee hourly costs were not considered (they are for the trimming processes).

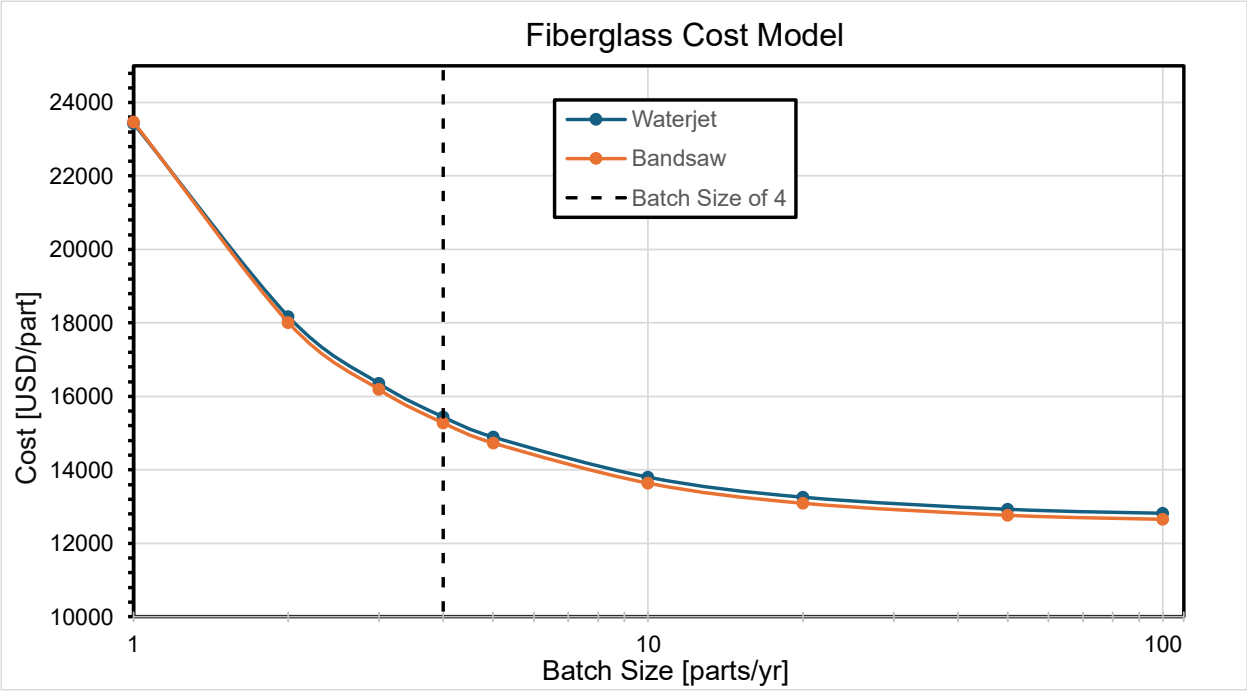


Figure 14: Fiberglass Cost as a Function of Batch Size

This behavior is intuitive given the low batch rates and proportionally large initial tooling cost. More specifically, by adding Autoclave molding as a fixed cost, it takes the batch size-driven decrease a long time to drastically lower the cost. The dashed line represents CPSS's target batch size, which implies that while tooling cost has lowered cost by $8191.125 from a batch size of one, it remains significantly above the asymptote, which begins in earnest at a batch size of around 10 parts per year. Nonetheless, despite roughly equal tooling costs (estimated), the waterjet has a larger capital cost compared to the bandsaw, which is shown with the small residual between the two processes. Thus, despite significant similarities, the bandsaw is the cheaper option, with a cost advantage at the target batch size of $157.41, which is sufficient cost saving to buy a rocket motor or two.

In terms of improvements, the one area that can be optimized is the material and overhead cost categories. Without the ability to dramatically alter the material utilization fraction, optimization in the material category would imply a new materials selection—a worthwhile exploit which is explored in a later section. Alternatively, the overhead cost can be improved by deconstructing the gross overhead cost rate term. Because the overhead rate involves the pay of both employees and the machines, it is the largest contribution to the overarching overhead cost expression.[5]

To decrease the overhead rate, the number of employees can be decreased. This is because despite the employees contributing to a higher batch rate, the operating and employment

[5] The overhead rate was assumed to be the number of employees * $20/hr wage + 2*(number of employees * $20/hr wage), in which the machine and running costs were assumed to be double the employee cost. As a result, the overhead rate is equal to the number of employees * $60.

costs imply that the overhead rate scales the batch rate by a factor of 60. Thus, the batch rate advantage does not offset the overhead cost. To explore this, I simulated the employment of two people instead of 10—a reasonable assumption for a club comprised of small sub-teams. The result is shown in Figure 15.

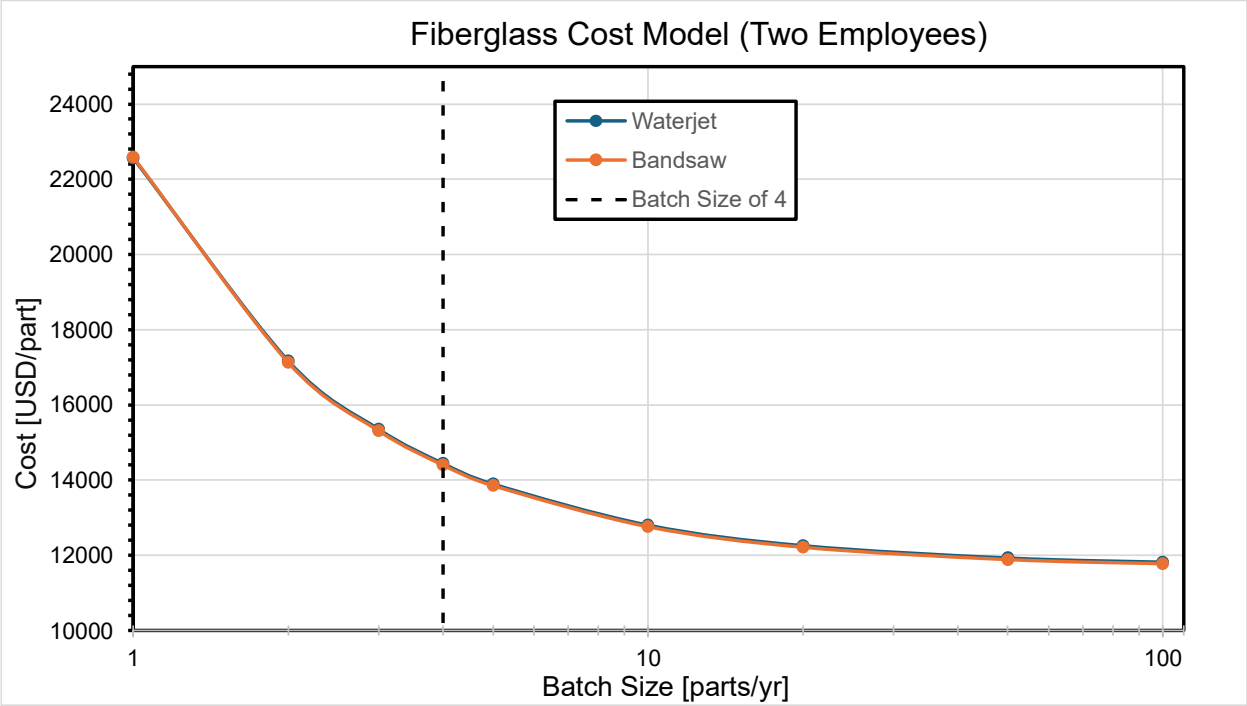


Figure 15: Fiberglass Cost Model for Two Employees

The overall graph behavior is similar to Figure 14, except for slightly lower costs around the board. It is difficult to determine with the log scale, however, at the target batch size of four, there is a cost benefit of $879.71 just by reducing the personnel from 10 to 2.[6] Moreover, with two people, the cost difference between the bandsaw and the waterjet remains significant at $157.41. Thus, there is significant evidence to recommend Fiberglass manufactured via autoclave molding and a bandsaw as the processes used. However, to be certain, extensive ecological analysis is required, including an SLCA comparison matrix and an Eco-Audit in Granta Edupack. These are completed in the following sections.

[6] In reality, the cost would be even lower, as students don't have to pay for the operation and maintenance of the machines. Moreover, club students are not paid, implying that the true cost for the airbrakes are simply the material cost.

Life-Cycle Analysis

To evaluate the environmental implications of the proposed manufacturing process—particularly in comparison to the traditional approach—a new life-cycle analysis was conducted. Although ecological impact is not a primary concern for CPSS, it remains important to ensure that the new method does not impose an undue environmental burden. Furthermore, identifying which life stages or material properties contribute most to the environmental impact can help highlight opportunities for improving sustainability without compromising the final product's performance. Thus, another Eco-Audit and SLCA assessment were conducted.

Fiberglass Eco-Audit

The Eco-Audit for the newly proposed airbrake manufacturing process was conducted, in accordance with the updated process. Fiberglass was selected as the material, with autoclave molding as the primary manufacturing method and a cutting or trimming operation as the secondary method. As before, a 25% material loss was assumed during secondary processing. Transportation impacts were modeled using the same assumptions applied to the traditionally manufactured aluminum airbrakes. The resulting energy consumption and CO_2 emissions across the product life cycle are compared to those of the traditional process in Figure 16 and Figure 17.

As illustrated, the Eco-Audit suggests that fiberglass airbrakes are, overall, more environmentally favorable than their aluminum counterparts. Although the fiberglass components consume more energy and emit more CO_2 during manufacturing—primarily due to the energy-intensive autoclave process—their significantly lower weight leads to reduced environmental impact during transportation. Furthermore, the raw fiberglass material was shown to consume less energy and emit more CO_2 than aluminum, despite typically being regarded as an energy-intensive composite. It is important to note, however, that the aluminum was modeled as a standard industrial grade. If the aluminum used in practice contains a higher proportion of recycled content, its environmental performance could be substantially better than reflected in this comparison.

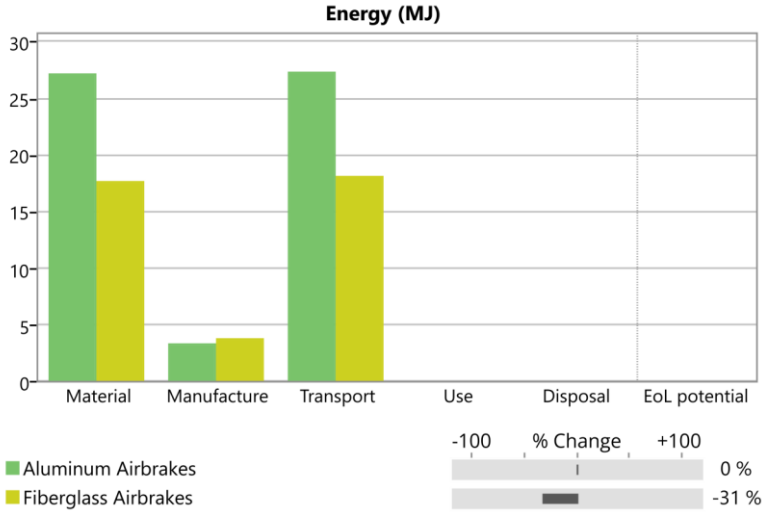


Figure 16. Energy Eco-Audit of Fiberglass Airbrakes

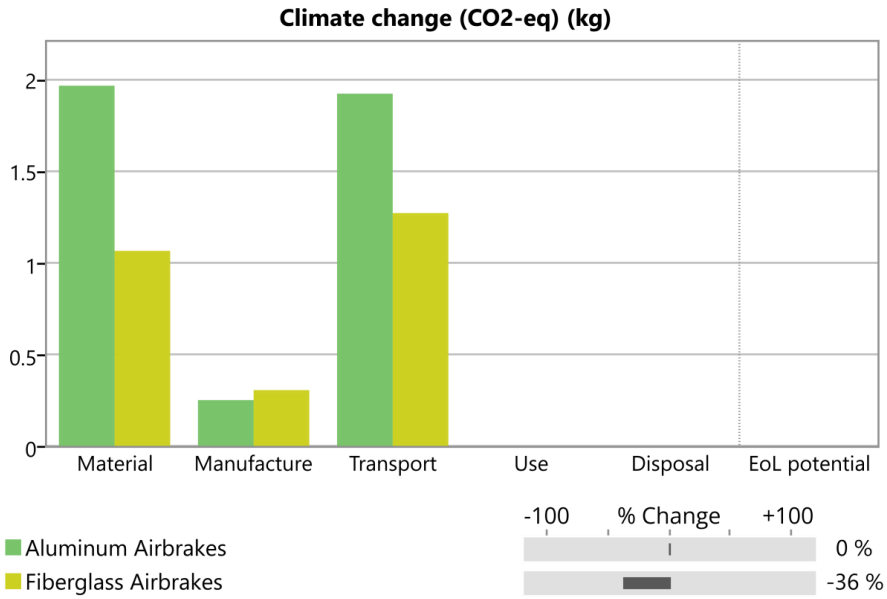


Figure 17. CO_2 Eco-Audit of Fiberglass Airbrakes

Fiberglass SLCA

The SLCA for the new fiberglass-based airbrakes is shown in Figure 18. As with the preliminary analysis, any life stage or category receiving a score of 12 or lower has been flagged as an area with the most potential for ecological improvement. It is immediately apparent that the new manufacturing method results in a lower overall SLCA score than the original method and features a greater number of areas needing attention. Specifically, the Premanufacture, Product Manufacture, and Recycling/Disposal life stages exhibit the most room for improvement, with Energy Usage, and Solid Residues emerging as the most critical categories.

Fiberglass Airbrakes						
	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	2	1	2	2	1	8
Product Manufacture	2	1	2	4	2	11
Product Delivery	4	4	4	4	4	20
Product Use	4	4	4	4	4	20
Recycling, Disposal	2	1	0	4	4	11
Total	14	11	12	18	15	70

Figure 18: SLCA Table for Fiberglass Airbrakes

The Premanufacture stage received the lowest score, largely due to the high energy intensity of producing both fiberglass and epoxy. Compounding this issue is the fact that fiberglass is not readily recyclable, and the market contains very little recycled content, resulting in a low

score for Material Choice as well. The Product Manufacture stage also performed poorly, primarily because of the use of an autoclave. While effective, autoclave curing consumes substantial energy and can produce gaseous emissions. Additionally, the use of epoxy, which is known for its toxicity in uncured form, further penalizes the environmental profile of this stage.

In contrast, the Product Delivery and Product Use stages remain unaffected by the manufacturing method and therefore scored just as well as they did under the traditional process. Since the airbrakes are manufactured in-house, no delivery stage is required, and their use involves neither energy consumption nor waste production.

The Recycling/Disposal stage also received a low score, again reflecting the challenges posed by epoxy/fiberglass composites. These materials are difficult to recycle and, in most cases, are simply discarded as solid waste. Even if recycling were attempted, the inseparability of epoxy from fiberglass would demand high energy input, further diminishing its environmental favorability.

Overall, the SLCA score for the new manufacturing method is 15 points lower than that of the traditional process—an outcome that contrasts with the results of the Eco-Audit. This discrepancy can be attributed to fundamental differences in the scope and focus of the two assessments. The Eco-Audit evaluates the actual practices, and material flows specific to CPSS operations, while the SLCA assesses the broader ecological potential of materials and processes, independent of how they are currently implemented. For example, while aluminum is highly recyclable and therefore scores well in the SLCA's end-of-life stage, CPSS does not typically recycle its aluminum components—an operational reality reflected in the Eco-Audit but not accounted for in the SLCA.

Another key distinction lies in how delivery is evaluated. The SLCA includes a Product Delivery stage, which receives a perfect score in this context due to the in-house nature of airbrake production. The Eco-Audit, however, incorporates the environmental cost of transporting stock material as part of its life-cycle assessment, thereby introducing emissions and energy usage that the SLCA does not capture. Furthermore, the Eco-Audit assumes the use typical grade of 6016-T6 aluminum, which contains a significant proportion of virgin material and thus carries a higher environmental burden. These differences in emphasis help explain the contrast between the two sets of results.

Despite this divergence, the overall SLCA score for the new method remains within an acceptable range. This is largely due to the perfect scores in the Product Delivery and Product Use stages, which help offset weaker performance in other stages. Nonetheless, the fact that every other stage received a score of 12 or lower highlights that sustainability can still be vastly improved across the product's life cycle.

Improvements

Despite Fiberglass's strong performance in the Ashby selection process—passing the ecological constraints, its poor performance in the SLCA matrix indicates that improvements are necessary. Under the advice of Dr. Galos, we investigated the potential efficacy of Basalt-based

composites, which are a somewhat new frontier in materials engineering, as it did not gain traction as an industrial-grade material until the mid-1980s [4]. Basalt composites boast a cheap and reliable alternative to other rigid fiber composites such as carbon fiber and fiberglass. Moreover, Basalt Fiber is worth exploring as a method to lower environmental impact, considering that "Basalt fiber is a green, healthy and environmentally friendly high-tech fiber product without environmental pollution" [5]. To do so, the "Synthesis" tool in Granta Edupack was used.

We created a Basalt fiber surrounded by an epoxy resin matrix with a reinforcement volume fraction of 60%. The aim was to determine if the composite can hold up against the other materials by running it through the Ashby Selection Method. The results of which are shown in Figure 19:

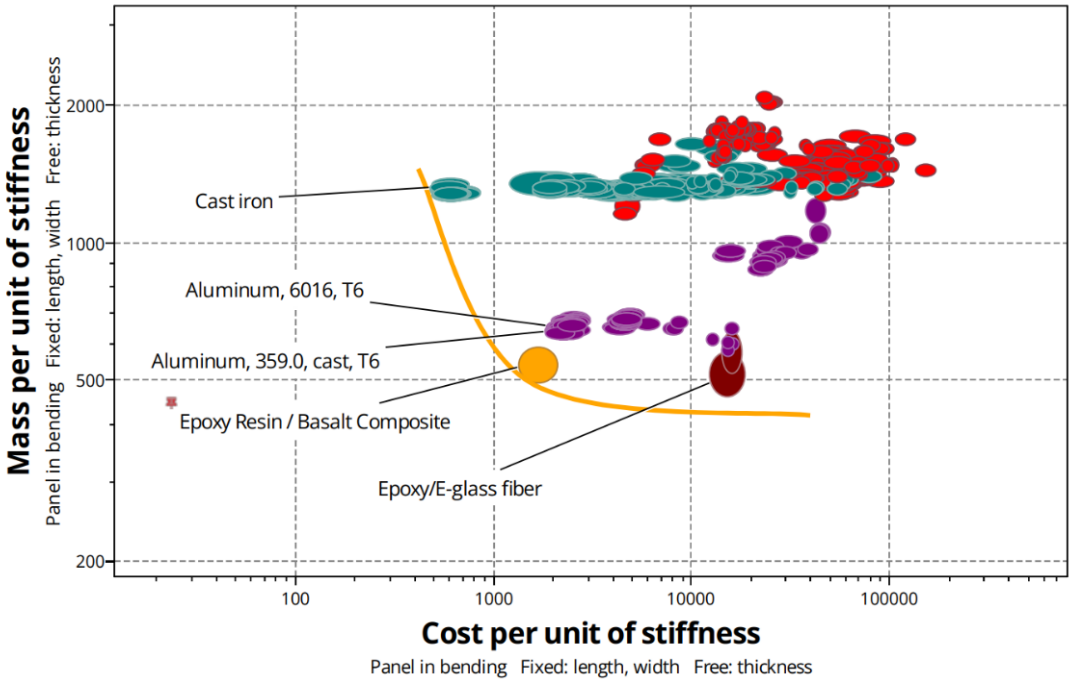


Figure 19: Ashby Plot with the Basalt Composite Highlighted

Admittedly somewhat lucky, the Basalt composite exceeded expectations during the Ashby selection process. From Figure 19, it is apparent that Basalt functions as a somewhat improved Aluminum, as it is in a similar well-rounded part of the curve, in which Cost and Mass per unit of Stiffness have relatively similar prominence. Given CPSS's emphasis on both Cost and Mass, Basalt's result from the Ashby selection indicates it is a strong candidate—rivaling the mass of Fiberglass with a Cost less than Aluminum. To be certain, we ran Basalt fiber through our WPI criteria, shown in Figure 20:

Material	Strength	B	Cost	B	Mass	B	Cor. Res.	B	WPI
Basalt Fiber	1920	100	1670	35.4	542	95.5	5	100	76.58

Figure 20: Basalt WPI

The WPI result contextualizes the strength of Basalt, which has a WPI advantage of ~8 compared to Fiberglass. Additionally, with Basalt being better in both cost, and roughly equal in mass, the solution appears to be extremely stable for a range of weighting factors. Thus, with improvements to cost, and negligible losses when it comes to mass, Basalt has significant evidence for being an improved material of choice. However, holistic cost and ecological analysis remain necessary.

Improving Cost Model

To determine what process is cost-optimized for Basalt fiber, another round of cost modeling is required. Fortunately, the manufacturing methods are the same as Fiberglass. Thus, the only change to the values used in the cost model is the mass material cost (mCm), which is shown in Figure 21:

	Autoclave Molding	Bandsaw	Waterjet
Material, mCm ($)	0.107916559	0.107916559	0.107916559

Figure 21: mCm for Basalt

Because the only difference between Basalt and Fiberglass (from a cost modeling perspective) is material cost, the graphs should be quite similar, with Basalt demonstrating a small advantage because of the cheaper material. The results of the cost model are shown below in Figure 22. Indeed, the cost model portrays a relatively invariant result, with the Bandsaw remaining the secondary process of choice with a cost advantage of $157.41—the same difference calculated for Fiberglass (sensible, as the material cost functions as a graphical shift along the y-axis). This is rationalized by the material cost's small contribution to the overall cost, implying it does not have much of an impact. For example, at the target batch size, Basalt edges out Fiberglass by a mere $2.

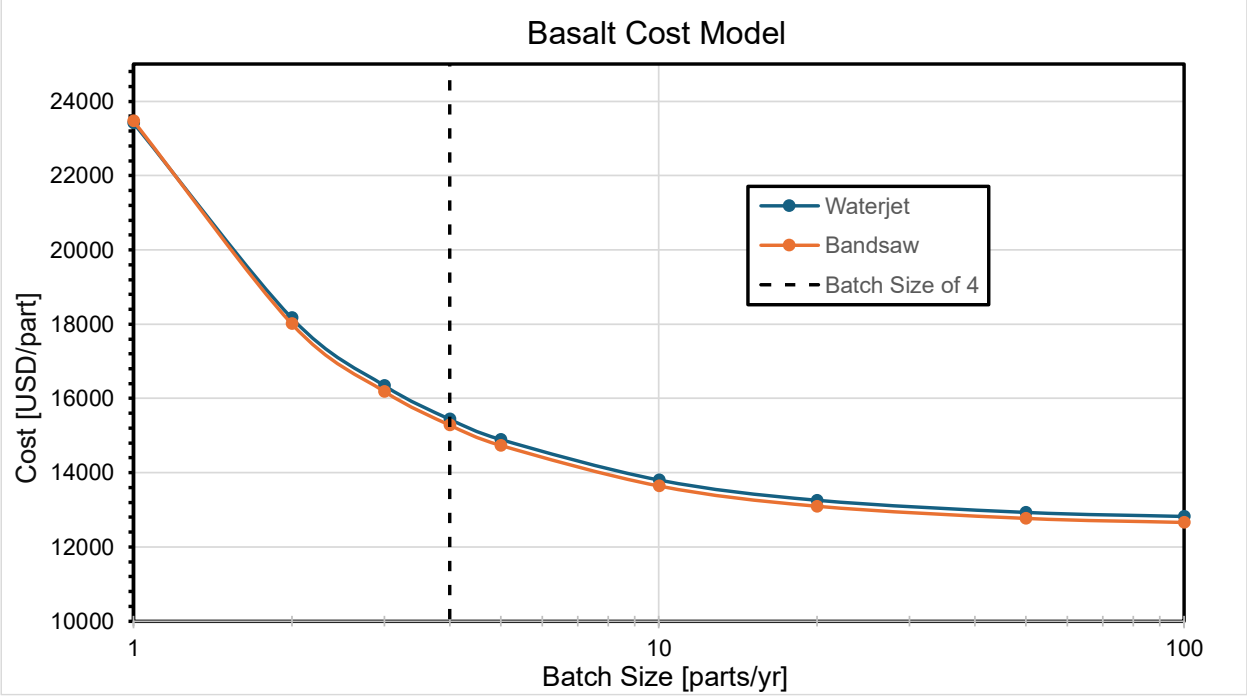


Figure 22: Basalt Cost as a Function of Batch Size

However, in reality, members of CPSS do not have to pay for the operation of the machines or personnel cost. Thus, the club's primary concern is the material cost, which, when considered alone, features an order of magnitude improvement of Basalt over Fiberglass. Nonetheless, even for the sake of this report, Basalt retains a small advantage. However, Fiberglass's primary drawback was its poor environmental impact, which illustrates an avenue in which Basalt can exert a more convincing victory as a selection.

Improving Sustainability

To evaluate the sustainability of the Basalt fiber, a similar approach to Fiberglass is used. Foremost, a qualitatively address the Basalt's environmental stressors throughout the phases of its life.

Basalt Airbrakes						
	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Premanufacture	3	2	3	3	2	13
Product Manufacture	3	2	2	3	2	12
Product Delivery	4	4	4	4	4	20
Product Use	4	4	4	4	4	20
Recycling, Disposal	4	4	3	4	4	19
Total	18	16	16	18	16	84

Figure 23: SLCA Table for Basalt Airbrakes

In Figure 23, there is a significant qualitative difference between Basalt and Fiberglass, with only two categories (Premanufacture and manufacture) being below 15. This is because despite Basalt being an abundant naturally occurring material with relatively low extraction impacts, melting and fiberization are energy-intensive. Moreover, mining Basalt is often a large-scale mining operation, contributing to a moderate score. For the manufacturing phase, there is relatively low waste, excluding resin or cleaning solvents. However, there is a high energy demand, especially considering that all materials will be manufactured primarily via the autoclave. In terms of delivery and use, Basalt Fiber is roughly equal in weight to Fiberglass (only slightly heavier) and has similar durability characteristics, thus, I elected to keep product delivery and use the same as for fiberglass. Lastly, for the disposal phase, while not broadly recyclable like metals, basalt composites are non-toxic and can be downcycled or used in cement fillers, yielding decent disposal performance. Ultimately, the SLCA is somewhat objective, although it strongly evidences Basalt's environmental advantage over Fiberglass, however, a quantitative resource like Granta is necessary for corroboration.

Thus, Granta's Eco-Audit feature was implemented using the same conditions as for Fiberglass, namely the 25% material loss, and consistent transport operations. The results from the Eco-Audit are shown below in Figure 24 and Figure 25.

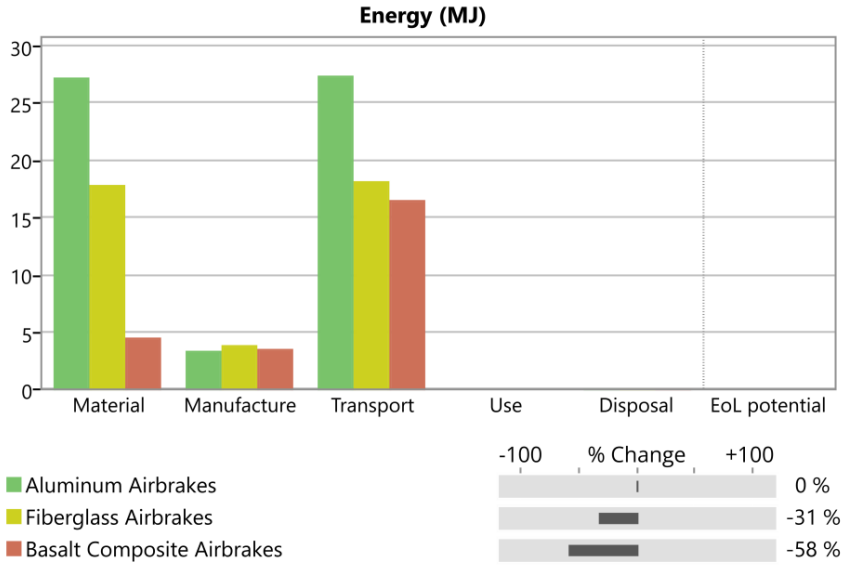


Figure 24: Energy Eco-Audit for Basalt

Figure 24 demonstrates a nice downward trend, in which the material cost decreased throughout the iterative process. However, the natural origin of Basalt plays a significant role in its energy requirements, demanding less than a third of the energy needed for Fiberglass. Moreover, Basalt fiber remains relatively equal to both Aluminum and Fiberglas during the manufacturing stage.

However, interestingly, Basalt also featured a smaller transport value, although it is less noticeable than the material differential. Ultimately, the drastic reduction in energy consumption throughout the improvement process further cements Basalt as a robust material selection.

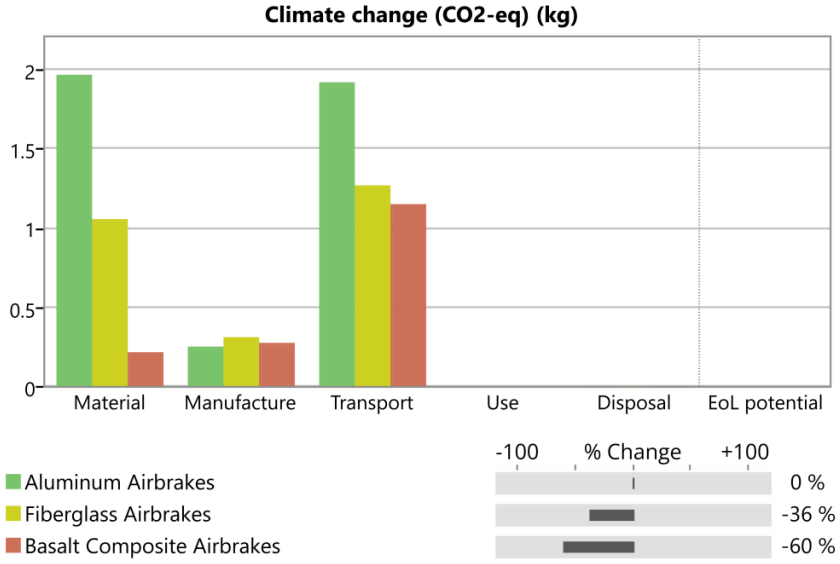


Figure 25: Carbon Dioxide Eco-Audit for Basalt

The carbon dioxide emissions shown in Figure 25 illustrate a similar trend, as carbon emissions are often a function of the required energy—especially if the energy is supplied from non-renewable sources. In this plot, Basalt appears to emit approximately one-quarter of Fiberglass's emissions, and one-eighth of Aluminum's.

From the Eco-Audit, it is clear that the SLCA holds fairly well, and that Basalt can confidently be considered to be the least environmentally intensive material. Moreover, despite CPSS being more performance focused—often electing to manufacture ecologically harmful materials in pursuit of weight and durability, Basalt fiber is a solid candidate for air brakes, as it has orders of magnitude less of an environmental impact than other considered materials while maintaining sufficient performance and economic characteristics.

Final Design Description

Ultimately, based on the proposed improvements and sustainability considerations, the final airbrake design will be constructed from a basalt fiber composite with an epoxy matrix. The airbrakes must reliably deploy into a perpendicular orientation to generate sufficient aerodynamic drag and decelerate a high-powered amateur rocket without compromising structural integrity. Since basalt fiber offers mechanical properties comparable to fiberglass, such as a high tensile strength, good thermal stability, and resistance to chemical degradation, it is a viable alternative that still meets the structural and performance demands of CPSS. A target fiber volume fraction

of 60% is specified to ensure the composite achieves the desired mechanical performance while maintaining manufacturability.

Given the similarity between epoxy–basalt and epoxy–fiberglass composites, the manufacturing process for the new airbrakes will mirror that used for the fiberglass airbrakes. The proposed method includes initial composite curing via autoclave molding, followed by trimming and shaping on either a band saw or waterjet cutter (the band saw would be most optimal in terms of cost, but are valid secondary processes). In should be noted, however, that basalt fiber pre-impregnated with epoxy resin for more consistent layups is not widely available in commercial markets. Consequently, CPSS will likely need to perform a wet lay-up, manually impregnating the basalt fiber with epoxy before autoclaving. Should prepreg basalt fiber become accessible to CPSS in the future, perhaps through custom orders with composite manufacturers like Composites One, the wet lay-up step can be skipped.

Conclusions and Recommendations

This report outlays the strategies used to provide a cumulative recommendation for the air brakes' process and material selection. CPSS has been manufacturing their air brakes out of 6061 Aluminum, which, when analyzed, is sub optimally heavy, expensive, and environmentally impactful. Thus, an Ashby selection was completed, which was then refined by a Saaty's pairwise comparison graph and a weighted property index. Additionally, a Granta-derived process selection and multi-parameter cost model was completed. The results of the selections indicated that Fiberglass manufactured with an autoclave and a bandsaw would be a suitable replacement for Aluminum, considering its lower mass, and structural performance. However, when Fiberglass's environmental impacts were considered through both an SLCA table and an Eco-Audit, it became apparent that despite outperforming Aluminum, Fiberglass remained ecologically intensive—thus alternatives were pursued.

Basalt fiber, in an epoxy matrix, was developed using Granta's synthesizer tool, which developed an additional candidate worth considering. The Basalt fiber was sufficient throughout a reiteration of the Ashby selection process, passing constraints and performing exceedingly well in an Ashby diagram. The fiber was then quantitatively ranked against Fiberglass, showing a significant outperformance. With Basalt fiber's success, it was then analyzed with respect to both cost and the environment, revealing marginal and drastic improvements, respectively. Iterating through the cost modeling remained invariant enough to retain the same process selection determined for Fiberglass. Thus, with respect to the multi-variable optimization between mass, cost and environmental impact, Basalt fiber signified an advantage in all three. Thus, the recommendation can be confidently made: CPSS should manufacture their rocket air brakes using 60% filled Basalt Fiber encased in an epoxy matrix by an autoclave, followed by liberal use of a bandsaw.

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