MTRL 280: Design Project Final Report
Group 10

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Introduction

Chosen Item & Function

The chosen item for the Materials Selection project is an ice hockey stick. Specifically, we will focus on the shaft of the stick. The stick is an essential piece of equipment in the sport of ice hockey. It is what connects the players to the puck, giving them the ability to shoot, pass, and puck handle [6]. Senior sticks range from 58 to 62 inches in length, with a long, thin shaft and a flat extension at one end called the blade. The shaft is typically made of composite materials or wood [6]. which can be customized with different flex ratings, lengths, and grips to suit the player's preferences and playing style [6]. Stick flex ratings are indicated by a number on the shaft, typically ranging from 50 to 110 [7]. The higher the number, the stiffer the stick, and vice versa [7]. However, different manufacturers may have slight variations in their flex rating systems [7]. The flex of a hockey stick is determined during the manufacturing process and can be increased if the shaft is cut shorter. A general rule of thumb for players is to use a stick flex that is half their body weight and adjust up or down based on personal preference. The lower the flex of the stick the "whippier" it is. Players may choose to use a "whippy" stick to generate medium to high shot speed but a lower amount of effort. This is called having a quick release. On the other hand, defensemen who usually have time to take slapshots in the game will opt for a high flex stick allowing them to generate a very high puck speed, with the trade-off of having a slow release.

Historical Evolution

Hockey was invented in the 1800s and the sticks were made from Hornbeam and Birch trees [5]. Hornbeam was particularly prized for its strength and was often called "ironwood." A deficit of Hornbeam in the 1900s led manufacturers to seek alternative materials [5]. Yellow birch and ash (See Figure 1) were used as replacements [4],[3],[5]. Another reason for a shift to yellow birch and ash was due to the evolving industry. Companies like Canadien and Sherwood began experimenting with fiberglass-wrapped blades in the 1950s [4],[5], and manufacturers began using fiberglass to reinforce the shaft of sticks, making them lighter, stronger, and cheaper to produce [6]. Sherwood and Canadien dominated the hockey stick market with lighter sticks made of aspen wood that was reinforced with fiberglass in the 70s [2],[4],[5]. In the 1990s, Aluminum shafts were developed and tested by NHL players [3],[5] and by the mid-90s, the first composite blade was produced [1],[5]. Just recently in 2021, companies started researching the use of Boron Fiber for hockey sticks [14],[5]. Boron has twice the stiffness when compared to Carbon, and twice the compression rating of the highest-end carbon fiber in the world [14].

Over the past decades, manufacturers have been able to significantly improve the performance and desirable characteristics of ice hockey sticks. However, manufacturers have not been able to adequately balance the durability with the increase in performance. Sticks of today are more prone to breaking compared to sticks of the past made from aluminum or wood.

Figure 1: Wooden hockey stick with a shaft made from solid white ash wood.
Source: Adapted from [2]

Stakeholder Analysis

Table 1: Stakeholder Identification

	Professional and High-Level Players	Coaches and Equipment Staff	Families of High-Level Minor Players	NHL, IIHF, Hockey Canada
User				
Customer				
Benefactor				

Green = Yes; Red = No

Table 2: Needs, Wants, and Requirements of Stakeholders

	Professional and High-Level Players	Coaches and Equipment Staff	Families of High high-level minor Players	NHL, IIHF, Hockey Canada
Needs	Durability, performance (e.g., flex, weight, balance), comfort in grip, and compatibility with their playing style	Equipment that enhances player performance, durability (to withstand frequent use), and suitability for a range of player sizes and skill levels.	Safety, size appropriate for youth players, durability.	Safe equipment for players, regulate the use of unfair equipment that gives an advantage.
Wants	Stylish design, brand reputation, endorsements by other professional players	Easy to store and transport, possibly with coaching/training-specific features (e.g., markings for hand placement).	Affordable price, appealing design for children	Professional leagues have a strong influence on the market so they want a stick that can be promoted well, this way they can expand their brand and tap into new players.
Requirements	Safety standards, league regulations for size and material	Compliance with league and training regulations, affordability for bulk purchases.	Compliance with youth league regulations, nontoxic materials, warranty or return policy	The equipment used must adhere to existing rules and regulations

Need Statement: A design that minimizes the mass in the shaft portion of a hockey stick, while being cost-effective.

After careful consideration and analysis of various stakeholders with differing needs and wants, all observations have been compiled into two different tables. Table 1 is color-coded and categorizes users, customers, and benefactors from the stakeholder groups. Whereas, Table 2 provides a brief description of each group's needs, wants, and requirements. Information has been collected from teammate Aadesh (a former high-level youth hockey player) and teammate Hamza.

The team has selected to design a hockey stick for high-performance usage and has identified that density is the most important factor to minimize. Since the primary user base will be professional players, the equipment they use will be purchased by their organizations. Therefore, cost is not a deterrent because it is understood that these individuals and clubs will pay for performance.

Mechanical Loading Analysis

In the realm of Materials Engineering, the selection of appropriate materials for specific applications necessitates a comprehensive understanding of the mechanical stresses involved [1]. In the context of an ice hockey stick, identifying and quantifying the primary modes of mechanical loading are crucial steps in designing and selecting the materials [6]. In fact, players use a mechanical aspect of the stick to their advantage. When shooting players flex the stick between their top hand and the ice with their bottom hand to load energy into the shaft, when the stick unflexes it transfers energy to the puck creating a slingshot effect [10]-[12].

There are several modes of mechanical loading within the shaft of the stick during play. However, the main form of loading is bending and can be modeled by a beam in 3-point bending. The standardized equation manufacturers use is provided below.

$\delta = Max\ Deflection$

$F = Force$

$L = Length$

$E = Young's\ Modulus$

$I = Second\ area\ moment\ of\ cross\ section$

$$\delta_{max} = \frac{FL^3}{48EI}$$

The free-body diagram of an ice hockey stick is shown here. F1 represents the top hand, F2 the bottom hand, and F the puck.

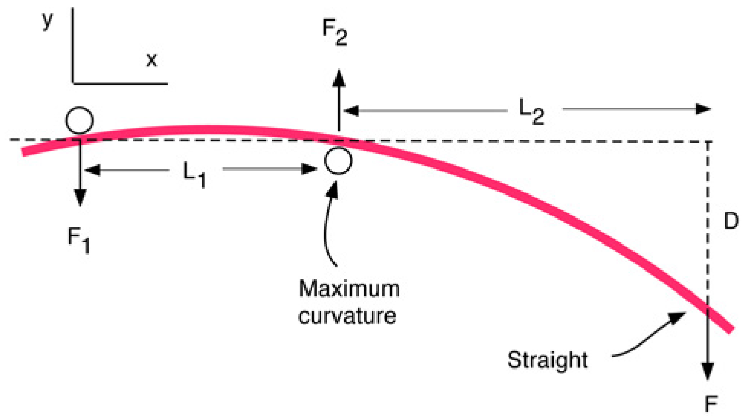


Figure 2: Free body diagram for rotation and three-point bending.
Source: Adapted from [17]

With bending, there will always be two more associated forces: tension, and compression. These forces act on the walls of the shaft and are designed to stay within the elastic region of deformation. Torsion is also an associated mode of loading with the shaft of a hockey stick and is mainly seen when receiving pucks on the blade. The free-body diagram is shown in Figure 2.

An ice hockey stick is a tool that deforms, and stores energy which can be modeled as a spring-mass system. Hooke's Law is given below [11]

$$F = k\delta$$

$F = Force$

$k = Spring\ Constant \left(\frac{N}{m}\right)$

$\delta = Static\ Deflection\ (m)$

Figure 3: Graph of Static deflection in meters vs Force Load in Newtons

Source: Adapted from [11]

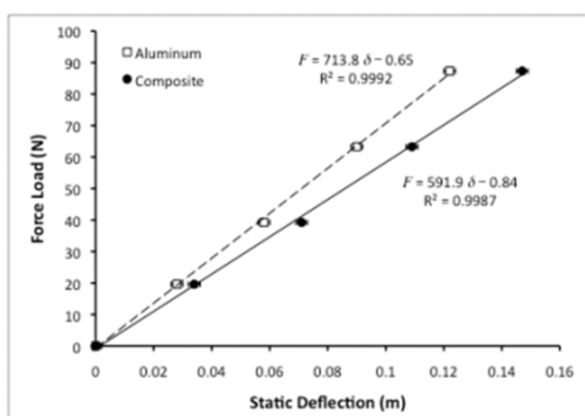


Figure 4: Chart of different materials and their flex and stiffness ratings

Source: Adapted from [11]

Stick	Stick Material	Flex Rating	Stiffness (N/m)	Young's Modulus (GPa)
S1	1" × 2" pine		3686	8.88
S2	Wood	52	7026	11.71
S3	Composite	85	6740	31.97
S4	Composite	85	8913	41.77
S5	Wood		9214	11.81
S6	Composite	85	9470	31.65
S7	Composite	85	9481	
S8	Composite	90	9237	
S9	Composite	100	8644	
S10	Composite	100	9077	
S11	Wood	85	10052	11.77
S12	Wood		10286	15.82
S13	Composite	100	10419	
S14	Composite	100	10868	
S15	Wood		10475	16.25
S16	Aluminum/wood		11420	54.62
S17	Graphite/wood	100	11939	
S18	Composite	110	11384	38.05
S19	Composite	110	13064	42.16

The maximum load that a composite ice hockey stick is accustomed to is fully dependent on the player using it. For example, an unskilled 135-pound player will not be able to fully utilize the mechanical flex while shooting and may only be able to put in 20 pounds of force on his 60-flex stick. However, a professional 215-pound player may be putting upwards of 150 pounds of force on his 90-flex stick, causing a deflection of several inches. To ensure players can utilize their stick to the maximum potential, every stick should be able to support 2.5 to 3 times the flex rating on the stick. Force versus displacement curves for aluminum and composite hockey sticks clamped at the butt end and loaded at the blade.

Identification of Objectives, Constraints, and Free Variables

Objectives

The first objective is to minimize mass. This is because the number one feature players look for in an ice hockey stick is its lightweight design. Firstly, it increases stick handling speed. Lighter sticks are easier to maneuver, allowing players to handle the puck more quickly and effectively, especially beneficial in tight situations requiring quick reactions. Secondly, a lighter stick can be moved faster, enabling quicker shots, potentially making it harder for goalies to react in time and leading to more scoring opportunities. Finally, lighter sticks can reduce player fatigue and lower the risk of injuries associated with heavier equipment, such as wrist, shoulder, and back strain. This aspect of product design is increasingly important as players and teams seek every advantage to maintain player health and longevity.

The second objective decided upon is to minimize cost. While costs may not seem significant to outsiders, most NHL teams have abundant resources and money at their disposal. However, promoting accessibility of the best products for teams in leagues with lower budgets such as the CHL, NCAA, ECHL, and SPHL, as well as individuals seeking a high-performing stick, necessitates cost minimization. Minimizing cost becomes more apparent when considering the brittle nature of modern sticks. During a hockey game, several sticks may break, with a rough low-end estimate suggesting an NHL player goes through 1.5 times the number of games in sticks per season, equating to around 123 sticks per 82-game season and approximately 2500 sticks per team per season.

Constraints

The first constraint for the shaft of the ice hockey stick is the length. According to the NHL and IIHF, the maximum allowed length from the top of the shaft to the heel of the blade is 63 inches. Players 78 inches or taller can apply for an exception allowing them to have sticks up to 65 inches in length. For simplicity, a constraint of 63 inches has been decided upon.

The second constraint relates to the operating temperature. While most rinks maintain a controlled air temperature of around 10 degrees Celsius, many players use the stick in other environments such as outdoor rinks or lakes during the winter, or on the street in the summer. Therefore, the chosen operating temperature range is from -20 to +30 degrees Celsius.

The next two constraints concern the loading of the stick and are assumptions made by Aadesh, based on his experience playing hockey. Due to the lack of information on deflection failure and force at failure of ice hockey sticks, a deflection of 4 inches is set. This is because anything above 4 inches of deflection or flex dramatically increases the chances of the stick breaking. Deflection below 4 inches does not provide an adequate amount of energy loading into the stick for a powerful shot. Secondly, the force of failure is set to 250 pounds, approximately 1100 newtons. This decision is based on the fact that the heaviest hockey players weigh around 250 pounds, and even during the heaviest shots, the maximum weight transfer to the stick would be around 50%. Thus, the heaviest player during their most powerful shot would only be putting 125 pounds of force on their stick, resulting in a factor of safety of 2.

Free Variables

The first free variable is the material used. This is ultimately what is being determined, so it must be free.

The next free variables pertain to the shape and geometry of the shaft. Although every ice hockey stick currently used has a rectangular cross-section, there are no rules governing the cross-section shape and area, allowing for the theoretical possibility of circular or hexagonal cross-sections for the shaft of a stick. Therefore, sectional shape and area are free variables.

Note: In the material indices derivation, a circular cross-section has been chosen for simplicity.

Derivation Of Material Indices

Minimizing Mass

The objective equation to minimize mass is:

$$m = \rho A L$$

Using a circular cross-section for simplicity, the area of a circle (A), leaving r as a free variable:

$$m = \rho \cdot \pi \mathrm{r}^2 \cdot \mathrm{L}$$

Since the force of failure is constrained, the following equation can be used for the constraint equation:

$$\mathrm{F_f} = \frac{\mathrm{C} \cdot \mathrm{Z} \cdot \sigma_y}{\mathrm{L}}$$

Where Z is equal to:

$$\frac{\pi \mathrm{r}^3}{4}$$

Solving for radius yields:

$$\mathrm{r}=\left(\frac{\mathrm{F_f}\cdot 4\mathrm{L}}{C\cdot\pi\cdot\sigma_y}\right)^{\frac{1}{3}}$$

Plugging in radius into the object equation:

$$\mathrm{m}=\rho\cdot\left(\pi\left(\frac{\mathrm{F_f}\cdot 4\mathrm{L}}{\mathrm{C}\cdot\pi\cdot\sigma_y}\right)^{\frac{2}{3}}\right)\cdot\mathrm{L}$$

Finally taking the inverse of the above equations and extracting material properties gives the first material index:

$$M=\frac{\sigma_y^{2/3}}{\rho}$$

Minimizing Cost

The objective equation related to cost is:

$$C=C_V\cdot V$$

Using a circular cross-section, the volume formula for a cylinder can be substituted into V:

$$\mathrm{C}=\mathrm{Cv}\cdot\pi r^2\cdot\mathrm{L}$$

The constraint equation is derived from the deflection of a bending beam:

$$\delta = \frac{\left(FL^3\right)}{(C_1 EI)}$$

Then solve for the radius and inserting into the altered objective equation:

$$\left(\frac{\mathrm{FL}^3 \cdot 4}{\mathrm{CE}\pi\delta}\right)^{\frac{1}{4}} = \mathrm{r}$$

Substitute inertia for:

$$\frac{\Pi r^4}{4}$$

Then substitute radius into the objective equation:

$$\mathrm{C} = \mathrm{Cv} \cdot \pi \left(\frac{\mathrm{FL}^3 \cdot 4}{\mathrm{CE}\pi\delta}\right)^{\frac{1}{2}} \cdot \mathrm{L}$$

Finally, taking the inverse, removing all constants and extracting material properties, resulting in the second material index:

$$M = \frac{E^{1/2}}{C_V}$$

Application of Materials Indices to Select Materials

An initial screening was performed on materials, where foams, ceramics, ferrous materials, and nonferrous materials (except Aluminum and Aluminum Alloys) were eliminated. Foams lack the necessary structural integrity and durability required for hockey sticks, leading to premature failure. Moreover, brittle materials like ceramics and ferrous materials, are prone to corrosion and breaking under stress, making them unsuitable for hockey stick construction. Nonferrous metals were screened due to them not being approved under Hockey Canada Guidelines. Nonferrous metals such as Lead are also toxic when used on their own, so they were screened out. While polymers can be suitable for certain applications, they vary widely in their mechanical properties. Some polymers may be too flexible and may not have the durability required for hockey stick construction. Therefore, for simplicity, they were screened out too.

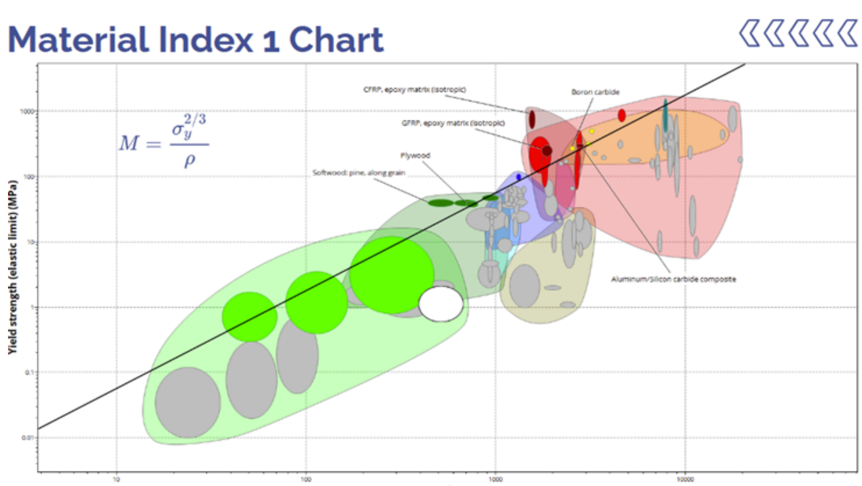
Material Selection was performed using two methods:

1) Applying both material indices onto material property charts.
2) Using a multi-constraint selection process.

Plotting Both Material Indices onto Material Property Charts

Using the first material index, the derivation of which is provided in the previous section, in CES software, Yield Strength was plotted on the Y-axis, and Density on the X-axis (figure 4).

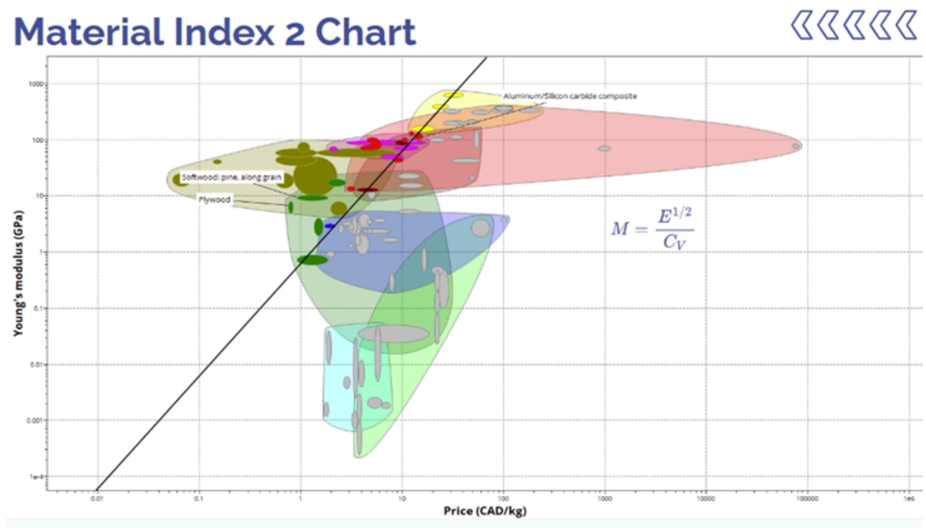
Figure 4: Graph of Yield Strength vs. Density with Material Index 1



Since the material index is raised to the exponent 2/3, the material index line will have a slope of 3/2. By adjusting the position of the index line upwards, the material index is maximized, leading to the identification of materials highlighted in Figure 1. These materials align with those currently utilized in the market for hockey sticks.

Currently, professionals predominantly use CFRP as the main material. This choice is logical as it offers the highest performance owing to its highest value for M. A comparison of M values is presented in Figure 3, revealing the following ranking of materials: 1) CFRP, 2) GFRP, 3) Pinewood, 4) Boron Carbide, and 5) Plywood.

Figure 5: Graph of Yield Strength vs. Density with Material Index 2



For the second materials index, Young's Modulus was plotted on the Y-axis, and Price on the X-axis (figure 5). Although our material index is E^1/2 / Cv, where Cv represents Cost per volume, the CES software lacks the specific Cv values. Instead, Price was utilized, which should yield a comparable trend for the graph as Cv would. With our material index raised to the exponent 1/2, the material index line will exhibit a slope of 2.

By adjusting the index line upwards, the material index is maximized, highlighting the best materials as Aluminum Silicon Carbide Composites, Pinewood, and Plywood. These materials correspond with those currently utilized in the market for hockey sticks. Over recent decades, hockey sticks have become more expensive primarily due to material advancements. Consequently, when considering cost minimization, current hockey stick materials like CFRP do not appear prominently on this chart.

Using a Multi-Constraint Selection Process

The second method for materials selection involved doing a multi-constraint selection. The choice of material needs to minimize cost (performance metric P1) and mass (performance metric P2). These metrics were derived previously in the Derivation of Material Indices section:

Performance Metric P1 (c = 1):

$$m = \rho \pi^{\frac{1}{3}} \left(\frac{4F_f}{c\sigma_y} \right)^{\frac{2}{3}} L^{\frac{5}{3}}$$

Performance Metric P2 (c = 1):

$$C = C_v \pi^{\frac{1}{2}} \left(\frac{4F}{cE\delta} \right)^{\frac{1}{2}} L^{\frac{5}{2}}$$

Note: c in the performance matrix is a constant. It is equal to 1 for failure occurring due to end loads.

Plugging in the values from the constraints determined in the objective, constraints, and free variable section into the performance equations, the performance equations were inserted into the CES software. The Cost performance equation was plugged into the axis property for the X axis, and the Mass performance equation was plugged into the axis property for the Y axis.

Figure 6: Graph optimizing for minimum mass and minimum cost

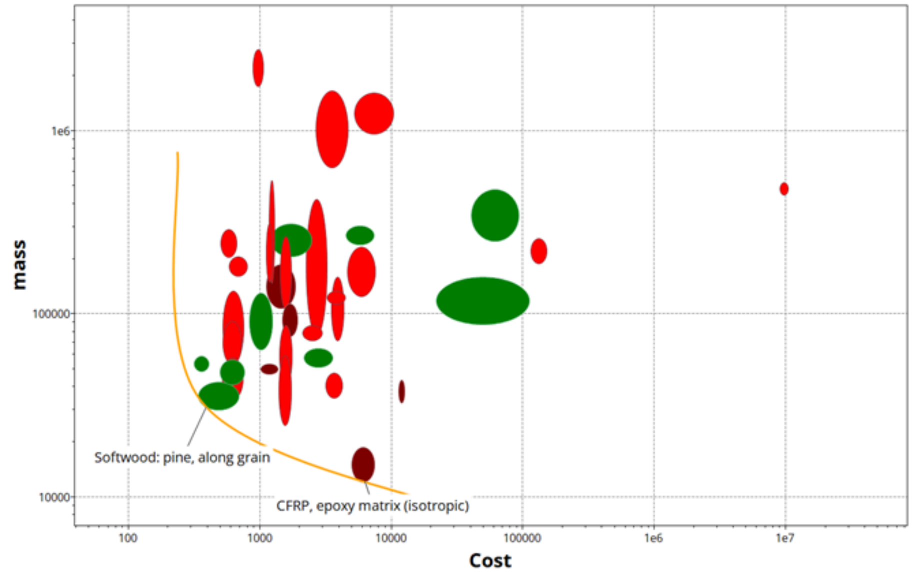
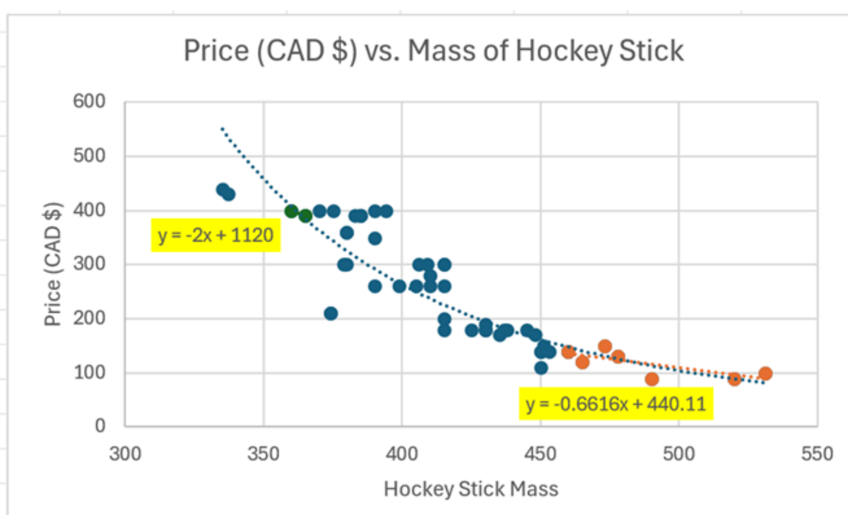


Figure 6 depicts the trade-off between mass and cost. The non-dominated solutions touch the trade-off surface; they offer the best compromise. This forms the Pareto set, which includes Pinewood and CFRP. The Pareto set in Figure 6 is labeled by the orange curve.

A penalty function will be applied, the minimum value of which gives the most preferable solution.

$$Z = \alpha_1 P_1 + \alpha_2 P_2 + \alpha_3 P_3 + \ \ldots.$$

Figure 7: Price vs. Hockey Stick Mass Plot



A curved best-fit line was plotted, and the first few points were used to draw a linear best-fit line, and the same was done for the last few points on the curve to draw another linear best-fit line (figure 7). The slope of these lines shows the exchange constants. The left-most best-fit line shows the exchange constant if price is not an issue and minimizing mass is of main concern. The equation $y = -2x + 1120$ is the equation for that best-fit line, with the slope -2 being the exchange constant. The right-most best-fit line shows the exchange constant is minimizing cost is of a concern. It is represented by the equation $y = -0.6616x + 440.11$. Here, the slope -0.6616 is the value of the exchange constant.

Now, these exchange constants can be plugged into the Z equations for all the probable materials from the Pareto set, and the penalty function (Z) can be calculated for each of them. Z (CFRP) = -27000, -2447.2. Z (pinewood) = -73000, -23979.2. The lowest Z values from the probable non-dominated solutions on the Pareto set, are -73 500 and -23979.2, both of which belong to pinewood, making it the optimal solution. The fact that Pinewood was the best material despite the two exchange constants used shows how it is not sensitive to varying exchange constants. It does not matter if the customer wants mass or cost to be a minimum, Pinewood is always the better material. Hockey sticks in the past have employed the use of the following types of woods: Ash, Hickory, Maple, Willow, Alder, and Yellow Birch. Pine was not used in the past for hockey sticks. That is because pine is a relatively soft wood and is prone to splintering, cracking, and breaking under the stresses and impacts faced during hockey gameplay. Pinewood sticks may also vary in quality and performance due to natural variations in wood grain, density, and moisture content. This inconsistency makes it challenging for professional players to find sticks that match their preferences and playing styles consistently. Pinewood lacks the performance characteristics required for elite-level hockey play. It has limited strength-to-weight ratio, flexibility, and responsiveness.

The graph in Figure 7 only optimizes mass and cost, while for professional hockey players other attributes like toughness should also be considered. CFRP is known for its exceptional strength-to-weight ratio, making it much stronger and more durable than Pinewood. This means that CFRP hockey sticks are less likely to break or deform during gameplay, providing greater reliability and longevity. CFRP hockey sticks offer consistent performance compared to pinewood sticks when it comes to responsiveness, energy transfer, and so on. A player does not need to worry about that when using a CFRP stick, and so can better focus on the game. The toughness of CFRP is also higher than pinewood, making it more resistant to fracture upon impact.

Therefore, the best material for a hockey stick shaft is Carbon Fiber Reinforced Polymer or CFRP. Their low Z value was widely influenced by their high cost, something that can be fixed by considering hybrid materials.

Consideration of Hybrid Materials

After considering both objectives of minimizing cost per volume and minimizing density, the optimal material for the hockey stick shaft emerged as Carbon Fiber Reinforced Polymer (CFRP). This material excels in strength, stiffness, and toughness without compromising on any aspect.

Despite its numerous advantages, CFRP does have one significant drawback: its cost. When compared to other materials, CFRP is notably expensive. According to the CES software, the price of CFRP ranges from $51.2 to $56.9 per kilogram of material.

Price	ⓘ	* 51.2	-	56.9	CAD/kg

Figure 8: CFRP price in CES Software

Consequently, experimentation with hybrid materials became necessary to gauge their performance relative to a hockey stick crafted solely from CFRP. Among the four types of hybrid materials considered—composites, lattice materials, segmented structures, and sandwich panels—the sandwich panel structure stood out for offering several advantages, particularly in designing a lightweight hockey stick shaft while keeping costs minimal.

Sandwich panel structures typically feature a lightweight core material sandwiched between two thin, stiff face sheets. This design offers an exceptional strength-to-weight ratio, resulting in significant weight reduction compared to solid structures or alternative materials. By reducing weight, players can achieve faster swing speeds and enhanced maneuverability, thereby improving their performance on the ice. Moreover, sandwich panel structures can prove cost-effective due to the efficient utilization of materials. The core material, often composed of foam or honeycomb structures, tends to be relatively inexpensive compared to solid materials like carbon fiber. However, carbon fiber will still be incorporated into the design. To maximize strength, carbon fiber can be utilized as one of the face sheets. Since minimal carbon fiber is used in this configuration, the overall cost would be the most economical when compared to other options.

When evaluating composites, it was discovered they can indeed offer substantial weight reduction compared to traditional materials such as wood. However, they may not achieve the same level of weight reduction as sandwich panel structures due to their solid construction. Regarding cost efficiency, composites can be pricier than sandwich panel structures, particularly when utilizing high-performance fibers like carbon fiber. Additionally, manufacturing composites may necessitate more sophisticated processes, leading to increased production costs.

When considering lattice materials, it was found that they can be very lightweight due to their open-cell structure, potentially rivaling sandwich panel structures in terms of weight reduction. While lattice materials can be lightweight, they may not be as cost-effective as sandwich panels. Manufacturing lattice structures can require precise fabrication techniques, increasing production costs. Additionally, the cost of materials for lattice structures may be higher than for sandwich panels.

When examining segmented structures, it was observed that they can be lightweight depending on the materials and design employed. Nevertheless, attaining an equivalent level of weight reduction as sandwich panel structures might pose challenges without compromising strength. Segmenting the structure could potentially elevate manufacturing complexity and cost. If the segments necessitate custom molds or machining, expenses could escalate further.

Given the earlier determination that CFRP is the optimal material, it will continue to be utilized. CFRP will be employed on the face of the panel due to its high cost. For the core, a cheaper, lighter material will be chosen, comprising the majority of the structure. This core material will be either foam or honeycomb. In the central region, where the stick experiences minimal stresses, a flexible, low-density material will be incorporated, despite its weaker properties.

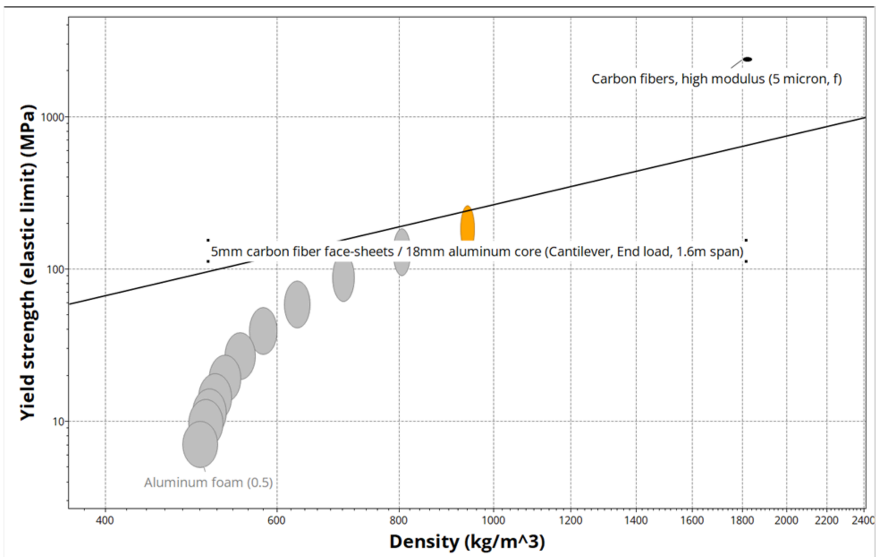


Figure 9: Graph of Yield Strength vs. Density (Aluminum foam)

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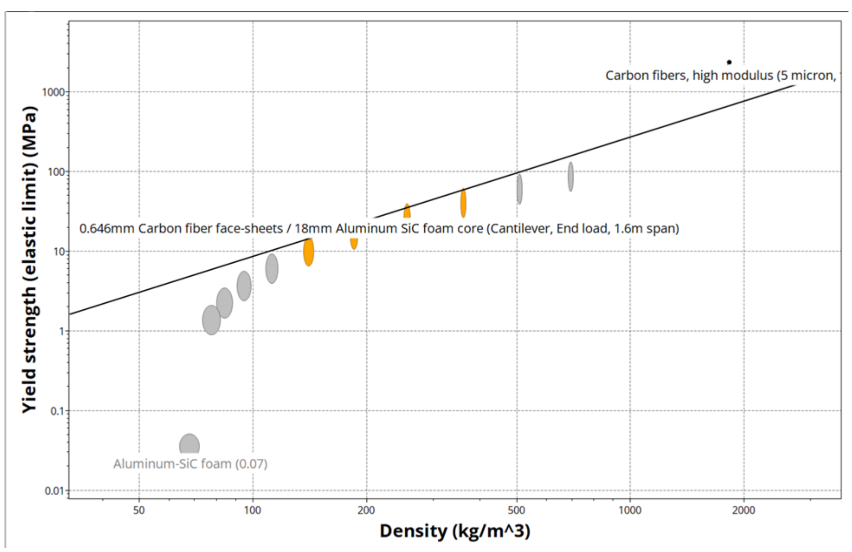


Figure 10: Graph of Yield Strength vs. Density (Aluminum- SiC foam)

In the CES software, two foam options are available: Aluminum and Aluminum SiC foam, positioned in the bottom left corner, while carbon fiber is situated in the top right-hand side of figures 9 and 10. The hybrid materials are located in the middle, occupying vacant space. Notably, the new hybrid material boasts an improved ratio of yield strength to density.

Using our materials index, a slope of 3/2 is derived. By inputting this slope into CES and maximizing the material index, the optimal hybrids are determined to be 5mm carbon fiber face sheets with an 18mm Aluminum foam core, and 0.646mm carbon fiber face sheets with an 18mm Aluminum SiC foam core. Both configurations are tested as 1.6-meter cantilever beams subjected to end loads.

Upon researching the typical thickness of a hockey stick shaft, it was found to range from 22 to 28 mm [18]. Thus, adjustments were made in the CES software to ensure the carbon fiber face sheet falls within the range of 5 mm, while the aluminum core remains at 18 mm. This configuration results in a total thickness of 28 mm, maximizing the thickness allowed for a hockey stick shaft.

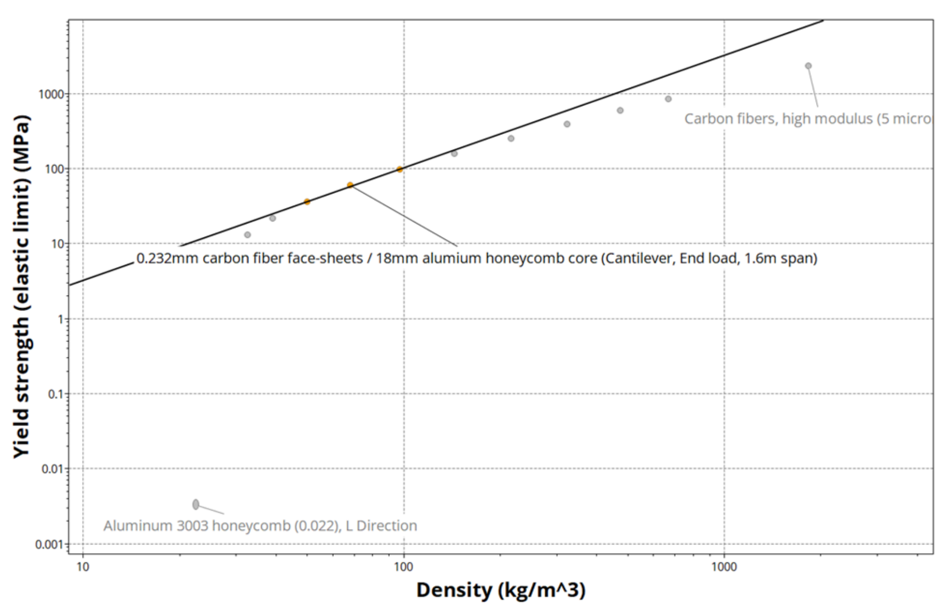


Figure 11: Graph of Yield Strength vs. Density (Aluminum 3003 honeycomb)

When conducting a similar analysis with Aluminum honeycomb, a comparable trend emerges, indicating that the hybrid material once again exhibits a superior ratio of yield strength to density (figure 11). Maximizing the material index with a slope of 3/2 yields the optimal configuration of 0.232 mm carbon fiber face sheets paired with an 18 mm aluminum honeycomb core. Like before, the shaft is tested as a 1.6-meter-long cantilever beam subjected to end loading.

Comparing the foam and honeycomb materials, it becomes evident that honeycomb material outperforms foam as the core of the sandwich panel. The graph illustrates that honeycomb provides higher yield strength while maintaining lower density than foams. Thus, the preferred hybrid material is determined to be 0.232 mm carbon fiber face sheets paired with an 18 mm aluminum honeycomb core.

Consideration of Process Selection

There are three process families: joining, finishing, and shaping. Joining does not apply because the shaft is a singular piece. Finishing can improve certain properties or aesthetics. It also typically occurs at the end of the manufacturing process. From the preliminary materials selection, foams, ceramics, ferrous materials, and nonferrous materials (except Aluminum and Aluminum Alloys) were eliminated. The process must allow for the selected material to be shaped.

Surface roughness is determined by the way the raw material is processed and can be considered to obtain a subset of more desirable processes. Surface roughness measurements are important as they display the expected behavior in slip. In the environment of a hockey stick, grip is very important[22]. Having a high grip or no grip has its pros and cons. With a non-grip finish, the user sliding their hands over the shaft is effortless, but the setback to not having that grip is that if they don't have a tight enough handle on the stick while shooting, their hand can slip and reduce the amount of power generated from the shot. Whereas with a high grip, it’s the opposite. The grip can be too tacky, which can inhibit the users' ability to slide their hands up and down the shaft. The benefit, however, is the extra grip provided locks the users' bottom hand in place to efficiently generate full power in their shots[22].

Thus, it seems optimal to opt for a moderate grip on the shaft, which allows for the ability for users to slide their hands over the shaft and maintain a tight enough handle when shooting. This is why it has been decided to go for a surface roughness range that satisfies a moderate slip, between the range of 10 µm - 15 µm[21]. As shown by Table 1.0, the relation which slip decreases as surface roughness increases.

Table 3: Surface Roughness vs Grip

Surface Roughness (Rz)	Grip
<10 µm	Low
10 µm -20µm	Moderate
>20µm	High

The batch size is large with roughly 527,098 players registered in Canada[23]. Thus, it has to be considered to be mass-produced.

Table 4: Translation of process requirements

Function	Shaping, and finishing the ice hockey stick shaft
Constraints	Material: CFRP, Possible aluminum core for hybrid material Shape: Rectangular prism Length:63 inches Deflection:4 Inches Mass:<500g Tolerance and precision: High precision Surface roughness: 10 μm -15 μm
Objective	Minimize cost
Free Variables	Choice of process Process operating conditions

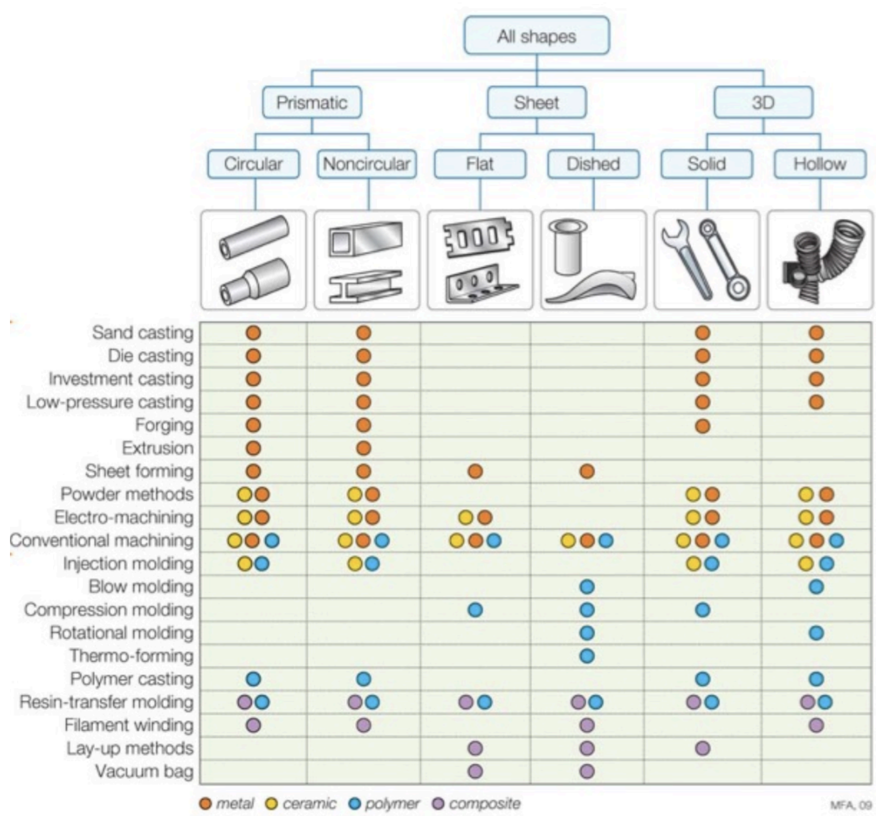
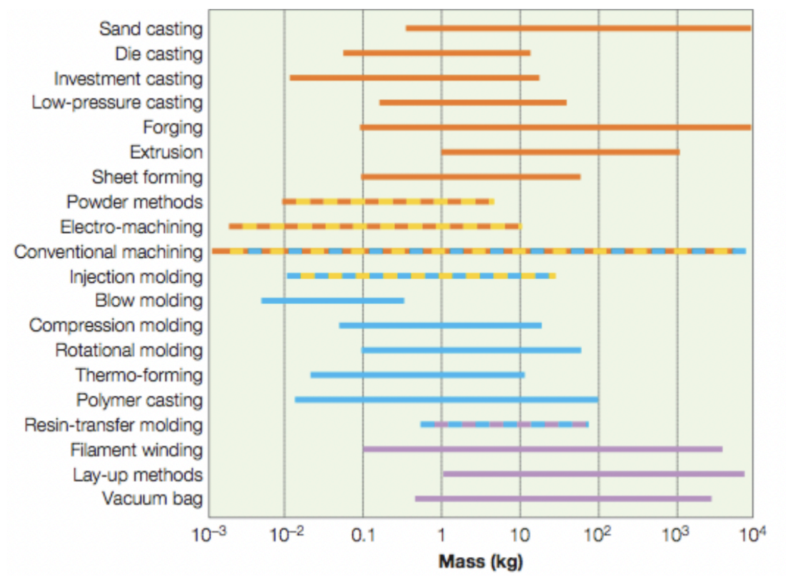


Figure 12:Processes with shape and material considerations

Since using CFRP, which is a composite, the options for shaping are limited to resin transfer molding, filament winding, layup methods, and vacuum bags as shown in Figure 12. However, since the shape is prismatic and non-circular, it narrows the options to resin transfer molding and filament winding as shown in Figure 12. Since joining is not applicable to this scenario, it will be ignored. Finishing is possible with every method.

Figure 13:Processes with mass considerations



As shown in Figure 13 are the mass allowances for the methods. Following the Constraint on mass both methods of RFM and filament winding are able to meet the mass constraint. Hence the determining factor will be cost.

Within the processes, they are unable to reach the desired surface roughness; therefore, this can be achieved with the finishing of the shaft. As shown in Table 3.0, surface roughness varies with different finishings, and as demonstrated, precision machining has the highest surface roughness. The aim is to achieve a surface roughness of 12.5µm. This is why precision machining has been opted as the finishing method[21].

Table 4:Finishing processes and their surface roughness

Process	Height of micro irregularities (μm)
Precision Turning	1.25 – 12.50
Grinding	0.90 – 5.00
Honing	0.13 – 1.25
Lapping	0.08 – 0.25
Super Finishing	0.01 – 0.25

The overall cost model:

$$C = [mC_m] + \frac{1}{n}[C_t] + \frac{1}{\dot{n}}[\dot{C}_L]$$

mCm: Cost of materials

Ct/n: Costs for equipment/tooling

ĊL/ṅ: Overhead costs for rent and electricity

The overhead cost also takes into account operating time such as capital write-off time and the fraction of the time for which equipment is productive.

To create a graphical representation of the cost model, a variety of fixed constants were integrated into the preprogrammed model. While overhead expenses, load factor, and the period for capital write-off time might differ across various processes, the model cannot adjust these parameters on a case-by-case basis. Instead, it relies on the standardized values for each process as supplied by the CES database to perform calculations. The relative cost index is thus graphed in the figure below.

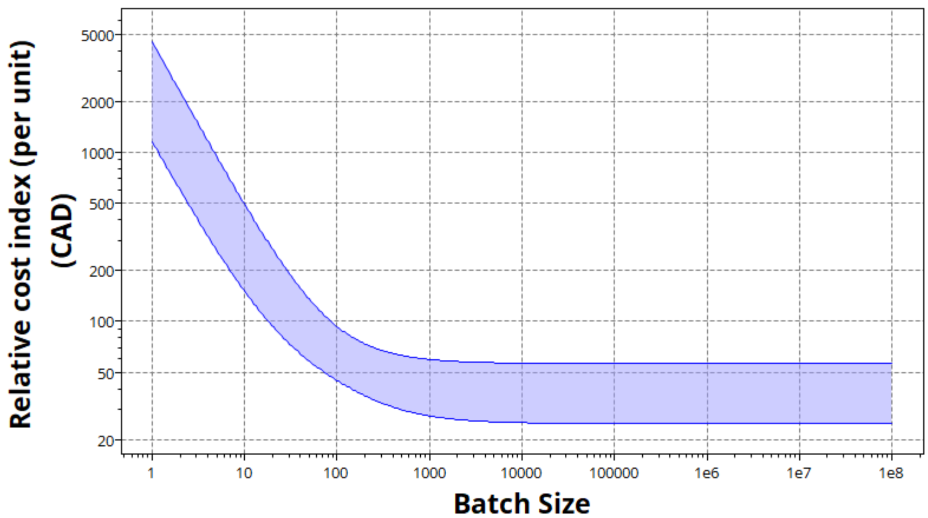


Figure 14: Resin Transfer Molding Cost Model

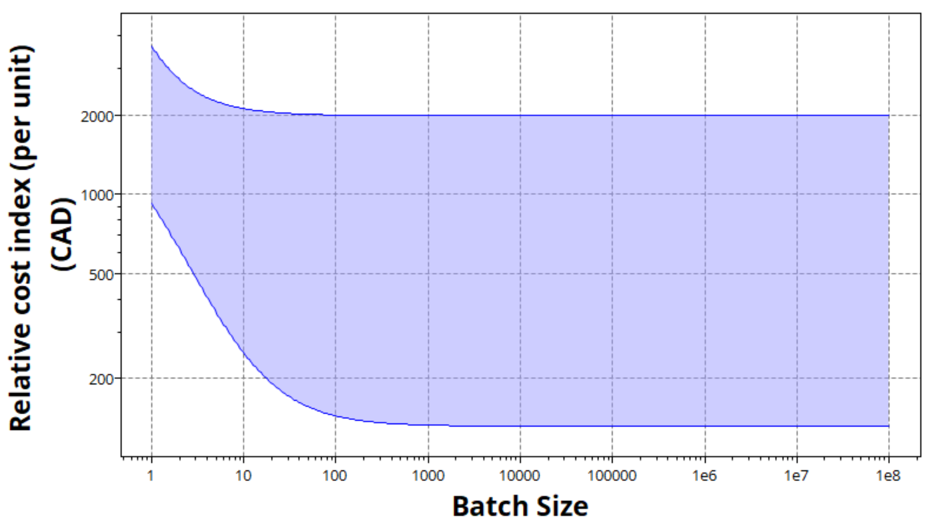


Figure:15 Filament Winding CES Cost Model

As displayed by Figure 14 and Figure 15 when having done the cost modeling for both the possible options for composite noncircular prism reaching a batch rate of 500,000 units as per the registered hockey players in Canada. It is clear that the Resin Transfer Molding method is the cheapest and hence it aligns with the already set constraints and is the chosen method.

Resin transfer molding (RTM) is a process used in composite manufacturing, allowing for the creation of complex geometries with high-quality surface finishes. The first step involves preparing a two-part mold that represents the negative of the desired non-circular prismatic shape[19]. These molds are typically made from materials that can withstand the pressures and temperatures involved in the RTM process[19].

Before the resin injection process begins in Resin Transfer Molding (RTM), the mold is pre-heated, a crucial step intended to reduce the viscosity of the resin. This reduction in viscosity is key as it facilitates the smoother flow of resin through the intricately laid carbon fibers, ensuring that every nook and cranny is reached without the formation of air pockets or voids[20]. The pre-heating of the mold not only aids in the even distribution of resin but also enhances the overall quality of the final composite material[20].

Once the mold reaches the desired temperature, the resin—already mixed with a hardener or catalyst to initiate the curing process—is injected under pressure. Depending on how complex the mold is, this injection might occur through one or multiple ports placed to optimize the flow of resin throughout the carbon fibers [20],[19]. The flow of the resin is meticulously controlled to ensure complete saturation of the fibers, a step that is important for achieving the strength and durability expected of Carbon Fiber Reinforced Polymers (CFRP)[20].

Summary

In this final report, the challenge addressed was the selection of the optimal material for the shaft of an ice hockey stick, focusing specifically on enhancing performance for professional-level players. The project began with an exploration into the history of hockey sticks, from their origins as simple wooden implements to the advanced composite materials used today. This historical context set the stage for detailed stakeholder analysis, highlighting diverse needs from durability and performance to cost-effectiveness, with an emphasis on professional players who prioritize performance attributes such as flex, weight, and balance over cost.

The approach was guided by several key assumptions critical to the project's direction. A primary user base of professional athletes was assumed, making performance the paramount concern. This informed the decision to prioritize materials that offer the best performance outcomes, without making cost a prohibitive factor. Design constraints were established based on regulatory standards and practical usage scenarios, including a maximum stick length of 63 inches and an operating temperature range between -20 to +30 degrees Celsius, to ensure usability across various playing conditions.

The material selection process was rigorously informed by mechanical loading analysis, identifying bending, tension, and torsion as primary forces acting on the stick shaft during gameplay. This analysis was pivotal in narrowing down material choices to those capable of withstanding such stresses while delivering optimal performance. The culmination of these findings pointed towards Carbon Fiber Reinforced Polymer (CFRP) as the superior material for the shaft, given its unparalleled strength-to-weight ratio, durability, and ability to maintain performance consistency, all critical for the demands of professional hockey.
Furthermore, the exploration into hybrid materials suggested that sandwich panel structures, combining CFRP with lightweight core materials, could offer a compelling balance of performance, cost, and weight advantages. This innovative approach has the potential to redefine material selection for hockey sticks, marrying traditional design elements with cutting-edge material science.

In determining the best manufacturing process, resin transfer molding emerged as the method of choice. This decision was influenced by the goal to minimize production costs while achieving the high precision and specific surface roughness needed for optimal grip and handling, aligning with the project's overarching objectives and constraints.

From the historical evolution of hockey sticks to the forefront of material science and manufacturing processes, this project aimed to blend tradition with innovation. The recommendation of CFRP, underscored by analysis and testing, reflects a commitment to pushing the boundaries of performance in professional ice hockey equipment. As a result, this project not only applied theoretical knowledge but also fostered creative thinking in solving real-world problems, setting the stage for further innovation in the design and manufacture of sports equipment.

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