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COST ESTIMATION MODEL FOR PAN BASED CARBON FIBER MANUFACTURING PROCESS

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KEYWORDS

Cost model; carbon fiber; manufacturing.

ABSTRACT

A polyacrilonitrile (PAN)-based carbon fiber manufacturing cost estimation model driven by mass is presented in this study. One of the biggest limiting factors in the large scale use of carbon fiber (CF) in manufacturing is its high cost. The costs involved in manufacturing the carbon fiber have been formalized into a cost model in order to facilitate the understanding of these factors. This can play a key role in manufacturing CF in a cost effective method. This cost model accounts for the fixed and variable costs involved in all stages of manufacturing, in addition to accounting for price elasticity.

INTRODUCTION

Carbon fiber was first synthesized and patented in 1880 by Thomas Alva Edison. It found application in the filaments of the light bulbs which were invented soon after [1]. Modern day carbon fibers were synthesized in the late 1950s and early 1960s by W. Watt in England, R. Shindo in Japan and R. Bacon in the U.S. [2].

Composite materials, especially carbon fiber based CFRPs (Carbon Fiber Reinforced Plastics) have several advantages over conventional materials, the most important being high strength to weight ratio. Hence, these materials are uniquely positioned to be used as structural components especially in the automotive industry, where they are currently used as to manufacture the body-in-white (BIW) and multiple trim components. CFRP is 35% lighter than aluminum and 60% lighter than steel for comparable structural stiffness and strength [3]. This is especially relevant in the context of the federal CAFE mileage standards [4, 7], which will be primarily achieved through manufacturing vehicles out of lighter, but equally functional materials. It has been found that using CFRP in the vehicle's BIW results in up to 10% reduction in the curb weight [3]. The current constraint in using CFRP is the high cost of the carbon fiber [5], up to $15/kg for a tensile modulus of 242 GPa, compared to $1.5/kg for stainless steel and aluminum [6]. It is estimated that by 2020, the automotive industry's reliance on carbon fiber will surge to 23,000 tons, up from 5,000 tons in 2015 [7].

While some studies have empirically estimated the distribution of cost for all the factors that contribute to the cost of manufacturing carbon fibers [8, 9], no formal cost model has been proposed in the literature. Researchers are of the opinion that unless the cost of carbon fiber is brought down to lower than $11/kg, it will not be a lucrative option for the automotive industry [8]. In order to reduce the price of manufacturing carbon fiber it is important not just to understand the source and contribution of all the factors, but also the sensitivity of these factors in the final cost. The research presented in this paper is an endeavor in that direction.

CARBON FIBER MANUFACTURING PROCESS

This section deals with a brief overview of the processes that go into the manufacturing of carbon fiber. The basic process for obtaining CF from polyacrylonitrile (PAN) precursor is presented in Figure 1. Five basic stages are identified: oxidation, carbonization, surface treatment, sizing, and winding [14, 15].

The process starts from the bobbins of PAN fiber. In the first stage *i.e.*, oxidation, the linear molecules of PAN-based polymer precursor are converted into cyclic structures. This cyclization mechanism basically consists of the incorporation of oxygen into the molecules at fixed temperature, which provides the stability to withstand the high temperatures it will face in the next stage, *i.e.* carbonization. In industrials terms, this means a controlled low-temperature heating over the range of 473 to 573 K in air for periods of time that may take up to several hours [12, 14-16]. This process is critical for obtaining high-quality CF. Empirical relationships like strength to grade of PAN used are established for the process parameters, including the fiber diameter [14].

The second stage is the carbonization, wherein the oxidized fiber enters an inert atmosphere inside a furnace where it is progressively heated.

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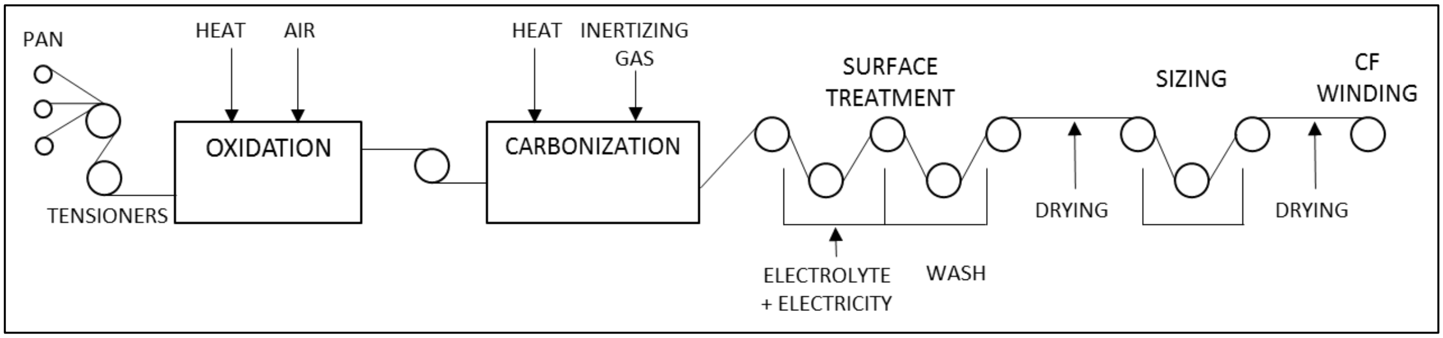

Figure 1: Schematic of CF Manufacturing Process (Adapted from [20])

At high temperatures oxygen reacts with CF and removes portions of precursor material, thereby reducing the yield. The atmosphere in the carbonization chamber is inert, so only non-carbon molecules are removed and exhausted from the furnace. This increases the carbon content of the precursor. Nitrogen is the inert gas of choice, and temperatures range from 1073 K to 1773 K [14]. As the fiber is carbonized, it loses mass and contracts in length and shrinks in diameter, resulting in a PAN to CF conversion ratio of around 2:1 [14]. This process typically takes less time than oxidation. At the end, a high strength fiber with crystallized carbon molecules, and a carbon content of 93 to 95 percent is obtained [14].

The third stage is surface treatment. The main purpose in this stage is to treat the fibers in order to enhance the adhesion between matrix resins and CF to form a reinforced composite. This process varies for each manufacturer, but a common method involves pulling the fiber through an electrochemical or electrolytic bath containing a sulfuric acid solution [14, 17]. This roughens the surface of the filaments, thereby increasing the surface area available for bonding the matrix resin. This treatment will result in a composite with up to twice the shear strength as compared with untreated fibers. Chemically, the electrically conductive fibers form the anode in the electrolysis, which causes carbonyl-containing groups to form on the smoother fiber surface; besides the mechanical properties this rough surface provides, the carbonyl groups also improve the cohesion with the matrix resin. After the treatment, the excess electrolyte is removed in a water washing [17].

The fourth stage is called the *sizing process*. Here, a coating is applied to protect and lubricate the fibers for the ease of handling [17]. The sizing materials need to be compatible with the matrix resin to allow for the penetration of the fiber bundle and interaction with the fiber surface. The sizing materials utilized in this process can be aqueous emulsifiers or resins, or even epoxy resins that are not soluble in water. The treatment can increase the weight of the fiber by 0.5 to 5 percent [14]. Finally, the fibers are dried again, and are wound on spools. This is a purely mechanical process called the *winding process*, and is not considered for this cost model.

COST MODEL

Calculating the cost for an engineering process requires knowledge of all the processes, initial investment, labor, parts, and materials cost to be analyzed amongst other costs. The knowledge of how these costs add up for the process is important to make choices on feasible alternatives [10]. Irrespective of what kind of engineering process is under consideration, engineering costs can be roughly divided into Fixed Costs and Variable Costs. Newman *et al.* [10] define these costs as: a) **Fixed Costs** are the constant cost that do not change regardless of the level of output or activity b) **Variable Costs** are those that depend on the level of activity or output.

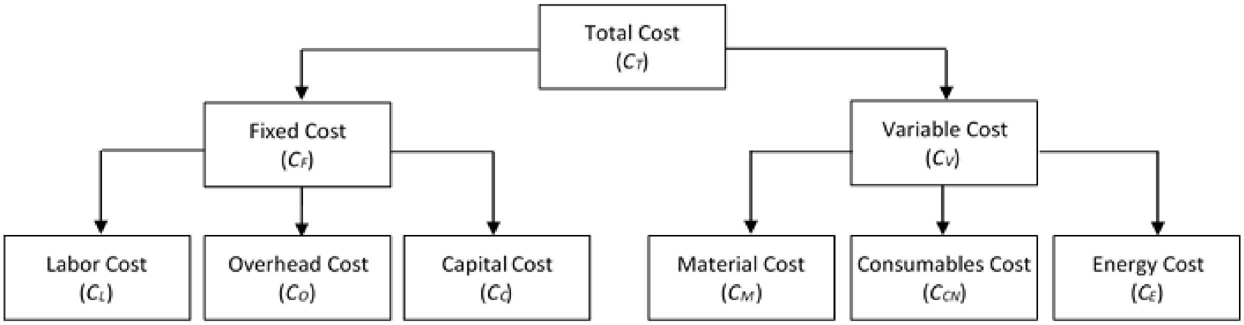

Figure 2: Cost estimation system

As can be seen in Figure 2, the total cost (C_T) has been divided into fixed costs (C_F) and variable costs (C_V). Since the model will consider the cost of making one kg of carbon fiber, the labor and the overhead costs can be considered as constant. At the same time, materials, consumables and energy cost are considered as variable. This is because even when the overall quantity of carbon fiber

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produced changes, the labor and overhead costs for 1 kg of carbon fiber will not change if the overall production increases or decreases. This also applies to the capital cost. Once the capital has been invested in the form of space and equipment, the production variation will not impact the capital cost. At the same time, material and energy cost will vary with the production quantity. In this cost model the material refers to the precursor, *i.e.* PAN; the consumables refer to the chemicals like sulfuric acid that are consumed in the manufacturing of carbon fiber; and energy cost refers to the electrical energy that goes in the manufacturing process.

Variation in the availability of different types of carbon fiber (CF) is limited. Leading manufacturers like Zoltek only offer a single type of two variants of their carbon fiber product [5]. Hence, CF production can be safely considered as a mass production process. Hence, it is a good candidate for applying a weight-based model, which accounts for expenses like material, energy and labor, as has been discussed above [11].

A brief description of the various costs discussed in the cost estimation system in Figure 2 is given as follows:

$C_T = \text{The total sum of costs involved in the manuf. process}$

$C_F = \text{Fixed Costs involved in the manufacturing process}$

$C_V = \text{Variable cost involved in the manufacturing process}$

$C_L = \text{Cost of human labor in the manufacturing process}$

$C_O = \text{Overhead costs on the labor cost}$

$C_C = \text{Initial investment in setting up the manuf. facility}$

$C_M = \text{Material cost invested in purchasing the precursor}$
(PAN in this case)

$C_{CN} = \text{Chemical reagents consumed in the manuf. process}$

$C_E = \text{Cost of electrical energy consumed in the process}$

Now that all the costs have been described, the cost model can be formulated as follows:

$$C_T = C_F + C_V \qquad (1)$$

Where:

$$C_F = C_L + C_O + C_C \qquad (2)$$

$$C_V = C_M + C_{CN} + C_E \qquad (3)$$

Substituting, equations 2 and 3 in 1, we get:

$$C_T = (C_L + C_O + C_C) + (C_M + C_{CN} + C_E) \qquad (4)$$

Hence, the total cost will account for the all the sub costs of the fixed and the variable costs.

Calculation of Fixed Costs:

As can be seen from Equation 4, the fixed cost is a summation of the labor (C_L), overhead (C_O) and capital (C_C) cost. This section will discuss the calculation of these costs.

The capital cost (C_C) will account for all the initial investment that has gone into setting up the facility. This will include costs like buying real estate, building infrastructure, and buying equipment. The labor cost (C_L) will account for the wages being paid to the employees of the manufacturing facility. This accounts only for the employees who are directly involved in the production process. Hence this does not include the cost for engineers, managers, finance and HR employees [10], who are accounted in the overhead cost (C_O).

Calculation of Variable Costs:

As can be seen from Equation 4, the variable cost is a summation of the materials (C_M), consumables (C_{CN}) and energy (C_E) cost. This section will discuss the calculation of these costs.

The C_M is considered to be the material cost incurred by the precursor material. Precursor forms the backbone of the carbon fiber. The precursor being considered in this case is PAN. There are several other precursors that are currently used in the industry, but the reason for this model focusing on PAN is that 96% of the carbon fiber being manufactured globally, as of 2012, is PAN based. This data has been reproduced from Frank *et al.* [12], and is presented in Table 1. Recent literature does not suggest a change in this trend.

$$C_M = \text{Precursor cost per kg} \cdot \text{Amount of precursor required}$$

Also, if we know the percentage yield (η) of carbon fiber from the precursor, the formula for the material cost becomes

$$C_M = \text{Precursor Cost per kg} \cdot \frac{\text{Amount of CF Required}}{\text{Yield Percentage } (\eta)} \qquad (5)$$

The amounts of consumables and energy that go into manufacturing carbon fibers will depend on all the four different stages of the process. The calculations of energy required for the heating processes are based on an ideal theoretical approach, which means that the values are underestimated. Several factors such as furnace efficiency, gas blowers, pumps, or material transportation in the process have to be considered for a more precise calculation of the energy demand. These factors vary widely among manufacturers, and therefore are difficult to account for in this model, so are estimated with a lump efficiency. However, in case they are known they can be implemented in the model by explicitly computing additional energy for each process stage.

Table 1: Precursor Preference in the Industry (Adapted from [12])

S.No.	**Manufacturer**	**Capacity (tons)**	
		PAN	**Pitch**
1	Toray Ind	9100	
2	Toho Tenax	8200	
3	Mitsuibishi Rayon	4700	
4	Zoltek	3500	
5	Hexcel	2300	
6	Formosa Plastics	1750	
7	Cytec Engineering Materials	1500	360
8	SGL Carbon Tech	1500	
9	Mitsuibishi Chemicals		750
10	Nippon Graphite		120
	Total	32,550	1,230

Oxidation: This process is energy intensive and there are no consumables involved, except for oxygen present in the air, which is free of cost. The energy consumed within the oxidation process can be modeled as the heat required for increasing the temperature of the PAN fibers. The specific heat C_p(T) in this case depends on the temperature, as shown in Figure 3. Hence the dominant cost is C_E, which can be calculated as:

$$dH = C_p(T)\, dT$$

$$H_{oxi} = \int_0^{H_{oxi}} dH = \eta \cdot \int_{T_i}^{T_f} C_p(T)\, dT$$

Where,

H_{oxi} = Total Heat Energy for Oxidation

η = Yield

T_i = Initial Tempreature

T_f = Final Tempreature

C_p = Specific Heat

Hence, the C_E for 1 kg of carbon fiber will be:

$$C_{E,oxi} = H_{oxi} \cdot \text{Cost per unit of electricity} \qquad (6)$$

Carbonization: After the oxidation process, the stabilized PAN fibers are heated in an inert atmosphere to convert into carbon fibers. A commonly utilized inertizer is nitrogen [14]. Hence the inputs to this process are energy in the form of heat and consumable nitrogen.

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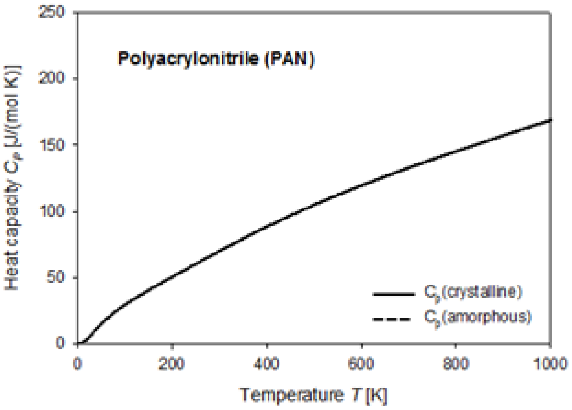

Figure 3: Variation of specific heat of PAN with temperature during oxidization [14]

Nitrogen is considered as a consumable because it reacts with hydrogen present in the PAN, and forms toxic gases like NH_3 and HCN [12]. The cost for the carbonization process is comprised of the consumable ($C_{CN,carb}$) and the energy cost ($C_{E,carb}$).

$$C_{CN,carb} = \text{Vol. of } N_2 \text{ required} \cdot \text{Cost per unit vol. of } N_2 \quad (7)$$

The flow of nitrogen is utilized by manufacturers as a parameter to control the process temperature, and therefore varies from one manufacturer to another. No specific values to tie it to the amount of carbon fiber being produced was found in the literature. In addition to the consumables, the carbonization process requires energy for heating up the precursor material that is gradually converted into CF. The specific heat utilized for the calculations is that for CF, which varies with temperature as shown in Figure 4. The specific heat of the inert gas is also a function of the temperature [2].

$$H_{carb,CF} = \int_{T_i}^{T_f} C_{p,CF}(T)\, dT$$

$$H_{carb,inert} = M_{inert} \cdot \int_{T_i}^{T_f} C_{p,inert}(T)\, dT$$

$$H_{carb} = H_{carb,CF} + H_{carb,inert}$$

$$C_{E,carb} = (H_{carb}) \text{ x Cost per unit Electricity} \quad (8)$$

Where,

$H_{carb,CF} =$ Heat Energy required to heat up the precursor

$H_{carb,inert} =$ Heat Energy required to heat up the gas

$H_{carb} =$ Total heat energy for carbonization process

$T_i =$ Initial temperature

$T_f =$ Final temperature

$C_{p,CF} =$ Specific Heat for the precursor

$C_{p,inert} =$ Specific Heat for the inert gas

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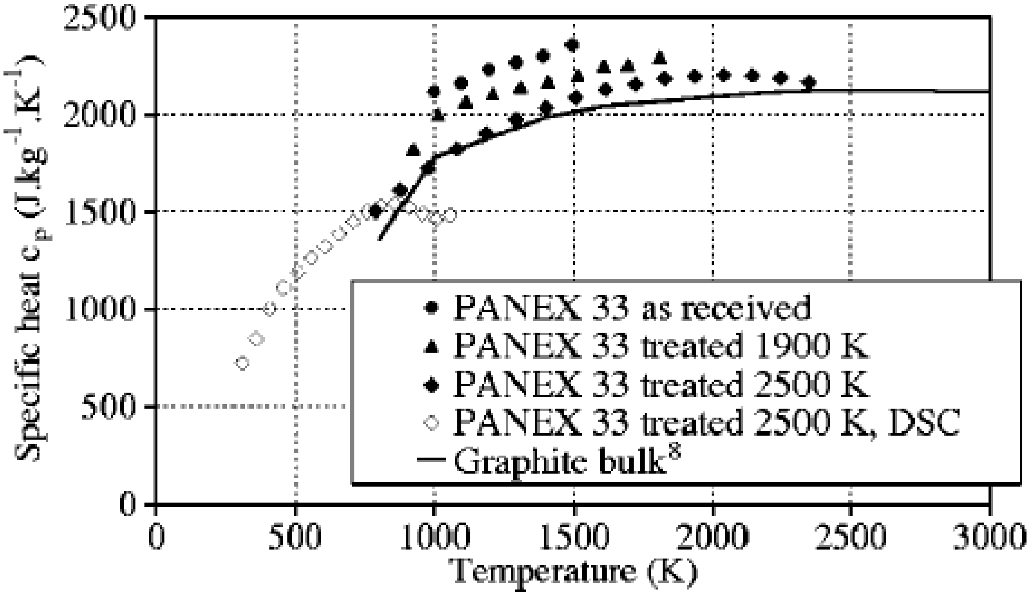

Figure 4: Variation of specific heat of different carbon fibers with temperature during carbonization [18]

Surface Treatment: After carbonization, the carbon fiber undergoes surface treatment to give it better binding properties. The process parameter driving the surface treatment cost is the addition of the sulfuric acid. The yield of the solution is expressed in kg of electrolyte solution that are made to react with the carbon fiber. The strength of this electrolyte solution is expressed as a product of the yield and the concentration and expressed as kg of electrolyte per kg of solution [18]. The mathematical expression for this consumable cost is as follows:

$$C_{CN,surf} = \lambda_{sol} \cdot C_{sol} \cdot \text{Cost per unit vol. of sulfuric acid} \quad (9)$$

Where:

λ_{sol} = electrolyte solution utilized per kg of CF

C_{sol} = Concentration of electrolyte solution per kg of CF

The electrolytic surface treatment requires an electrical input. This heat energy consumption depends on the process being carried out and varies from manufacturer to manufacturer. This cost model is based per kg of carbon fiber produced and is given by [18].

$$H_{surf} = \frac{4\Omega}{\rho\phi}$$

$$C_{E,surf} = H_{surf} \cdot \text{Cost per unit Electricity} \quad (10)$$

Where,

Ω = Energy for surface treatment parameter

ρ = Density of the carbon Fiber

ϕ = Diameter of Individual Fibers

Sizing: In this process an epoxy based emulsion is used. It is the contributor to the consumable cost. It depends on the yield, and is expressed as a ratio of the emulsion's mass per kg of carbon fiber being processed [18]. This cost can be expressed as follows:

$$C_{CN,sizing} = \lambda_{emuls} \cdot \text{Cost per unit volume of Epoxy Resin}$$

$$\lambda_{emuls} = \text{epoxy solution utilized per kg of CF} \quad (11)$$

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In addition to the consumable cost, there is also an energy requirement to be considered. This is the energy required for heating the fibers to the corresponding temperatures. This heat is supplied in two stages, pre and post sizing. The energy related to both of these processes can be calculated as [18]:

$$H_{siz,pre} = \int_{T_{i,pre}}^{T_{f,pre}} C_{p,CF}(T)\, dT$$

$$H_{siz,post} = \int_{T_{i,post}}^{T_{f,post}} C_{p,CF}(T)\, dT$$

And,

$$H_{siz} = H_{siz,pre} + H_{siz,post}$$

$$C_{E,siz} = H_{siz} \text{ x Cost per unit Electricity} \qquad (12)$$

Where symbols have their usual meanings. While the type of epoxy resin used is usually proprietary information, the calculations in this model will be based on the product from DDH Imex Inc.

Price Elasticity

The cost of materials, consumables and energy changes with the quantity of these goods being purchased. Even while considering the cost model for manufacturing 1 kg of carbon fiber. If these inputs are purchased *en masse*, they tend to reduce its specific cost. This is reflected in the cost of carbon fiber as well. An illustration of this is the exponential drop in the cost of carbon fiber per kg [5]. The price drops from $300/Kg if the output is 1 ton/year to $15/kg if the output is 35 tons/year.

This is actually a well-documented phenomenon. As the supply of a commodity goes up, its market price goes down [13]. This phenomenon is represented by the Marshallian Supply and Demand Cross Curve, as represented in Figure 5. The other dimension to this theory is that as the demand for a particular commodity increases, its price goes up. This fluctuation in price caused by the change in the demand and supply of the commodity is called price elasticity and can be defined mathematically as [13]:

$$\in = \frac{dQ/Q}{dP/P}$$

Where,

$\in$ = Elasticity of the Price

Q = Initial Quantity

P = Initial Price

dQ/Q = Change in Quantity

dP/P = Change in Price

This model will look at the demand curve, as we know that more demand for carbon fiber in the industry leads to lower prices. Moreover, the supply of industrial chemicals remains unchained. It is common knowledge that sulfuric acid and nitrogen are very widely industrial chemicals and are easily available. The same goes for electricity and PAN. Hence, when the demand for these industrial inputs goes up, their prices are driven down. The elasticity for industrial chemicals in developed nations (Organisation for Economic Co-operation and Development, OECD) is considered to be 0.4 [19].

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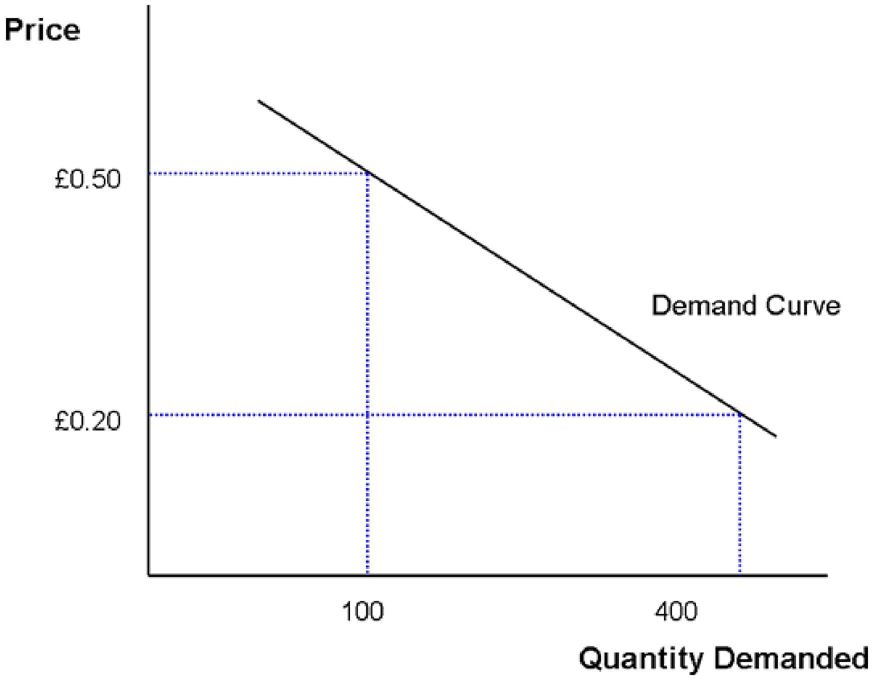

Figure 5: A generic Marshallian Demand Curve [13]

VALIDATION OF COST MODEL

Now that the cost model has been proposed, it must be tested in order to see how well it works in different situations. To do so, this model is applied across three manufacturers located in three different countries over three different continents. Their regular carbon fiber products and cost has been displayed in Table 2; the three selected manufacturers are located in the U.S., Germany and Japan. Their carbon fiber prices per kg are known. In the next experimental step, the prices for fixed and variable costs that go into manufacturing carbon fiber in each of these countries was calculated. Thereafter, these costs will be compared to see how well the experimental results overlap with the actual cost of carbon fiber.

The biggest challenge faced in this study was that the manufacturers for the carbon fibers and those of industrial chemicals were not very forthcoming with the prices for their products. Hence, sometimes, secondary sources like news articles and commodity trading websites were used as sources. This is bound to have had an impact on the accuracy of the results.

Table 2: Cost per Kg of PAN based carbon fiber

S.No.	Country	Manufacturer	Cost / Kg	References
1	U.S.A.	Zoltek	$15	6
2	Germany	SGL Group	$20	21
3	Japan	Mitsuibishi	$17.99	eBay

First, the fixed cost, *i.e.* the labor and the overhead cost will be calculated for each of these three countries. The overhead costs were assumed to be 75% for the American manufacturing and 60% for the Japanese manufacturing operations, based on a 1985 study published in the Harvard Business Review [22]. Due to the lack of further published information, the overhead costs for the German manufacturing operations will be assumed to be equivalent to the American costs.

The minimum wage in all these three countries was studied to find the labor cost. This was done so as to offset any pay differentials that the three different companies might have. For the U.S., the Federal minimum wage of $7.25/hour was considered to offset the minimum wage differentials that occur across the various states in the U.S. For Germany, this wage was considered €8.50/hour [23] which converts to $9.35/hour. For Japan, the minimum wage is $6.30/ hour [24].

As far as the time taken for each of the processes is concerned the major contributors are oxidation and carbonization. The surface treatment and sizing are almost instantaneous. To obtain a carbon fiber with tensile modulus 35 Mpsi, the oxidation time is about 105 minutes and the carbonization time 70 minutes [25]. Combined, these processes take 175 minutes, which is about 2.9 hours. These timings are for an industrial production batch of about 1 metric ton. It can be argued that the associates need not be manning these

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process while they are underway, but it is impossible to estimate the level of automation from the literature. Hence it will be assumed that the associated man these processes throughout.

For the sake of simplicity, the capital investment cost and the amortization on it will not be considered as a part of this study. This is because these costs are almost impossible to be public knowledge and cannot be found anywhere in the literature. The results of these calculations are shown in Table 3.

Table 3: Fixed Cost (C_F) for manufacturing carbon fiber

Country	**Min. Wage**	**Time (hrs)**	**Overhead (%)**	**C_F**	**C_F/Kg**
U.S.A.	\$7.25/hr	2.9	75	\$36.75	\$0.004
Germany	\$9.35/hr	2.9	75	\$47.25	\$0.005
Japan	\$6.30/hr	2.9	60	\$29.32	\$0.003

To calculate the variable costs, the consumable (C_{CN}) and energy (C_E) input costs were surveyed from a variety of online resources including vendor websites and Government reports.

To gather data on the chemical consumables, an online resource [26] was used. This resource has the process from various chemical manufacturers and retailers from different countries. Prices were used interchangeably from manufacturers and retailers. This was done because all the prices for all the consumables from the three different countries were not readily available from either the manufacturers or the retailers in those countries. Also, very few Japanese prices were available, hence the process from manufacturers in China were used. This was done because for a carbon fiber manufacturer in Japan, it would not be unusual to buy raw materials from a Chinese vendor, given the geographical proximity. Similarly, if German vendors were not available for a consumable, British process from British vendors were used.

To gather data on the electricity consumption, the reports from the Government Agencies were used. In the case of the U.S., the statistics from U.S. Department of Energy were used [27]. Since the Zoltek group has a manufacturing facility in the state of Missouri, the industrial electricity input rates as charged in Missouri were used. For Germany, the unit cost of electricity was obtained from a report by Fraunhofer [28]. For Japan, no such data was found, hence the price of electricity put out by Tokyo Electric Power Company for large scale consumers (> 300kWh/month) was used in the calculation [29].

For both the consumable and energy costs for Germany and Japan, the cost was converted from Euro and Yen respectively into U.S. Dollars using the conversion rate of 1 Euro = 1.1 USD and 1 Yen = 0.08 USD. The data for the cost of consumables and energy has been laid out in Table 4. Factors like inflation, Purchasing Power Parity and transportation costs have not been taken into account in the model or the validation procedure.

Table 4: Precursor, consumables and energy specific costs for manufacturing CF

Item	**USA**	**Germany**	**Japan**
PAN	\$4/kg	\$5/kg	\$3.3kg
Energy	c7.6/kWh (Missouri)	c0.05/kWh	c23.9/kWh
Nitrogen	\$0.06/L	\$0.09/L	0.06/L
Sulfuric acid	\$16,200/Kg	\$16,200/Kg	\$121.50/5g
Epoxy resin emulsion	\$194/Kg	\$93/500g	\$75/500g

This section contains a detailed discussion on calculation on consumable and energy cost using the proposed cost model.

Oxidation: For this stage, the initial and final temperatures are T_i = 298 K and T_f = 473 K. The typical process yield of η = 55% is considered for 1 mol of PAN that weighs 53 g [16]. To obtain 1 Kg of carbon fiber, the energy to heat up the PAN in the oxidation process then is:

$$H_{oxi} = 0.55 \cdot \int_{298}^{473} C_p(T)\, dT = 0.4899\ \frac{MJ}{Kg_{CF}}$$

The $C_{E,oxi}$ is calculated from Equation 6, for the three different countries, and is presented in Table 5.

Table 5: Energy cost for Oxidation process

Country	$C_{E,oxi}$ (Cents)	$C_{E,oxi}$ (Elastic) (Cents)
U.S.A.	102	40.8
Germany	0.07	0.028
Japan	41.71	16.64

Carbonization: Morgan [18] modeled the reactions that take place within the carbonization process, and calculated the mass balance required for producing 1 kg of carbon fiber. It works out to be .94 Kg of nitrogen per kg of carbon fiber to be produced. Hence the consumables cost for the carbonization process are calculated and presented in Table 6.

Table 6: Consumable cost for Carbonization process

Country	$C_{CN,carb}$ ($)	$C_{CN,carb}$ (Elastic) ($)
U.S.A.	0.06	0.024
Germany	0.08	0.032
Japan	0.06	0.024

The temperature for the carbonization process are T_i = 573 K and T_f = 1573 K. Then, the energy required for this stage is

$$H_{carb,CF} = \int_{573}^{1573} C_{p,CF}(T)\, dT = 1.91 \frac{MJ}{Kg_{CF}}$$

Apart from heating the carbon fiber, heat energy is also required to heat up the nitrogen. The initial temperature of nitrogen is ambient temperature, and the heat energy required is calculated as follows [18]:

$$H_{carb,N_2} \approx 0.94 \frac{Kg_{N_2}}{Kg_{CF}} \cdot 1.157 \frac{KJ}{Kg_{N_2} \cdot K} (1573 - 298)K = 1.39 \frac{MJ}{Kg_{CF}}$$

And, the total heat energy required is:

$$H_{carb} = H_{carb,CF} + H_{carb,N_2} = 3.3 \frac{MJ}{Kg_{CF}}$$

The energy cost for the carbonization process is calculated and presented in Table 7.

Table 7: Energy cost for carbonization process

Country	$C_{E,carb}$ (cents)	$C_{E,carb}$ (Elastic) (cents)
U.S.A.	89.57	35.8
Germany	0.58	0.23
Japan	281.67	112.67

Surface treatment: As has been discussed earlier, the parameters for this process are proprietary. Hence the parameters were taken from the mass balance equations in the literature. It was found that 0.002 kg of electrolyte is used from processing every kg of carbon fiber. The concentration of the electrolyte is 20 g of sulfuric acid for every 400 g of electrolyte. From Equation 9, it is found that .0001 kg of sulfuric acid is required in the synthesis of 1 kg of carbon fiber [18, 17].

The consumable cost for the surface treatment process is calculated and presented in Table 8.

Table 8: Consumable cost for Surface Treatment process

Country	$C_{CN,surf}$ ($)	$C_{CN,surf}$ (Elastic) ($)
U.S.A.	1.62	0.65
Germany	1.62	0.65
Japan	2.43	0.97

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Process parameters tend to vary the outcome of the surface treatment process. For the process being followed in this study [17], it has been found that the density of the final carbon fiber is is ρ = 1.6 g/cm^3, and its fiber diameter is φ = 6 µm. Then, the heat energy is calculated to be:

$$H_{surf} = 2\left(\frac{V \cdot A \cdot min}{m^2}\right)\left(\frac{60\ s}{min} \cdot \frac{J/s}{V \cdot A}\right)\frac{4}{1600\frac{Kg}{m^3} \cdot 6\ \mu m} = 0.05\ \frac{MJ}{Kg_{CF}}$$

The energy cost for the surface treatment process is calculated and presented in Table 9.

Table 9: Energy cost for Surface Treatment process

Country	**$C_{E,surf}$ (cents)**	**$C_{E,surf}$ (Elastic) (cents)**
U.S.A.	1.35	0.54
Germany	0.027	0.011
Japan	6.2	2.48

Sizing: According to research [18], the yield for this process is 1%. It means that for every 1 kg of carbon fiber produced, 0.001Kg of epoxy resin is required. The epoxy resin used for sizing is also proprietary, hence a DDH epoxy was used for this model validation. The consumables cost for the surface treatment process is calculated and presented in Table 10.

Table 10: Consumable cost for Sizing process

Country	**$C_{CN,siz}$ ($)**	**$C_{CN,siz}$ (Elastic) ($)**
U.S.A.	0.19	0.076
Germany	0.18	0.072
Japan	0.15	0.06

The energy consumption in the sizing process is due to pre and post drying sub-processes. The pre-drying for the sizing stage is a heating process of the CF from T_i = 308 K to T_f = 373 K. Then, the energy required is:

$$H_{siz,pre} = \int_{308}^{373} C_{p,CF}(T)\ dT = 0.05\ \frac{MJ}{Kg_{CF}}$$

The post-drying is a heating process from T_i = 333 K to T_f = 443 K. Then, the energy required is:

$$H_{siz,post} = \int_{333}^{443} C_{p,CF}(T)\ dT = 0.1\ \frac{MJ}{Kg_{CF}}$$

Using Equation 12, the total energy required is:

$$H_{siz} = 0.15\ \frac{MJ}{Kg_{CF}}$$

The energy cost for the carbonization process is calculated and presented in Table 11.

Table 11: Energy cost for Sizing process

Country	**$C_{E,siz}$ (cents)**	**$C_{E,siz}$ (Elastic) (cents)**
U.S.A.	4.07	1.6
Germany	0.2	0.08
Japan	23.64	9.4

The most important component in all of these processes is PAN, which is the precursor and forms the backbone of the carbon fiber. Its cost is calculated for a 55% yield process using Equation 5, and is presented in Table 12. The difference here is that the elasticity has already been taken into account, by virtue of obtaining the exact cost at an industrial scale from [8].

Table 12: PAN cost for CF manufacturing process

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Country	C_M ($)
U.S.A.	7.2
Germany	9.09
Japan	5.45

Results and Discussion:

Now that all the costs that go into manufacturing the carbon fiber have been computed from the cost model, the result must be compared to the known market values of the carbon fibers. The comparison will be done based on the fixed costs and elastic value of the variable costs that have been calculated in the previous section.

Table 13: Comparison of market price and predicted costs for CF manufacturing process

Country	Market price $/Kg	Predicted cost $/Kg	Percent error
U.S.A.	15	8.72	41.9 %
Germany	20	9.85	50.8 %
Japan	17.99	6.89	61.7 %

From Table 13 it can be seen that the worst prediction of this model was for the Japan test case, and the best one was for the U.S. test case. This can be attributed to a wide range of factors including, but not limited to: a) lack of accurate data on industrial chemicals input b) difference in the process parameters c) choice of reagent d) price elasticity.

Lack of accurate data in industrial chemicals input: The source used for looking up the costs of industrial chemicals had multiple different manufacturers and retailers from the same countries selling their respective products at different prices which had a lot of variation in them. Wherever possible, the average was averaged, but it still seems to be too complex of a market for a simple mathematical function as arithmetic mean to account for the differences.

Difference in the process parameters: The calculations were based on process parameter information extracted from different academic resources. It was made sure that the process parameters were leading to a carbon fiber of similar strength and physical properties. This way of retrieving information obviously lacks coherence. Moreover, the process parameters will vary from academics to the industry and also vary within industry. Most of the times these parameters are proprietary and are not disclosed to the academic community. Energy calculations are ideal and do not account for furnaces inefficiencies, blowers or pumps power consumption, material transport in the process, etc. Due to the lack of this information, the results are underestimated.

Choice of reagent: This factor comes into play in all the three stages except for oxidation. The choice of nitrogen instead of argon in the carbonization can result in an error, since the market price of these two reagents is different. Similarly for surface treatment, if the sulfuric acid is replaced by a different agent, it will affect the cost model. In Sizing, the choice of epoxy resin can have the same effect.

Price elasticity: The price elasticity in this model has been assumed to be linear. This is not very realistic and can contribute to the error.

Although this model is very robust and can accommodate all of the above factors listed above, there need to be more willingness in the industry to share data. It is important to note that the cost calculated by the authors is the manufacturing cost. In practice, the manufacturers sell the product for more than the manufacturing cost. This difference is known as the markup. The markup is variable and will be different for different companies.

Some amount of difficulty was experienced in being able to obtain market prices for the cost German and Japanese companies. Moreover, the actual industrial data was not available. Once these resources are available, the model will definitely give out better results.

Proposed Improvements:

There is some further scope to refine this model. First and foremost, a careful relationship of the elasticity of industrial reagents should be carried out to enhance the accuracy of this model. This will ensure that the model will not only give better results for present scenarios where accurate data is not available, but also can predict the future costs more accurately. To further fine tune this model, a sensitivity analysis must be done to understand what parameter(s) causes the most change in the results.

FUTURE DIRECTIONS

As the need for manufacturing low-cost carbon fiber keeps growing, research efforts on that behalf are being conducted. Recent advances have been made in the development of lignin as an alternative precursor. This polymer offers the advantages of being a low cost, abundant and renewable resource [8]. The properties for the lignin-based carbon fiber are not as good as the conventional carbon fibers, but undergoing research indicates that those downsides can be overcome by the identification of more suitable types of lignin for

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the manufacturing process [8]. The US Department Of Energy has estimated that the cost for a suitable lignin precursor, including the required processing and an adjustment for a carbon fiber yield of ~55%, would end up in $1.52/kg, resulting in a carbon fiber cost of $6.27/kg. This is substantially lower than PAN precursors, which start from $2.2/kg, and the derived carbon fiber cost is above $12.25/kg [8].

With that in consideration, it is proposed to further develop cost models for carbon fibers which consider the new tendencies in carbon fiber technologies, particularly lignin-based CF. Cost models provide an insight for the overall price of products, allowing to identify opportunities of improvements. The cost of the precursor is just one element of the final cost of carbon fiber, and even if it is relatively low, the cost for processing it could make the technology non-viable. Hence the cost model can help on weighting the costs for each element of a given technology, and analyze where the efforts have to be focused on.

CONCLUSION

This study has focused on developing a cost model for the PAN based carbon fiber manufacturing. The cost for four stages of processing, *i.e.* Oxidation, Carbonization, Surface Treatment and Sizing were considered, in addition to the PAN precursor cost. The cost model was verified against known market prices from three different carbon fiber manufacturers located in three different countries over three different continents. The countries chosen were U.S., Germany and Japan. It was found that given the prices of inputs (chemical reagents and energy) the cost model could predict the carbon fiber's market value per kg within an error range of 61.70% to 41.87%. The salient feature of the model is that the cost elasticity has also been incorporated into the model. This was done to account for the falling cost inputs as there is a demand for them by the carbon fiber manufacturers. The causes of error were: a) lack of accurate data on industrial chemicals input b) difference in the process parameters c) choice of reagent d) price elasticity. It was found that the model is robust enough to accommodate a change in the choice of reagents and energy inputs as well as a change in market prices.

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