TECHNICAL COST MODELING METHODOLOGY FOR NOVEL MANUFACTURING

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ABSTRACT

The automotive industry's interest in utilizing composites within mainstream production vehicles continues to expand as it seeks methods to meet increasingly strict mileage and emissions regulations. However, traditional costing methods are incapable of determining the manufacturing costs associated with the novel materials and manufacturing processes required for high volume production of composite parts due to the lack of historical manufacturing information.

This research effort develops a method that reduces the complex composite manufacturing systems to fungible, upgradable, and linkable individual processes. Employing Technical Cost Modeling (TCM), this method shall accurately quantify the value of pursuing composite manufacturing by integrating technical data from computer-aided part design simulation tools and manufacturing process modeling to deliver an accurate cost estimate.

We investigate one high-volume capable, novel manufacturing process appealing to the automotive industry: hybrid molding. In hybrid molding, a structural preform is over-molded with a thermoplastic to create the final part. The Composite Manufacturing & Simulation Center has developed an intensive part performance design model to determine optimal processing conditions which are used as process inputs for the TCM.

1. INTRODUCTION

Weight reduction is one aspect of modern design that may be captured through the use of composite materials. Though applicable and beneficial in almost any product's design, weight reduction is particularly beneficial to the transportation sector, where it is often referred to as lightweighting. [1] Properly lightweighted parts in vehicles may increase fuel efficiency or reduce engine load leading to reduced emissions for internal combustion engines or increase the range of electric vehicles. However, composite material processing and manufacturing technologies to meet the production demands of the automotive industry are only in the infant stages, thus their costs are difficult to capture via traditional costing methods due to a lack of an historical database of similar part variants or cost estimation relationships. [2]

Adoption of composites manufacturing to high-throughput industries is capable via two routes. Adaptation of existing aerospace technologies to mass-production, such as High Pressure-

SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.

Resin Transfer Molding or Automatic Tape Laying, through advancements in new material systems and automation is one possibility. New materials are being developed that reduce the need of an autoclave, a major source to manufacturing cycle time, known as out-of-autoclave materials. The second route is through adaptation of current automotive mass-production technologies by converting existing manufacturing equipment and introducing tailored preforms. A tailored preform is a framework of composite that provides customized structural strength that can then be over-molded to provide the desired finish. Existing injection molding machines can be converted to accept these tailored preforms, transforming the process to what is known as hybrid molding. [3] Though in the early stages of adoption by the automotive industry, determining the manufacturing costs is possible through the use of a TCM coupled with Computer Aided Engineering (CAE) design tools.

The following TCM methodology shall focus on hybrid molding, though is applicable for the other manufacturing processes discussed above.

1.1 Technical Cost Modeling

TCM is a form of bottom-up cost estimation. Bottom-up cost estimation may be performed for any part as it sequentially follows a part from raw material input to final part output, summing all the costs associated with each manufacturing step along the way. This is beneficial as costs are extremely detailed and individual part features can be identified by cost for redesign. However, it requires extensive knowledge of the manufacturing processes and the part design to truly capture all the processing steps. [4]

TCM deviates from bottom-up cost estimation as it draws processing conditions from the chemistry and physics involved in various manufacturing steps. For example, if a preform requires preheating prior to over-molding, the material characteristics are used to calculate the required time spent in and the set temperature of the preheat oven. This information may then be utilized to calculate the time the oven is in-use and the electrical consumption. The processing parameters utilized within the proposed TCM are extracted from a series of CAE tools used to design the optimal designed-for-manufacturing part.

1.2 Hybrid Molding

Hybrid molding involves creating a structural backbone, typically of a continuous fiber fabric or tow and known as a preform, followed by injection of a polymer to create three-dimensional complex geometries. Inserts, such as bushings or threaded joints, may be incorporated into the preform to provide reinforced connection points. Over-molding finalizes the shape and may provide high quality surface finishes desired in the automotive industry. The tailored preform and possible discontinuous reinforcing fiber included in the polymer provide the strength that is required for structural components, overcoming the weakness of the pure or discontinuous fiber-reinforced polymer.

1.2.1 Hybrid Molding Process Overview

To test this TCM concept, the hybrid molding process of a test coupon utilizing thermoplastic tape was chosen. The process starts with the loading of bobbins composed of 50% e-glass and 50% polypropylene tape onto a creel, then the tape is fed into the EELCEE QEE-TECH® Preforming Cell (QTC). Within the Preforming Cell, the tape is heated and consolidated within an infrared oven, then fed through the Layup Head and laid-up into the preform shape on the XYZ Table. The test coupon preform layup is performed on a jig that holds two aluminum bushings that the tape is wrapped around. Once the layup is complete, the tape is cut and the transfer robot removes the preform from the jig, places two new bushings for the next layup cycle, and transfers the completed preform into the Krauss Maffei *FiberForm* Injection Molding machine where the preform is over-molded with polypropylene to complete the test coupon. Once the injection cycle is complete, the transfer robot transfers the test coupon to the trimming and quality assurance station. There, the sprue and cold runner are trimmed and the part is scanned with a Hexagon Leica T-Scan 5 laser scanner to compare it to the digital product definition. This process is illustrated in Figure 1.

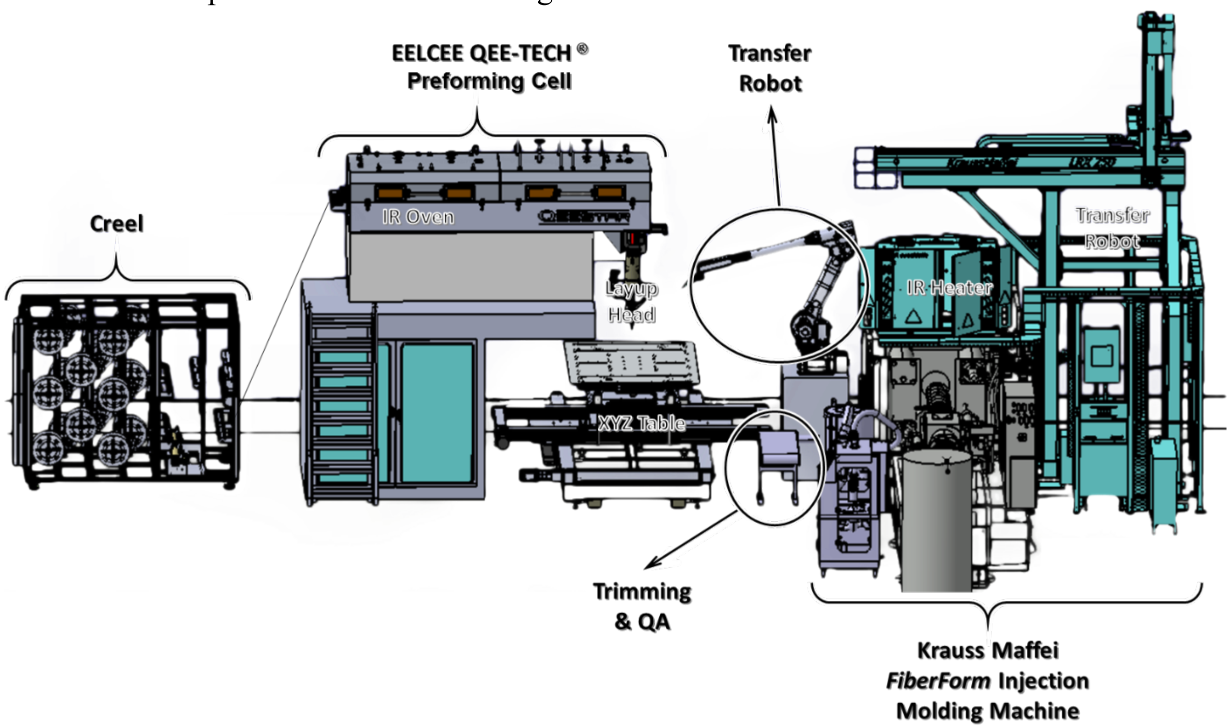

Figure 1. Hybrid molding process overview for production of continuous thermoplastic tape preform over-molded with polypropylene.

2. METHODOLOGY

Implementing a TCM is a complex and involved endeavor. However, for manufacturing processes that are not in-use currently, a TCM captures the manufacturing costs required to make sound financial decisions. The following general steps may be employed to develop a TCM:

1) Receive basic part design details.
2) Receive desired economic analysis (if any).
3) Identify cost drivers to be analyzed.
4) Develop process flow.
5) Develop cost driver analysis.
6) Identify or receive processing conditions.
7) Receive refined/final part design details.
8) Execute model.
9) Refine and improve.

These steps may be worked concurrently and shall be discussed in detail below to develop the TCM for the process described in *Section 1.2.1*.

2.1 Receive basic part design details

The final designed part, the test coupon, requiring cost estimation is composed of three materials; two aluminum bushings weighing 61.118 g, two 610 mm lengths of 50 % e-glass and 50 % polypropylene (thermoplastic) tape (TP Tape) consolidated into one Tow (TP Tow) of area 15.4 mm^2, and 105.722 mm^3 of injected polypropylene. The sprue and cold runner are composed of 15.5239 mm^3 of polypropylene as well. The test coupon is visualized in Figure 2.

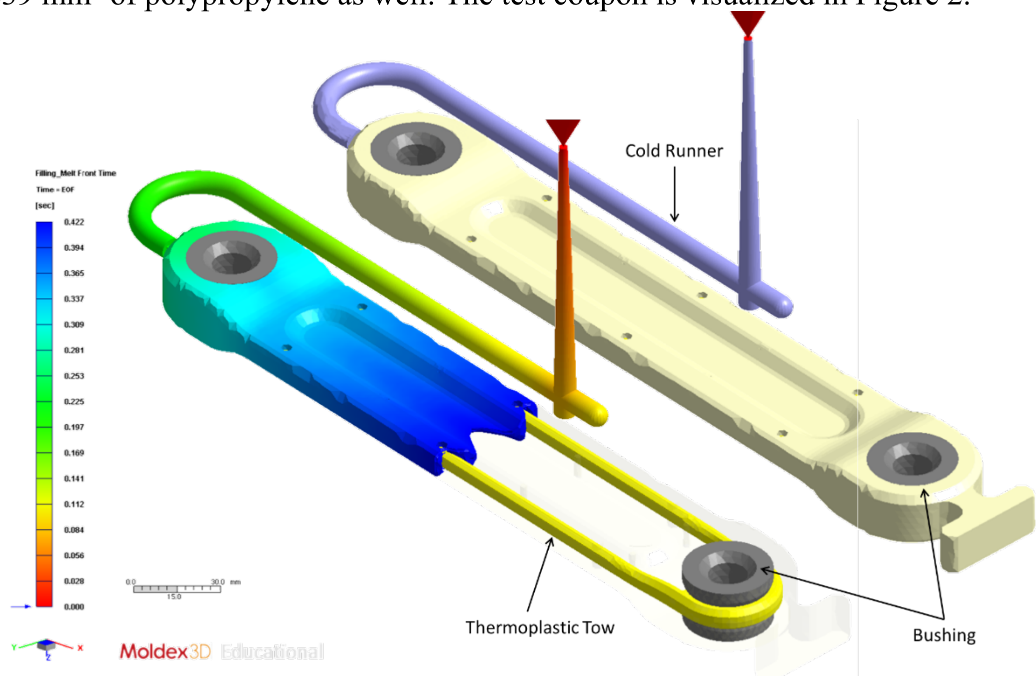

Figure 2. Test Coupon illustration as ejected from the injection molding machine (right) and as filling progresses to show exposed TP Tow and aluminum bushing

Receipt of the basic part design allows the possible process flows, or manufacturing routes, to be developed for comparison purposes.

2.2 Receive desired economic analysis

One process flow shall be investigated at this time, however, five scenarios shall be presented. A cost breakdown for the cost drivers highlighted in section 2.3 is the desired economic analysis for this investigation. The first scenario is the base case and subsequent scenarios are altered from it as described in Table 1.

Table 1. Scenarios desired for economic comparisons.

Scenario	1	2	3	4	5
Description	Base Case	25% Increase in Equipment Cost	50% Increase of Injection Cycle Time	10% Reject at Inspection	Workers Replace Robots

2.3 Identify cost drivers to be analyzed

This TCM is designed to capture the manufacturing cost subset of the total operating cost. Overhead and business environment costs that make up the sales revenue are company specific and are left out of the analysis at this time. Cost drivers that are included in this TCM are highlighted in Figure 3 in purple.

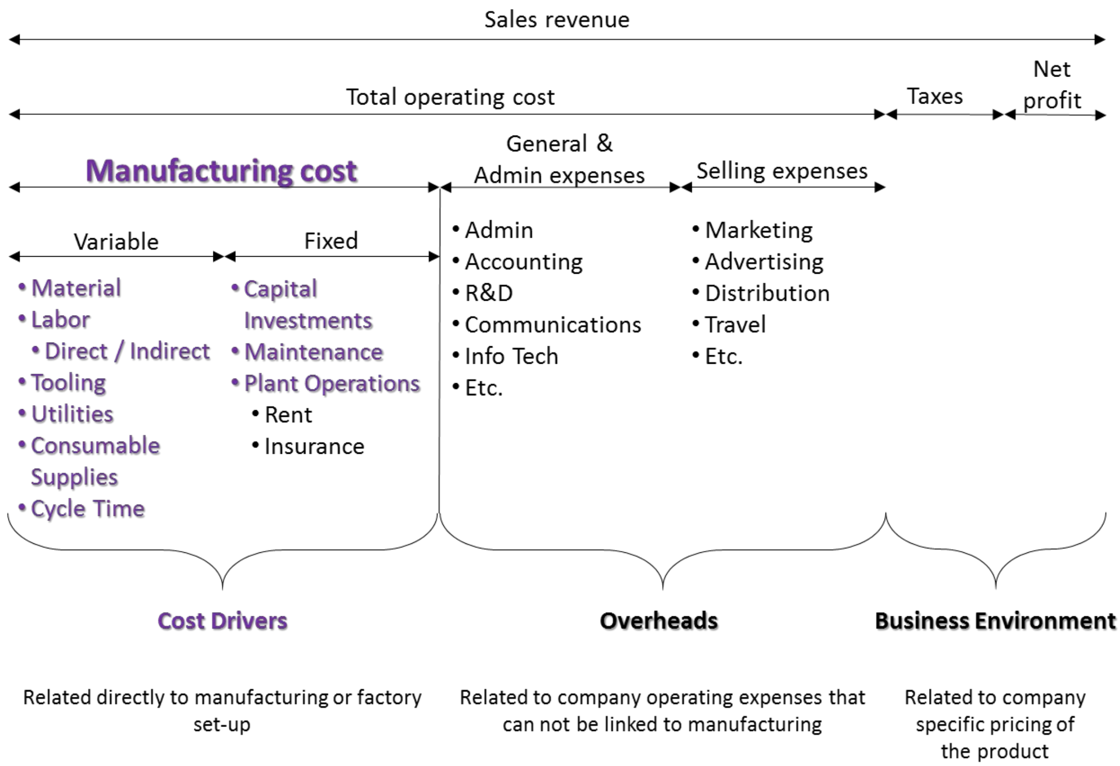

Figure 3. Cost drivers to be analyzed within TCM. [adapted from 5]

2.4 Develop process flow

One possible manufacturing route is investigated in this paper and is presented in section 1.2.1. Overall, there are six process steps that make up the TCM:

1. Preforming & bushing insert
2. Transfer to injection molding
3. Injection molding
4. Transfer to trim and QC
5. Ultrasonic cutting
6. Quality control

2.5 Develop cost driver analysis

The cost driver analysis consists of the equations used to calculate the manufacturing cost per part. For the presented TCM, the total cost per part, C_{man}, is captured with Equation 1.

$$C_{man} = \sum C_{material,i} + C_{equip} + C_{tool,pp} + C_{plant,pp} + C_{AEnergy,pp} + C_{L-cons} + C_{E-cons} + C_{maint} + \sum C_{labor,i} \quad [1]$$

Where $C_{material,i}$ is the cost of each respective material, C_{equip} is the equipment cost, $C_{tool,pp}$ is the tooling cost, $C_{plant,pp}$ is the plant operating cost, $C_{AEnergy,pp}$ is the electricity cost, $C_{L\text{-}cons,pp}$ and $C_{E\text{-}cons,pp}$ are the consumable cost for labor and equipment respectively, C_{maint} is the equipment maintenance cost, and $C_{labor,i}$ is either the direct or indirect labor cost.

Each process step requires the cycle time, $t_{cycle,i}$, and the amount of total equipment required, $N_{equipment,i}$, to be known to determine the individual cost drivers for each process i. The cycle time and number of equipment required is given by Equations 2 and 3, respectively.

$$t_{Cycle,i} = \frac{t_{Process,equip,i}}{N_{Parts/Cycle,i}} \quad [2]$$

$$N_{Equipment,i} = \left\lceil \frac{R_{Production,actual}}{\left({t_{Shift\ op}}/{t_{Cycle,i}} \right) \cdot N_{Shift}} \right\rceil \quad [3]$$

Where $R_{Production,actual}$ is the actual production rate in parts per year, $t_{Shift\ op}$ is the available shift operating time, N_{Shift} is the number of shifts per day, $t_{Process,equip,i}$ is the machine processing time, and $N_{Parts/Cycle,i}$ is the number of parts produced during one unit of processing time, or cycle. In the presented manufacturing line, each process only makes one part per cycle.

The cost of equipment, C_{equip}, must capture the value of money to the company, pretax. Comparing alternate manufacturing lines is best done with an annual cost comparison method known as Equivalent Uniform Annual Cost (EUAC). The EUAC may be used to compare different processes that may have different lifespans, as a company assesses an interest rate, or their cost of capital to the initial capital investment of the equipment. The EUAC for a manufacturing line is shown in Equation 4 [6].

$$C_{Equip} = \sum C_{Equip,ind} \cdot \frac{i_{CoC} \cdot (1 + i_{CoC})^{t_{PL}}}{(1 + i_{CoC})^{t_{PL}} - 1} * \frac{1}{PV_{Desired}} \quad [4]$$

Where i_{CoC} is the cost of capital interest rate, $C_{Equip,ind}$ is the cost of each piece of equipment in the process, and $PV_{Desired}$ is the customer's desired production value per year. An alternate way to view this is the annual loan payment required across the timespan t_{PL} and at interest rate i_{CoC} [6]. Thus, altering the i_{CoC} represents acquiring funding from different sources or companies. A small business may charge a smaller i_{CoC} as their overheads and rate of return demanded by the controlling members are less than when compared to a large business or a bank.

Tooling replacement varies due to the materials and the process involved. For high-volume production levels, steel is typically utilized for its durability and longevity when it comes to tool wear and processing condition variations. The amount of tooling required, N_{Tools}, is dependent upon the total number of parts produced across the lifetime of the manufacturing line, $N_{Parts,ML}$, and the tool life in number of parts, TL_{Parts} , see Equation 5. The tooling cost per part, $C_{Tool,pp}$ is found via Equation 6 where C_{Tool} is the cost of the tool required for a process step.

$$N_{Tools} = \frac{N_{Parts,ML}}{TL_{Parts}} \quad [5]$$

$$C_{Tool,pp} = \frac{N_{Tools} \cdot C_{Tool}}{t_{Prod} \cdot PV_{Desired}} \quad [6]$$

Annual maintenance costs, C_{maint}, are typically provided by the equipment manufacturers or are taken into account as a flat rate of the total purchase cost of all equipment, $C_{equip,i}$. This rate varies from company to company as it is based on their experience with their existing equipment, but, from experience, is between 1-5 %. Some companies prefer to account for both the equipment manufacturer's annual maintenance costs, $C_{maint,EM,annual,i}$, as well as the maintenance cost rate, $i_{Maint,i}$, see Equation 7. This provides a more conservative estimation and/or allows for budgeting of unforeseen contingencies.

$$C_{Maint,i} = \left(C_{Maint,EM,annual,i} + i_{Maint,i} \cdot C_{Equip,i}\right) \cdot N_{Equipment,i} \quad [7]$$

The cost to operate the plant is based on the square footage that the manufacturing line encompasses and is calculated via Equation 8 [adapted from 7].

$$C_{Plant,pp} = \frac{U_{eff} \cdot A_{Equip} \cdot N_{equip} \cdot C_{Pops}}{PV_{Desired}} \quad [8]$$

Where $C_{Plant,pp}$ is the cost of plant operations per part, U_{eff} is the effective utilization of the equipment, A_{Equip} is the area the equipment occupies, N_{equip} is the number of the particular equipment required to meet the production volume desired, and C_{Pops} is the cost or plant operations per square foot. U_{eff} is 100% if the equipment is dedicated, otherwise, it is calculated from the desired production rate, $PV_{Desired}$, and the available production rate for all equipment, PV_{act}, as shown in Equation 9 [adapted from 7]. For the presented manufacturing line, the equipment is dedicated.

$$U_{eff} = \frac{PV_{Desired}}{PV_{act}} \cdot 100\% \quad [9]$$

Energy usage may be divided into two categories, active and standby. Active energy usage accounts for the energy used while the equipment is in operation while standby energy usage is the energy that is drawn while the equipment is *Off* or in *Standby Mode*. Equipment typically continues to draw power while in these two modes to keep functions ready to operate.

The cost of active energy is based on the hours per year that the equipment is in operation as shown in Equation 10 [adapted from 7]. For the presented analysis, only the active energy is accounted for.

$$C_{ActiveEnergy,pp} = \frac{t_{act,100\%\,op} \cdot P_{Equip} \cdot N_{equip} \cdot C_{Energy}}{PV_{Desired}} \quad [10]$$

The cost of direct labor is based on the hours per year that the equipment is in operation and the number of laborers required for the equipment as shown in Equation 11 [adapted from 7].

$$C_{DL,pp} = \frac{t_{act,100\%\,op} \cdot N_{DP,Equip} \cdot N_{equip} \cdot C_{DL}}{PV_{Desired}} \quad [11]$$

Where $C_{DL,pp}$ is the cost of direct labor per part, $N_{DP,Equip}$ is the number of laborers per equipment, and C_{DL} is the cost per hour of direct labor.

The cost of indirect labor is based on the hours per year that the equipment is in operation and the number of laborers required for the equipment as shown in Equation 12 [adapted from 7].

$$C_{IdL,pp} = \frac{t_{act,100\%\,op} \cdot N_{DP,Equip} \cdot N_{equip} \cdot C_{IdL} \cdot R_{Id \to D}}{PV_{Desired}} \quad [12]$$

Where $C_{IdL,pp}$ is the cost of indirect labor per part, $R_{Id \to D}$ is the ratio of indirect to direct laborers per equipment, and C_{IdL} is the cost per hour of indirect labor.

The cost of labor-related consumables is based on the hours per year that the equipment is in operation and the number of laborers required for the equipment as shown in Equation 13 [adapted from 7].

$$C_{L-cons,pp} = \frac{t_{act,100\%\,op} \cdot N_{DP,Equip} \cdot N_{equip} \cdot C_{C,L}}{PV_{Desired}} \quad [13]$$

Where $C_{L-cons,pp}$ is the cost of labor-related consumables per part and $C_{C,L}$ is the cost per hour of labor related consumables.

The cost of equipment-related consumables is based on the output pounds of material that the equipment is produces as shown in Equation 14.

$$C_{E-cons,pp} = \frac{\sum M_{Mat,i} \cdot C_{C,E}}{PV_{Desired}} \quad [14]$$

Where $C_{E-cons,pp}$ is the cost of equipment-related consumables per part, $M_{Mat,i}$ is the weight of Material 1 utilized by the equipment, and $C_{C,E}$ is the cost per kg of equipment related consumables.

Calculating the cost of material for each process step may vary depending upon how the material usage is calculated. For the injection over-molding, the volume of the material used, V_{IM_Mat}, is extracted from the simulation results, as discussed in Section 2.8. The cost per part for the polymer used is found via Equation 15.

$$C_{IM\ Mat,pp} = \frac{PV_{IN,Act} \cdot V_{IM\ Mat} \cdot \rho_{IM\ Mat} \cdot C_{Mat\ IM,pkg}}{PV_{Desired}} \quad [15]$$

Where $PV_{IN,Act}$ is the actual production rate required for the process step, ρ_{IM_Mat} is the density of the injected material, and $C_{Mat\_IM,pkg}$ is the cost per kg of the injected material.

2.6 Identify or receive processing conditions

The processing conditions are the specifics that define the manufacturing line. These include the time available for manufacturing, number of shifts operating per day, labor rates, utility costs, equipment and tooling costs, maintenance rates, and cost of capital. Some of these rates or costs are location specific, so possible alternate economic analysis scenarios could be conducted for different locations across the country or the world. Tables 2 and 3 highlight the processing conditions utilized for this TCM.

Table 2. Processing conditions for hybrid molding manufacturing line.

Location	West Lafayette, IN	Project duration	5 years	Electricity rate	6.66 ¢/kWh
Working days	240	Direct labor rate	\$30 /hr	Cost of capital	3 %
No. of shifts	3	Indirect labor rate	\$70 /hr	Amortization time	15 years
Hours per shift	8	Plant operating rate	\$1,507 /m^2	Maintenance rate	3 % of equipment cost per year

Table 3. Equipment inputs for base case scenario.

Process step	Preforming & Bushing Insert	Transfer to Injection Molding	Injection Molding	Transfer to Trim & QC	Ultrasonic Trimming	Quality Control
Equipment	EELCEE QEE-TECH®	Yaskawa MH50	Krauss Maffei *FiberForm*	Same Yaskawa MH50	Sonofile SF3441	Yaskawa MH12 / T-Scan 5
Cost	\$452,000	\$75,000	\$510,000	\$0	\$15,000	\$50,000 / \$215,000
Tooling cost	\$20,000	\$17,500	\$60,000	\$0	\$1,500	\$0

Cycle time	32 sec	9 sec	50 sec	12 sec	3 sec	20 sec

2.7 Receive refined/final part design details

The structural performance and processing parameters of a hybrid molded part are captured through the use of CAE design tools. To obtain the optimal hybrid molded part design, the physical preforming, polymer solidification kinetics, thermal contraction, residual stresses, and deformations, among other phenomenon, must be accounted for. To fully capture the manufacturing of a hybrid molded part and the performance aspects of the final part, the Process Simulation Workflow (PSW) developed at the Composite Manufacturing and Simulation Center, Purdue University, and detailed in Goodsell et al. was utilized for the test coupon. [3] There are vast processing parameters that are able to be extracted from this PSW, but the relevant parameters for this investigation may be found in Table 4.

Table 4. Processing parameters extracted from process simulation workflow used for costing purposes.

Material 1	Polypropylene (PP)	Material 1 density	0.905 g/cm^3
Material 2 (insert)	Aluminum	Material 2 density	2.6989 g/cm^3
Material 3 (insert)	PP, 50 % GF	Material 3 density	1.49 g/cm^3
Part volume (injected)	105.722 cm^3	Cold runner volume	15.5239 cm^3
Insert volume	39.0639 cm^3		
Fill time	0.55 s	Mold opening time	5.00 s
Pack time	2.45 s	Cooling time	23.10 s

For the presented manufacturing process, only a small fraction of the available data from the PSW is utilized. Other manufacturing processes may require more. The data in Table 4 is extracted via a Python program from the commercial injection molding software Moldex3D. This data is transferred to the TCM that is executed in Microsoft Excel.

The material and their densities are used to determine the weight per part. Material 3, the part of the insert that is the TP tape, is needed to determine the melt temperature. Knowing the melt temperature is required to determine the temperature settings for the IR oven in the QTC where consolidation occurs. The temperature settings influence how much electricity is used instead of the conservative amount, i.e. the max kW usage, that is generally utilized within cost models.

Moldex3D provides some of the process steps that comprise the overall cycle time of the injection molding process. Overall, there are nine process steps for injection molding that must be accounted for to capture how long the equipment is actually in-use. These are: loading the preform into the mold, mold closing / press cycle, evacuate mold, injection filling, packing, cooling, mold opening, demolding, and part transfer out. There are a variety of injection molding cycle time estimation techniques that may be utilized to predict the time required for the process steps not captured in Table 4, one such method is Boothroyd et al.'s *Design for Injection Molding*. [8] Other cycle times for equipment utilized come from modeling equations based on movement rates, part dimensions, part complexity, and distances. These modeling equations are not discussed within the purview of this paper.

3. MODEL EXECUTION

The product of any manufacturing cost model is the manufacturing cost per part. The further the manufacturing cost may be broken down, the more a company knows where efforts must be placed to reduce costs in the long term. In the short term, the overall manufacturing cost allows a company interested in producing new products to be able to compare and contrast difference manufacturing routes. The cost segmentation per part for the five scenarios discussed in section 2.2 is found in Figure 4.

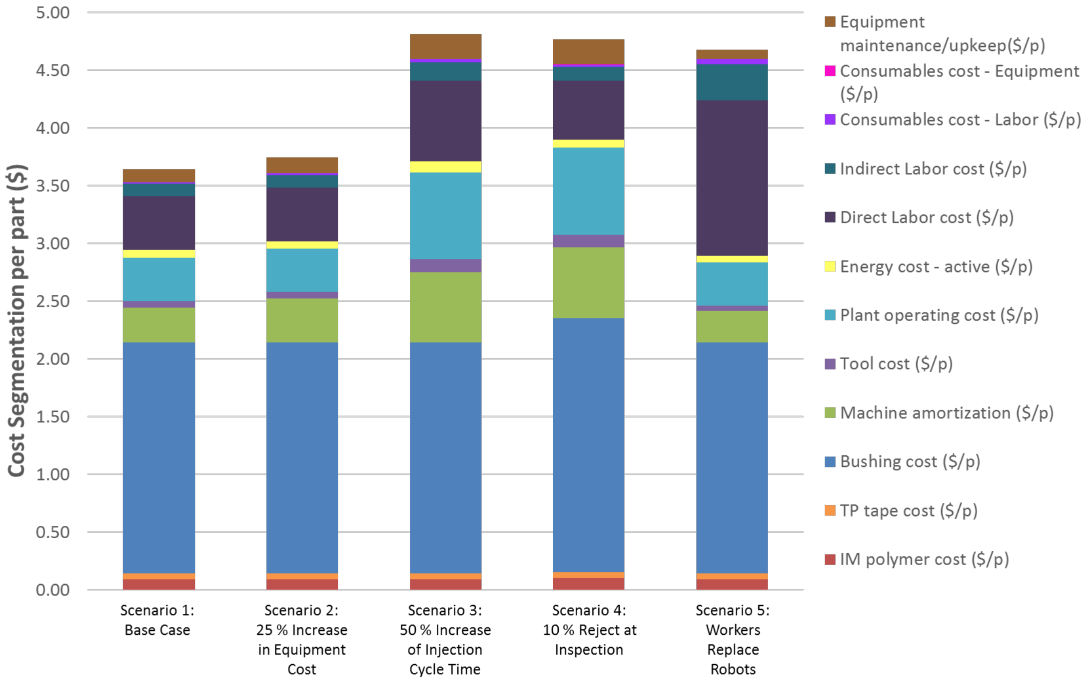

Figure 4. Cost segmentation for the base case and four augmentations for the hybrid molding manufacturing process to produce 360,000 test coupons per year.

The desired production volume of 360,000 parts per year was chosen as it is on the cusp of what is possible to produce within the available time per year. The bottle-neck process, the process that has the longest cycle time, is the injection over-molding. Thus, when that cycle time is increased, such as in scenario 3 by 50 %, or more parts are required to be produced, such as in scenario 4 where 10 % of the final parts are rejected, an additional manufacturing line is required to meet the production volume demand. For scenario 4, this increases all the manufacturing costs, as additional equipment and material is necessary. In scenario 3, where only time is a factor, additional equipment and the cost drivers around that equipment increase; such as labor, energy, and plant operating costs.

Scenario 2, an increase of 25 % in equipment costs, only results in a change to the machine amortization. Scenario 5 replaces the two robots, accounting for $125,000 of the equipment costs and $17,500 in tooling costs, the tool cost and equipment amortization cost per part is reduced. However, additional direct labor, one for the transfer and one for the quality control, is now required, leading to increases in direct and, subsequently, indirect labor costs.

Comparing part cost segmentation is useful, but breaking these costs out per manufacturing process step provides focus areas for possible cost or time reduction. Figures 5 and 6 compare the base case, scenario 1, to an increase in injection molding cycle time, scenario 3, and when workers replace robots, scenario 5, respectively.

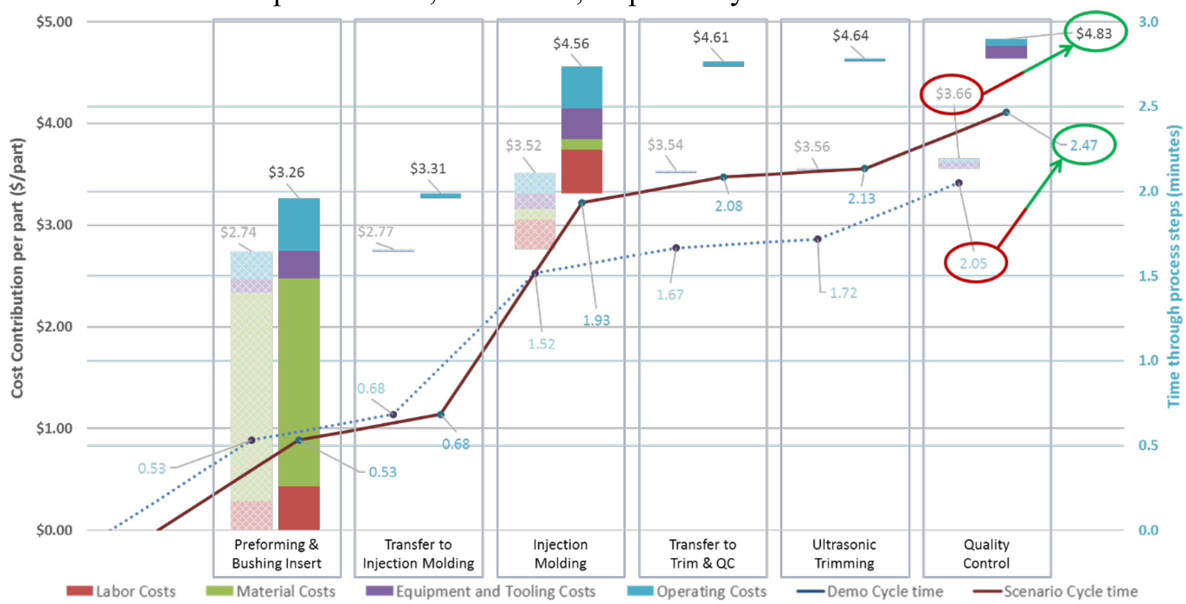

Figure 5. Base case (scenario 1: dotted line for time and left stacked columns for cost) comparison to a 50 % increase in injection molding cycle time (scenario 3: solid line for time and right stacked columns for cost).

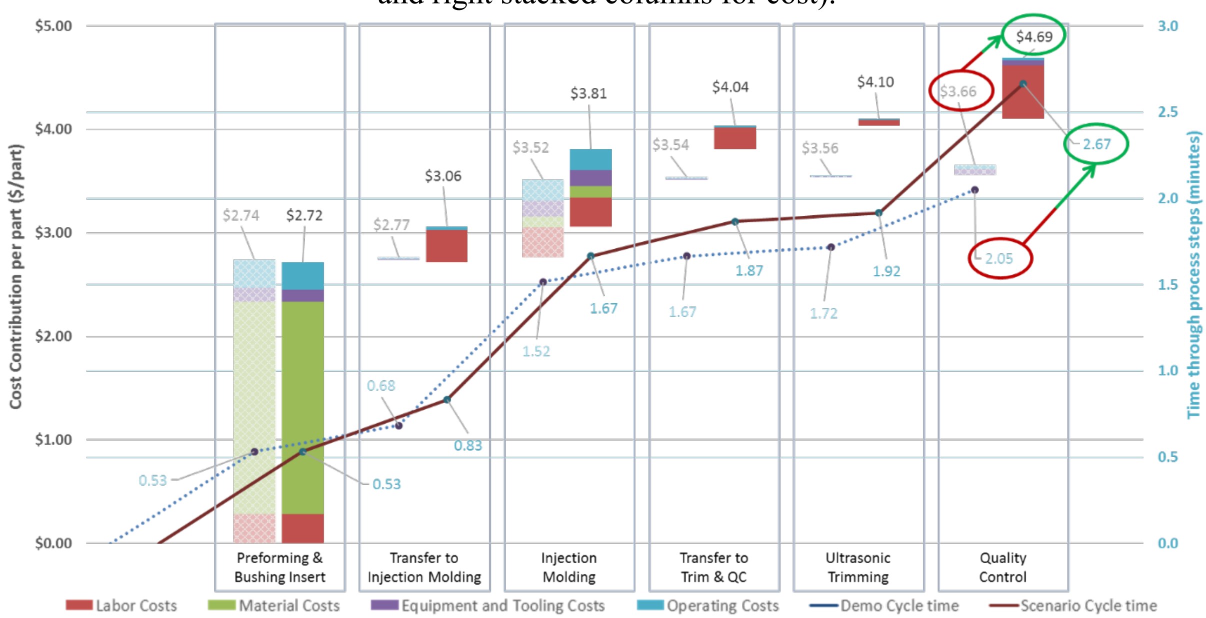

Figure 6. Base case (scenario 1: dotted line for time and left stacked columns for cost) comparison to workers replacing robots (scenario 5: solid line for time and right stacked columns for cost).

In Figure 5, as discussed earlier, an additional manufacturing line is required now to meet the production volume demand of 360,000 parts per year. This increases the cost per part from $3.66 per part to $4.83 per part. Due to the increase in cycle time, the time the part spends throughout the entire manufacturing process increases from 2.05 mins to 2.47 mins. For these scenarios, the equipment is fully dedicated to the test coupons production. However, scenario 3's overall utilization rate is only 72 %, meaning a portion of the cost per part could be offset by producing another part in the time not utilized.

In Figure 6, it is important to note that the cost of the transfer robot was part of the QTC Cell package of equipment. Thus, its purchase cost was included with the "Preforming & Bushing Insert" process, leading to the reduction in cost for that process step. The cost per part for this scenario is increased from $3.66 to $4.69 per part due to the increase in labor required. The time the part spends throughout the entire manufacturing process also increases due to the increased time to transfer and scan the part, from 2.05 mins to 2.67 mins. This does not affect the amount of parts able to be produced negatively in this case, as the total transfer time and scan time, individually, are less than the cycle time for the injection molding machine.

4. CONCLUSIONS

Bringing new parts to market that utilize novel materials or manufacturing methods is difficult to justify due to the lack of knowledge at the business level as to the costs involved. Technical cost modeling is intensive in its approaches, but required to capture manufacturing costs prior to installation and operation of a manufacturing line. Extracting processing parameters from commercially available and proven CAE tools may increase the accuracy of cost estimation as the processing parameters that are to be utilized by the actual equipment can be determined.

The hybrid molding manufacturing line investigated shows that the basic technical cost model formulation is sound and extraction of manufacturing process parameters is possible from the commercially available Moldex3D injection molding software.

4.1 Future research

Expansion of the equipment database is necessary to truly compare manufacturing routes with one another, or to determine how previously purchased equipment may affect either the processing parameters or the cost per part, as changing equipment may result in different movement rates or equipment costs. Hybrid molding with different preform materials also requires a slightly different approach to the process simulation workflow, which may yield different processing parameters that may be extracted for different process steps, such as pre-heating process parameters. Finally, real-time integration of processing parameters from a manufacturing into the TCM would provide plant operators with real time cost information or cost impact due to manufacturing interruptions.

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