Manufacturing Cost Relationships for Vacuum Bag-Only Prepreg Processing

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Abstract: Vacuum bag-only (VBO) prepregs enable the out-of-autoclave (OoA) manufacture of high-performance composite structures and increase the material, part and process selection space. However, manufacturing choices involve economic as well as technical considerations. To understand these relationships, we developed a technical cost model that captures the distinctive characteristics of VBO prepreg processing (including vacuum-induced air evacuation and resin cure) and estimates the costs associated with materials, equipment and labor. We applied the model to realistic manufacturing cases and used a parametric study to evaluate the effects of part characteristics, material use efficiency, and cure efficiency. The results indicate that prepreg cost, part size, prepreg waste, and the air evacuation capacity of the material have the strongest influence on part costs, and demonstrate that cost modeling can guide efforts to improve or optimize processing by identifying the most economically valuable modifications.

INTRODUCTION

The traditional manufacturing method for composite structures in the aerospace industry is autoclave prepreg processing [1]. Layers of fiber beds pre-impregnated with a catalyzed but uncured thermoset polymer resin, or prepreg, are stacked on a tool plate to form a laminate. The

Please cite the article as: T. Centea and S.R. Nutt, **"Manufacturing Cost Relationships for Vacuum Bag-Only Prepreg Processing"** J. Compos Mat 50 [17] (2016) 2305-2321 DOI: **10.1177/0021998315602949**

layers then are enclosed within a vacuum bag assembly and cured at elevated temperature and pressure within a pressurized oven called an autoclave. Heating polymerizes the resin matrix, while applied pressure compacts the fiber bed, conforms the laminate to the tool, ensures that the resin fully infiltrates the pore volume, and mitigates porosity by suppressing nucleation or collapsing existing voids. Autoclave processing can be used to consistently produce high quality parts. However, autoclaves are expensive to acquire and operate, particularly for the large structures increasingly used in aerospace applications. Furthermore, autoclave ownership, shape and availability can restrict design and manufacturing by limiting part sizes, production rates, and subcontractor choices. As a result, in recent decades, several non-autoclave processes have been developed.

Vacuum Bag-Only Prepreg Processing

Vacuum bag-only (VBO) prepregs represent a significant step towards viable out-of-autoclave (OoA) manufacturing of high-performance composites [2]. While ostensibly similar to their autoclave counterparts, VBO prepregs can be used to produce parts with high microstructural quality, dimensional accuracy, and mechanical performance under compaction derived solely from atmospheric pressure (101.3 kPa or 1 atm). By eliminating the need for a pressurized curing vessel, such materials address two limitations of autoclave processing. The first is the low-cost fabrication of structural composites, which has traditionally been impeded by the capital expenditures and operating expenses associated with autoclaves. Such applications are well-suited to low-to-medium value/size parts, hand layup (since automation equipment is also expensive), and a wide variety of inexpensive cure environments, including convection ovens, hot drape formers, heating blankets and integrally heated tools. The second is the production of large-scale integrated structures (for example, airframes or rocket fairings), for which sufficiently large autoclaves are prohibitively

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expensive or simply do not exist. In such cases, the embodied value of the part and the limited out-life of the prepreg often justify investments in automated material deposition such as automated fiber or tape placement (AFP/ATP). For both cases, identifying optimal manufacturing choices within the expanded OoA design and processing space requires a detailed understanding of the dominant variables. However, the present study focuses exclusively on the low-cost manufacturing of small and intermediate-sized parts by VBO prepreg processing and hand layup, which can be described using a generic model with widely applicable results. Though understanding manufacturing costs for the VBO cure of large, integrated structures is also of interest, the unique characteristics of such parts and of the infrastructure used to produce them are better suited for analysis based on individual case studies rather than generic models.

The fundamental phenomena governing VBO prepreg processing have been recently reviewed [3]. The major consequence of lower compaction pressure is a reduction in the capacity to suppress defects, particularly with respect to porosity. During VBO cure, the void content can be controlled/eliminated if the air entrapped between and within plies is evacuated in the early stages of cure. VBO prepregs are partially impregnated, consisting of dry, micro-porous regions surrounded by resin-rich areas. The dry areas form a permeable vascular network that allows entrapped gases to migrate to the laminate boundaries in both the in-plane and through-thickness directions. During cure, the remaining dry areas are infiltrated with surrounding resin. The combined air evacuation and resin cure steps govern the duration of the VBO processing cycle.

The literature confirms that autoclave quality is achievable, but that defect suppression is sensitive to material selection and process parameters. Thus, comprehending the impact of manufacturing choices is necessary for successful part fabrication. However, manufacturing choices influence cost as well as technical performance. As a result, studies that clarify the relationships between technical and economic performance are desirable. In addition, efforts to improve the efficiency and sustainability of OoA/VBO are currently underway (for example, [4]). For best effect, such activities should be guided by an understanding of the expected economic benefits of potential technical developments.

Cost Analysis Studies

Boyd and Maskell [5] reported part cost data collected by a prepreg manufacturer (Cytec Fiberite). Assembly costs were identified as the largest single contributor (45%), followed by layup costs (25%), materials (15%), cure (10%) and fasteners (5%). In their work, material and process specifics were not provided. Repecka and Boyd [6] mentioned that the costs associated with autoclave manufacturing are usually higher than the direct material costs due to the capital investment and the need for high-pressure and high-temperature tooling. The capital investments and tooling costs required to produce autoclave parts were also cited by material suppliers as motivating factors for the development of OoA methods and VBO prepregs [2,6–8].

The detailed economic performance of a composite manufacturing process can be analyzed using techniques ranging from experience-based estimates to sophisticated flow simulations of entire virtual factories [9]. Early methods relied primarily on historical data or empirical fitting. While practical, such approaches are difficult to adapt to evolving materials and processes. As a result, technical cost modeling (TCM) has been favored for part cost estimation because one can combine technical and economic data using parametric relationships [9]. TCM uses activity-based accountancy, which sub-divides the total cost of a part into the "primitive" steps used to produce it. However, TCM differs from purely activity-based costing by estimating sub-costs through a combination of engineering and economic characteristics, rather than solely from historical data. Technical cost modeling can be applied to any manufacturing process by identifying the appropriate sub-steps and their interactions. Typically, the model inputs include both direct cost data and non-monetary variables such as material properties and process parameters, which are converted into economic units using relationships such as the ones described in this work. TCM can be used to analyze any manufacturing process, provided appropriate mathematical relationships are used to capture its characteristics.

Zaloom and Miller [10] reviewed several legacy cost estimation methods, including the commonly cited Air Force Flight Dynamics Laboratory "Advanced Composite Cost Estimating Manual" (ACCEM) [11]. While practical, many of these approaches rely on historical data. Gutowski and colleagues analyzed a large industrial dataset relating part and process characteristics to labor time [12], and later proposed a theoretical first-order model for labor costs which exhibited good agreement with ACCEM [13]. The "Cost Optimization Software for Transport Aircraft Design Evaluations" (COSTADE) was developed in the mid-1990s by industrial, governmental and academic partners, and uses both TCM principles and historical inputs for structural design, factory layout and manufacturing optimization [14]. Wakeman and Manson [9] describe a manufacturing cost simulation that combines technical cost modeling with discrete event simulation to analyze an entire production line, accounting for rate mismatches and buffers between different operations. Versions of this model were used to analyze the processing of commingled yarn composites [15], manufacturing methods for automotive applications [16], and non-autoclave processes for aerospace [17,18]. Other examples of cost studies include the analysis of structural reaction injection molding (SRIM) [19] using discrete event simulations, and of the press-forming of thermoplastic sandwich panels [20]. In general, manufacturing cost studies vary widely in intent, scope, focus and approach.

Efforts to specifically analyze VBO prepreg processing are limited but enlightening. Witik et al. [17] used TCM to compare prepreg processing in a conventional oven, a microwave oven, and an autoclave to resin infusion in conventional or microwave ovens. Their analysis indicated that, for each method, material costs account for the majority of the total part cost, with labor and infrastructure costs secondary, and tooling, consumables and energy tertiary. Resin infusion in a conventional oven was identified as the most cost-effective method, though VBO prepreg processing in a conventional oven was also shown to reduce costs relative to the autoclave benchmark due to lower capital and energy costs. Tong et al. [21] obtained similar results during a simpler cost analysis of the VBO manufacturing of L-shaped parts. In both cases, a single set of material properties and process conditions was analyzed in detail, though Witik et al. [17] also provided results from a limited sensitivity study, showing material costs and labor rates to dominate. This existing literature provides a basis for evaluating VBO prepreg processing, particularly in comparison with traditional autoclave and other competing methods. However, an improved understanding of the economic influence of the material, part, and processing choices enabled by OOA prepreg fabrication is desirable.

Objectives and Structure

In this work, we investigate the relationships between key VBO prepreg material, part and process parameters and manufacturing costs. We develop a technical cost model to estimate material, equipment, and labor cost components based on a generic representation of VBO prepreg processing. The model is then used to assess realistic manufacturing cases for small and large flat parts, and to carry out a parametric study on the influence of part characteristics, material use and cure efficiency. The results clarify the relative economic importance of key manufacturing choices. They indicate that prepreg cost, part size, the capacity to evacuate air effectively and the reduction of in-process waste have the strongest influence on part costs, and motivate the most desirable technical improvements.

MODEL DEVELOPMENT

VBO Prepreg Process

The traditional VBO prepreg process for small to medium-sized parts can be synthesized into a sequence of generic steps for which technical and economic performance may be related, as shown in Figure 1. The part design, materials and manufacturing equipment are first selected. Then, the tooling is cleaned and a mold release agent is applied.

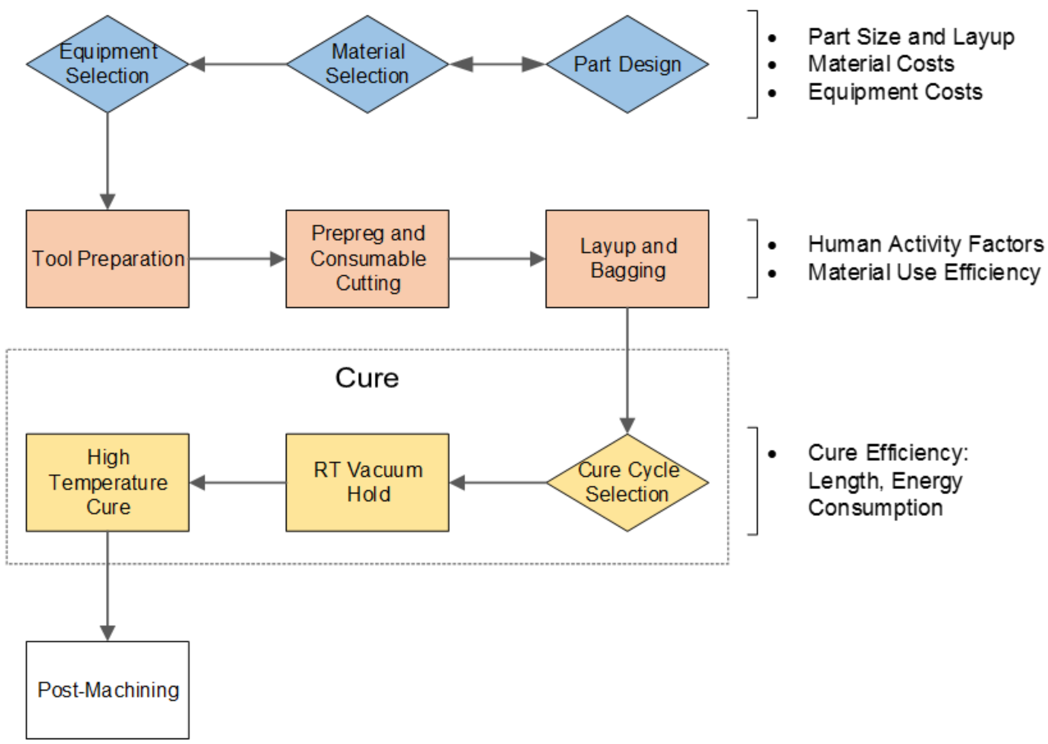

Figure 1: Flowchart of a traditional VBO prepreg manufacturing process for a given part, and key issues affecting manufacturing cost.

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VBO prepreg plies and consumables are hand-cut to the required size and shape. The consumables consist of tool-side non-perforated release film, bag-side perforated release film and breather, perimeter edge breathing dams made of sealant tape wrapped in fiberglass boat cloth, and a vacuum bag. The prepreg plies are manually stacked on the tool to form the laminate, with or without intermediate debulking, and the bag is assembled, sealed and leak-tested. Then, a cure cycle is selected based on the chosen prepreg resin and cure set-up. Curing consists of a room-temperature vacuum hold to evacuate entrapped air, followed by one or more high-temperature ramps and dwells. Vacuum is drawn using a stand-alone, dedicated vacuum pump, while heat is imparted using a convection oven or other non-autoclave set-up. An instrumentation system (consisting of a computer, a digital acquisition system and temperature sensors) is used for basic process monitoring. No human activities are associated with the room-temperature hold or cure, other than placing and removing the part from the oven, and de-bagging. Finally, post-machining is carried out on the manufactured part: most typically, the edges are trimmed to a predetermined depth to remove resin flash.

This paradigm, while simple, includes several factors that can affect manufacturing cost, as summarized on the right side of Figure 1. Design, material and equipment selections govern the part size and layup (amount of material) as well as direct material and equipment costs. Prior to cure, the material use efficiency is affected by prepreg and consumable cutting, which can generate waste as plies are extracted from roll stock. Moreover, the duration and efficiency of human activities influence labor costs. During cure, the duration of the RT vacuum hold varies widely as a function of part size and the air evacuation capacity of the prepreg, expressed in terms of in-plane and transverse Darcy permeability values. The length of the HT cure cycle is governed by the cure kinetics of the resin at a given dwell temperature and the heat-up and cool-down ramp rates achievable by the cure set-up. In addition, energy consumption during cure directly influences operating costs. Finally, post-machining can generate further waste. In this manuscript, we investigate the relative importance and potential coupling of such factors within the context of manufacturing costs.

Note that manufacturing protocols for VBO prepreg parts can also vary due to organizational practices. In addition, in some cases, equipment may be shared between different production runs, or several parts may be cured simultaneously. The steps described above and shown in Figure 1 are not intended to capture a specific manufacturer's production practices. Rather, they form a simple, generic paradigm that embodies the key relationships between material, process and cost.

Cost Modeling

The net monetary value of a composite part consists of the net economic life cycle benefits minus the manufacturing costs and overheads associated with production and disposal. Overhead costs (such as indirect costs and taxes) are non-technical and company-specific, while monetary life cycle benefits depend on the application rather than the manufacturing process. As a result, the present study focuses exclusively on manufacturing costs, which can be directly related to technical variables, and which should be minimized.

The cost modeling framework is shown schematically in Figure 2, and consisted of inputs and input calculations and cost calculations. The specific relationships and calculations involved in each stage are described in detail below. The chosen modeling approach assumes that the process flow for a given part is linear (or sequential), without parallel steps, rate mismatches, or buffers. As a result, in addition to part costs, the production time per part, the number of parts produced per fixed production period and/or the total production time required for a given part volume can easily be determined.

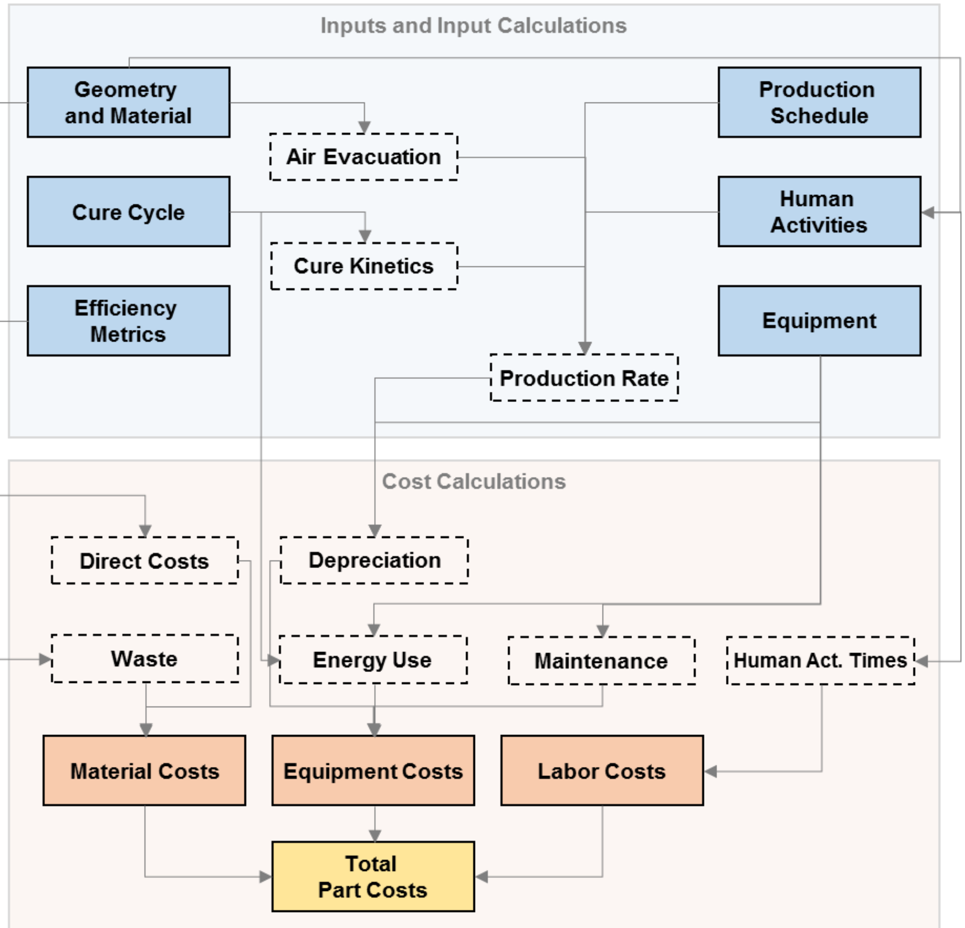

Figure 2: Schematic of the technical cost model.

Input and Input Calculations

The geometry and material inputs were used to define the functional unit: a flat laminate of length (L), width (W) and thickness (h) made from a given prepreg. Geometric complexity was not considered within this study, but can be included by modifying subordinate factors such as layup time and consumable use (as suggested by Gutowski et al. [13]). Material inputs included the fiber areal weight of the prepreg (A_w), cured ply thickness (CPT), in-plane air permeability (K) and cure kinetics, expressed as a rate of cure equation of form $d\alpha/dt = f(\alpha,T)$, where α is the degree of cure. The CPT was used to relate the part thickness to the required number of plies (n_{plies}).

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The cure cycle module provided information about the RT vacuum hold and high-temperature cure. The in-plane permeability and part dimensions were used in conjunction with a gas transport model proposed by Arafath et al. [22] to calculate the vacuum hold time t_{evac} required to evacuate a desired air mass fraction (m/m_0), chosen here as 0.99:

$$t_{evac} = \frac{\mu}{P_0}\frac{(\sqrt{LW})^2}{K}\left[-\frac{1}{0.9}\ln\left(\frac{m}{m_0}\right)\right]^{1/0.6} \tag{1}$$

In Eq. (1), μ is the dynamic viscosity of air at ambient temperature, and P_0 is the initial (ambient) pressure. Air evacuation was assumed to occur solely in-plane, as a worst case scenario, since studies have suggested that out-of-plane gas transfer can be unpredictable in common VBO prepreg product forms [23,24]. The high-temperature cycle was defined in terms of an initial ramp rate, a dwell temperature of known duration, and a second ramp to a post-cure temperature dwell of known duration.

The human activities provided data for the calculation of "human activity times" (which also depended on geometry and material). The equipment inputs included capital cost, acquisition and energy consumption data used to calculate equipment costs. Finally, efficiency metric inputs related to material waste factors and the efficiency of human activities. The detailed computations associated with all inputs are described below.

The production schedule included the length of the production run in years ($n_{production}$), the number of annual production days (n_{days}) and the number of daily eight-hour shifts (n_{shifts}). Along with the human activity times and cure times (described below), these values were used to calculate the production rate, or number of parts produced per day (n_{parts}), as well as the total production volume during the production run time.

Cost Calculations

The total manufacturing costs (C_{total}) were expressed on a per-part basis, as either monetary values ($) or specific monetary values ($/kg of cured material). They were divided, within this study, into labor costs (C_{labor}), material costs ($C_{material}$) and equipment costs ($C_{equipment}$):

$$C_{total} = C_{labor} + C_{material} + C_{equipment} \tag{2}$$

The labor costs were calculated based on the sum of all human activities required to produce the part. The nature, sequence and duration of these activities can vary between companies and industrial sectors as well as with operator experience. For this study, we chose a generic series of discrete tasks necessary for VBO prepreg processing. Chronologically, they consisted of cutting the prepreg, cutting consumables, cleaning and releasing the mold, laying up the prepreg plies to form a laminate (with or without intermittent debulking), assembling and leak-testing the vacuum bag, inserting and removing the tool from the oven, and removing the part from the vacuum bag. For simplicity, a single human operator was assumed to work exclusively on a single part throughout the steps outlined above. The required time for a given activity ($t_{activity,i}$) was defined, as shown in Eq. (3), using an overhead time ($t_{overhead}$), a reference time (t_{ref}) and a power law dependence on an extensive property, the prepreg area (A), as suggested by Gutowski et al. [13]. $F_{scale,1}$ and $F_{scale,2}$ are efficiency constants for a given activity.

$$t_{activity,i} = t_{overhead,i} + \left(t_{ref,i}\right)\left(1 + F_{scale,1}\left(A - A_{ref}\right)^{F_{scale,2}}\right) \tag{3}$$

The resulting total labor cost (C_{labor}) was calculated using a constant hourly wage (W_{hourly}):

$$C_{labor} = W_{hourly} \sum_i t_{activity,i} \tag{4}$$

The material costs were composed of the direct and indirect (waste) costs for both prepreg ($C_{m,prepreg}$) and consumables ($C_{m,consumables}$):

$$C_{material} = C_{m,prepreg} + \sum_i C_{m,consumable,i} \tag{5}$$

$$C_{m,prepreg} = \left(1/(1 - F_{waste,prepreg})\right)\left[(L + L_{trim})(W + W_{trim}) n_{plies}\right] AC_{prepreg} \tag{6}$$

$$C_{m,consumable,i} = \left(1/(1 - F_{waste,consumable,i})\right) \left[(L + L_{trim} + L_{overhang,i})(W + W_{trim} + W_{overhang,i}) AC_{consumable,i}\right] \tag{7}$$

In Eq. (6), L_{trim} and W_{trim} are the dimensions of the post-cure edge trim cuts, for a part with final dimensions L and W. $AC_{prepreg}$ is the prepreg areal cost, and $F_{waste,prepreg}$ is the waste factor of the prepreg (where zero denotes no waste and $F_{waste,prepreg} \leq 1$). In Eq. (7), $L_{overhang,i}$ and $W_{overhang,i}$ denote the extra dimensions of the consumables (relative to the part size), $F_{waste,consumable,i}$ controls the consumable waste, and $AC_{consumable,i}$ is the consumable areal cost. Eq. (7) applies to the tool and bag-side release films, breather and vacuum bag. The cost of the breathing edge dams was calculated based on the perimeter of the untrimmed laminate length multiplied by the linear cost of the sealant tape and fiberglass boat cloth, and the cost of the bag sealant tape was equal to the perimeter of the vacuum bag multiplied by the linear cost of the tape.

The equipment costs were determined by calculating the depreciation ($C_{depreciation}$), maintenance ($C_{maintenance}$) and electrical ($C_{electrical}$) expenses associated with each capital asset required to process the part. Capital assets included the oven, vacuum pump, instrumentation, aluminum tooling and vacuum accessories such as vacuum fittings, valves and hoses.

$$C_{equipment,i} = C_{depreciation,i} + C_{maintenance,i} + C_{electricity,i} \tag{8}$$

Straight-line depreciation was assumed, with the depreciation charge per part calculated as:

$$C_{depreciation,i} = \frac{C_{acquisition,i} - C_{salvage,i}}{(n_{life})(n_{days})(n_{parts})} \tag{9}$$

In Eq. (9), $C_{acquisition}$ is the initial purchase price of the item, $C_{salvage}$ is the expected salvage value, n_{life} is the useful life of the item in years, and n_{days} and n_{parts} are the number of working days per year and the number of parts per day, as previously defined.

To capture the influence of part size on infrastructure, the oven and tool were scaled proportionally to the untrimmed part surface area *A*. Based on data obtained from oven vendors, the purchase price was assumed to vary linearly with surface area, according to two constants (*M* and *N*):

$$C_{acquisition,i} = M_i + N_i A \tag{10}$$

Annual maintenance costs were approximated from experience, and distributed equally over the number of parts produced per year. Oven energy consumption was assumed to be equivalent to that reported by Witik et al. [17] for an oven with volumetric capacity of 0.79 m^3,

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and scaled linearly with vessel area. The vacuum pump electricity use was similarly computed based on data from Witik et al. [17]. Instrumentation energy consumption was assumed to equal that of a standard desktop computer.

Implementation and Application

We implemented the model within a numerical framework (Mathworks MATLAB R2014b), and introduced input data associated with the processing of a common VBO prepreg (Cytec Industries 5320-1 epoxy resin, T650-35 8HS carbon fabric). Table A.1 in the Appendix summarizes the model inputs, which were estimated from literature, material and equipment vendors, or experience. Material properties and process models for the 5320-1 resin were also obtained from previous published studies [25,26].

The model was then used to analyze realistic case studies and perform a parametric sensitivity analysis on major part, material and processing factors. The realistic case studies analyzed the detailed manufacturing costs of flat laminates measuring 0.1 m^2 and 2.5 m^2 in order to identify the dominant cost contributors for small and large parts. For these case studies, results are reported in terms of comprehensive material, equipment and labor cost components.

The parametric study was used to assess the sensitivity of manufacturing costs to key part characteristics and efficiency metrics, and provide an economic context to the expanded decision space enabled by OoA manufacture. The variable parameters were chosen based on the major cost contributors identified in the realistic case studies, and are shown in Table 1.

Table 1: Parametric study factors and ranges.

Factor	Low Limit	High Limit	Baseline
Part Characteristics			
Part Size	0.1 m^2	2.5 m^2	0.1 m^2
Prepreg Cost	\$10/m^2	\$150/m^2	\$110/m^2
Prepreg In-Plane Permeability	1E-15 m^2	1E-13 m^2	1E-14 m^2
Material Use Efficiency			
Prepreg Waste Factor	0	0.5	0.3
Edge Trim Depth	0 mm	25 mm	10 mm
Cure Efficiency			
Cure Dwell Temperature	90°C	120°C	120 °C
Cure Ramp Rate	1°C/min	50 °C/min	1 °C/min
Resin Cure Rate Factor	0.2	5	1
Energy Cost	0.05 \$/kWh	0.30 \$/kWh	0.07 \$/kWh

The prepreg costs provided by material suppliers or reported in the literature vary widely with product form, fiber bed architecture and fiber volume fraction, resin system and properties, purchase quantities, and the perceived novelty of the prepreg technology (e.g. [17,27] and the information provided by the supplier in Table A.1). Consequently, the prepreg cost input was varied between \$10/m^2 and \$150/m^2, in order to extend the analysis to both low-cost (e.g. fiberglass, natural or recycled fibers) and high-cost (carbon fiber) prepreg materials. Part size ranged between 0.1 m^2 and 2.5 m^2. The prepreg in-plane permeability covered a wide but representative range for VBO product forms, materials and fiber bed architectures, based on previously published data ([23,24]). The prepreg waste factor varied from zero (no waste) to 50% waste during ply cutting, while the edge trim depth explored the effect of removing laminate edges with cut depths of 0 mm (none) to 25 mm. The cure dwell temperatures are representative of manufacturer recommendations for a wide range of VBO prepregs. The cure ramp rates varied within a range that encompasses both ovens and non-traditional set-ups (heat blankets, integrally heated tools). The resin cure length factor estimates the influence of faster or slower cure kinetics by multiplying the actual cure time required by the 5320-1 resin at a given temperature. Finally, energy consumption costs covering a wide range of North American industrial conditions were studied; this parameter can also be used as a measure of overall energy consumption. In all cases, a production run time of ten years was assumed in order to compute production volumes (based on estimated production rates). Altogether, the chosen parameters covered a wide cross-section of choices of material types, and of decisions available to part and process designers. Results are typically reported in terms of specific total cost as a function of one or more of the varied factors. The baseline values listed in Table A.1 were used for all inputs other than those explicitly varied, unless otherwise specified.

MODEL DEVELOPMENT

Realistic Cases

Figure 3 shows manufacturing costs for 0.1 m^2 and 2.5 m^2 flat laminates composed of 8 plies and weighing 0.44 kg and 11.9 kg, respectively. In both cases, material costs constituted the major cost component, with approximately 76% of total costs for the smaller laminate and 95% for the larger. For the 0.1 m^2 part, labor and equipment comprised 20.5% and 3%, respectively, whereas for 2.5 m^2, they amounted to 1.73% and 3.03%, respectively. The detailed influence of part size is discussed in an upcoming section.

Material costs were dominated by the prepreg costs, with consumables contributing less than 10%. For the small part, the equipment costs associated with the oven, vacuum pump and instrumentation and tooling were comparable, while those of the vacuum accessories were negligible. For the larger part, the oven contribution was dominant due to the larger size required

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to cure the part. For most capital assets, the depreciation charge was larger than the contributions of maintenance and energy costs. For both laminate sizes, human activities accounted for less than 15% of the total production time, with the longest activity being debulking every ply (likely excessive for this relatively small flat part, but assumed as a worst-case scenario). For the 0.1 m^2 laminate, the room-temperature vacuum hold and cure times accounted for the remaining 22% and 65% of the manufacturing time, respectively. In contrast, for the 2.5 m^2 part, the vacuum hold contributed 85%, whereas cure comprised only 12%, suggesting that the time required for in-plane air evacuation becomes a dominant portion of processing time for large parts. Note that in all cases considered in this manuscript, the vacuum hold or oven cure periods were longer than the human activity times, and therefore rate-limiting.

The production rate (assuming a linear/sequential process flow) was 1.64 parts/day and 0.29 parts/day for the 0.1 m^2 and 2.5 m^2 cases, respectively, leading to production volumes (over a ten-year period) of 4109 units and 727 units. As previously noted, these rate and volume predictions do not account for productivity improvements such as parallel operations, and may not fully capture a practical implementation of VBO processing. However, they provide useful comparative information about the time required to produce a part for a given set of sequential operations and manufacturing decisions. These results show the relative importance of individual cost components for a given set of model inputs. The following sections expands on this data by clarifying the sensitivity of the manufacturing cost to variations in part and cure characteristics.

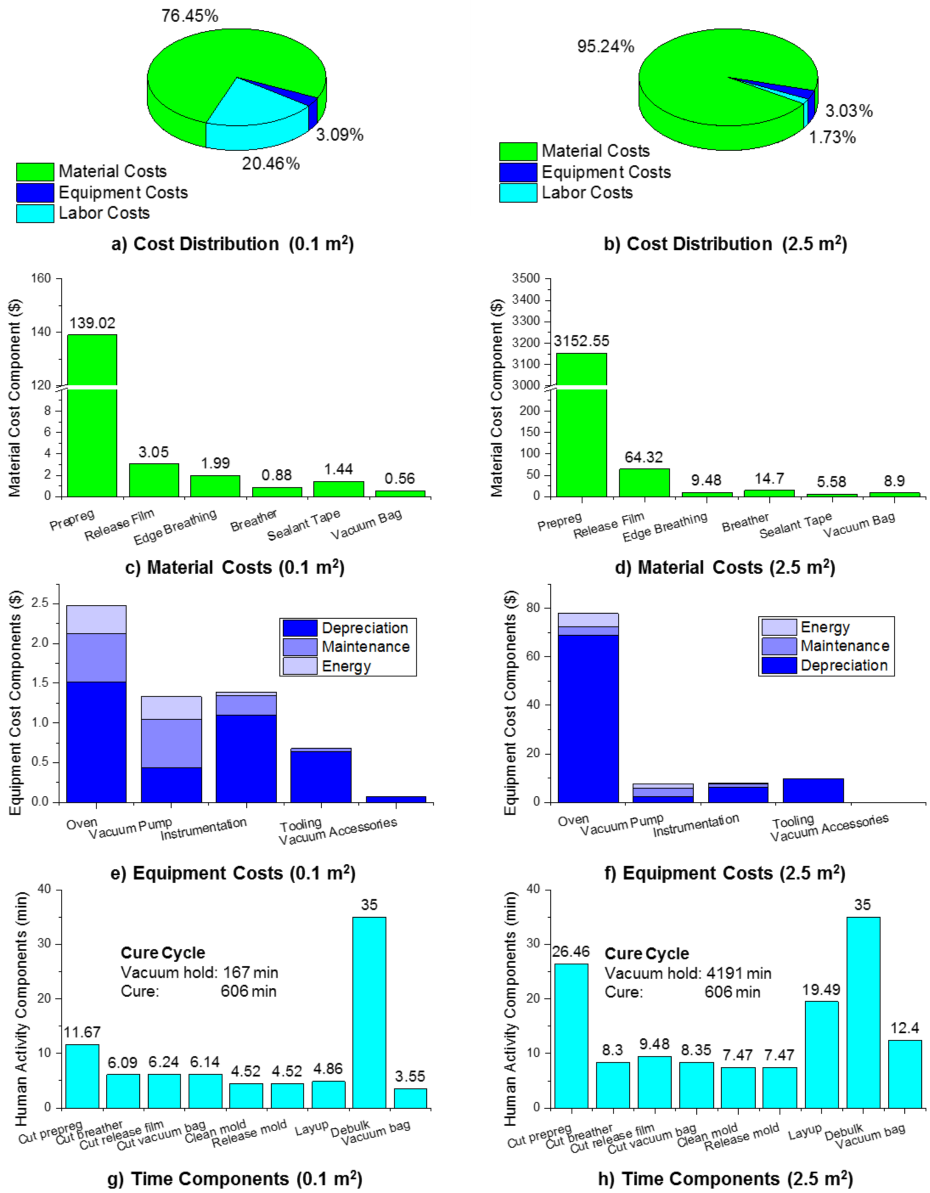

Figure 3: Manufacturing costs for single 0.1 m2 and 2.5 m2 parts produced under baseline conditions.

Parametric Study

Figure 4 shows the effect of prepreg cost, prepreg waste factor, and edge trim depth on specific total cost for laminates with in-plane areas of 0.1 m^2 and 2.5 m^2. In both cases, an increase in prepreg costs was predicted to substantially increase specific total part costs. For the chosen prepreg cost range of \$10/m^2 to \$150/m^2, the predicted specific total part costs varied between \$100/kg to \$600/kg.

Figure 4 (a) shows that the amount of prepreg waste can substantially affect the cost per kilogram of cured part if prepreg costs are high. For example, for a 0.1 m^2 part and the manufacturer-specified cost of the 5320-1 prepreg (\$110/m^2), a reduction of only ten percentage points in waste factor (from 30% to 20%) reduced specific total part costs by 9%. Note that, while not explicitly shown, the influence of consumable waste is limited on a per-part basis due to the relatively small contribution of the vacuum bag assembly to material costs – for the same part, a reduction in waste from 30% to 20% led to only a 1% reduction in total cost. In both cases, the production rates and ten-year volumes are equal to those of the baseline (1.64 parts/day and 4109 units for the 0.1 m^2 parts, and 0.29 parts/day and 727 units for the 2.5 m^2 part), since the prepreg cost and waste factors do not affect processing time within the model.

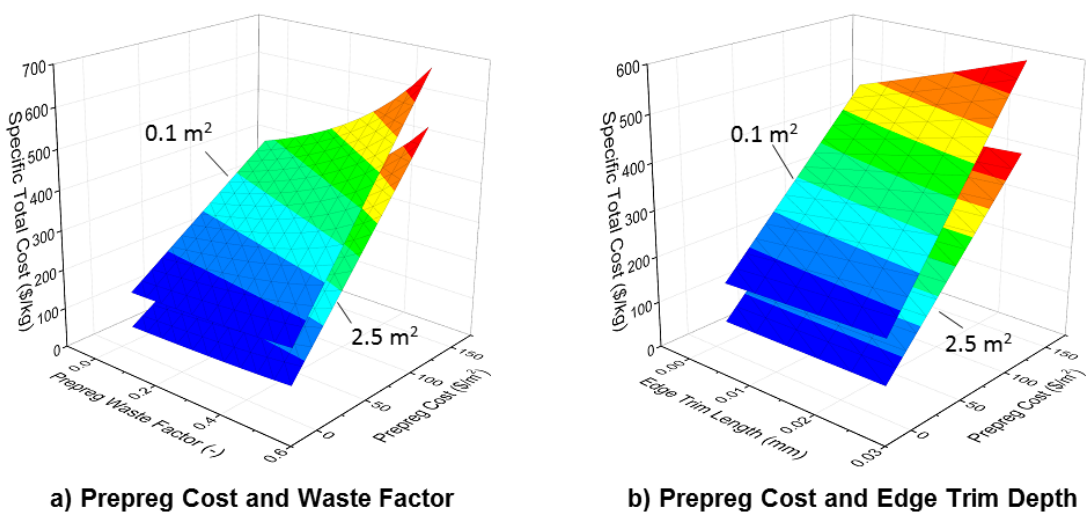

Figure 4: (a) Effect of prepreg cost and prepreg waste factor on specific total costs for 0.1 m2 and 2.5 m2 laminates. (b) Effect of prepreg cost and edge trim length on specific total costs for 0.1 m2 and 2.5 m2 laminates.

Figure 4 (b) shows that post-cure waste (edge trimming) had a comparatively smaller impact, but remained significant for high prepreg costs. An increase in edge trim width resulted in higher specific total costs, both due to material waste and because larger tool plate was required to accommodate the untrimmed part size. For the 0.1 m^2 laminate, an increase in edge trim width from 10 mm to 25 mm raised the specific total cost by 14%. However, the influence of edge trim width decreased with increasing part size, since the part weight increases faster with part area than the perimeter length, and gradually reduces the amount of removed material relative to the total mass of the cured part. For example, for a 2.5 m^2 part, the same 10 mm to 25 mm increase in trim width raised specific total cost by only 3.5%. For all cases considered in Figure 4, the larger 2.5 m^2 part was associated with lower specific total costs than its 0.1 m^2 counterpart due to the redistribution in cost components discussed in Section 3.1 As with Figure 4 (a), the production rates and volumes remain equal to the baseline.

Figure 5 and 6 clarify the direct effect of part size on costs by examining the coupling between area and prepreg in-plane permeability. Results are reported in terms of specific total cost as well as individual material, equipment and labor cost components. Figure 5 (a) shows that an increase in part size decreased specific total costs for high and intermediate permeabilities (10^{-13} m^2 to 10^{-14} m^2). However, as the permeability was reduced towards 10^{-15} m^2, the trend reversed, leading to higher specific total costs. The specific material and labor costs decreased with part size, particularly between 0 m^2 and 1 m^2 as shown in Figure 5 (b) and Figure 6. The reduction in specific material costs is attributed to the increasingly limited contribution of the edge trim waste, which can comprise a significant fraction of the initial laminate for small parts, but decreased for larger ones. The decrease in labor costs is largely explained by the fact that, as shown in Figure 3,

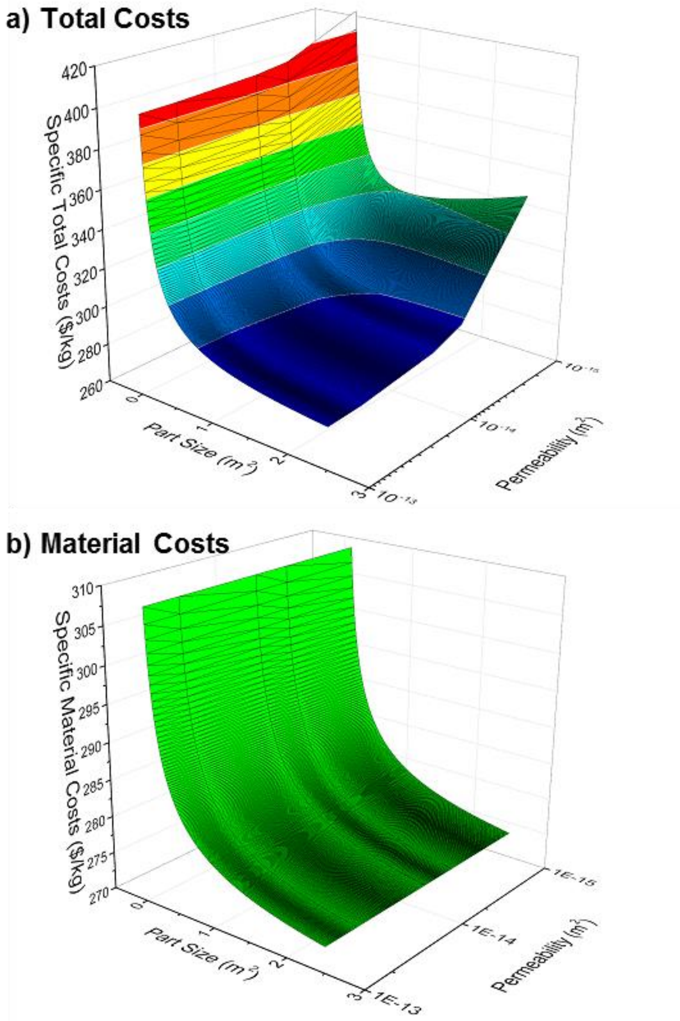

Figure 5: Effect of part size and permeability on (a) specific total costs and (b) specific material costs.

the major time component to labor was intermittent debulking, which theoretically does not scale with in-plane area. Conversely, Figure 6 also shows that specific equipment costs were largely insensitive to part size at intermediate and high permeabilities, but increased dramatically for large, low-permeability parts. In such conditions, the room temperature vacuum hold time required for air evacuation increased exponentially, reducing the production rate and hence decreasing the number of parts over which equipment costs were depreciated. For a given part size, the in-plane permeability had a notable effect on total cost when increased from low (10^{-15} m^2) to intermediate

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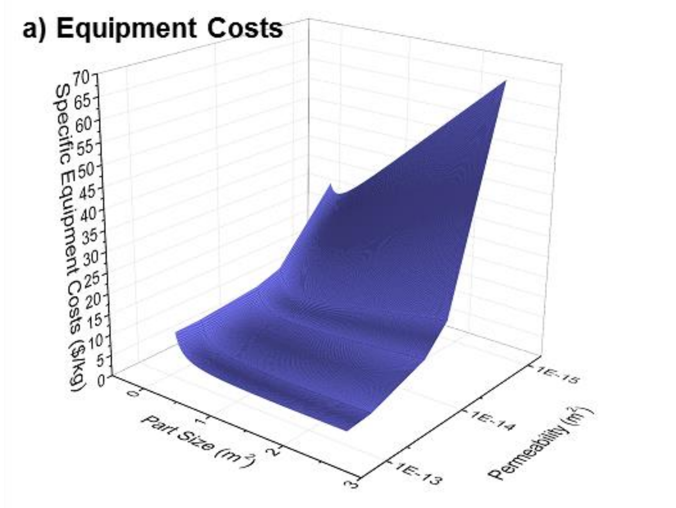


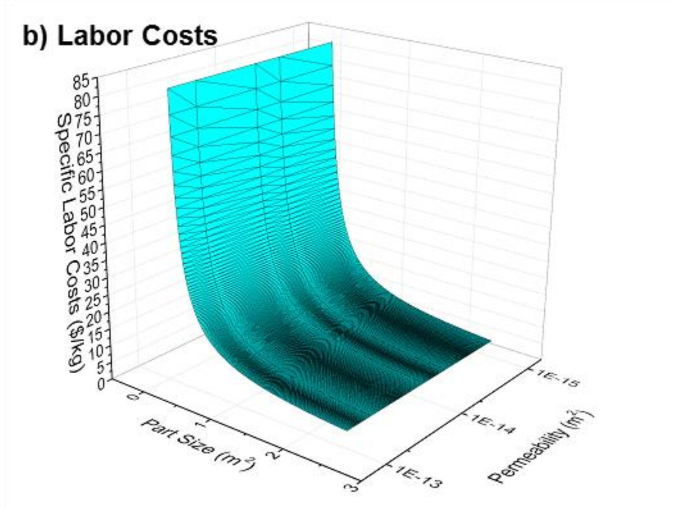


Figure 6: Effect of part size and permeability on (a) specific equipment costs and (b) specific labor costs.

(10^{-14} m^2) levels due to decreased vacuum hold times (25 h versus 3 h for a 0.1 m^2 part, respectively). However, the relationship between K and evacuation time is non-linear, and further increases in permeability brought diminishing specific total cost reductions.

Figure 7 clarifies the influence of part size and in-plane permeability on production rate, in terms of parts per day. Predicted production rates rose with decreasing part size, since larger parts were associated with longer human activity times and room temperature air evacuation dwells.

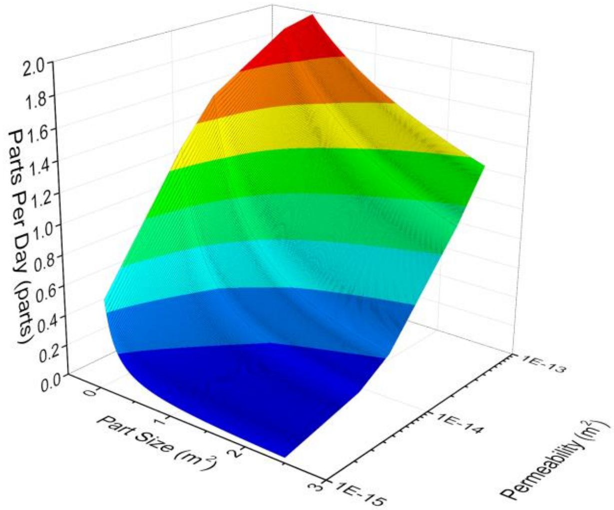
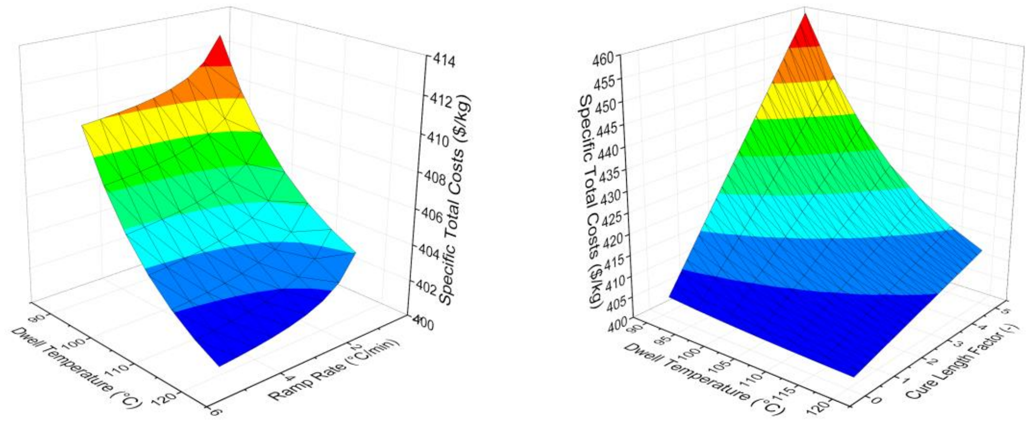


Figure 7: Effect of part size and permeability on production rate, in parts per day.

Production rates also rose with higher permeabilities due to shorter air evacuation times. The highest estimated production rate for these part size and permeability ranges (approx. 2 parts/day) corresponded to the smallest parts (0.1 m^2) and highest permeability (1E-13 m^2); in this case, the cure time remained as a fixed, limiting factor. The lowest rate (0.034 parts/day) corresponded to an area in which low permeabilities and large part sizes combine to dramatically limit production rates (as per Eq. (1)), and explain the increase in specific part costs observed for those conditions. As expected, identical trends were observed for the relationship between part size, permeability and ten-year production volume.

Figure 8 shows the influence of the resin cure kinetics on specific total costs for a 0.1 m^2 part. In Figure 8 (a), faster ramp rates and higher dwell temperatures reduced specific total costs by decreasing cure times, increasing production rates, and decreasing depreciation costs per part. However, within this cure cycle selection space, with production rates varying by a factor of 2.5 (from 0.9 parts/day and 2249 units at 90°C and 1°C/min to 2.3 parts/day and 5687 units at 120°C



a) Dwell Temperature and Ramp Rate **b) Dwell Temperature and Cure Length**

Figure 8: (a) Effect of dwell temperature and ramp rate on specific total costs for a 0.1 m2 laminate. (b) Effect of dwell temperature and cure rate on specific total costs for a 0.1 m2 laminate.

and 5°C/min), the maximum reduction in specific total costs was only about 4% due to the relatively low contribution of the equipment cost component. Figure 8 (b) shows the effect of a cure length factor used to modify the polymerization/cross-linking time required by the chosen 5320-1 resin at a given dwell temperature. At high dwell temperatures, the cure rate had a relatively small influence, since the required dwell time was already short and the contribution to the total manufacturing time was limited. Conversely, at low dwell temperatures, where the nominal dwell times were generally long, an increase in dwell time had a more pronounced effect, slowing down production rates and increasing depreciation per part. For example, at 120°C, a five-fold increase in cure length reduced the production rate from 1.64 parts/day to 0.9 parts/day, and raised specific total costs by 2.5%. Conversely, at 90°C, the same five-fold increase in cure time decreased the number of parts produced per day from 0.9 parts/day to 0.28 parts/day, and increased specific total costs by 11.3%. The same trends were observed in larger parts, although these results are omitted for clarity from Figure 8.

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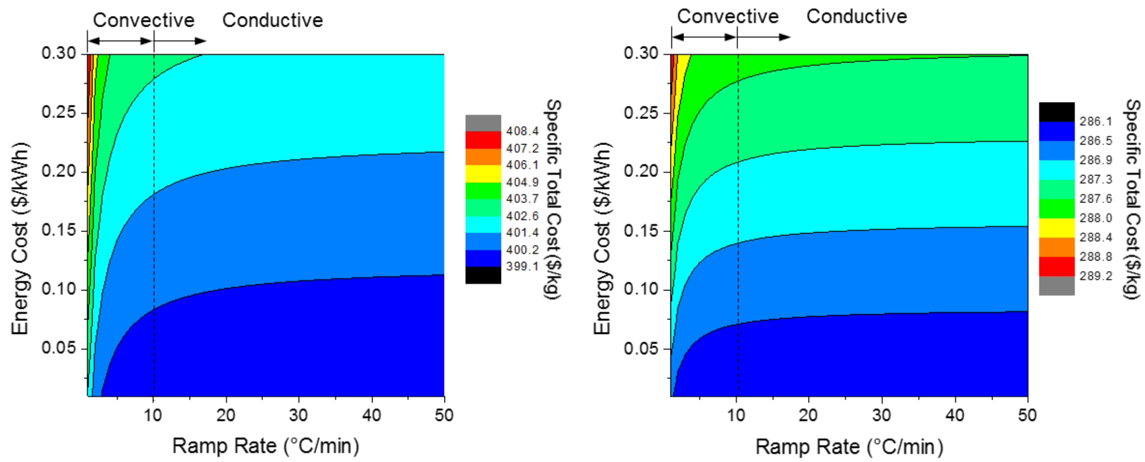

a) Part Size: 0.1 m² **b) Part Size: 2.5 m²**

Figure 9: Effect of ramp rate and energy costs on specific total costs for (a) 0.1 m2 and (b) 2.5 m2 laminates. Note that the color patterns do not conform to the same numerical scale.

Figure 9 depicts the interaction between two key characteristics of cure: the ramp rate achievable by the cure set-up and the energy costs. Note that while the latter was specified as a consumer cost (in $/kWh) for convenience, its influence on specific total costs is analogous to that of the total energy consumption of the manufacturing process (in kWh) for a given consumer cost. For both 0.1 m^2 and 2.5 m^2 parts, higher energy costs directly increased total equipment costs, with large parts being slightly more sensitive. However, the effect was relatively minor due to the relatively small contribution of equipment costs to total part costs. Higher ramp rates decreased specific total costs by permitting more parts to be produced per time period (as explained previously in Figure 8). However, the effect was significantly non-linear, with most benefits occurring as the ramp rate was varied between 0.5°C/min and 10°C/min. The results thus suggest that, for the scenarios analyzed in this study, the capacity to heat a part faster than 10°C/min does not provide a major benefit in terms of specific total costs. Note, however, that in Figure 9, the capital cost associated with the cure set-up was maintained constant for a given part size. Cure set-ups that achieve high ramp rates and low energy costs (such as integrally heated tools) with a

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lower capital cost than a convection oven may provide more significant benefits. Furthermore, as previously discussed, rapid cure may enable the use of composites in applications requiring higher production rates, such as automotive and consumer goods.

Discussion

The relative importance of the parameters included in this study is summarized in Figure 10. Results are reported in terms of the sensitivity of the specific total cost to individual factors, over a prescribed range, relative to baseline cases with part sizes of 0.1 m^2 (top) and 2.5 m^2 (bottom). Positive variations indicate higher costs and are undesirable, while conversely, negative variations are beneficial. These results can guide manufacturing considerations, as discussed below.

The cost of the “raw” prepreg was identified as the most important driver of both absolute and specific manufacturing costs, due to the dominant contribution of the prepreg component (rather than consumables) to material costs, and of material costs (rather than equipment or labor) to the total part costs. For example, a 36% increase in prepreg cost (from \$110/m^2 to \$150/m^2) led to increases of 28% and 34% for small and large parts, respectively). Similarly, reductions in prepreg cost led to proportional decreases in specific total costs. These results clearly indicate that, if VBO processing is viable for a given part, and in the absence of major capital expenditures, the availability and selection of lower-cost material is the most direct means of substantially reducing total manufacturing costs.

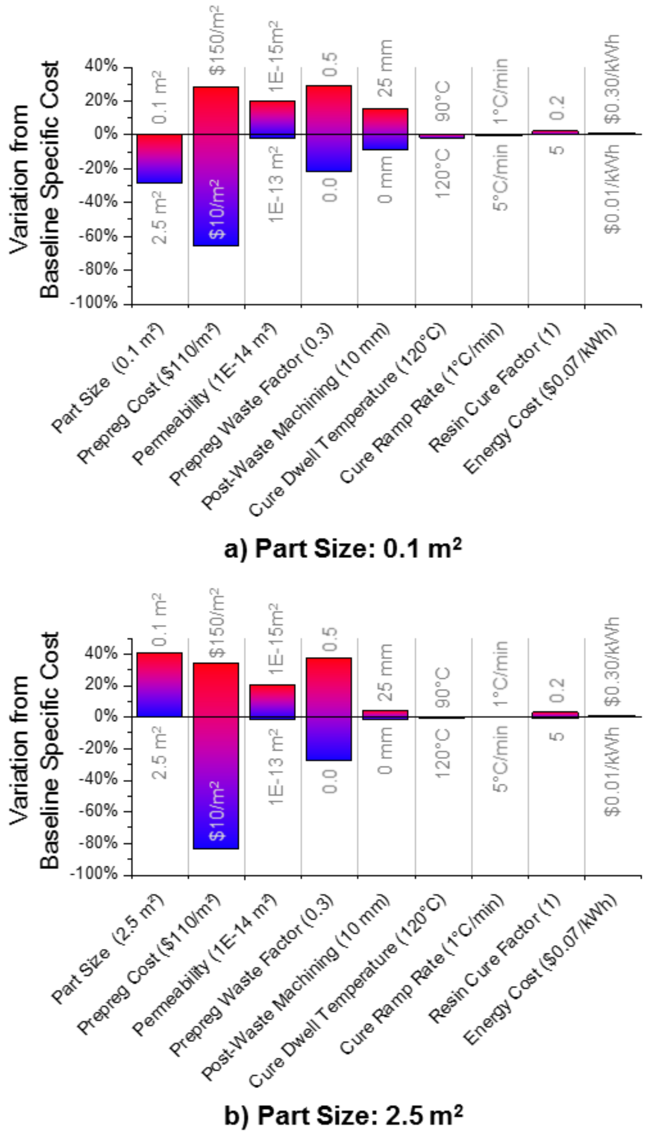

Figure 10: Sensitivity of specific total costs to material, part and process factors, relative to baseline cases with part sizes of (A) 0.1 m2 and (B) 2.5 m2. The baseline value of each factor is shown on the x-axis label, while the range of variation is indicated by the data labels.

The results also indicate that significant cost reductions can be achieved by reducing prepreg waste, particularly for high-cost prepregs. In extremis, eliminating in-process waste (from 30% to zero) lowered the specific total cost by 22% for the case of the small part and by 28% for the large part. Several possible avenues for waste reduction exist, including optimized nesting of the ply cut-outs from roll stock, net-shape ply-cutting, accurate deposition, and material use scheduling that prevents out-time and freezer time specifications from being exceeded. To a lesser extent, costs can also be reduced by producing near-net shape parts that require limited (or no) removal of excess material after cure. However, the benefits of such optimizations decrease for larger parts: in this case study, reducing the edge trim depth from 10 mm to zero lowered specific total costs by 9% for a 0.1 m^2 part, but only by 2% for a 2.5 m^2 laminate. Edge trim and other post-cure finishing operations can be avoided by accurate ply cutting and layup, as well as by defect reduction strategies that allow cured parts to meet specifications for microstructural quality, dimensional tolerances and surface finish. Finally, some costs associated with in-process waste can be recovered by recycling or reusing scrap material. Several avenues have been proposed by other authors, including recovering high-value reinforcements and directly reusing uncured scrap as a molding compound, and are well-reviewed in [28–30].

Our results showed that for a given prepreg, larger part dimensions usually decrease specific total costs per part (despite the larger infrastructure investments required) by distributing labor costs and fixed equipment costs over a larger quantity of material. For this model and case studies, increasing the part area by a factor of 25 led to a decrease of 29% in specific total costs. We also predicted that parts requiring long air evacuation times (due to a combination of geometry and low in-plane permeability) increase specific total costs by limiting the production rate. For a 2.5 m^2 part, an order-of-magnitude reduction in permeability (from 1E-14 m^2 to 1E-15 m^2) raised costs by 20%. Large part sizes and low in-plane permeability values also led to the lowest predicted production rates within our modeling framework. The literature on VBO prepreg processing has consistently emphasized the importance of air evacuation to achieve successful VBO cure, and advocated both in-plane and through-thickness air removal strategies. The in-plane "breathing" approach assumed within this study is generally reliable and consistent. Since the time required for air evacuation increases quadratically with flow distance (or part size) [22], through-thickness air removal can be particularly beneficial for large parts, as it is independent of in-plane dimensions. However, recent studies have indicated that some common VBO prepreg product forms may have minimal and unpredictable out-of-plane permeabilities. The development of prepreg product forms with high transverse permeabilities (e.g. [31]) and of vacuum bagging strategies that enable rapid and/or size-independent gas evacuation could significantly reduce processing times for large parts, increase production rates, and decrease costs per part.

The resin cure kinetics (or the necessary temperature and time for cure) were predicted to have a comparatively small effect on specific total costs. For both small and large parts, the variations in specific total cost with dwell temperature, ramp rate and cure length factor were lower than ± 3%. Nevertheless, fast-curing resins can be highly beneficial if they enable the use of composite materials and non-autoclave processes in applications requiring high production rates.

We predicted that equipment and energy costs are lower than those incurred from materials and labor due to the use of low-cost infrastructure, and that the sensitivity of the total cost to variations in base energy costs are low (less than 1% over the studied range for both small and large parts). However, these areas may be associated with relatively direct opportunities for cost reductions. Reducing cure cycle times through higher-temperature, faster cure cycles can increase production rates and reduce depreciation per part. Moreover, energy-efficient cure set-ups (such as integrally heated tools that heat conductively rather than convectively) can also provide small but direct benefits, particularly if they also reduce the overall capital investment in thermal equipment and tooling.

Limitations and Future Work. The results discussed above are predicted on the basis of simplifying assumptions. The model is based on a generic VBO prepreg process composed of a series of necessary steps. However, it may not account for unique industry, company or application-specific operations that significant impact costs. Moreover, the input data is broadly representative but necessarily non-specific.

Finally, as mentioned in the introduction, the analysis and conclusions derived from our model may not be applicable to the manufacture of large, integrated structures or to complex production environments due to the omission of process flow non-linearity and automation. Non-linear process flows can involve multiple parallel production lines, rate mismatches between different operations, buffering or discrete events. Such characteristics may be present in the manufacturing of large structures composed of multiple sub-sections, or in situations where equipment is highly shared, and may significantly affect the cost relationships of VBO prepreg processing. The analysis of such environments poses challenges because the specific characteristics of a non-linear process flow (e.g., the nature and number of parallel operations, the degree of rate mismatch between successive steps, and the use of buffers) can vary with material, part, and process decisions. Non-linearity can dramatically increase the manufacturing decision space, and hence the number of variables that must be accounted for during modeling. However, non-linear process flow descriptions can enable the analysis of realistic situations, in which target production volumes and time periods are defined and process sequences capable of meeting these targets must be identified. Process flow analysis was considered outside of the scope of the current work, but remains a desirable area for further work. Automation may substantially increase material laydown rates and reduce human labor costs and time prior to cure, at the cost of significant capital and operating expenses. The relative benefits (or downsides) associated with introducing such infrastructure are difficult to assess due to the various scales at which automation is possible and the unique characteristics and costs of a given system. However, as with the case of complex process flows, detailed studies on the effect of automation on the costs of non-autoclave processing would be a valuable contribution to the literature.

Despite these limitations, the resulted reported here are consistent with previous studies (for example, Witik et al. [17]). As a result, this work complements existing knowledge by clarifying existing techno-economic relationships for VBO processing and suggesting possible approaches for reducing manufacturing costs.

CONCLUSIONS

We investigated the costs relationships associated with the VBO prepreg processing of composite parts. First, we described a technical cost model capable of estimating material, equipment and labor contributions. Then, we used the model to evaluate the effect of parameters associated with material and part characteristics, material use efficiency and cure efficiency. The results were reported on a per-part basis and analyzed in terms of specific total costs, segregated costs, and production rate. The key technical improvements desired for reducing costs were identified as (1) a reduction in prepreg costs, (2) the efficient use of prepreg material through reduced in-process and post-cure waste, and (3) a decrease in vacuum hold times for large parts through effective air evacuation strategies. These insights, though subject to the assumptions used to develop the model, can be used to minimize part cost while optimizing part quality.

Generally, cost models such as the one presented here can provide a much-needed economic complement to technical research on composites manufacturing. Currently, numerous competing non-autoclave processes, in conjunction with several automation options, claim to increase efficiency and reduce costs. However, the degree of validity of these claims is unknown or poorly quantified. As evidenced in recent literature comparing OoA and autoclave costs (e.g., [17]) and in this article, cost modeling can be a useful tool to evaluate the intrinsic cost relationships of a manufacturing process. In addition, by clarifying the economic importance of specific material, part and processing characteristics, cost modeling can identify opportunities for improving a given manufacturing approach. Such information is beneficial to material suppliers, part manufacturers, and research institutions by highlighting areas where investments are likely to yield the highest returns.

As the commercial applications of composite materials increase, and as composites expand into higher-volume markets and larger parts, the efficiency of available manufacturing methods will grow in importance. As a result, technical research will need to be complemented by studies that assess the economic, environmental and societal impact of the production and use of composite parts. The present study seeks to expand the limited body of literature on these topics and contribute to this shift.

ACKNOWLEDGEMENTS

The authors are grateful for financial support from the National Science Foundation, through the G8 Research Councils Multilateral Initiative on Materials Efficiency and the “Sustainable Manufacturing Through Out-of-Autoclave Prepregs” project (NSF CMMI-1229011). The project’s partner academic institutions (the University of Bristol, the Technical University Munich, and McGill University) and industrial advisory board are also acknowledged for their input.

APPENDIX

Table A.1: Model inputs and reference values for the parametric study.

Constant	#	Unit	Constant	#	Unit
Material Properties			Instrum. Acquisition Cost[4]	5000	$
Cured Ply Thick. (5320-1/8HS)[1]	0.40	mm	Instrum. Annual Maintenance[3]	100	$/year
Resin Content (5320-1/8HS)[1]	0.37	by wt.	Tooling Cost (Aluminum)[4]	591	$/m^2
In-Plane Permeability[2]	1E-14	m^2	Tool Durability[3]	250	parts
Production Schedule			Tool Lifetime Maintenance[3]	20	$/tool
Production Run[3]	10	years	Vac. Hose Acquisition Cost[4]	25.25	$/m
Annual Working Days[3]	250	days	Vac. Fitting Acquisition Cost[4]	25	$/fitting
Daily Shifts[3]	3	shifts	Vacuum Valves[4]	25	$/valve
Material Costs			Equipment Lifetime[3]	10	years
Prepreg (Woven)[4]	110	$/m^2	Equipment Salvage Value Rate[3]	10	%
Vacuum Bag[4]	2.15	$/m^2	**Labor Costs**		
Release Film (Non-Perf.) [4]	8.61	$/m^2	Hourly Wage[3]	23	$/hour
Breather[4]	3.66	$/m^2	**Human Activity Times**		
Sealant Tape[4]	0.82	$/m	Cut Overhead Time[3]	5	min
Fiberglass Boat Cloth[4]	0.66	$/m	Cut Time for 0.1 m^2 [(3)]	0.75	min
Material Use			Mold Prep. Overhead Time[3]	4	min
Prepreg Use Ratio[3]	0.7	-	Clean Mold Time for 0.1 m^2 [(3)]	1	min
Part Edge Trim Length[3]	6.3	mm	Release Mold Time for 0.1 m^2 [(3)]	1	min
Consumable Use Ratio[3]	0.7	-	Release Mold Dry Time[3]	5	min
Release Film Overhang (Tool)[3]	25.4	mm	Layup Overhead Time	0.5	min
Release Film Overhang (Bag)[3]	6.3	mm	Layup Time for 0.1 m^2	0.75	min
Breather Overhang (Length)[3]	127	mm	Vac. Bagging Overhead Time	2	min
Breather Overhang (Width)[3]	25.4	mm	Vac. Bagging Time for 0.1 m^2 [(3)]	3	min
Vacuum Bag Overhang (Length)[3]	152.4	mm	Debulk Time for One Ply	5	min
Vacuum Bag Overhang (Width)[3]	50.8	mm	Plies Per Debulk	1	ply
Equipment Costs			Leak Test Time	5	min
Energy Cost[5]	0.07	$/kWh	Oven Insertion Time	5	min
Oven Acquisition Cost[6]	Variable		Oven Removal Time	5	min
Oven Annual Maintenance[3]	250	$/year	De-Bagging	5	min
Oven Energy Consumption[7]	Variable		Scale Factor 1 (Linear)	1.5	-
Pump Acquisition Cost[8]	2000	$	Scale Factor 2 (Power)	0.6	-
Pump Annual Maintenance[3]	250	$/year			
Pump Energy Consumption[7]	0.005	kWh/min			

Notes:

[1] Cytec Engineered Materials (personal communication) [25]

[2] Approximated from Louis et al. [23]

[3] Assumed (unless otherwise specified)

[4] Approximated from vendor data

[5] United States Energy Information Office

[6] 12769(SA)+3511.20, where SA is the oven surface area in m^2.

[7] Witik et al. [17]

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