PERFORMANCE INFORMED TECHNICAL COST MODELING FOR NOVEL MANUFACTURING

by

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To my fellow members of the United States Armed Forces.

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LIST OF ABBREVIATIONS

The abbreviations in this list are used throughout this document. Brands and product names may not be included.

ACCEM	Advanced Composite Cost Estimating Manual
A-SMC	Advanced-Sheet Molding Compound
CAD	Computer Aided Drafting or Design
CAE	Computer Aided Engineering
CAFE	Corporate Average Fuel Economy
CER	Cost Estimation Relationship
CF	Carbon Fiber
CFRP	Carbon Fiber Reinforced Polymer
CM-TP	Compression Molding of ThermoPlastics
CoC	Cost of Capital
COLA	Cost Of Living Allowance
DURA	DURA Automotive Systems
EE	Engineering Estimate
ES-A/ES-B	Equipment Supplier A or B
EUAC	Equivalent Uniform Annual Cost
GF	Glass Fiber
GFRP	Glass Fiber Reinforced Polymer
HP-RTM	High Pressure-Resin Transfer Molding
MACRS	Modified Accelerated Cost Recovery System
MDLab	Manufacturing Design Labratory
NASA	National Aeronautics and Space Administration
NMC	New Material Cost
NPV	Net Present Value
PP	PolyPropylene
PPY	Parts Per Year
Prepreg	PRE-imPREGnated
QC	Quality Control
QTC	EELCEE QEE-TECH® Preforming Cell
SCF	Standard Cubic Foot
SF	intercontinental Shipping Factor
T1P	Tier 1 Producer
TCM	Technical Cost Modeling or Model
TP	ThermoPlastic
TS	ThermoSet
U.S.	United States
ZC	ground based Zone Cost

ABSTRACT

Inaccurate cost estimates contribute to lost implementation opportunity of novel manufacturing technologies or lost revenue due to under-bidding or loss of an over-bid contract. High-volume, long-term orders, such as those the automotive industry begets, are desired as they lock in revenue streams for months into years. However, high-rate composite materials and their manufacturing processes are novel among the industry and traditional costing methods have not advanced at a proportional rate. This research effort developed a method to reduce the complex composite manufacturing systems to fungible, upgradable, and linkable individual processes that derive their manufacturing parameters from the performance part design process. Employing technical cost modeling, this method accurately quantifies the value of pursuing composite manufacturing by integrating impregnation, solidification, heat transfer, kinetics, and additional technical data from computer-aided part design simulation tools to deliver an accurate cost estimate.

Cost modeling provides a quantitative result that weighs heavily in the decision making process for adoption of a new manufacturing method. In this dissertation, three case studies were investigated for three different management decision cases: part production management, in-house manufacturing management, and global manufacturing management.

Part production management is the decision making process for selecting a certain manufacturing method. A case study with a Tier 1 Part Producer was conducted to provide a comparison of two emerging novel preforming systems versus their in-use, metals based high-rate manufacturing line in manufacturing a structural automotive part. Determining material usage was the primary cost driver focus. Equipment Supplier A's process operated by seaming single layers of thermoplastic tape into rolls and then stacking prior to consolidation and resulted in a scrap rate of 23-28% with a cost of $32.87-36.01 per kilogram saved depending on the input tape width. Equipment Supplier B's layup process, essentially a multi-head automatic tape layup machine, resulted in scrap rate of 20-27% with a cost of $34.48-36.67 per kilogram saved depending on the input tape width. This exceeded the Tier 1 Part Producer's requirement of $6.6-11 per kilogram saved and led to them to abandon this application as a feasible project and instead look for a different part with a higher return regarding cost for weight saved.

In-house manufacturing management is the decision making process governing manufacturing operating procedures. A case study for the Manufacturing Design Laboratory's (MDLab) hybrid molding line was undertaken to determine the manufacturing cost for a composite test coupon. Processing parameters were obtained from three sources: performance design computer aided engineering (CAE), common industry transfer estimation times, and a calculated preform layup time. Compared to a similarly shaped test coupon made of aluminum, highly-automated manufacturing realizes weight savings of 46.25% and cost savings of 16.5%. Low-automation manufacturing captures the same weight savings, but has a cost for weight saved penalty, cost increase, of $9.89 per kilogram, showing how influential the labor contribution is to manufacturing cost.

Global manufacturing management is the decision making process governing manufacturing location. Various manufacturing cost drivers are location dependent, thus a dataset was developed to alter these parameters for the U.S. states. Global comparisons are accomplished through indexing of global cost of living allowances and labor rates. Within the U.S., high-automation manufacturing costs in the West Coast/Pacific are 20.1% greater compared to the Midwest and similarly, low-automation costs are 21.2% greater. Globally, high-automation manufacturing costs in North America are 52.1% greater compared to Asia while low-automation costs are 116.5% greater. These variations highlight why we see geographically clustered manufacturing centers within the states and major manufacturing relocations due to cost sensitive and labor sensitive production.

1. INTRODUCTION

Composite materials provide strength-to-weight ratios that rival steel, however, manufacturing analogous parts is more expensive in a composite material due to the unique processing, tooling, and raw material cost [1]. Composites possess unique properties that allow design engineers to further reduce an assembly's final weight and overall cost by integrating multiple components into one seamless part, known as "part consolidation", eliminating joint assemblies that increase weight and cost [2]. For decades, the aerospace industry has advanced composite manufacturing techniques and design processes to reduce the weight of aircraft, a process called "light-weighting." They can recoup from $300 up to $900 per pound of reduced weight through decreased life cycle costs attributed to increased load capacity or reduced fuel consumption [2, 3].

To meet intensifying mileage requirements or CO_2 regulations from countries around the world, the automotive industry has embraced light-weighting and has broadened its adoption of composites. Light-weighting benefits go beyond just the industry reported rule of thumb that a 10% reduction in vehicle weight yields a 7% increase in fuel economy [4, 5]. Lighter vehicles, if properly designed, provide enhanced ride characteristics like better handling and acceleration. Composite materials, when utilized and designed correctly, also absorb more energy in crashes than their metal counterparts, enhancing safety [6]. Unfortunately, the automotive industry places a much lower economic value on light-weighting compared to the aerospace industry [7]. This low value limits the implementation of most currently utilized composite manufacturing routes due to their high manufacturing cost. Large production volumes are necessary for the automotive industry to not only reduce costs, but to meet customer demand for their products. Thus, during a project start-up, controlling cost becomes the primary objective.

Determining the manufacturing costs during the product design stage can steer the usage of materials or manufacturing techniques, which, in turn, can steer the design of the product itself. When working with new processes and materials, determining a manufacturing cost becomes difficult. A manufacturing method that is cost-efficient for low volume may not be efficient for high volume. Thus, determining the manufacturing volume can influence the manufacturing technique which can influence the materials involved. The ability to provide an accurate cost of a product allows a business to bid for production effectively while mitigating the risk of under- or over-bidding that results in financial loss or loss of the contract, respectively.

Composite material cost estimation has been studied extensively across the aeronautical, aerospace, and wind-power generation sectors. These fields center around low-volume orders where the equipment utilized does not have the capability to transfer to high-volume production, nor the capability to produce acceptable automotive finished surfaces. Recent advances in material sciences have begun to reduce the cost of carbon fiber and have introduced polymers and additives that allow a component to be manufactured and cured to a solid state in minutes instead of hours. Advances in Computer-Aided-Engineering (CAE) tools allow optimum manufacturing parameters to be determined well before the manufacturing line is installed. This combination of lower cost, fast throughput, and performance design is opening the potential use of Carbon and Glass Fiber Reinforced Polymers (CFRP and GFRP, respectively) in areas that were not economically feasible in the past. Composites are often a replacement alternative which require quantifying the potential benefit of these materials compared to traditional materials such as steel or aluminum.

1.1 Objectives and Outline

1.1.1 Research Objectives

The goal of this research is to address the following question:

How can composite performance design tools be integrated with an economic modeling tool to provide an accurate and precise representation of manufacturing times and cost?

To answer this question the following objectives shall be pursued:

I. Create a methodology for predicting system performance by integration of performance simulation and Technical Cost Modeling (TCM)
II. Identify physics-based cost drivers derived from the processing characteristics of the composite system
III. Provide economic quantitative indicator
    a. Decrease time necessary to determine decision for change or implementation for the manufacturing method

1.1.2 Dissertation Outline

This dissertation is presented across six (6) chapters. The first chapter discusses what Technical Cost Modeling (TCM) is, the background, and why it is a necessary tool for novel high rate manufacturing processes. The second chapter lays out the building blocks followed to construct a cost model from the ground up. The third chapter discusses utilization of TCM for part production management and includes work completed with a Tier 1 automotive part producer. The fourth chapter builds upon chapter two (2) by integrating the processing parameters extracted from CAE tools for hybrid molding. It presents case studies for the MDLab test coupon that is hybrid molded to demonstrate the roll that TCM can play in in-house manufacturing management. The fifth chapter expands on chapter four (4) by taking a manufacturing cost to and converting it for cost comparisons both domestically across the United States and globally. The sixth chapter discusses how future work may utilize the TCM as a baseline that can be compared to the physical and digital threads of data of an actual manufacturing line to track costs in real time. The dissertation flow is shown in Figure 1.

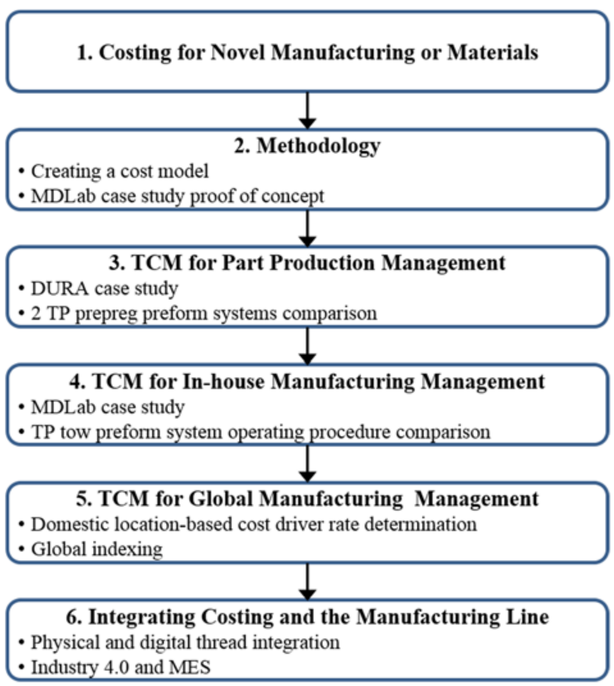

Figure 1. Dissertation flowchart.

1.2 Background

1.2.1 Automotive Industry Composite Adoption

In 2015, the transportation sector contributed 1,806.6 Million Metric Tons CO_2 equivalent, or 27.4% of total greenhouse gas emissions within the U.S. [8]. The primary contributor within the sector were the 250 million registered vehicles in the U.S., which dwarfs any other transportation sector contributor [9]. In response to the emerging environmental concerns, U.S. regulators created fuel economy thresholds through the Corporate Average Fuel Economy (CAFE) standards [10]. To meet both consumer and regulatory requirements, the automotive industry has focused on drivetrain efficiency and light-weighting.

The benefits of light-weighting have been understood since Henry Ford. Released in 1903, Ford expounded about his Ford Model A,

Excess weight kills any self-propelled vehicle…Strength has nothing to do with weight… Whenever any one suggests to me that I might increase weight or add a part, I look into decreasing weight and eliminating a part! The car that I designed…would have been lighter if I had known how to make it so [11].

Utilizing CFRP materials versus steel may reduce the weight of a part by more than 60% in some cases [12]. A composite material is a material comprised of two or more components that are combined on both a macroscopic and a microscopic scale. The constituents have different properties and typically are comprised of a matrix to bind the constituents together and fibers that provide strength and stiffness [13]. Design engineers unfamiliar with composites may experience difficulties due to composite's anisotropic nature, which requires more attention to load paths than design in metal. These materials are associated with high costs due to their prevalence and development in the very high performance driven aerospace industry, but recent technological advances and increased production of carbon fiber has made their use in high-volume production an interesting alternative to traditional materials.

Unfortunately, the perceived cost and aerospace dominated application has made implementing composites in the other industries, like the automotive industry, difficult. Materials are chosen during the concept phase of the production timeline, often based on prior knowledge of the design engineers. This time accounts for the least cost incurred, but commits the most costs for production. As the part development moves closer to production, any changes to material or design incurs great costs [3]. Traditional automotive design engineers and economists have very limited exposure to designing and costing with composite materials. For the engineers, this requires new training and education for them to move out of their isotropic metal comfort zone. For the economists, this requires utilizing new costing methods that allow them to cost novel materials and manufacturing methods [14].

1.2.2 Composite Manufacturing Process

Manufacturing a component from composites is a complex chain of processes composed of several individual processes requiring a vast array of equipment. Disregarding the material cost, it is this fact that has prevented composites to be competitive in industries outside of aerospace and niche producers. Components made from metal could have as little as one process step; raw material is delivered in the form of rolled sheet metal, fed into a stamping machine, and stamped and formed simultaneously to create a useable part. Composites, on the other hand, are derived from multiple raw materials and combined to produce a useable part. This transformation from raw material to useable part is broken into three distinct manufacturing sections to be further investigated: base material forming, preform forming, and part finalization.

1.2.2.1 Base Material Forming

Base material forming is the process of converting the raw materials a composite is composed of into a form that is convenient for manufacturing. This can take on one of two forms; dry composite forming or pre-impregnated composite forming. Both forms have their own pros and cons and are used in various manufacturing methods.

In dry composite forming the individual fibers are taken from their spools and processed to create tows, non-crimp fabric, woven fabrics, or a part preform. This step is akin to fabric processing in the clothing industry. A tow is a bundle of fibers. This bundle can range in size, the thicker the bundle the larger the number of individual fibers, and forms the basis of the other dry-formed materials. Bundles laid in the same direction and held together with minimal binding create non-crimp fabric. Unidirectional-based composites exhibit the greatest strength due to the negligible bending the fibers experience in their base material-formed state, however, care must be taken in the part design to ensure that loads are distributed correctly to maximize this benefit. Fibers or bundles may be woven to produce fabrics. The weave pattern dictates the shear properties of the fibers and allows for bi-axial in-plane loading. Tows may also be woven into tubes or rope that provide alternatives for load distribution paths to design engineers.

Pre-impregnated composite forming expands on the base that dry-forming has produced. The dry tows, sheets, or fabric are impregnated with resin to form a material that is ready for processing into a part. Fiber may be impregnated with a variety of materials, however, the most common are ThermoSet (TS) or ThermoPlastic (TP) resins. TSs require an activation step, often in the form of heat, to induce a reaction that cross-links the polymer strands and leads to a solid material once fully cured. TPs are a solid polymer which, upon heating, melts and allows it to be consolidated or shaped to the desired form. Cooling solidifies the TP and leads to the solid material. Which material is ultimately utilized in the final part is dictated by the design engineer or customer specifications. The seemingly infinite combination of raw materials and fiber designs may be reduced by knowledgeable design engineers, part design simulation tools that can iterate through various combinations, and cost analysis to determine the ideal combination.

1.2.2.2 Preform Forming

Preform forming is the conversion of the formed material into the initial shape of the desired part. This typically consist of taking dry or PRE-imPREGnated (prepreg) material, cutting it to shape, stacking it to the correct thickness, and consolidating it. Several specific high-throughput preforming processes shall be discussed later. During the preforming process, the fiber direction is established for the final piece. This requires accurate and precise layup of material, and thus utilizes some level of automation for high-volume production. Determination of the proper fiber direction is conducted by the design engineer with the aid of simulation tools such as Dassault Systèmes's® CATIA and refined through performance simulation tools such as ESI's® PAM FORM and Convergent's® COMPRO.

1.2.2.3 Part Finalization

Part finalization is the morphing of the preform into the desired shape. If beginning with a dry preform, the preform must be shaped then resin must be added and cured. One intermediate to high-volume capable process for this is HP-RTM. If beginning with a prepreg based preform, the preform must be shaped and the resin cured. TP based prepreg must be heated, then, once shaped, it solidifies to maintain the desired shape. TS based prepreg must be activated and sufficient time allowed within the shaping mold to allow for cross-linking and vitrification to maintain the desired shape. One high-volume capable process for production with TP-based prepreg is Hybrid Molding. Further processing may be required to reach the final dimensions or to add other features of the design to the part. These processes may include, but are not limited to; trimming, injection overmolding, fastener installation, and assembly.

The above is a broad generalization of the process to go from raw material to finished composite-based part and was presented to provide a glimpse of the complex nature of composite manufacturing. Despite the complexities involved with composites manufacturing, the potential for component integration is exceptional [15]. This leads to less joining or fasteners required to assemble a part and thus leads to reduced weight, material required, and assembly steps, which can result in reduced manufacturing costs. Reducing assembly steps may also reduce the number of workers or amount of automation required to reach the final product, further reducing manufacturing costs. This is why a holistic approach to part design and cost modeling of the entire manufacturing line, instead of focusing on a single process step or piece of equipment, is required.

1.2.3 Cost Modeling

Costing methods traditionally fall into three categories: activity based, parametric, or bottom-up. Activity based, also known as analogous, methods rely on a designer's knowledge and judgement and historical data. The designer must recognize what is similar and different to past designs and estimate how those differences affect the cost compared to the part that was made in the past. Since activity based costing relies on historical data, it is not appropriate for novel materials or processes [16]. Parametric costing, also known as function costing, relies on developing Cost Estimation Relationships (CERs) that are mathematical relationships between a parameter, e.g. size or shape, and the cost to produce that parameter. This requires historical databases to draw from to determine those relationships, and those relationships are only valid within the available range, but, once those historical databases are established, it is possible to determine costs that scale with size, complexity, and production volume [17]. Bottom-up costing, also known as resource-based, looks at each step in a manufacturing process and determines their cost contributors, e.g. material, labor, utilities. Each sub-process's cost contributors are then added together to determine a final cost. This approach requires knowledge of the final product design and manufacturing method to be accurate [3, 17].

The most widely utilized cost model for composite materials is Northrop Corporation's Advanced Composite Cost Estimating Manual (ACCEM) that was developed with the U.S. Air Force in 1976. This bottom-up based model relies heavily on empirical correlations for labor time estimates. Its age and reliance on labor-intensive manufacturing techniques makes it difficult to translate to high-volume market needs [3, 18]. NASA and the large aerospace companies have driven further development of composite cost models, however, most of these models are proprietary and what is available to the public is insufficient to generate new models for outside businesses.

Technical Cost Modeling (TCM) draws components from these three methods to deliver an accurate, flexible, and easily manipulated costing method. A TCM is constructed from the logical progression of the manufacturing process steps, like the bottom-up method. Approaching the manufacturing process in this manner allows the TCM designer to identify where potential costs may be generated from. These costs, known as cost drivers, vary from process to process, but have direct influence on the final cost of the part. Figure 2 illustrates the breakdown of cost drivers and categorizes them to what portion of the total operating costs they apply to. TCM then utilizes parametric relationships that are approximated or experimentally obtained to fill in missing data from the databases that activity based models rely on to deliver event driven costs for labor, materials, scrap allowances, and cycle times [19, 20].

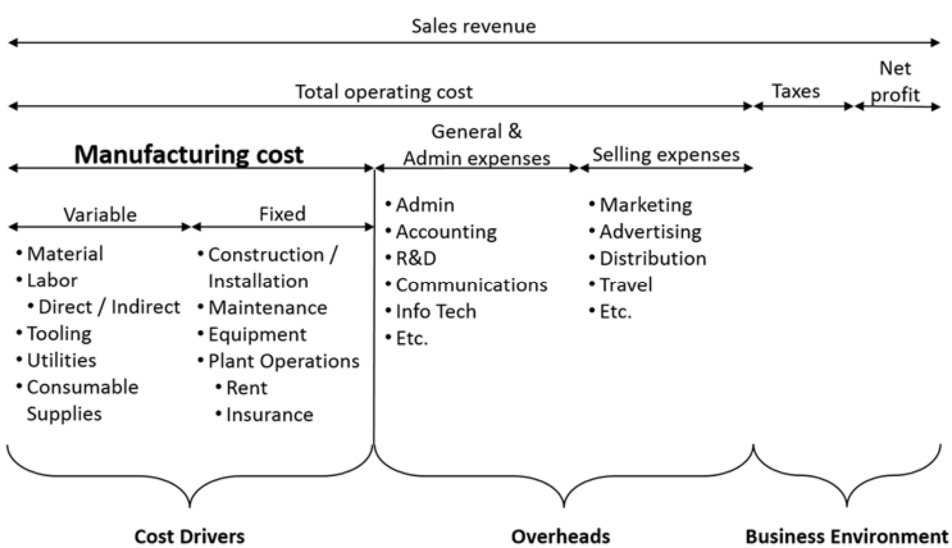

Figure 2. Modeled manufacturing costs (adapted from [21]).

The more costs included increase the accuracy of the cost model, however, often gathering the data required to calculate a plethora of cost drivers is difficult if not impossible, especially early on in the design process or if the equipment/process is novel. Figure 2 breaks out cost drivers that are components of the manufacturing cost. Cost drivers contributing to the *Overheads* and *Business Environment* categories are individual to each company, thus are difficult to capture unless supplied. However, to calculate the Net Present Value (NPV) of a process, these must be supplied.

The few automotive industry specific cost models focus on part manufacturability and time studies. Verrey et al. investigated how varying TS and TP resins can alter the cycle times required to produce a part by utilizing reaction kinetics to estimate the degree of cure and thus the time required for a part to reach its gel state. They also determined that varying preform construction techniques can reduce scrap [22]. Karlsson's *Development of a Technical Cost Model for Composites* focuses on three high-rate production processes; High Pressure-Resin Transfer Molding (HP-RTM), Advanced-Sheet Molding Compound (A-SMC), and Compression Molding of ThermoPlastics (CM-TP). A-SMC and CM-TP both utilize prepreg sheets that are cut to shape, stacked, consolidated, placed in a mold, and compressed to obtain the desired shape. A-SMC utilizes TS prepreg, requiring heating and potentially cooling of the mold to induce cross-linking, while CM-TP utilizes TP prepreg, requiring only time within the cool mold to solidify. Though capable of reaching high production volumes, A-SMC and CM-TP are rather established processes, thus are not a primary aspect of this current research. Karlsson's model utilizes simplified 1D geometries for most processing steps and relies heavily on user-provided cycle times for processing operations [23]. Martensson et al. investigated how strategic part design can reduce the number of components and joints required in a composite part and placing manufacturing constraints upon designers can lead to parts designed for manufacturability that reduce tooling costs through reduced part complexity [2, 24, 25].

These state-of-the-art cost models rely heavily on simplified mechanisms to broadly estimate the manufacturing time and material quantities that are the basis of the financial aspect of a cost model. Integrating the optimal manufacturing parameters that CAE tools identify is the primary goal of this research. Incorporating the part-design simulation tool's exact technical aspects of the manufacturing process shall increase the accuracy of the manufacturing time and material usage, thus increasing the cost model accuracy.

1.2.4 Performance Simulation and Cost Modeling in the Part Design Process

An issue companies face is *when to cost estimate* and *at what detail is costing required*. The product design process varies from company to company, and several generalized flowcharts exist to aid in guiding the part design, material selection, and process selection. However, when to cost is generally not considered throughout these design processes, as costing is often considered within other departments than the research & design department.

In order to identify where simulation or database tools can aid the design process and where costing and what depth of costing should be utilized through the design process, two established design process flowcharts shall be investigated. Norton outlines a ten (10)-step part design process [26] that is integrated into Ashby's material and process selection flowchart [27] in Figure 3. Along the left and right borders, the contributions from the simulation tools and the depth of cost modeling recommended are linked to the design process steps.

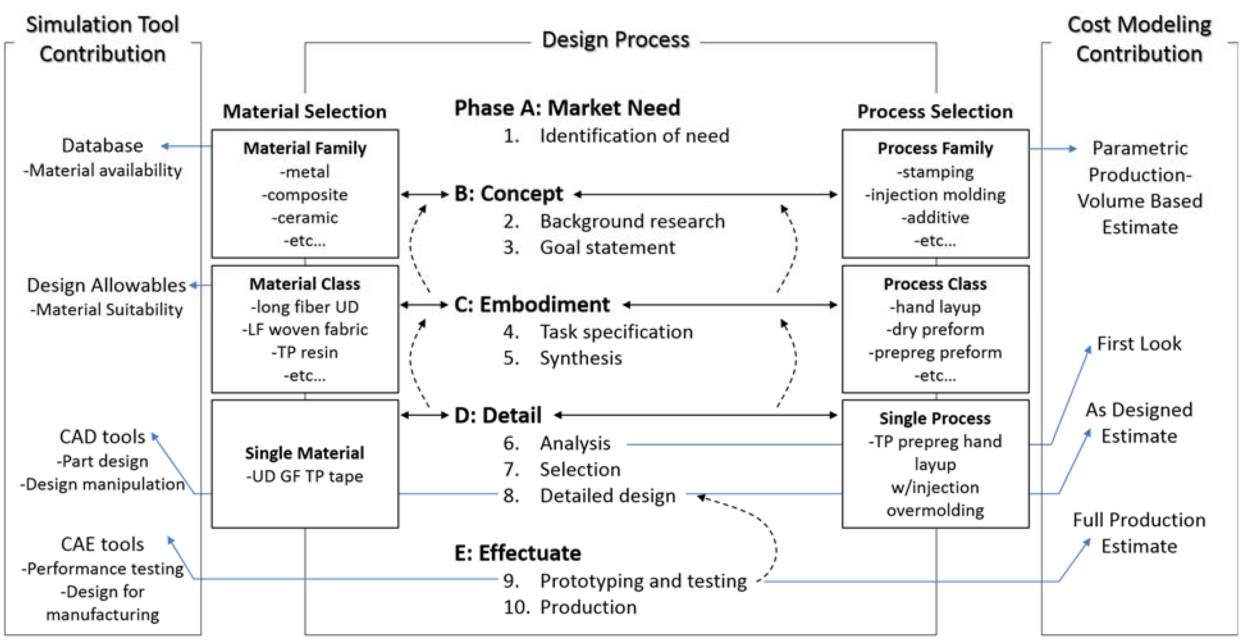

Figure 3. Identifying where performance simulation tools and cost modeling contribute throughout the part design process (adapted from [26, 27]).

Ashby splits the design process into five (5) phases; *Market Need*, *Concept*, *Embodiment*, *Detail*, and *Product Specification*. To mesh with Norton's part design steps, the *Product Specification* phase shall be modified to be the *Effectuate* phase. As Ashby works through the phases, the material and process selection narrows from a "global", or "family", viewpoint during the *Concept* phase, down to the specific material and process to be utilized in the *Detail* phase.

The first phase, *Market Need*, is where the problem or need is identified. At this step, no material or process decisions are made or specified, it is simply the idea creation. Norton's first design step is captured in this phase.

The second phase, *Concept*, is where the idea is expanded and researched to begin to define and understand the problem (Norton Step 2, Background Research) and shape the idea into a clear problem statement (Norton Step 3, Goal Statement). The possible material and process families are investigated during this phase. Though cost is not usually a factor during this phase, the materials that fit the concept, in terms or strength, finish, and availability are. Each of those materials investigated may have multiple means to process them, which need to be identified. Here, database availability may help to identify those possibilities. If historical knowledge of manufacturing process families are known, parametric production-volume based comparisons may be undertaken to provide order of magnitude estimations.

The third phase, *Embodiment*, is where the new product goal is bound in scope with specific details (Norton Step 4, Task Specification) and as many concepts are generated that meet those details (Norton Step 5, Synthesis). Cost is typically not considered during the Synthesis step, but may be a bound placed on the product, which may restrict the material and process class that is selected during this phase. Here, knowledge of the materials and process may help guide the selection.

The fourth phase, *Embodiment*, is where the concepts are compared (Norton Step 6, Analysis), the best concept is selected (Norton Step 7, Selection), and the design is drafted (Norton Step 8, Detailed Design). During the Analysis step, a *First Look* cost analysis may be used, as it does not require expansive details of the final design, but may incorporate equipment and rough material amounts to determine if the specifications are not exceeded. During the Selection step, the specific material and process is selected. Utilizing Computer Aided Design (CAD) tools, the selected concept is drafted. This design can then be fed into a cost model to produce an *As-designed* estimate and identify if the selected process can meet the production demands within an acceptable cost margin.

The fifth phase, *Effectuate*, is where the designed concept is prototyped and tested (Norton Step 9, Prototyping and Testing) and placed into production (Norton Step 10, Production). During the Prototyping and Testing step, performance simulation tools play a significant role. These tools allow unlimited testing to be conducted and flaws in the design identified and corrected without a part being produced. The cost savings from these tools is not easy to quantify, but is obvious as the timeframe to conduct physical testing on all the simulated iterations is considered. Once the design is finalized, a *Full-Production* estimate can be conducted, as the specifications are fully understood.

1.2.5 Defining *times* for a manufacturing setting

Defining *time* in a manufacturing setting can be quite confusing. Different companies and areas within companies may use the same term for different meanings or have different terms for the same meanings. Figure 4 outlines some of these times.

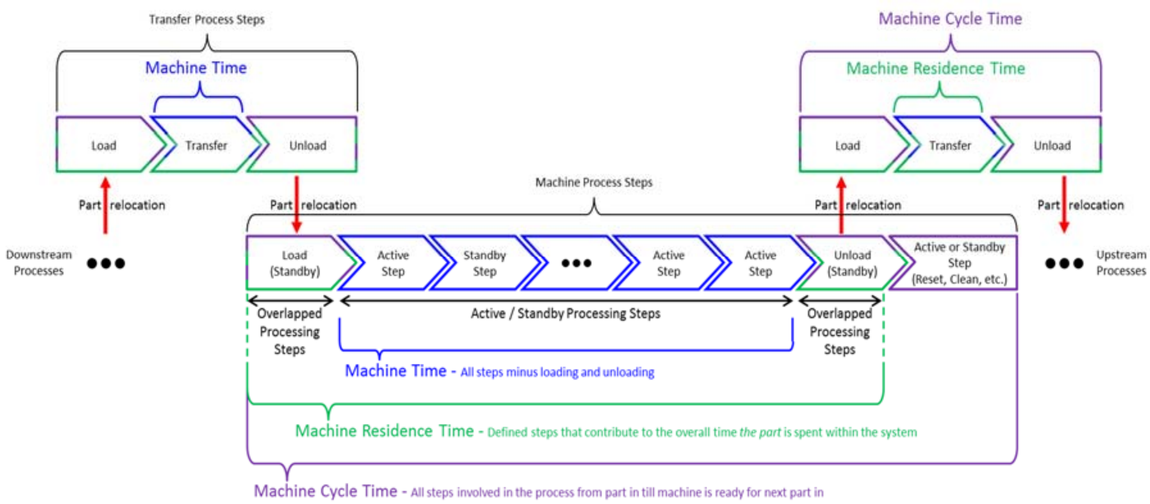

Figure 4. Useful times involved in a manufacturing process. Process steps shown are generic and are a portion of a larger, continuous manufacturing line.

1.2.5.1 Takt time

Takt time, t_{takt}, is the cadence that must be kept to produce a part to meet custom demand, or production volume. It relies on the production time that is available and is calculated as shown in Equation 1.

$$t_{takt} = \frac{Production\ time\ available}{Customer\ demand}$$

Equation 1

1.2.5.2 Machine cycle time

Machine cycle time is the summation of all the process step times that a machine is involved with. It includes all process steps from part in till the machine is ready for the next part in.

1.2.5.3 Machine takt time

Machine takt time, $t_{takt,machine}$, is the time a process takes to deliver a part. This is dependent upon the number of parts produced per cycle, N_{parts}, the amount of equipment necessary to meet the required production, N_{equip}, and the cycle time to complete one cycle, t_{cycle}, and is calculated via Equation 2.

$$t_{takt,machine} = \frac{t_{cycle}}{N_{parts} \cdot N_{equip}}$$

Equation 2

1.2.5.4 Machine residence time

Machine residence time is composed of defined machine process steps that the part is physically within the machine.

1.2.5.5 Machine time

Machine time is composed of defined machine process steps that the part is physically within the machine and is undergoing manufacturing processes. It excludes loading and unloading process steps.

1.2.5.6 Part residence time

Part residence time is the sum of all machine residence time. It equates to the time it takes a particle of raw material in to be transformed to final product out.

1.3 Summary

This chapter presented the research question and objectives along with a brief background in composites manufacturing and cost modeling. A deep dive was taken to explore the part design process and identify where throughout this process current state-of-the-art simulation tools would be useful as well as where cost estimates should be conducted and to what degree of accuracy the cost estimate shall be. Simulation tools can reduce the time, effort, and resources committed to a new design project while the cost estimates can determine if the project is economically feasible at all. Finally, times utilized in manufacturing were defined that are used throughout the remainder of this dissertation.

2. CONSTRUCTING A TECHNICAL COST MODEL

This chapter discusses the inner workings of a technical cost model. There are two primary sections to this chapter. The first section covers the methodology and was prepared as a technical paper for and presented at The Society for the Advancement of Material and Process Engineering (SAMPE) 2019 annual conference. The second section covers the miscellaneous work that has been developed as features beyond that described in the SAMPE work.

2.1 Technical Cost Modeling Methodology for Novel Manufacturing

Note: The following sections were originally published under this title for SAMPE-2019 [28]. There are some word selection changes and reordering of the TCM development steps for this dissertation which shall be annotated with (*Altered*) after the change. References have been condensed into the *Reference section*.

2.1.1 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.

2.1.2 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 [7]. 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 [15].

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-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 [29]. 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.

2.1.2.1 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 [3].

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.

2.1.2.2 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.

2.1.2.2.1 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 5 (*Altered*).

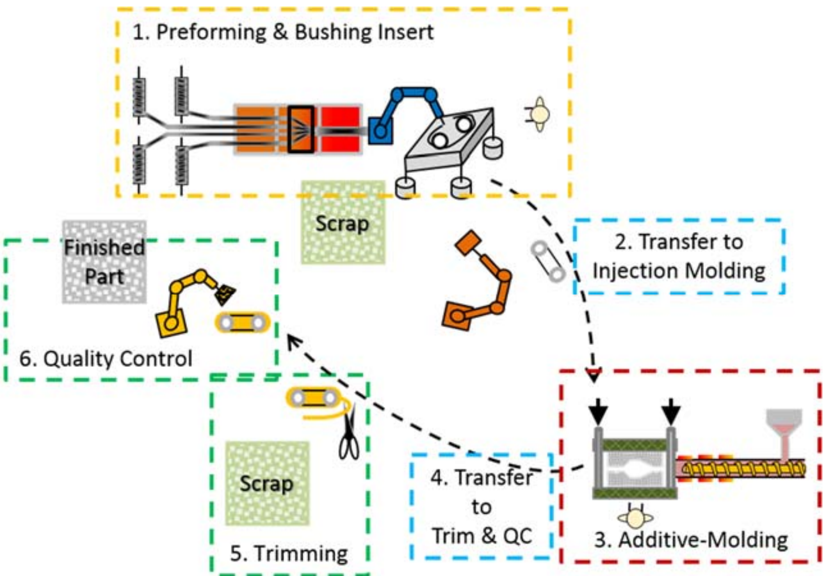

Figure 5. Hybrid molding process overview for production of continuous thermoplastic tape preform over-molded with polypropylene.

2.1.3 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 (*Altered*):

1) Receive basic part design details.
2) Receive desired economic analysis.
3) Develop process flow.
4) Identify cost drivers to be analyzed.
5) Develop model.
6) 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* 2.1.2.2.1.

2.1.3.1 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 6.

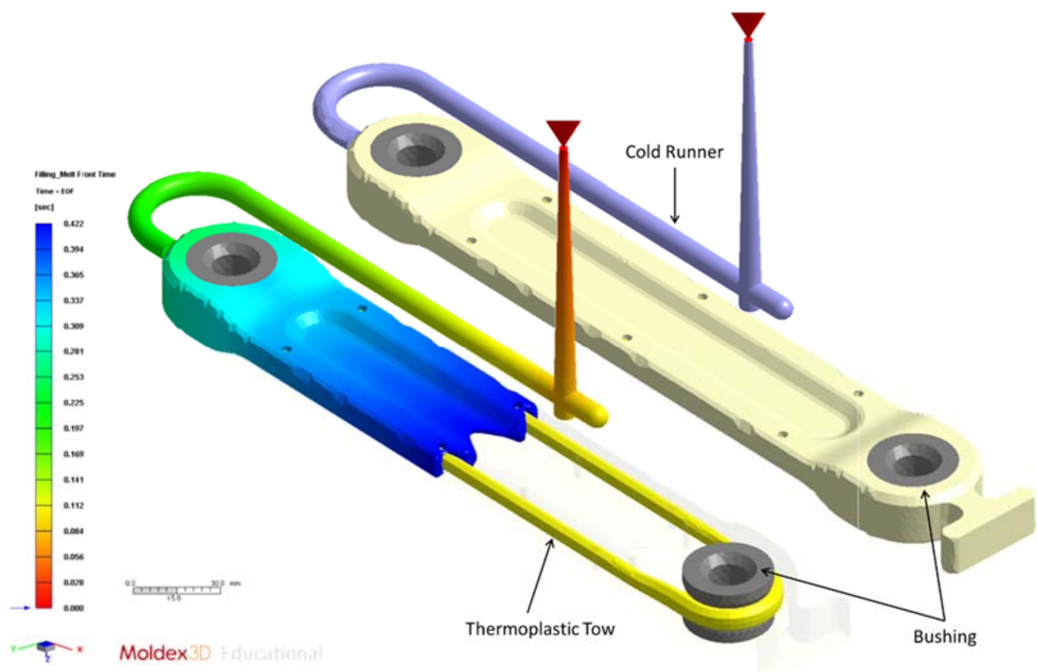

Figure 6. Test Coupon illustration as ejected from the injection molding machine (right) and as filling progresses to show exposed TP Tow and aluminum bushing.

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

2.1.3.2 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 2.1.3.4* 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

2.1.3.3 Develop process flow

One possible manufacturing route is investigated in this paper and is presented in *Section 2.1.2.2.1*. 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

2.1.3.4 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 7 in purple.

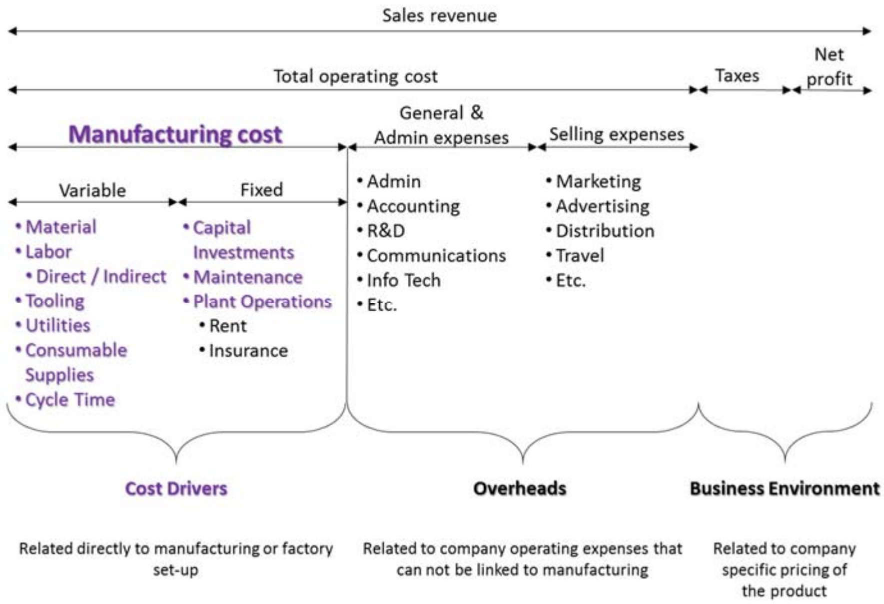

Figure 7. Cost drivers to be analyzed within TCM (adapted from [21]).

2.1.3.5 Develop model

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 3.

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

Equation 3

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 Equation 4 and Equation 5, respectively.

$$t_{Cycle,i} = \frac{t_{Process,equip,i}}{N_{Parts/Cycle,i}}$$

Equation 4

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

Equation 5

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 6 [30].

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

Equation 6

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} [30]. 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 7. The tooling cost per part, $C_{Tool,pp}$ is found via Equation 8 where C_{Tool} is the cost of the tool required for a process step.

$$N_{Tools} = \frac{N_{Parts,ML}}{TL_{Parts}}$$

Equation 7

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

Equation 8

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 9. This provides a more conservative estimation and/or allows for budgeting of unforeseen contingencies.

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

Equation 9

The cost to operate the plant is based on the square footage that the manufacturing line encompasses and is calculated via Equation 10 [adapted from 7].

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

Equation 10

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 11 (adapted from [31]). For the presented manufacturing line, the equipment is dedicated.

$$U_{eff} = \frac{PV_{Desired}}{PV_{act}} \cdot 100\%$$

Equation 11

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 12 (adapted from [31]). For the presented analysis, only the active energy is accounted for.

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

Equation 12

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 13 (adapted from [31]).

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

Equation 13

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 14 (adapted from [31]).

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

Equation 14

Where $C_{IdL,pp}$ is the cost of indirect labor per part, $R_{Id\rightarrow D}$ 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 15 (adapted from [31]).

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

Equation 15

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 16.

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

Equation 16

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 2.1.3.7*. The cost per part for the polymer used is found via Equation 17.

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

Equation 17

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.

2.1.3.6 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. Table 2 and Table 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 /m²	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

2.1.3.7 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 [29]. 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* [32]. 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.

2.1.4 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 2.1.3.2* is found in Figure 8.

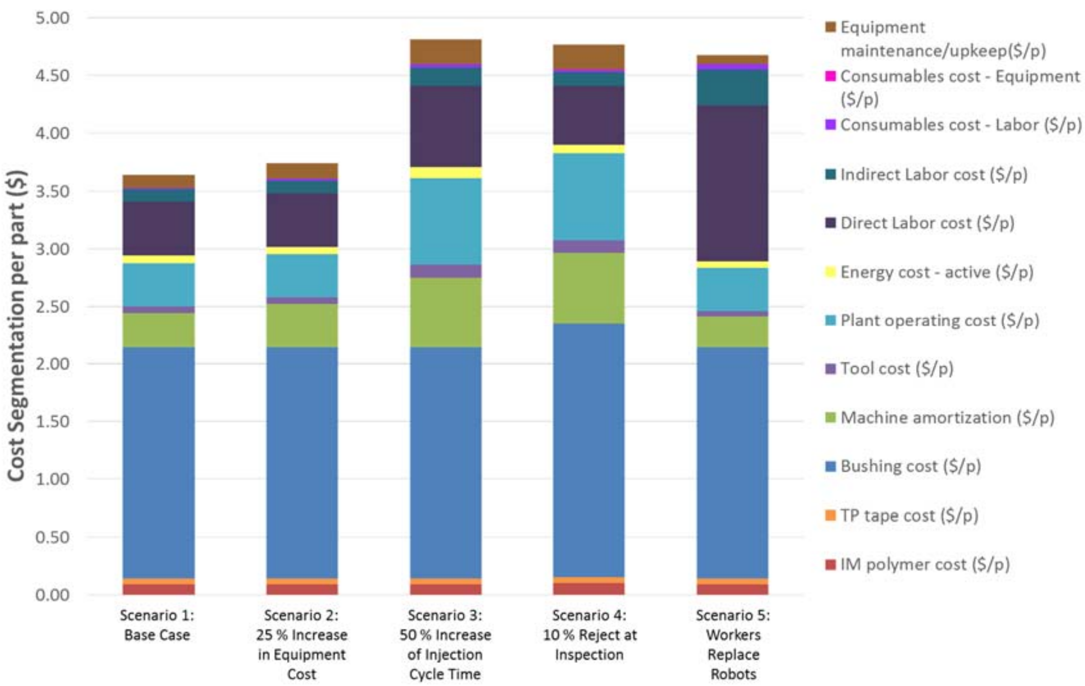

Figure 8. Cost segmentation for the base case and four augmentations for the hybrid molding manufacturing process to produce 360,000 test coupons per year.

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. Figure 9 and Figure 10 compare the base case, scenario 1, to an increase in injection molding cycle time, scenario 3, and when workers replace robots, scenario 5, respectively.

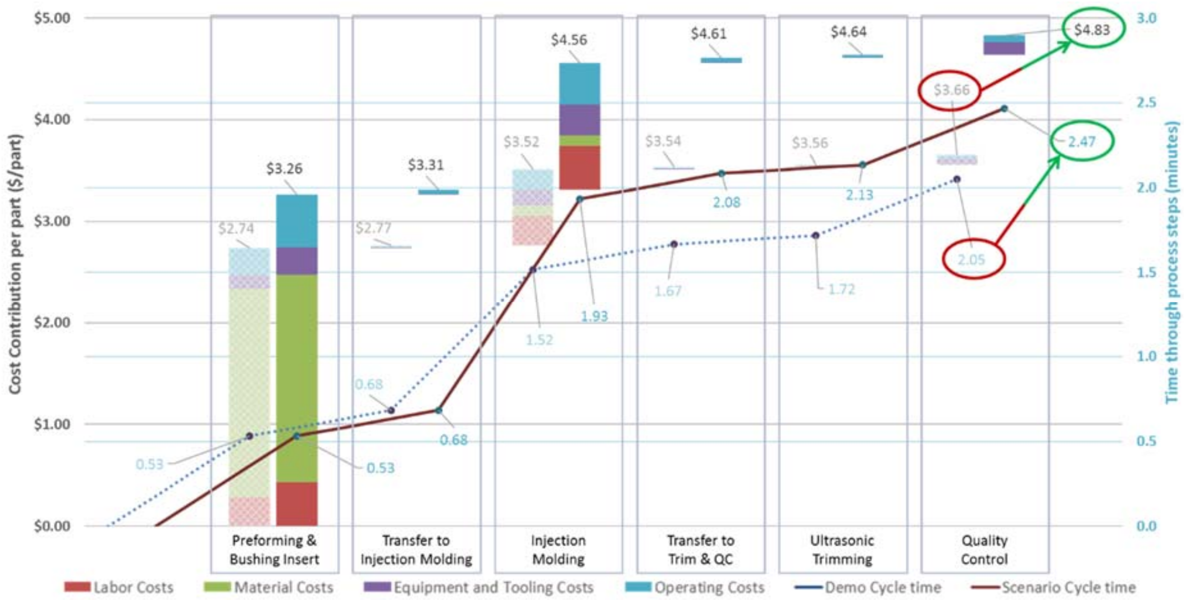

Figure 9. Base case (scenario 1: dotted line for time and left stacked columns for cost) comparison to a 50 % increase in injection molding cycle time (scenario 3: solid line for time and right stacked columns for cost).

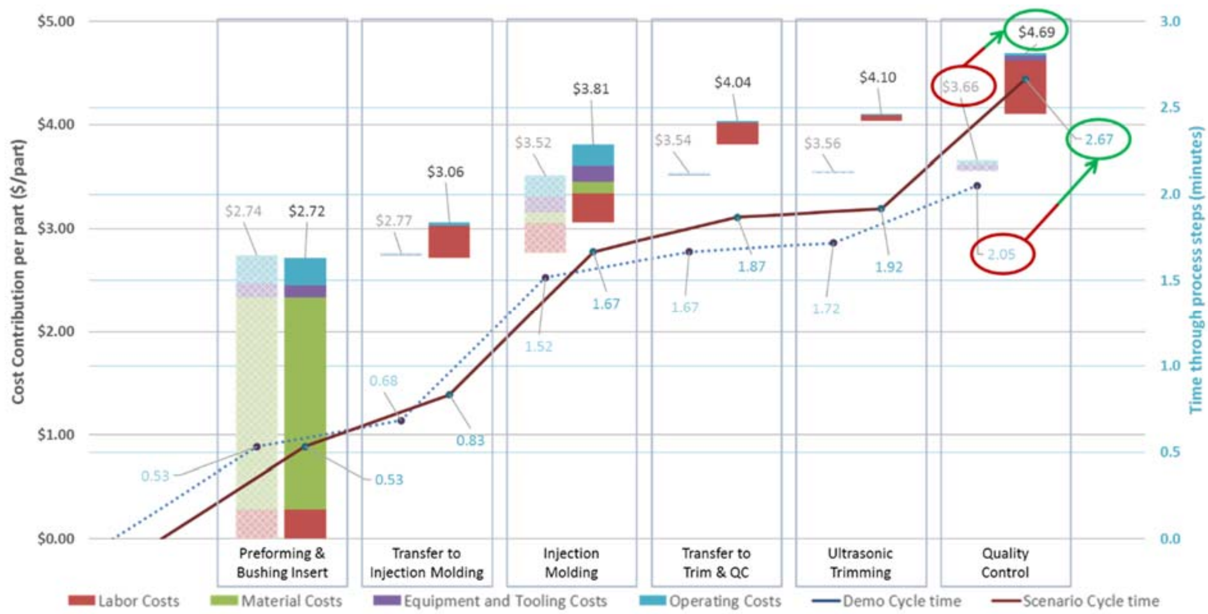

Figure 10. Base case (scenario 1: dotted line for time and left stacked columns for cost) comparison to workers replacing robots (scenario 5: solid line for time and right stacked columns for cost).

In Figure 9, 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 10, 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.

2.1.5 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.

2.1.5.1 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.

2.2 Additional cost model features

The beauty of developing a cost model from scratch is that you can build in features that you desire or add in levels of details. One feature that is often overlooked is the impact of intra-process storage space and the associated cost. Other utilities may also want to be investigated, and equations for them are discussed here.

2.2.1 Intra-processing storage space

Storage may be required between subsequent operations due to processing time differences. Determination of where (and if) storage is placed is determined by comparing the previous equipment's machine takt time and the next equipment's machine takt time surrounding a transfer point. If the next equipment's takt time is greater, storage shall be required. This intra-processing storage is often called buffer.

Storage not only increases the footprint required for the manufacturing line, but also increases the demand on the transfer point, be it automation or labor doing the transfer. A transfer is required when the downstream machine takt time is greater than the upstream machine takt time surrounding a transfer point, as illustrated in Equation 18.

$$\begin{cases} t_{takt,machine\ previous} > t_{takt,machine\ next}, storage\ required;\ B = 1 \\ t_{takt,machine\ previous} \leq t_{takt,machine\ next}, storage\ NOT\ required;\ B = 0 \end{cases}$$

Equation 18

Machine takt time, $t_{takt,machine}$, is the time a process takes to deliver a part and was detailed earlier in Equation 2. B is a variable used to denote if a transfer to storage is required.

Knowing that intra-process storage is required allows the number of transfers that occurs around the transfer point to be fully calculated. The total number of transfers is dependent upon the maximum number of equipment from either the previous process or the next process and if storage is necessary as shown in Equation 19.

$$N_{transfer,i} = max \begin{Bmatrix} N_{equipment,next} \\ N_{equipment,previous} \end{Bmatrix} + B$$

Equation 19

Where $N_{transfer,i}$ is the number of transfers conducted at transfer point i. The number of transfers directly impacts the utilization of the transfer equipment or laborers.

Determining the average amount of parts within the storage queue is accomplished via Little's Law. Little's Law provides the average number of parts at a measurement location, L, is equal to the average arrival rate of parts, λ, multiplied by the average wait time that parts endure, W, as given in Equation 20 [33].

$$L = \lceil \lambda W \rceil$$

Equation 20

For this model's purposes, the measurement location is taken at transfer points. The arrival rate of parts is the inverse of the previous process's machine takt time. The "previous process" is the equipment prior to the transfer point, or the equipment that the transfer point is unloading the part from. Currently, the "previous process" machine takt time utilized is the max machine takt time from all previous equipment prior to the transfer point. This allows the time storage conditions to be adjusted for the actual part delivery time. The wait time that parts endure is the next process's machine takt time. The "next process" is the equipment after the transfer point, or the equipment that the transfer point is loading the part into. It is important to note that Little's Law is taken at steady state conditions [33].

Little's Law provides the average number of parts between processes. However, if additional storage space needs to be accounted for, this needs to be manually entered. Additional storage space may be necessary based on expert knowledge, a buffer against equipment instability, or other reasons. The number of parts at a storage location, $N_{parts,storage}$, is then calculated via Equation 21.

$$N_{parts,storage} = L + L_{manual}$$

Equation 21

Where L_{manual} is the number of parts within the storage queue that are manually entered.

The number of parts at a storage location may then be used to find the area that the parts within storage occupies. There are various storage conditions that may apply, as parts may require temperature controlled storage or special fixtures depending on the materials and the state at the time of storage. These conditions affect the cost of storage, such as electricity costs or jig costs. The area is calculated via the bounding box area of the part and whether the parts are stored in a horizontal or vertical stacked arrangement. This is shown in Equation 22.

$$A_{storage} = \left\lceil \frac{N_{parts,storage}}{N_{parts,vertical}} \right\rceil \cdot A_{B.B.} \cdot \left(1 + S_{buffer\ space}\right)$$

Equation 22

Where $A_{storage}$ is the area required for storage of parts, $N_{parts,vertical}$ is the number of parts in a vertical stack, $A_{B.B.}$ is the area of the bounding box of the part, and $S_{buffer\ space}$ is a safety factor. Inclusion of a safety factor allows for allowance of greater storage space than is required by the part currently under design. This provides future flexibility of the equipment to handle greater component sizes without additional equipment purchases.

It is important to remember that storage impacts costs across many dimensions. The number of transfers occurring is increased, which may require additional equipment or laborers to handle the additional load. Plant operating space increases as storage space increases. Capital investment costs increase. If temperature controlled storage is necessary, electrical costs have to be considered as well.

Future work may include incorporating process instability, which can result in a build-up of Work-In-Progress (WIP) surrounding equipment that is not operating at peak efficiency. Optimal placement of WIP buffer within the processing line is a stochastic system problem that still needs to be investigated.

2.2.2 Additional cost driver equations

Standby energy costs

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 was discussed in Equation 12. The cost of standby energy is based on the hours per year that the equipment is not in operation, which includes a percentage of the time the plant is closed, as shown in Equation 23.

$$C_{Standby\ Energy,pp} = \frac{\left[8{,}760 \cdot U_{eff} + t_{avail} \cdot \left(1 - U_{eff}\right) - t_{act,100\%\ op}\right] \cdot P_{Equip} \cdot N_{equip} \cdot C_{Energy}}{PV_{Desired}}$$

Equation 23

Where $C_{Active\ Energy,pp}$ is the cost of active energy per part, $t_{act,100\%\ op}$ is the actual operational time of the equipment at 100% time efficiency, P_{Equip} is the machine power expressed in kW, and C_{Energy} is the cost per kWh. $C_{Standby\ Energy,pp}$ is the cost of standby energy per part, t_{avail} is the available production time based on the days per year worked and the hours per day worked, U_{eff} is the equipment utilization rate, and 8,760 comes from the total hours per year.

Water cost

Water is utilized within the trimming operations, as they are water jet cutters. The cost of water is based on the hours per year that the equipment is in operation as shown in Equation 24.

$$C_{Water,pp} = \frac{t_{act,100\%\ op} \cdot WC_{Equip} \cdot N_{equip} \cdot C_{Water}}{1{,}000 \cdot PV_{Desired}}$$

Equation 24

Where $C_{Water,pp}$ is the cost of water per part, WC_{Equip} is the water consumption per equipment expressed in ft^3 per hour, and C_{Water} is the cost per 1,000 ft^3.

Sewage cost

Since water is utilized within the trimming processes, it must be disposed of. The cost of sewage is based on the hours per year that the equipment is in operation as shown in Equation 25.

$$C_{Sewage,pp} = \frac{t_{act,100\%\ op} \cdot S_{Equip} \cdot N_{equip} \cdot C_{Sewage}}{1{,}000 \cdot PV_{Desired}}$$

Equation 25

Where $C_{Sewage,pp}$ is the cost of water per part, S_{Equip} is the sewage production per equipment expressed in ft^3 per hour, and C_{Sewage} is the cost per 1,000 ft^3.

Compressed air cost

Water jet cutters require compressed air to operate. The cost of compressed air is based on the hours per year that the equipment is in operation as shown in Equation 26.

$$C_{CA,pp} = \frac{t_{act,100\%\ op} \cdot CA_{Equip} \cdot N_{equip} \cdot C_{CA}}{PV_{Desired}}$$

Equation 26

Where $C_{CA,pp}$ is the cost of compressed air per part, CA_{Equip} is the compressed air usage per equipment expressed in Standard Cubic Feet (SCF) per hour, and C_{CA} is the cost of compressed air per SCF.

2.3 Summary

This chapter presented the methodology and equations behind creating a cost model from scratch. These building blocks form the basis for tracking all the costs associated with manufacturing. A nine-step process was presented to guide a cost estimator in what level of detail is necessary at what point in the cost model creation. The manufacturing cost was determined for a hybrid molded test coupon to demonstrate the capabilities of the cost model. This model is refined and expanded upon in Chapter 4.

3. TECHNICAL COST MODELING FOR PART PRODUCTION MANAGEMENT

Part production management is the decision making process for selecting a certain manufacturing method. Management decisions early in the design process greatly influence the course of a project. A project partner, DURA AUTOMOTIVE SYSTEMS, hereon referred to as Tier 1 Producer or T1P, sought counsel in selecting which processing route was better suited for their needs for an automotive part they were designing. T1P was working with two equipment manufacturers, GLOBE® and FILL®, hereon referred to as Equipment Supplier A or B, respectively (ES-A, ES-B), to develop new, high-rate thermoplastic layup and consolidation equipment, and desired a cost analysis of not only the equipment, but also the subsequent complete manufacturing line in order to serve as a financial data point for their system selection.

Being as the two systems were under development, neither manufacturer could provide exact details on how the systems operated in terms of component movement speeds that influence cycle times. Thus, cycle times could not be tailored for the specific part, and cycle times used throughout the scenarios investigated for the layup and consolidation systems were set to the maximum times desired by T1P, both being 60 seconds. However, material usage, a significant cost contributor in composites, could be thoroughly explored for each system, and is discussed in detail in the following chapter.

The need for the complete manufacturing line cost estimation ultimately forced the design team to begin to expand their focus beyond the layup equipment and to begin to not only look at downstream processing steps, but to also begin to refine their part design for the additive molding that was needed to provide structural supports, fittings, and finishing to various areas across the part. Since the part design was fluid, best guess estimations for additive molding materials and processing parameters were utilized to fill out the manufacturing line and equipment cost drivers.

The hybrid molded part T1P requested analysis on was a passenger vehicle rear package shelf. T1P's current steel fabricated part had a manufacturing cost of $15 and weighted 3.38kg. The go/no-go decision for converting the part from steel to metal was based on a final part weight savings of $6.6-11/kg at an annual production volume of 372,000.

This chapter presents a case study with T1P to provide a comparison of two novel thermoplastic preform manufacturing systems versus their in-use, metals based high-rate manufacturing line for manufacturing a via hybrid molding. The two preforming systems, consisting of layup and consolidation machines, were under research and development at ES-A and ES-B, meaning that actual mechanical movement rates were unavailable and part processing speeds were limited to T1P's project goals of producing one preform per minute. Thus, material usage became the primary focus, as scrap costs in composite layup processes often play a significant role in the manufacturing cost.

This chapter follows the TCM development steps outlined in *Section 2.1.3* for the T1P project comparison of two layup and consolidation preforming systems.

3.1 Tier 1 Producer basic part design details

T1P selected a Ford Fusion rear package shelf to demonstrate the capabilities of TCM. The part was under development with on-going design work being completed by T1P and material and performance testing work completed by Purdue University within the Composites Manufacturing and Simulation Center (CMSC). An image of one of the part design iterations is shown in Figure 11 [34].

Figure 11. Potential Ford Fusion rear package shelf under design by T1P [34].

Specifications for the package shelf include [35, 36]:

- BASF Ultratape B3EG12 UD01; glass fiber polyamide-6 based TP prepreg
- Areal weight: 433 g/m^2
- Roll currently available in 6.25" width, 350m length, and 0.25mm thickness
- Currently available roll weight: 25kg

- Bounding Box dimensions: 48” x 48”
- Number of layers (sheets): 6
- Layup orientation: [0/60/-60/-60/60/0]
- Additive-molded with TBD material for structural ribs and connection points

Throughout this chapter, the BASF GF-TP tape shall be referred to as *Material 1*. Material 1’s usage amount is calculated via the laid area. Determining the laid area is examined extensively for each preforming system in *Section 3.4 T1P analyzed cost drivers*. The yet-to-be-determined by the T1P team additive molding material shall be referred to as *Material 2*. Its usage amount is calculated via the weight used and has been estimated for First Look purposes at 1.0 pound per part. 54

3.2 T1P desired economic analysis

As part of T1P’s feasibility study to determine the best method of Preform Forming, they requested six (6) scenarios to be cost modeled as shown in Table 5 [35].

Table 5. Processing scenarios for T1P proposed production scheme.

Scenario	1	2	3	4	5	6
Preform System	ES-A	ES-A	ES-A	ES-B	ES-B	ES-B
Production Volume	372,000	372,000	372,000	372,000	372,000	372,000
Tape Input (in)	13	13	25	13	13	1.9685
Tape Cost ($/lb)	3.50	3.20	4.00	3.50	3.20	3.84
Exclusions	Patch System	Patch System	Patch System	None	None	Tape Slitting

These scenarios shall be discussed in more detail in *Section 3.3 T1P hybrid molding process flow*. Besides the six (6) scenarios described above, T1P requested the following cost breakdown:

- Cost for slit material
- Cost for consolidated preform
- Cost for net-shape trimming
- Cost for finishing cell

3.3 T1P hybrid molding process flow

Production of the rear package shelf is proposed to be conducted in the following manner; consolidated preforms are produced via either the ES-A or ES-B process. The consolidated preform is then transferred from the consolidator via robot to be net-shaped trimmed. Then, a finishing cell managed by an additional robot takes the net-shape preform and moves it through the finishing processes. First, the robot places it in an IR oven till the preform is pliable. It then removes the preform from the oven and places it into an injection molding machine where the preform is shaped to form as the mold is closed and an as-of-now unknown amount of an unknown resin is over-molded onto the preform to create connection points and stiffening ribs. The robot then removes the over-molded part and places it to be finished trimmed. Finally, the robot transfers the part to an inspection station. Figure 12 illustrates the proposed process. For reference later on, all actions conducted after the preforms are consolidated shall be referred to as the *Finishing Process*.

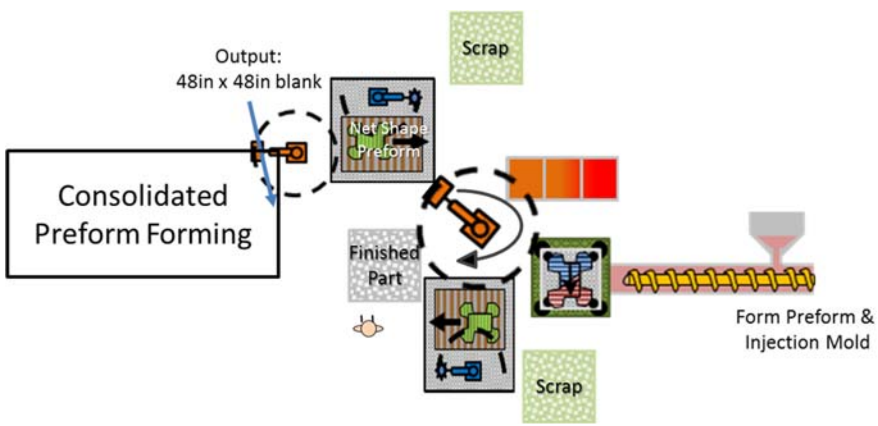

Figure 12. T1P proposed production scheme (symbols adapted from [21]).

The ES-A Preform system, scenarios 1, 2, and 3 operate as follows: tape material is fed into the ES-A Seamers where it is seamed to the appropriate dimensions. At this time, if patching is required, a laborer or robot shall patch the tape. For this analysis, this patch system is excluded. The rolls are then transferred to the ES-A Consolidator, consolidated, and cut to their appropriate size. The preforms then move into the *finishing process*. Varying items are the tape input width and the tape cost per pound.

The ES-B Preform system, scenarios 4 and 5, operate as follows: tape material is fed through a slitter that slices the tape into 50mm widths appropriate for the Multilayer machine, ES-

B's laying and seaming system. The slit tape is fed into the Multilayer and the part is laid out. A robot then transfers the unconsolidated preform into the *finishing process*. ES-B scenario 6 is different in that it utilizes 50mm tape as the input, so slitting is not required. Scenarios 4 and 5 differ in the tape cost per pound.

More details on the ES-A and ES-B Preform Forming systems are presented in *Section 3.4 T1P analyzed cost drivers*.

3.4 T1P analyzed cost drivers

The following cost drivers are to be analyzed for the T1P TCM:

- Material 1 value IN
- Material 2 value IN
- Machine depreciation
- Tool cost
- Plant operating cost
- Energy cost
- Water cost
- Sewage cost
- Compressed air cost
- Direct Labor cost
- Indirect Labor cost
- Consumables cost - Labor
- Consumables cost - Equipment
- Equipment maintenance/upkeep

3.5 T1P model specifics

This section shall discuss how the calculations were performed for the T1P cost drivers outlined in *Section 3.4 T1P analyzed cost drivers*.

3.5.1 Equipment Supplier A Preform Forming

There are two machine layout versions for the ES-A Preform Forming process, a "0°" seaming process, and an "any other" angle seaming process.

The "0°" seaming process feeds two rolls of TP prepreg tape in next to each other, align them edge to edge. These tapes are fed underneath a pneumatically actuated heated strip that "seams" the edges with a butt weld. The seamed tape, is gathered onto an output roll and fed back through the seaming process to produce a wider tape, or fed to the ES-A Consolidator to be stacked, consolidated, and cut to the bounding box dimensions of the part to be made.

The "any other" angle seamer feeds from a single roll of TP prepreg tape, cuts the tape to length, moves the cut tape to the pneumatically actuated heated strip, aligns it against the edge of the previous cut tape at the desired angle, and the heated strip runs through a cycle to butt weld the cut tapes together. This is repeated until the desired length of roll is reached. The width of the output roll is controlled as the tape is cut and laid. Once the desired output roll length is reached, it is fed into the ES-A Consolidator. A rendering of the "any other" angle seamer set up for a 90° and a 45° seam are shown in Figure 13 [37].

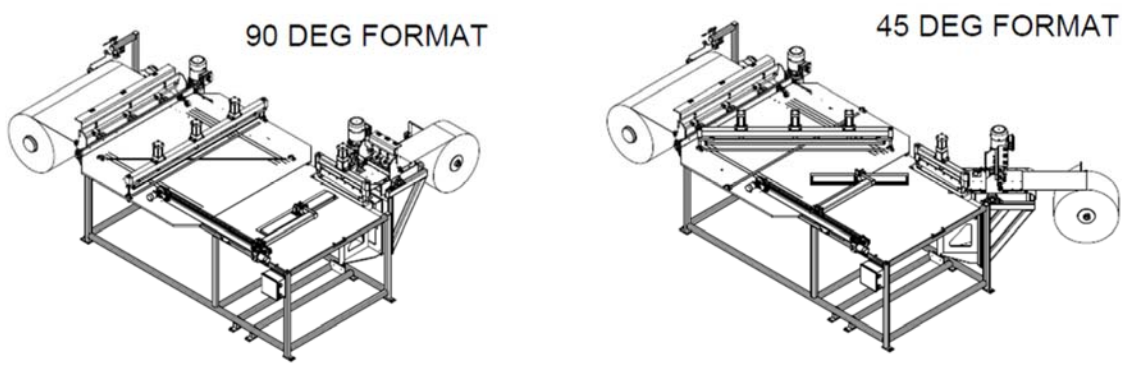

Figure 13. ES-A Seamer configured to cut and lay TP prepreg tape at either 90° or 45° angles [37].

The actions equipment undergoes to create one part are defined as the process cycle steps. The ES-A Seamer process cycle steps are shown in Figure 14. Knowing these steps makes it possible to visualize the process and determine the cycle time.

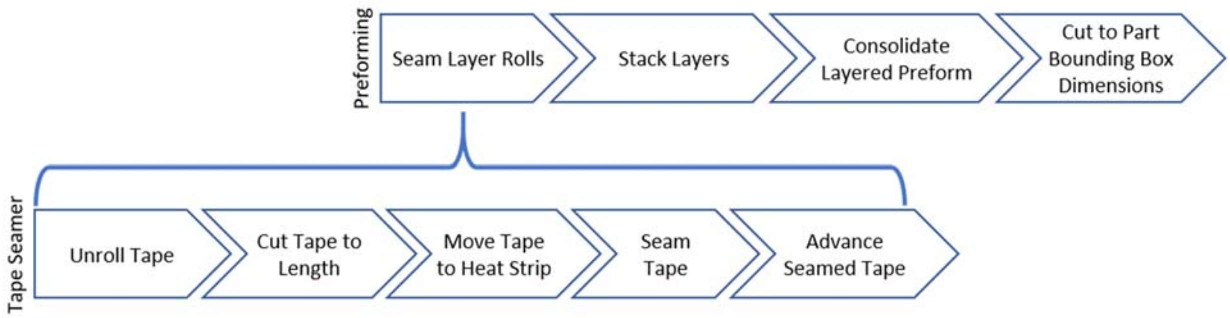

Figure 14. ES-A Seamer Process Cycle Steps.

Though multiple process cycle steps are shown in Figure 14, many of these steps are done simultaneously, and thus do not contribute to the cycle time. Instead, determining the cycle time to make one part for the ES-A seamers is dependent upon the number of layers, the angles of each layer, and the bounding box dimensions of the final part. These contributors also dictate the amount of scrap that shall be produced. Simulating one part of width W_s and length L_s, Figure 15 shows the laid area and the scrap area that must be accounted for in the "any angle," "0°," and "90°" scenarios. The Seamer layup is symmetric across 0°, meaning that a 30° layup and a -30° layup shall be calculated in the same manner, the only difference is the output roll roll-up direction. Layup angles are restricted from 90° to -90°.

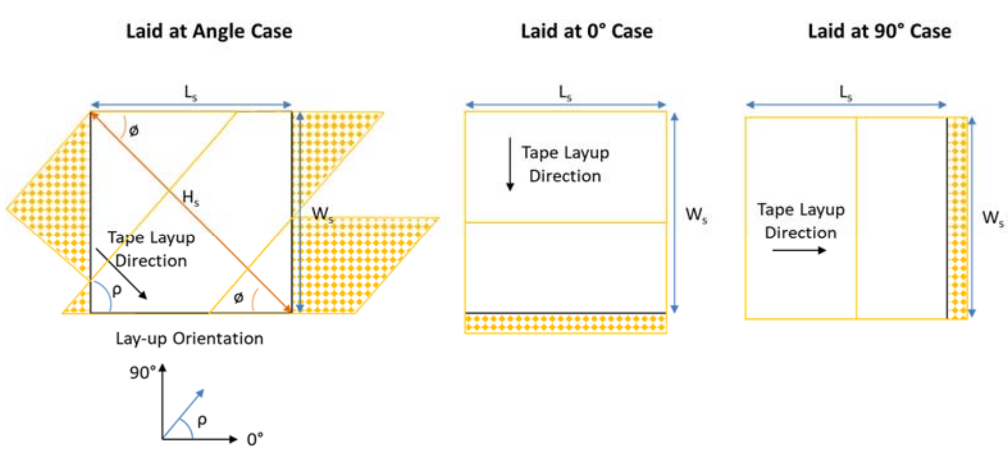

Figure 15. ES-A part laid area and scrap laid area (yellow hashmarks) for "any angle," "0°," and "90°" scenarios, respectively.

To determine the number of input tapes required for each scenario, Equation 27, Equation 28, or Equation 29 are utilized.

$$\#T_{Total,\rho°} = \frac{H_s}{x_4}$$

Equation 27

$$\#T_{Total,0°} = \frac{W_s}{W_{Tape}}$$

Equation 28

$$\#T_{Total,90°} = \frac{L_s}{W_{Tape}}$$

Equation 29

Where $\#T_{Total,i}$ is the total number of tapes for the layup angle, H_s is the length of the hypotenuse of the laid sheet, calculated from Equation 30, x_4 is the length of tape along H_s (see Figure 16), and W_{Tape} is the width of the tape. For the subscript, $\rho°$, this is valid for any layup angle between 0° and 90°. Of course, all these totals have to be rounded up to get the whole number of tapes required.

$$H_s = \sqrt{{L_s}^2 + {W_s}^2}$$

Equation 30

Determining the scrap area for the ES-A seamer process is straight forward for either the 0° or 90° scenarios, as shown in Equation 31 and Equation 32.

$$A_{Scrap,0°} = \left[L_s \cdot \left(W\#T_{Total,0°} \cdot W_{Tape}\right)\right] - (L_s \cdot W_s)$$

Equation 31

$$A_{Scrap,90°} = \left[L_s \cdot \left(W\#T_{Total,90°} \cdot W_{Tape}\right)\right] - (L_s \cdot W_s)$$

Equation 32

Where $A_{Scrap,i}$ is the scrap area and $W\#T_{Total,i}$ is the number of tapes rounded up to the nearest whole number. These essentially amount to the entire area laid minus the total number of parts laid multiplied by their bounding box area. However, calculating the scrap area for the "any other" angle layup becomes more intensive. The "any other" layup must be broken into different types of areas to determine the scrap area laid, as shown in Figure 16.

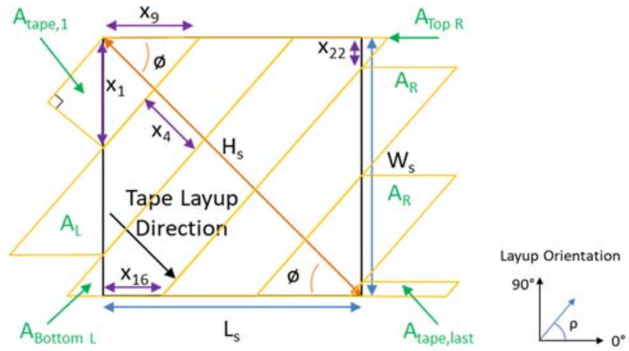

Figure 16. Defining the scrap areas laid from an "any angle" ES-A Seamer.

The distances denoted in Figure 16, but unmentioned until now, x_1, x_9, x_{16}, and x_{22} are required to calculate the number of tapes along the sides of the bounding box. These values are important when calculating the triangular areas of the various pieces of scrap, but shall not be discussed in detail in this paper.

It must be noted that the tape layup is assumed to begin with the first tape being laid that it's edge aligns with one of the corners of the bounding box. The first tape from the roll has a squared off end, but once trimmed to the layup angle, subsequent tapes have a different leading edge. As input rolls requiring changing, this first angle cut must be made, producing an area of scrap. The scrap area for the "any angle" scenario is calculated via Equation 33.

$$A_{scrap,\rho^\circ} = A_{tape,1} + \lfloor \#T_L \rfloor \cdot A_L + \lfloor \#T_R \rfloor \cdot A_R + \sum_{Bottom\ L}^{Top\ R} A_i + A_{tape,last}$$

Equation 33

Where A_{scrap,ρ° is the scrap area at the laid angle, $A_{tape,1}$ is the area of the first tape laid with the squared off end, $\#T_i$ is the number of tapes along the left or right side of the bounding box, A_L and A_R is the triangular area of scrap along the left or right side, respectively, of the bounding box from tapes laid with the appropriately cut end angle, A_i is the triangular area of either the top right or bottom left overhanging triangular areas, and $A_{tape,last}$ is the area of the last tape laid. The symbol $\lfloor\rfloor$, represents the floor function, meaning that value is rounded down to the nearest whole number.

Once the number of tapes laid is known, the total seaming time per sheet may be found. The first step is to determine the number of seams per sheet, as shown in Equation 34.

$$\#_{Seams,sheet\ j} = \#T_{Total,i} - 1$$

Equation 34

The time to seam the sheet then is the number of seams multiplied by the rate, or time, to seam one seam, as given in Equation 35.

$$t_{Seaming,sheet\ j} = \#_{Seams,sheet\ j} \cdot Rate_{Seaming,i}$$

Equation 35

Here, $Rate_{Seaming,i}$ is the time to complete one seam. For the 90° and "any angle" scenarios, the pneumatically actuated heater strip is sized to complete one seam across the width of the sheet at the max angle.

Equation 34 and Equation 35 are applicable to the 90° and "any angle" scenarios, but not the 0° scenario, as that is effectively a continuous process. The number of seams required for 0° is the same as Equation 34, however the seaming time is based on the length of the output roll, as given in Equation 36.

$$t_{Seaming,sheet\ 0°} = \#_{Seams,sheet\ 0°} \cdot \frac{L_s}{Rate_{Seaming,0°}}$$

Equation 36

Here, $Rate_{Seaming,0°}$ is an actual rate since the 0° seamer is a continuous process. To complete the butt weld requires 12 seconds of heating. So a 48" heating strip results in a 4 in/sec seaming rate.

The total cycle time to seam one preform for the ES-A Seamer is the sum of the seaming times for each layer, as shown in Equation 37.

$$t_{Seam,preform} = \sum_{0°}^{90°} t_{Seaming,sheet\ i}$$

Equation 37

The minimum number of ES-A Seamers required, assuming a 0° layer and at least one other angled layer, is two (2).

Once the above and other factors are known, such as the input tape roll length and the output tape roll length, other pertinent information can be determined about the process. This includes the total number of input tape rolls needed, total number of output rolls needed, the number of seamers required, the storage space required, and even the number of shelves or racking required in the storage space if such detail is required.

The second portion of the ES-A Preform Forming portion is the ES-A Consolidator. At this time, this equipment is still under design, so specifications are not completely known. However, the basic premise is that the output rolls from the ES-A Seamers are fed into the Consolidator so that the sheets are stacked in the correct order, then heated, pressed, cooled, and cut to the bounding box dimensions to form one preform. ES-A has only provided a linear rate of consolidation, $Rate_{Consolidator}$, so the cycle time for the ES-A Consolidator, $t_{Consolidate,Globe}$, is based on the sheet length of the bounding box, as shown in Equation 38.

$$t_{Consolidate,Globe} = \frac{L_s}{Rate_{Consolidator}}$$

Equation 38

3.5.2 Equipment Supplier B Preform Forming

The ES-B Preform Process begins is composed of two parts similar to the ES-A Preform Process. The first stage is the TP prepreg tape laydown, which takes place in the ES-B Multilayer. The second stage is consolidation, taking place within the ES-B Consolidator.

The ES-B Multilayer is similar in operation to an Automatic Tape Laying machine, with the main difference being that there are multiple unwinding units laying tape simultaneously. The prototype Multilayer has sixteen (16) unwinding units that simultaneously lay and butt weld 50mm tape onto a rotatable and moveable stacking table. The unwinding units are capable of cutting the tape, advancing, and restarting the laying process, which allows for large cutouts within the part to not be filled in during preform manufacturing, which reduces material usage. Layup scrap is similar to the ES-A Seamer for 0° and 90° sheet layups, but is different for any angle between them, as illustrated in Figure 17. The Multilayer layup is symmetric across 0°, meaning that a 30° layup and a -30° layup shall be calculated in the same manner, the only difference is the stacking table position. Layup angles are restricted from 90° to -90°.

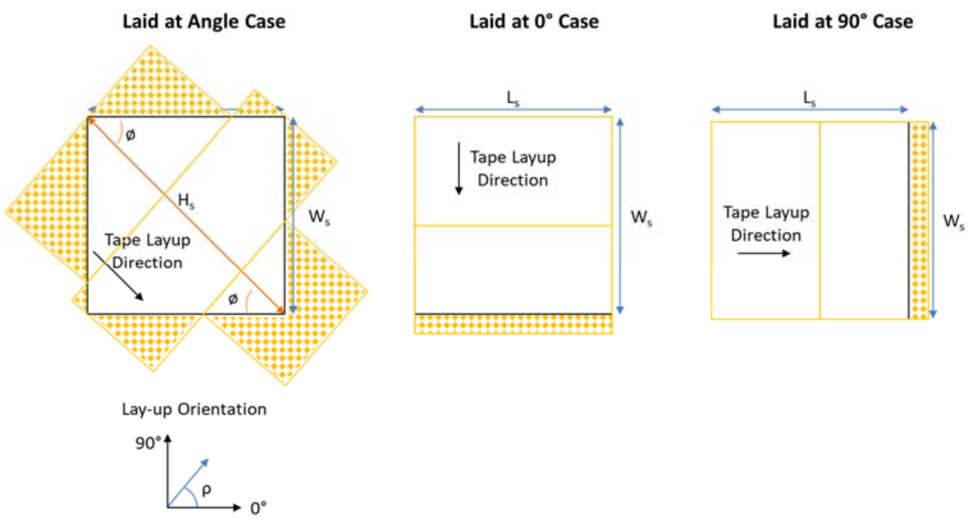

Figure 17. ES-B part laid area and scrap laid area (yellow hash marks) for “any angle,” “0°,” and “90°” scenarios, respectively.

The number of tapes required for the three Multilayer scenarios in Figure 17 are the same as for the ES-A Seamer. “Any angle” requires Equation 27, 0° requires Equation 28, and 90° requires Equation 29. However, the tape width is limited to the unwinding unit width of 50mm, resulting in more seams required for the same bounding box dimensions when compared to the ES-A Seamer.

The ES-B Multilayer process is executed in the following manner: The unwinding units laydown and weld the first pass of tape. If called for, individual unwinding units cut the tape, advance forward, and continue laydown when there is a large enough cutout that exceeds the tape width. Once the first pass is complete, the unwinding units reset to their starting location while the stacking table either rotates to the next sheet’s layup angle or moves laterally to position the unwinding units for their next pass. This is repeated until the all the layers of the preform are completed. Upon completion of the last pass of the unwinding units, the unwinding units return to their starting location while the stacking table moves to the unloading area where an external unloading unit removes the preform. The stacking table returns to the layup area and the next preform may begin to be laid. These cycle process steps are shown in Figure 18 and a rendering of the Multilayer unit is shown in Figure 19 [38].

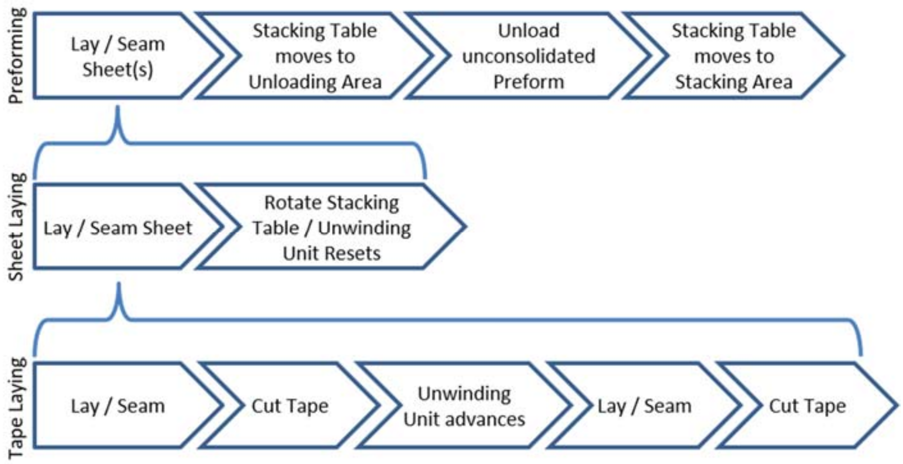

Figure 18. ES-B Multilayer Process Cycle Steps.

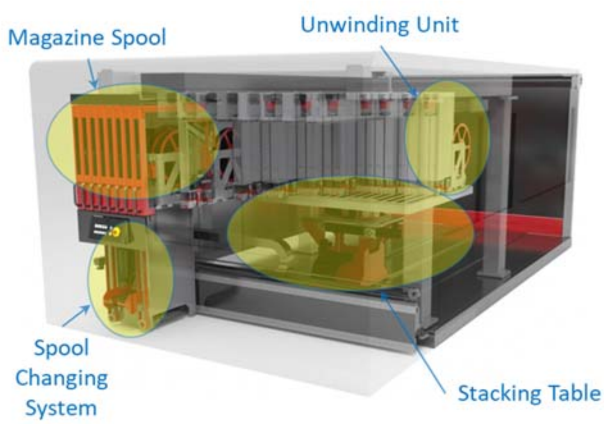

Figure 19. ES-B Multilayer configuration [38].

The ES-B Multilayer has more contributing components to its cycle time than the ES-A Seamer. Beyond requiring the bounding box dimensions, tape width, number of layers, and layup angle per layer as the ES-A Seamer requires, the Multilayer also requires the number of cutouts greater than the tape width and the area of those cutouts. The cutout area reduces the amount of tape laid, reducing material usage and thus cost, while the number of cutouts contributes to the cycle time.

Cycle time for the ES-B Multilayer is derived from the longest laid length of tape per pass. Other contributors include the number of cutouts along the greatest tape length per pass, reset time, stacking table movements to and from the unload area, and unloading time. The cycle time is calculated via Equation 39.

$$t_{cycle,Multilayer} = \sum_{Pass\ i}^{Last\ Pass} \left[\frac{L_{T,longest,i}}{v_{Layup}} + \begin{cases} t_{Table,i}, t_{Table,i} > t_{UU\ reset,i} \\ t_{UU\ reset,i}, t_{UU\ reset,i} > t_{Table,i} \\ 0, i = Last\ Pass \end{cases} \right] + \frac{2 \cdot L_{S \to UL}}{v_{ST}} + t_{UL}$$

Equation 39

$$t_{Table,i} = \frac{\left(\angle_{Layup,i} - \angle_{Layup,i+1}\right)}{\omega_{Table}}$$

Equation 40

$$t_{UU\ reset,i} = \frac{L_{T,longest,i}}{v_{UU\ reset}}$$

Equation 41

Where $L_{T,longest,i}$ is the length of the longest pass, v_{Layup} is the layup speed, $t_{Table,i}$ is the time for the stacking table to rotate to the next layup angle, $t_{UU\ reset,i}$ is the time for the unwinding units to return to their starting position, $L_{S \to UL}$ is the travel distance from the stacking location to the unloading area, v_{ST} is the stacking table travel speed, and t_{UL} is the time to unload the preform. $t_{Table,i}$ is based on the rotation from the current layup angle, $\angle_{Layup,i}$, to the next layup angle, $\angle_{Layup,i+1}$, and the stacking table angular velocity, ω_{Table}, as shown in Equation 40. $t_{UU\ reset,i}$ is based on the length of the longest tape laid and the unwinding unit reset speed, $v_{UU\ reset}$, as shown in Equation 41.

Calculating the area of scrap for the Multilayer is significantly more involved than the ES-A Seamer. Unlike in the ES-A Seamer, all the tapes laid by the Multilayer are laid with squared off ends. This creates triangular areas of scrap around the entire bounding box area, as illustrated in the "any angle" scenario in Figure 17. Each corner of the bounding box present two (2) scenarios for scrap, the first being the tape aligns perfectly with the corner, the second being that the tape overlaps the corner. These two (2) scenarios are illustrated in Figure 20 for the bottom left corner of the bounding box.

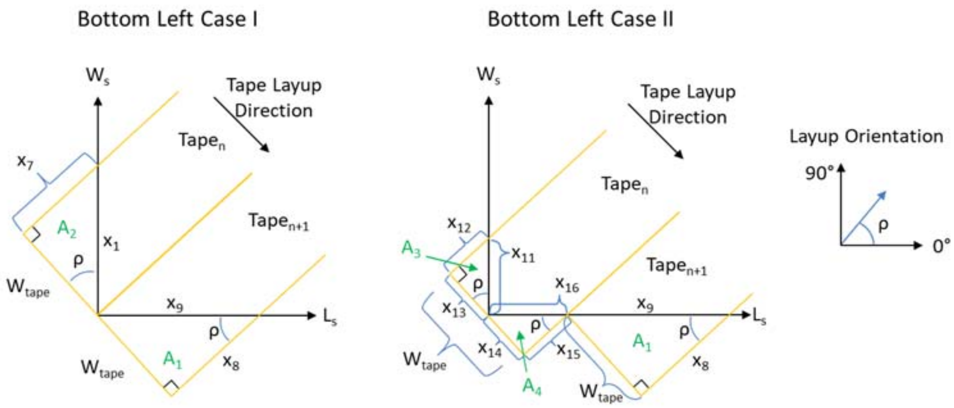

Figure 20. Bottom left corner tape layup scenarios for the ES-B Multilayer. Case I presents tape laid perfectly in-line with the corner. Case II presents tape overlapping the corner and the subsequent tape laid.

As tapes overlap the bounding box corners, a tricky accounting process begins to play a role regarding which tape is where on the piece. Tracking this is important, as the longest tape length determines the laying time. As the layup angle approaches 0° or 90°, there is a greater chance for one tape to make up one side, for example the first tape laid at an angle of 5° may cover the entire top of the bounding box. This sort of layup requires bounding of various lengths of the laid tape, else a situation as illustrated in Figure 21 may present itself.

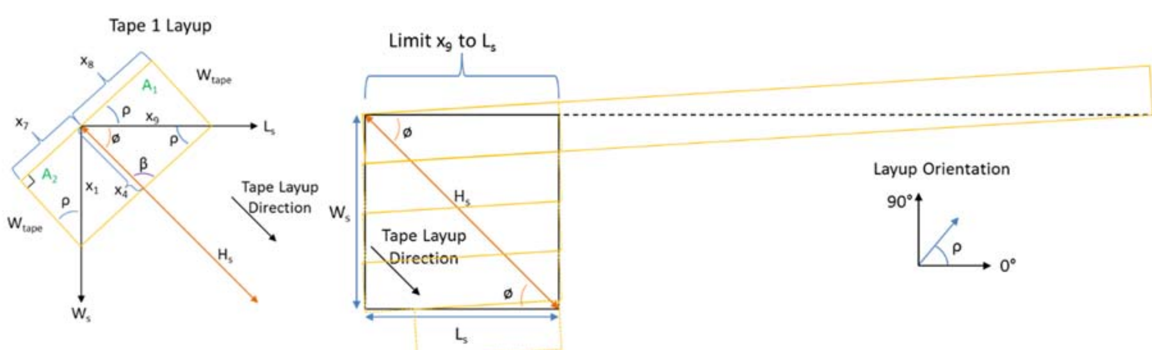

Figure 21. Example of values requiring limiting for ES-B Multilayer tape layup. "Tape 1 Layup" is presented to identify where x_9 is on a tape laid that conforms to the bounds of L_s and W_s.

Bounds must be put into place for the first tape laid of a sheet, restricting its length to either L_s or W_s depending on the angle laid. The same restrictions must also be placed on the last tape laid.

Bounding restrictions in place and layup scenarios identified, the scrap are for the preform may be calculated. For 0° and 90° laid sheets, the scrap area calculations are the same as for the ES-A Seamer, Equation 31 and Equation 32, respectively. However, for the "any angle" scenarios, the scrap area must take into account the areas along the top and bottom of the bounding box that don't occur in the ES-A Seaming process, as shown in Equation 42.

$$A_{Scrap,\rho°,i} = \left(\lfloor \#T_{Top} \rfloor + \lfloor \#T_{Bottom} \rfloor\right) \cdot A_1 + \left(\lfloor \#T_L \rfloor + \lfloor \#T_R \rfloor\right) \cdot A_2 + A_{S,Last} + \sum_{Bottom\ L}^{Top\ R} A_{Overlap}$$

Equation 42

Where $A_{Scrap,\rho°,i}$ is the total area of scrap for sheet i, $\#T_{Top}$, $\#T_{Bottom}$, $\#T_L$, and $\#T_R$ are the number of tapes along the top edge, bottom edge, left edge, and right edge of the bounding box, respectively, A_1 is the triangular scrap areas along the top and bottom edges of the bounding box, A_2 is the triangular scrap areas along the left and right edges of the bounding box, $A_{S,Last}$ is the scrap area of the last laid tape, and $A_{Overlap}$ is the sum of the scrap areas from tapes that overlap the bottom left and top right corners, as demonstrated in Figure 21.

The second portion of the ES-B Preform Forming process is the ES-B Consolidator. The ES-B Consolidator consolidates one preform at a time. The preform is placed into the lower portion of tooling, the top portion is fitted, secured, and tightened to the desired pressure. The tooling is then lifted to a conveyor that moves it through a heating and a cooling zone and onto another lift. The second lift lowers the tooling to a conveyor that returns the tooling to the starting position where the upper tool half is removed and the consolidated preform is removed. Four (4) pieces of tooling are supplied with the ES-B Consolidator, and cycle times of 60 seconds are capable according to ES-B. No information has been provided as to conveyor speeds, heating or cooling rates, or lift speeds, so calculating the cycle time by other means is not available at this time. This process is illustrated in Figure 22 and broken into its process cycle steps in Figure 23 [38].

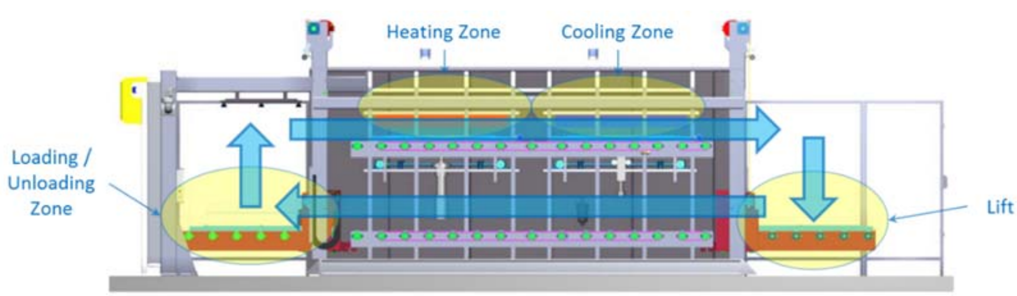

Figure 22. ES-B Consolidator configuration [38].

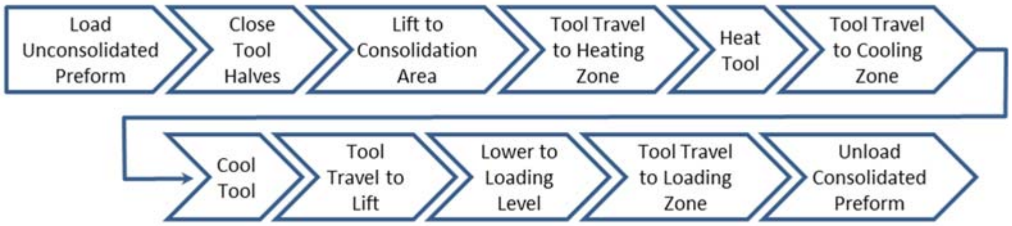

Figure 23. ES-B Consolidator process cycle steps.

3.5.3 Other model equations

Material 1's value per part, which is area laid based, is calculated via Equation 43.

$$C_{Mat\ 1,pp} = \frac{PV_{IN,Act} \cdot (A_{Laid,PP} \cdot W_{Areal,Mat\ 1}) \cdot C_{Mat\ 1,plb}}{PV_{Desired}}$$

Equation 43

Where $C_{Mat\ 1,pp}$ is the cost of Material 1 per part, $PV_{IN,Act}$ is the actual production rate required for the process, $A_{Laid,PP}$ is the area of Material 1 laid per part, $W_{Areal,Mat\ 1}$ is the areal weight of Material 1, $C_{Mat\ 1,plb}$ is the cost per pound of Material 1, and $PV_{Desired}$ is the customer demand.

Material 2's value per part, which is weight based, is calculated via Equation 44.

$$C_{Mat\ 2,pp} = \frac{PV_{IN,Act} \cdot M_{Mat\ 2} \cdot C_{Mat\ 2,plb}}{PV_{Desired}}$$

Equation 44

Where $M_{Mat\ 2}$ is the weight of Material 2 used in the process.

All other cost drivers are calculated from the cost driver equations presented in *Chapter 0*

CONSTRUCTING A TECHNICAL COST MODEL.

Two (2) Preform Forming processes utilizing TP prepreg tape have been presented. Though CAE tools may be capable of retrieving the data presented here, the part has not been finalized, nor the actual CAD drawings provided, making analysis via CAE impossible. What has been demonstrated above demonstrates the detail that is possible to achieve even with a *First Look* cost model approach.

Information regarding the equipment in either the net-shape trimming portion or the *finishing process* are available in APPENDIX A. Discussion regarding *Part Finalization* via hybrid molding shall be discussed briefly in section *V.B.2. Extracting Cost Driver Data from CAE*.

3.6 T1P processing conditions

Process conditions for the T1P TCM are based off of received information or the location of the plant. The plant is set to be located in Detroit, MI. Process conditions are outlined in Table 6. Items highlighted in red are values still awaiting finalization.

Table 6. Processing conditions for the T1P TCM.

Processing Conditions:				Utilities Costs:		
Category	Units	Values		Category	Units	Values
Hours per Shift	hours	8		Plant Operating Costs	$/sf/yr	140
# of Shifts	#	3		Electricity	$/kWh	0.0738
Days per Year:	days	240		Water	$/1000ft^3	23.76
Time Efficiency:	%	90%		Sewage	$/1000ft^3	52.73
Reject Rate:	%	0%		Compressed Air	$/SCF	0.00016
				Consumables - Labor	$/hr	1
				Consumables - Equipment	$/output lb	Per equipment data
Labor:				Capital Costs:		
Direct	$/hr	60		Cost of Capital:	%	12%
# Direct	(transfer = 0) (inspect=1)	0.5		Amortization Time (yrs):	years	11
Indirect	$/hr	80		Payments per Year:	#	1

Indirect to direct ratio	(transfer = 0)	0.05		Maintenance costs:	%	3% (unless given otherwise)

3.7 T1P final part refinement details

T1P was still in the process of finalizing their design as material testing to ensure the material meets the automotive requirements was still underway. The model results presented forthcoming may be considered a *First Look* estimate.

3.8 T1P model execution

Though refinement for the part design and manufacturing process design is still required, a *First Look* estimate may be produced. T1P requested an economic analysis of the six (6) scenarios broken out by processing step as shown in Table 7 for the desired production volume of 372,000 Parts Per Year (PPY). Note that these processes are *dedicated*, not utilized.

Table 7. T1P requested processing step breakout economic analysis at desired 372,000 ppy – dedicated (all costs in $/part).

	Scenario 1: ES-A $3.50 13in Tape	Scenario 2: ES-A $3.20 13in Tape	Scenario 3: ES-A $4.00 25in Tape	Scenario 4: ES-B $3.50 13in Tape	Scenario 5: ES-B $3.20 13in Tape	Scenario 6: ES-B $3.84 2in Tape
Cost for slit material	0.00	0.00	0.00	4.84	4.60	0.00
Cost for preform	37.99	35.34	39.23	35.02	32.54	37.83
Cost for net-shape trimming	4.02	4.02	4.02	3.59	3.59	3.59
Cost for finishing cell	17.01	17.01	17.01	17.01	17.01	17.01
Total Cost	58.41	55.76	59.65	60.47	57.75	58.43

Figure 24 shows the cost segmentation at the desired production volume of 372,000 ppy for the six (6) utilized scenarios. The values are broken out in Table 8.

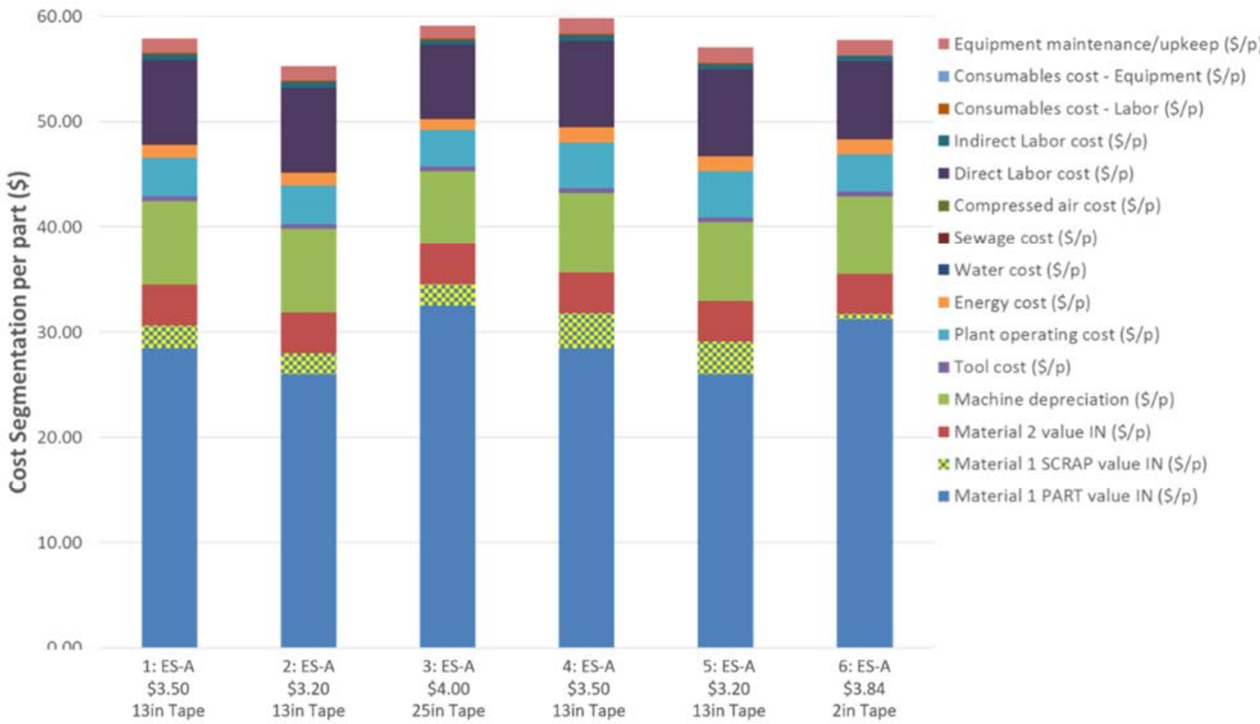

Figure 24. Cost segmentation per part for a production volume of 372,000 ppy for the 6 T1P dedicated manufacturing scenarios.

Table 8. Cost segmentation per part for the 6 T1P manufacturing scenarios.

	Scenario 1: ES-A $3.50 13in Tape	Scenario 2: ES-A $3.20 13in Tape	Scenario 3: ES-A $4.00 25in Tape	Scenario 4: ES-B $3.50 13in Tape	Scenario 5: ES-B $3.20 13in Tape	Scenario 6: ES-B $3.84 2in Tape
Material 1 value IN	30.65	28.02	34.58	31.80	29.08	31.70
Material 2 value IN	3.85	3.85	3.85	3.85	3.85	3.85
Machine depreciation	8.39	8.39	7.31	8.13	8.13	7.92
Tooling	0.44	0.44	0.44	0.44	0.44	0.44
Plant operations	3.69	3.69	3.45	4.35	4.35	3.54
Energy	1.19	1.19	1.04	1.44	1.44	1.43
Water	0.03	0.03	0.03	0.03	0.03	0.03
Sewage	0.07	0.07	0.07	0.07	0.07	0.07
Compressed air	0	0.00	0	0.00	0	0.00
Direct Labor	7.98	7.98	6.96	8.08	8.08	7.28
Indirect Labor	0.53	0.53	0.46	0.54	0.54	0.49
Consumables - Labor	0.13	0.13	0.12	0.13	0.13	0.12
Consumables - Equipment	0.02	0.02	0.02	0.02	0.02	0.02
Equipment maintenance	1.43	1.40	1.32	1.58	1.58	1.54
Total Cost	58.41	55.76	59.65	60.47	57.75	58.43

Second to material costs, the main contributing cost came from equipment amortization. The number of each equipment required for each scenario is broken out in Table 9. The equipment was not grouped into work cells, thus the number required is the amount of equipment required to meet the desired production rate in the time available. The equipment cost, tooling cost, and equipment cycle times are listed in Table 10.

Table 9. Equipment required for each T1P scenario.

Equipment:	Preform System:	1: ES-A $3.50 13in Tape	2: ES-A $3.20 13in Tape	3: ES-A $4.00 25in Tape	4: ES-B $3.50 13in Tape	5: ES-B $3.20 13in Tape	6: ES-B $3.84 2in Tape
Seamer	ES-A	6	6	3	N/A	N/A	N/A
Consolidated Preformer	ES-A	1	1	1	N/A	N/A	N/A
Tape Slitter	ES-B	N/A	N/A	N/A	2	2	0
Multilayer	ES-B	N/A	N/A	N/A	3	3	3
Consolidator	ES-B	N/A	N/A	N/A	2	2	2
Transfer Robot	Both	4	4	4	5	5	5
Water Jet Trimmer	Both	6	6	6	6	6	6
IR Oven	Both	3	3	3	3	3	3
Injection Molder	Both	3	3	3	3	3	3

Table 10. Equipment and tool costs and equipment cycle times for the T1P equpment.

Equipment:	Preform System:	Cost:	Tooling Cost:	Cycle Time (s):
Seamer	ES-A	$800,000.00		154
Consolidated Preformer	ES-A	$2,500,000.00		24
Tape Slitter	ES-B	$233,500.00		87
Multilayer	ES-B	$1,233,000.00		111
Consolidator	ES-B	$1,105,600.00	Jigs included	60
Transfer Robot	Both	$100,000.00	EOAT required	5
Water Jet Trimmer	Both	$350,200.00	Jig required	116
IR Oven	Both	$85,000.00		125
Injection Molder	Both	$2,500,000.00	$275,000.00	60

Figure 25 shows the cost per part for the six (6) utilized scenarios across a range of production volumes.

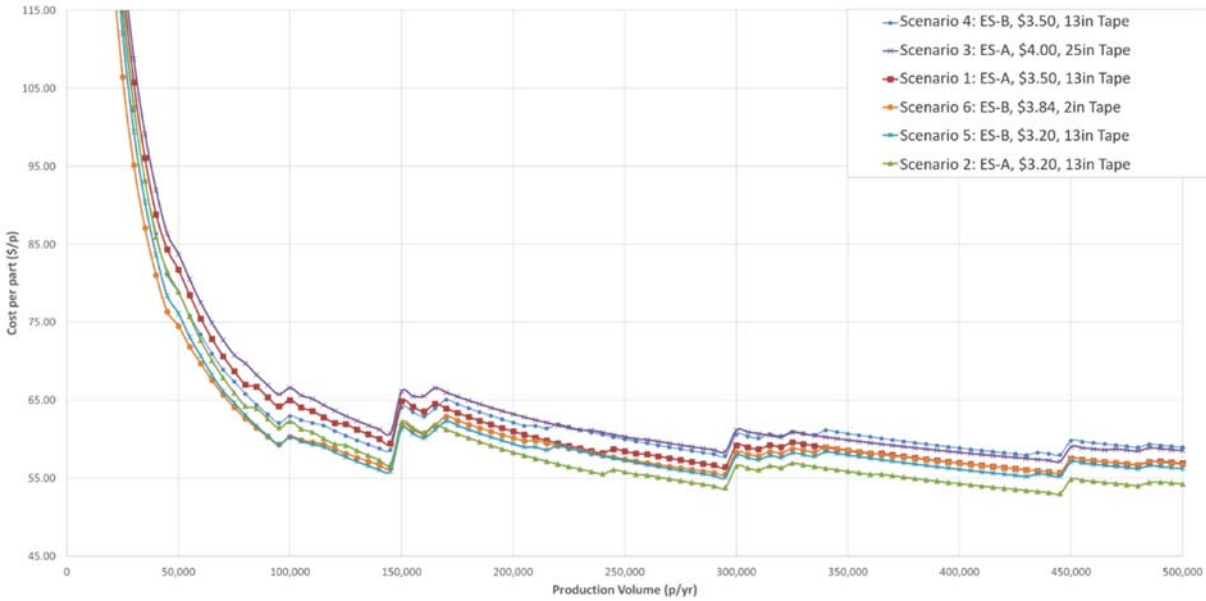

Figure 25. Scale-up costs per part across increasing production volumes for the 6 T1P dedicated manufacturing scenarios.

The hybrid molded rear package shelf ultimately weighed in at 2.14kg. This resulted in a weight savings of 1.24kg compared to the steel package shelf that weighed 3.38kg. On average, this resulted in a cost per kg saved of $35.01/kg. The cost per weight saved, C_{ws}, is calculated via Equation 45 where C_A and C_B are the manufacturing costs and W_A and W_B are the part weights. Cost/Part A is the metal part which Cost/Part B is the composite part. Scenario breakouts of the total cost per kg saved is given in Table 11.

$$C_{ws} = \frac{C_B - C_A}{W_A - W_B}$$

Equation 45

Table 11. Total cost per kg saved for T1P scenarios.

	Scenario 1: ES-A Glass Fiber, \$3.50 - 13in Tape	Scenario 2: ES-A Glass Fiber, \$3.20 - 13in Tape	Scenario 3: ES-A Glass Fiber, \$4.00 - 25in Tape	Scenario 4: ES-B Glass Fiber, \$3.50 - 13in Tape	Scenario 5: ES-B Glass Fiber, \$3.20 - 13in Tape	Scenario 6: ES-B Glass Fiber, \$3.84 - 1.9685in Tape
Total Cost (\$/p)	58.41	55.76	59.65	60.47	57.75	58.43
Total Cost per kg saved (\$/kg)	35.01	32.87	36.01	36.67	34.48	35.02

It is important to note that the cost per part and cost segmentation values presented in Table 7, Figure 24, Table 8, and Figure 25 are for the entire manufacturing line in a *dedicated* capacity. This means that costs such as equipment, maintenance, and plant operations are fully accounted for by the desired part production. Cost per part decreases as both production volume increases and the number of equipment in use stays the same since the number of parts the manufacturing costs are distributed amongst increases. As additional equipment investments are needed to meet increasing production volumes, the cost per part increases. The *utilization* case was not desired and is not available.

3.9 Conclusions for the T1P cost model

At this point in the feasibility study, the ES-A system appears to be the lowest cost choice for T1P. However, final refinement is necessary as the following details may alter the outcomes of the model:

- ES-B: Cycle time is based off their first test layup of 111 sec per part. They have been working to reduce the cycle time. Reduction in cycle time shall reduce the equipment required which shall greater reduce the capital cost required, and thus, reduce the overall cost per part.
- ES-B: Cutout areas need to be accounted for. This shall reduce the material required, though it may influence the cycle time due to the time to make the cuts during layup is added.
- ES-A: Lap weld capability needs to be accounted for. This shall decrease the well cycle by an estimated four (4) seconds, resulting in an eight (8) second weld time. However, lap welding may increase the material usage due to the smaller output roll capable of

being produced. The overlapping of material within the part means that more tape may be required to be seamed together to reach the bounding box dimensions for the part as well.

Another consideration is the flexibility of the system, for which ES-B comes out ahead. The multi-unwinding unit layup process ES-B utilizes allows for flexibility in the parts it can layup since not every layup head has to be used each pass. This means much smaller parts can be preformed. The ability to cut tape as the unwinding units advance means less tape may be wasted for parts that have larger cutouts.

The part under investigation, a rear package shelf for a passenger vehicle, was composed of six layers of thermoplastic prepreg and, with the additive molding material, weighs 4.71 pounds. The ES-A process operated by seaming single layers of thermoplastic tape into rolls and then stacking prior to consolidation. This method had the advantage of less moving parts and resulted in a scrap rate of 23-28% across the three scenarios investigated with a cost of $32.87-36.01 per kilogram saved. The ES-B layup process, essentially a multi-head automatic tape layup machine, resulted in scrap rate of 20-27% across the three scenarios investigated with a cost of $34.48-36.67 per kilogram saved. Neither equipment manufacturing route met T1P's requirement of $6.6-11 per kilogram saved and led to the T1P team to abandon the rear package shelf as a feasible project and instead look for a different part with a higher return regarding weight savings.

3.10 Summary

This chapter delved into how technical cost modeling may be used for part production management decisions. A case study was presented with a Tier 1 Part Producer who was interested in determining which Equipment Supplier, A or B, was going to supply TP preforming and consolidation equipment for manufacturing a structural component for an automobile. Equations to model the material usage and layup times had to be created, as well determining what the rest of the manufacturing line was to be to capture the full line's manufacturing costs. Ultimately, the economic quantitative indicator desired, the cost per kilogram saved, showed that the chosen structural component was not economically feasible through either Equipment Supplier's equipment and spurred a search for a different component with a greater potential for success.

4. TECHNICAL COST MODELING FOR IN-HOUSE MANUFACTURING MANAGEMENT

In-house manufacturing management is the decision-making process governing manufacturing operation procedures. This chapter shall focus on the benefits a TCM brings to the operations management of a manufacturing line as it allows decision makers to alter processing parameters to see the results in an economic form. A case study of the Manufacturing Design Laboratory's test coupon shall be presented, comparing the *engineering estimate* based model verse the *pre-production* and *production adjusted* initial test run of the equipment and programming. The processing parameters that form the base of both models were extracted from the CMSC's design app for hybrid molding and shall be discussed in detail.

4.1 Introduction

Composite materials provide lightweight yet unique performance characteristics that are increasingly appealing to more producers in broader product categories as novel technologies are easing manufacturability and increasing production rates. Advances in computer aided design (CAD) and engineering (CAE) tools is spearheading the transition to composites with tools that can simulate the manufacturing process and alter part or tooling designs to ensure parts can be produced to specifications. However, the decision to implement composites' manufacturing ultimately still comes down to the cost or cost benefit received from transitioning from steel or aluminum into composites. With the lack of historical databases regarding composites' manufacturing, a technical cost modeling approach is necessary to provide the manufacturing cost.

One such novel manufacturing process that is currently intensively studied is hybrid molding. Hybrid molding utilizes a preform that provides the underlying structure and some form of additive molding that completes the part, providing the desired surface finish or connection points. The preform minimizes material usage as it delivers performance where it is designed for and needed. The term "additive molding" is used here since it encompasses processes such as injection over molding that typically over-molds both sides of a preform to compression molding processes that typically cover only one side of a preform. Preforms can be created through a variety of manufacturing processes, such as automatic tape layup or automatic tape placement.

CAE simulation tools provide processing parameters that can guide operating settings of the actual manufacturing equipment. Theses parameters come from the heat or pressure being applied, cooling liquid flow rates required, material volumes required to fill a mold, or other parameters influencing the chemistry and physics of the composite material that is captured within the simulation. However, these simulations do not cover additional operating/managerial decisions that are needed to fully articulate operating procedures. Knowledge of the process allows models that cover the mechanical operations of the preforming operations to be created. Altering the model inputs allows different manufacturing scenarios to be studied.

4.2 MDLab test coupon

The hybrid molded part under investigation for this work, a test coupon, is comprised of three component materials. Two aluminum bushings are wrapped with a 50% E-glass / 50% polypropylene thermoplastic tow to form the rigid preform that is then overmolded with polypropylene. Figure 26 illustrates the test coupon during overmolding and with the cold runner removed.

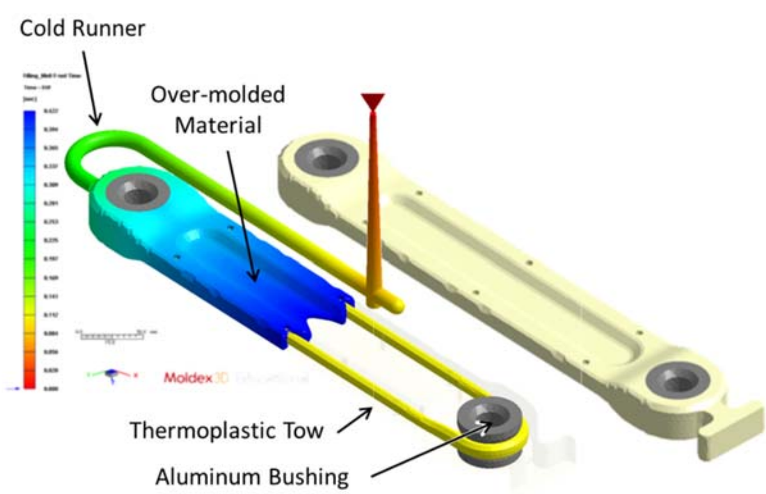

Figure 26. The test coupon during overmolding (left) and the finished test coupon (right).

4.3 Hybrid molding process description

Creation of the test coupon is a six step manufacturing process. During the first process step, thermoplastic tape is loaded onto bobbins onto a creel system that maintains tension on the tape as it proceeds through an infrared oven where it is consolidated into the full tow. It is then fed through a heated layup head that maintains the material in a pliable state so that it can be formed into the preform shape on a 3-axis layup table. The aluminum bushings are placed via robot into the layup jig prior to tow layup. The second process step begins once the preform is laid up and the tow severed; a robot transfers the preform to the injection molding machine where it is overmolded; the third process step. Once the molding cycle is complete, the robot removes the part and transfers it to the trimming and quality control station, completing the fourth process step. During the fifth process step, the cold runner is trimmed off. The final process step consists of a second robot scanning the test coupon with a non-contact laser scanner for quality control (Leica T-Scan 5) and, if within specifications, the part is complete. This manufacturing process is illustrated and further broken down into the equipment operation steps in Figure 27.

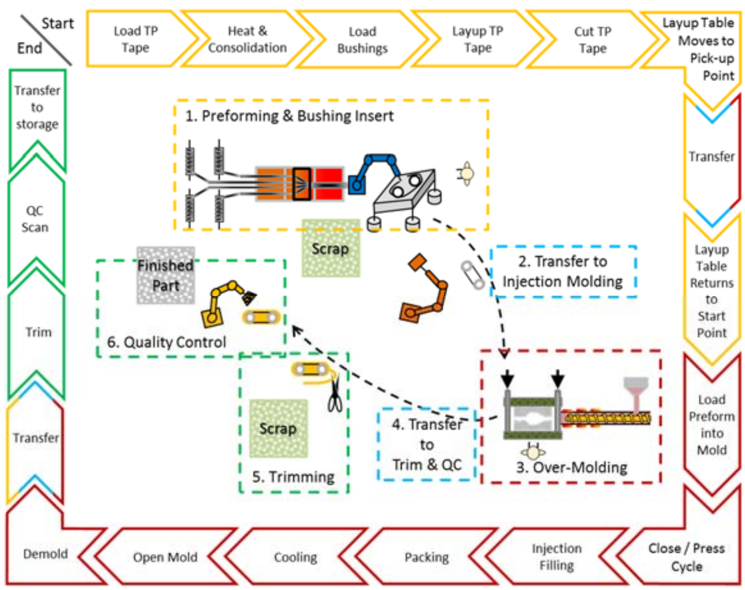

Figure 27. The six manufacturing process steps for hybrid molding the test coupon surrounded by the equipment operation steps .

Note: color coded to represent which process step is involved.

One important aspect of cost modeling is how to manage time. For this hybrid molding manufacturing line investigation, the six process steps are grouped as a work cell. By grouping them as a work cell, it treats the process steps as linked in terms of production time available. Thus, the slowest process step time dictates when an additional manufacturing line is required instead of simply an additional piece of equipment and potentially storage points before the bottleneck process. Besides the amount of equipment required, the slowest process step dictates how long labor is required for each process step. Utilities are calculated from the individual process step cycle times. For the work that follows, electricity usage is split into active use and standby use. Active use being the time during which a part is processed, controlled by the process step cycle time. Standby use is the other amount of time during a shift. Standby time can be calculated in two ways, accounting for the entire year, as in Equation 46, or only accounting for the shift time utilized, as in Equation 47.

$$t_{standby,yr} = \left[t_{shift} \cdot N_{shift} - t_{op}\right] + \left[U_{eff} \cdot \left(8760 - t_{shift} \cdot N_{shift}\right)\right]$$

Equation 46

$$t_{standby,shift} = \left[t_{shift} \cdot N_{shift} - t_{op}\right]$$

Equation 47

$t_{standby,yr}$ is the standby time accounting for the entire year, t_{shift} is the total time available in a shift for a year, N_{shift} is the number of shifts operating, t_{op} is the time spent making parts across the year, U_{eff} is the effective utilization of the equipment, 8760 is the total number of hours within one year, and $t_{standby,shift}$ is the standby time accounting for only shift time worked. For the investigations that follows, shift standby time is utilized.

4.4 Technical Cost Modeling

The cost analysis was carried out utilizing the method described previously in *Technical Cost Modeling Methodology for Novel Manufacturing* [28]. This method requires developing fungible, yet individual equipment models that produce cycle time and material usage information. As each equipment model is fungible, it allows for different processes to be easily interchanged or processing parameters to be altered for parametric studies.

4.4.1 TCM inputs

The greater fidelity desired in a cost estimate, the more complex the estimation becomes and the number of inputs required can increase dramatically. Obtaining these inputs is often the most tedious portion of executing a cost model. These inputs fit into either the physical thread or the digital thread. The physical thread is equipment and logistics related while the digital thread is data and connectivity related. For this work, these inputs come from three collection categories; business, performance design, and manufacturing knowledge.

4.4.1.1 TCM inputs: Business inputs

Plant operations, equipment operating rates, and utility costs are components of the physical thread, and require knowledge of the location, business, and manufacturing operation. Plant operational overheads are the costs of to maintain the manufacturing environment and include insurance, janitorial service, and interior environmental control. Equipment operating rates include the capital costs, utilities usage rates during operation and in stand-by mode, and required labor dedication. The physical thread inputs for each process step are given in Table 12 and the operations costs are given in Table 13.

Table 12. Model inputs for the physical thread: equipment related.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trimming	6. Quality Control
Direct Labor	0.5	0	0.5	0	0	0
Labor Ratio	0.1	0	0.1	0	0	0
Machine Power (kW)	55.6	3.5	12	3.5	1	3.5
Cost	$452,000	$75,000	$510,000	$0	$15,000	$265,000
Tool Cost	$20,000	$17,500	$60,000	$0	$1,500	$0

Table 13. Model inputs for the physical thread: operations related.

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
Known No. of shutdowns	4	Production volume per year	100,000		

Equipment cost and tooling cost is typically part of the equipment related physical thread. However, the two cases that shall be presented within this chapter, the *engineering estimates* and the *pre-production,* utilize slightly different inputs for those, as the *engineering estimates* case is calculated from parametric costing equations.

Material usage and equipment operating times, aka cycle times, are components of the digital thread, and can be extracted from the CAE tools that are used in the design for manufacturing process. It is important to note that cycle times cannot be fully extracted from the CAE tools. Additional knowledge of the process step is required to get the complete cycle time that a piece of equipment is in use for. The CAE tools only provide the portion of cycle time directly related to material interactions and do not include mechanical aspects of the equipment required to position the part or material for that processing step.

4.4.1.2 TCM inputs: Performance Design processing parameter extraction

For this work, the CAE tools utilized are part of a hybrid molding design for manufacturing workflow app developed at the Indiana Manufacturing Institute and explained in detail by *Goodsell et* al [29]. The workflow app begins with the part design in CATIA, where the design parameters are translated into the digital representative of the part. The CAD model is imported into Moldex3D where the filling, packing, and cooling aspects of injection molding are simulated along with the part warping upon removal from the mold. Finally, the performance of the part was tested in LS-DYNA. If warpage or performance is subpar, the geometry of the part or the mold can be digitally altered till the desired specifications are met. This digital alteration can be conducted as many times as needed, reducing the potential costs in having to have physical molds altered after initial trial runs or longer cooling times required. This loop is illustrated in Figure 28 where the dashed lines represent the digital data thread that is applicable to a physical manufacturing operation step, and are inputs to the cost model. Table 14 gives the processing parameters extracted from the Moldex3D module reports. Processing parameters are extracted via Python.

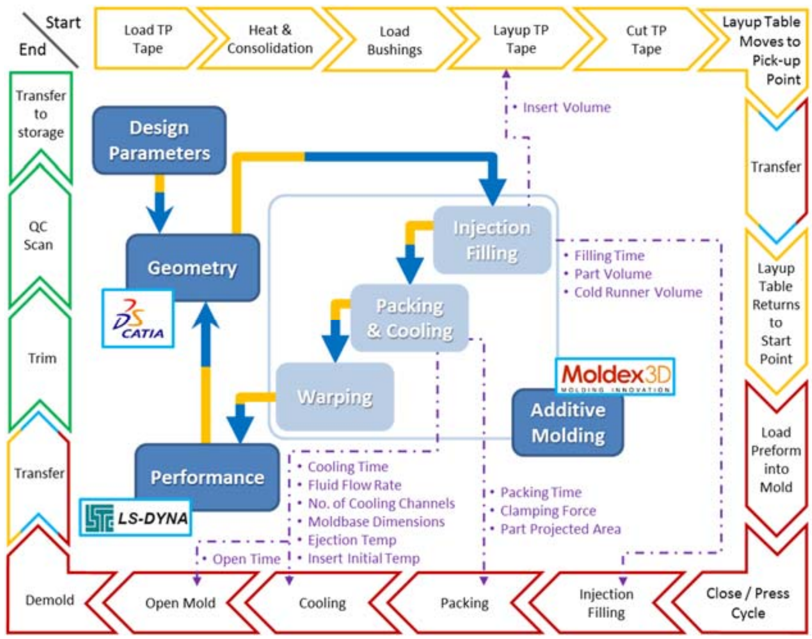

Figure 28. The hybrid molding design for manufacturing workflow app flow surrounded by the equipment operation steps and the processing parameters extracted from the workflow modules.

Table 14. Processing parameters extracted from the Moldex3D modules that contribute to the cost model.

Processing Parameter	Fill Module	Pack Module	Cool Module
Material 1			Polypropylene (PP)
Material 2 (insert)			Aluminum
Material 3 (insert)			PP, 60 % GF
Material 1 Density			0.905 g/cm^3
Material 2 Density			2.6989 g/cm^3
Material 3 Density			1.49 g/cm^3
Insert Volume	39.0639 cc		
Part Volume	105.722 cc		
Cold Runner Volume	15.5239 cc		
Filling Time	0.548425 sec		
Packing Time		2.45157 sec	
Clamping Force		110.1 ton	
Part Projected Area		149.092 cm^2	
Cooling Time			85.000001 sec
Cooling Fluid Flow Rate			120 cc/sec
Number of Cooling Channels			2
Moldbase Volume			50 x 30 x 32.5 (cm)
Ejection Temperature			90 °C
Insert Initial Temperature			30 °C
Open Time			5 sec

Specifically, the injection molded material molded within Moldex3D is SABIC PP 571P and the tow is ASAHI Thermylene P7-60FG-0790.

These processing parameters allow various factors to be calculated for the estimate. The times given contribute to the overall cycle time of the injection molding machine, $t_{cycle,IM}$, see Equation 48.

$$t_{cycle,IM} = t_{load} + t_{close} + t_{fill} + t_{pack} + t_{cool} + t_{open} + t_{demold}$$

Equation 48

To complete the injection molding machine total cycle time, t_{load}, t_{close}, and t_{demold} are still required. The given mold opening time allows the closing time to be estimated based off of *Boothroyd et al*'s findings via Equation 49 [32].

$$t_{close} = 0.4 \cdot t_{open}$$

Equation 49

The mold loading time, t_{load}, is assumed to consume one third of the time that the transfer/loading robot takes to transfer the preform from the layup table to the mold. Demolding time, t_{demold}, is assumed to consume one third of the time that the transfer robot takes to transfer the part from the mold to the next process step. If the part were to simply be ejected from the mold, 1 second is an appropriate time for this to occur [32]. From literature reviews of manufacturing cost estimates, 5 seconds is generally allotted for transfers, but many factors can influence this that are not addressed within this work. [22, 23, 39]

If a specific injection molding machine is not being utilized for the cost estimation, the clamping force, F_{clamp}, allows the injection molding machine cost, C_{IM}, to be estimated via Equation 50.

$$C_{IM} = \frac{(1 + \varsigma) \cdot 1{,}470 \cdot F_{clamp}}{0.8}$$

Equation 50

Where ς is a sizing factor utilized for future manufacturing flexibility if desired. This is derived from *Martensson et al.*'s work for costing presses [2, 23], of which is roughly 80% of the cost of an injection molding machine from experience.

Part volume and cold runner volume make up the total volume of injected material, which can be converted to the cost per part. The volume of the bushings are known, as they are custom ordered for this part from an outside entity. This means the length of the tow, L_{tow}, within the part can be determined via Equation 51.

$$L_{tow} = \frac{V_{insert} - (N_{bushing} \cdot V_{bushing})}{N_{tape} \cdot A_{tape}}$$

Equation 51

Where V_{insert} is the volume of the insert, $N_{bushing}$ is the number of bushings within one part, $V_{bushing}$ is the volume of one bushing, N_{tape} is the number of tapes within the tow within one part, and A_{tape} is the area of one tape. However, within the model, tow length was calculated differently, which shall be discussed at a later point in *Section 4.4.1.4.1*.

The injection mold, layup jig, and end of arm tooling costs can be estimated by adapting *Joshi et al.*'s cost factor estimate, $CF_{estimate}$, equation for cast parts, see Equation 52. Using various part geometries, listed in Table 15 for the test coupon, adjustment factors to the cost factor estimate equation are given in Equation 53- Equation 55.

$$CF_{estimate} = 5.7 + 10.8 \cdot C_{PR} + 18 \cdot C_{AR} + 32.7 \cdot C_{NC} + 29 \cdot C_{OR} + 6.9 \cdot C_{TR} + 0.7 \cdot C_{DR}$$

Equation 52

$$C_{IMmold} = CF_{estimate} \cdot 1.33 \cdot 10^3$$

Equation 53

$$C_{LUjig} = CF_{estimate} \cdot N_{bushing} \cdot 0.225 \cdot 10^3$$

Equation 54

$$C_{EOAT} = CF_{estimate} \cdot 0.39 \cdot 10^3$$

Equation 55

Table 15. Adjustment factors to the cost factor estimate equation for the test coupon.

Part Volume	Part Surface Area	No. of Cores	Core Volume	Min Thickness	Max Thickness	Total Length	Total Width	Total Height	Draw Distance
144,790	40,440	1	160,300	2	20	357	68	112.5	112.5

4.4.1.3 TCM inputs: Manufacturing knowledge

A third component of cost estimation requires specific knowledge of the manufacturing process or equipment involved. This may involve movement speeds, sources of material scrap, processing steps that are not directly related to the pat layup, such as the layup table movement to and from the pick-up point, or operational decisions surrounding how the equipment is run or what parts are acceptable. The focus of the following sections shall focus on the first process step in the hybrid molding process described earlier; preforming and bushing insert, and the cooling water portion of the third process step; injection molding.

4.4.1.4 EELCEE QEE-TECH® Preforming Cell

One feature about hybrid molding is the flexibility it provides in terms of what materials may be used. The structural components for a hybrid molded part may be metal, fabric, tow, tape, or other materials. Since composites are often sought to replace metal components, focus shall be applied to hybrid molded parts utilizing fabric, tape, tow, or a combination of these. Further, the majority of the research presented is thermoplastic resin based fabric, tow, or tapes.

The EELCEE QEE-TECH® preforming cell (QTC) is an automated robotic cell that transforms thermoplastic tape or commingled yarn into a 3-dimensional shaped preform. EELCEE refers to these preforms as QEE-FORMs® [40]. The material is fed from bobbins on a creel to an IR oven where it is heated and consolidated. The consolidated material is fed into a layup head that feeds the material onto a jig that is set up on a 3-axis table. The layup head has heaters to maintain the material at its layup temperature, coolers to cool the material so it maintains that laid shape, and is also rotatable and has 2-axis tilt to aid in layup flexibility. The jig has pneumatics to brace the material during layup and to cut it. The jig braces may be heated or cooled if needed to aid in the layup process. Tension throughout the cell is controlled via tensioners on the creel and the material is secured at the jig during the layup process. Finally, a robot completes the preform cell to transfer the preform from the jig to the next process, typically the injection molding machine. The QTC is shown in Figure 29.

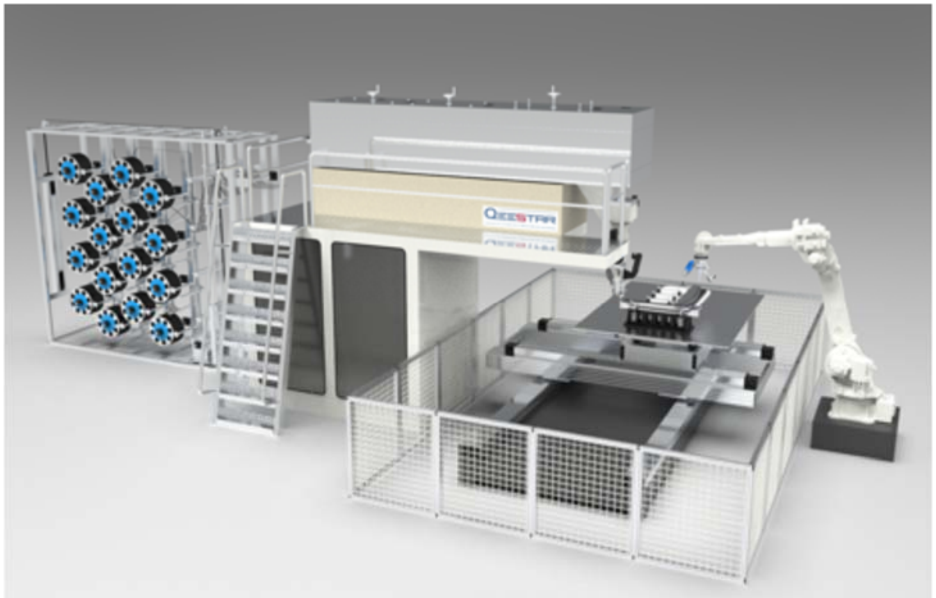

Figure 29. EELCEE QEE-TECH preforming cell [40].

Material usage and cycle time for the QTC depends on the processing setting that are selected for the cell. Four overarching processing questions dictate how material usage and cycle time are calculated:

1. How is QEE-FORM® area determined?
2. How is tow layup speed determined?
3. When creel ends, is old end of tape joined with new end of tape (forming a joint?)
4. Is (are) oven set temperature(s) known?

To best explain the interconnectivity of these questions and to guide the way through the equations that are required, decision trees shall be presented and discussed for each overarching question.

4.4.1.4.1 How is QEE-FORM® area determined?

The area of the tow that makes up the QEE-FORM® determines the number of tapes and/or the number of laps that must be used and/or made to form the QEE-FORM®. To achieve the fastest layup time, the minimal number of laps must be used, thus one (1) is the ideal number of layup laps. The number of tapes that are required to achieve the area of the QEE-FORM® tow must be known or determined to form the final tow area within one lap. If there is not enough bobbins loaded or enough tape area to form the final tow area, then additional laps may be required. Furthermore, if the tape areas are greater than the desired tow area, additional material is being used, which leads to additional material costs and potentially a quality assurance issue if the thicker tow is unacceptable. The decision tree for the QEE-FORM® area determination is shown in Figure 30.

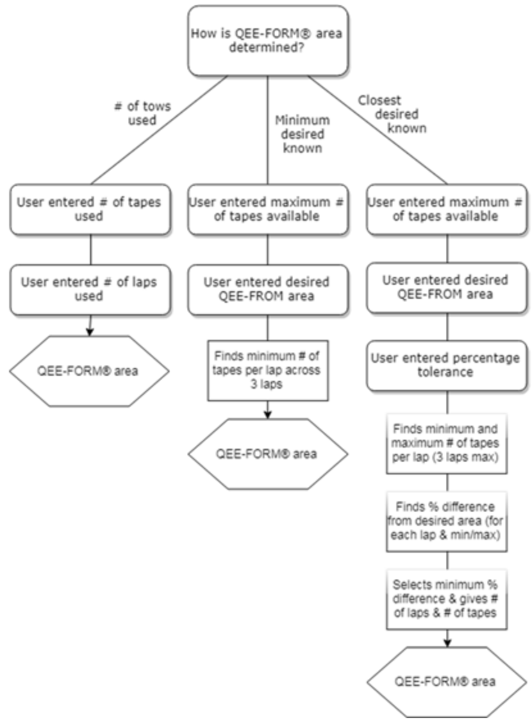

Figure 30. Decision tree for determining QEE-FORM® area.

The simplest QEE-FORM® area determination is made when the user knows the number of tapes to be used, $N_{tape,QTC}$. This knowledge goes hand in hand with knowing the number of laps that then have to be made, $N_{laps,QTC}$, and knowing the individual tape area, $A_{tape,QTC}$. The QEE-FORM® area, A_{QF}, is determined by Equation 56.

$$A_{QF} = N_{tape,QTC} \cdot N_{laps,QTC} \cdot A_{tape,QTC}$$

Equation 56

Where $A_{tape,QTC}$ is the area of an individual tape.

If the number of tapes and laps are not known, the desired QEE-FORM® area, $A_{desired,QTC}$, and the maximum number of tapes available, $N_{\max tapes,QTC}$, must be known. Using this information, either the “minimum desired known” or the “closest desired known” may be found. The “minimum desired known” finds the number of tapes and laps required to have a QEE-FORM® area that is equal to or exceeds the desired QEE-FORM® area. The “closest desired known” option finds the number of tapes and laps that are within a user entered acceptable tolerance and may result in a QEE-FORM® area that is larger or smaller than the desired QEE-FORM® area.

For the "closest desired known", two checks per lap need to be made, the number of tapes needed for that lap and the percent difference of the resulting QEE-FORM® area from the desired QEE-FORM® area. The number of tapes needs to be checked for the minimum number and the maximum number per lap. The minimum number of tapes, $N_{tape,QTC\,min}$, the maximum number of tapes, $N_{tape,QTC\,max}$, and the percent difference, $\%_{diff}$, are shown in Equation 57 -Equation 59, respectively.

$$N_{tape,QTC\,min} = \left\lfloor \frac{A_{desired,QTC} / N_{laps,QTC}}{A_{tape,QTC}} \right\rfloor$$

Equation 57

$$N_{tape,QTC\,max} = \left\lceil \frac{A_{desired,QTC} / N_{laps,QTC}}{A_{tape,QTC}} \right\rceil$$

Equation 58

$$\%_{diff} = \frac{\left[N_{tape,QTC\,i} \cdot A_{tape,QTC} \cdot N_{laps,QTC}\right] - A_{desired,QTC}}{A_{desired,QTC}} \cdot 100\%$$

Equation 59

It is important to note that both $N_{tape,QTC\,min}$ and $N_{tape,QTC\,max}$ must be, at a minimum, one (1) and that the $N_{laps,QTC}$ term here represents the number of laps per iteration. Overall, three iterations are run, meaning the numbers are checked for 1 lap, 2 laps, and 3 laps and the smallest percent difference on the smallest number of laps is chosen.

For the "minimum desired known", one check per lap is necessary. Equation 58 is utilized and if $N_{tape,QTC\,max}$ exceeds $N_{\max tapes,QTC}$, then an additional lap is necessary to be checked. Again, three iterations are checked for 1 lap, 2 laps, and 3 laps. If 1 lap is found to be sufficient, the calculation stops there.

4.4.1.4.2 How is tow layup speed determined?

Layup speed may be determined by four different methods: Imported from CAE tool, Set by User, Determined by Time in Oven, or Shape Factor. Imported or Set by User options are straightforward and are simply the time it takes to layup the part, t_{layup}. If the actual layup speed, v_{layup}, is wanted for these options, it is found via Equation 60.

$$v_{layup} = \frac{L_{tow}}{t_{layup}}$$

Equation 60

Where L_{tow} is the length of tow used in the preform. *Determined by Time in Oven* and *Shape Factor* are more involved and shall be discussed in detail below.

4.4.1.4.3 Shape Factor for Layup Speed

The "shape factor" is a means to assess the complexity of a tow preform layup. The shape factor is a acts as a speed restrictor, reducing the time to layup a preform of great complexity compared to an equivalent layup length of a simple preform. The simplest layup is a straight line and would have a shape factor of one (1). Curves and height changes complicate the layup, and thus increase the shape factor. For the test coupon, the layup path consists of two "straight" lengths of 254mm each, 16 90° curves of with a radius of 15.875mm, and no height change, as illustrated in Figure 31.

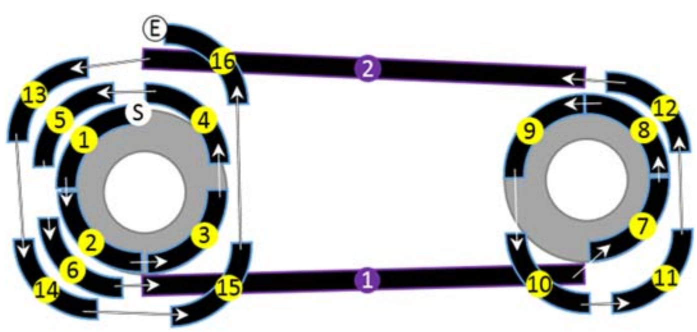

Figure 31. Straight and curved sections of the test coupon layup path.

Determining the shape factor requires knowledge of the "straight" sections, "curved" sections, and the "height" change along the layup path. A "straight" section is deemed anything above the radii chosen for the largest curve. The "curve" sections are dictated by the radius of their curve. This also allows the length of material used in a curve to be calculated, as shown in Equation 61.

$$L_{curve} = 2 \cdot \pi \cdot r_{curve} \cdot \frac{90°}{360°}$$

Equation 61

Where L_{curve} is the length of the curve of radius r_{curve} along a 90° section of the curve. The "height" change is controlled via a different, slower motor that physically raises or lowers the layup XYZ-table of the QTC. Either the total height change per lap or the number of changes and the average height change per change must be known to determine the height change's influence on the shape complexity. The shape complexity factor is found via Equation 62 for when there is a mix of straight and curved lengths.

$$F_{complex} = 1 + \frac{\sum L_{curve} + L_{height}}{\sum L_{straight}}$$

Equation 62

Where $L_{straight}$ is the length of the straight sections of tow and L_{height} is height change per lap. For the case where only curved lengths are used, the chape complexity is found via

$$F_{complex} = 1 + \frac{\sum L_{radius,i} \cdot N_{curve,i}}{\sum L_{curve}}$$

Where $L_{radius,i}$ is the length of the radius for a given curve and $N_{curve,i}$ is the number of curves at the given radius. The length of tow laid is the sum of L_{curve} and $L_{straight}$. To find the total length of tow laid, the number of tapes that make up the tow must be known and multiplied by the length of tow laid.

The shape factor based layup time, $t_{layup,SF}$, is then found via Equation 63 where $v_{straight}$ is the max relative head speed in the "straight" direction and v_{curve} is the max relative head speed for each "curve" section.

$$t_{layup,SF} = \left(\frac{\sum \mathrm{L_{straight}}}{\mathrm{v_{straight}}} + \sum \frac{\mathrm{L_{curve,i}}}{\mathrm{v_{curve,i}}}\right) \cdot \mathrm{F_{shape}}$$

Equation 63

The QTC comes with three layup speed settings, 4,000mm/min, 8,000mm/min, and 12,000mm/min. Normal layup operation is done at 8,000mm/min for straight lengths and

4,000mm/min for curved lengths. This is only a fraction of the maximum table movement speed, which is 20,000mm/min for both the x- and y-axis.

Comparing trial test coupon preform layups to the times calculated via the complexity factor, it was found that the complexity factor was underestimating that layup times. This is due to the fact that the layup speed settings for the QTC do not take into account the startup and stopping acceleration and deceleration. Ultimately, the actual layup speed is ~one third of the QTC set speed. This means a correction factor is needed to be applied to the complexity factor to adjust for the acceleration and deceleration concerns. This adjusted complexity factor, the shape factor, F_{shape}, may be found via

$$F_{shape} = \gamma \cdot F_{complex}$$

Equation 64

Where γ is the speed correction factor.

Estimation of the speed correction factor requires knowing the average maximum table speed, the set speeds for straight and curve segments, and the percentage for each segment. This estimation is conducted via Equation 65.

$$\gamma = v_{table,avg} \cdot \left[\left(\frac{1}{v_{straight}} \cdot \frac{\sum L_{straight}}{L_{total}} \right) + \left(\frac{1}{v_{curve,i}} \cdot \frac{\sum L_{curve,i}}{L_{total}} \right) \right]$$

Equation 65

Where $v_{table,avg}$ is the average maximum table speed and L_{total} is the total length of the tow layup, which is the sum of all straight, $L_{straight}$, and curve, $L_{curve,i}$, segments. Utilizing the average maximum table speed for the MDLab QTC system, 20,000mm/min, and the lengths and speeds given in Table 16, the estimated speed correction is 3.6. Determining the correction factor is demonstrated in Table 16. A breakout for each segment of the test coupon is available in APPENDIX B.

Table 16. Lengths, times, and QTC speeds needed to find the Shape Factor.

Known run time (sec)		60		
Lengths (mm)	Straight	508	Curve	399
QTC speed setting (mm/min)	Straight	8,000	Curve	4,000
Shape complexity (SC)		1.79		
Layup time (SC based, sec)	Straight	6.8199	Curve	10.71315
Calculated speed correction factor		3.6		
Calculate shape factor (SF)		6.43		
Estimated layup time (from SF, sec)		62.95		

For the test coupon shown in Figure 31, the shape complexity is 1.785 and the speed correction factor is 3.60. The decision tree for shape factor determination is shown in Figure 32.

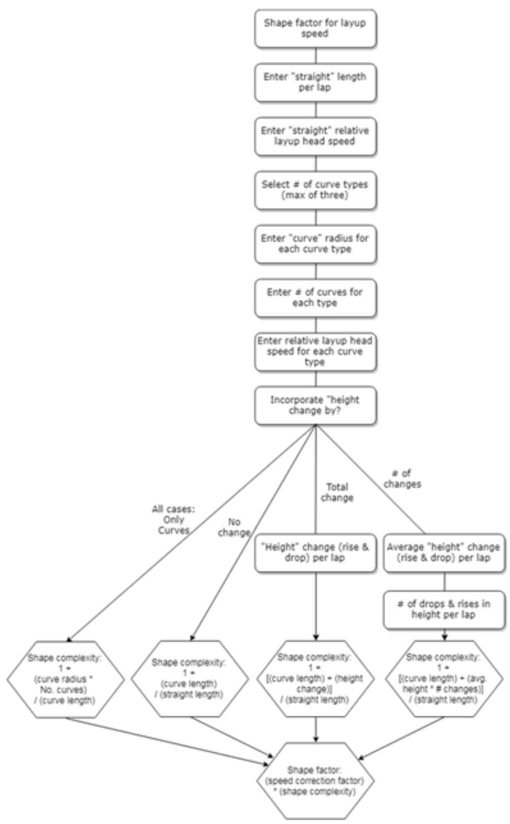

Figure 32. Shape factor decision tree.

4.4.1.4.4 Determined by Time in Oven

Use of heating throughout composite manufacturing processes is inevitable. Thermoplastic processing requires heating to either the melt temperature, or close to it, or the heat deflection temperature for consolidation purposes or bending/deforming without introducing defects, respectively [27]. Thermosets may require heat for activation, curing, or reduce their viscosity to be able to flow and infiltrate the cavities of a mold [41, 42]. Inserts or molds may have to be heated to improve draping, enhance part cohesion, or ensure proper processing conditions are met. Determining correct operating temperatures and time required for heating relates directly to energy usage and is thus an important contributor to the utilities costs.

For the cost models presented within this work, all heating and cooling information that is not available from simulation tools shall be determined through the means of unsteady heat conduction. In unsteady heat conduction, the composite components considered are treated as solid bodies where the surface is exposed to an elevated or lowered temperature that then is transmitted to the midpoint or mid-plane to reach a desired temperature. Thus, the internal temperature varies with time. Determining the time taken to heat material from one temperature to the next ordinarily requires differential equations. However, there are a number of geometrical shapes, such as cylinders and flat plates that have solutions worked out in the form of specialized charts and are available in most heat transfer texts. [43]

There are a variety of ways that heating conditions may be determined. The simplest is *user entered* data. For this data, the user knows either the time spent in the oven or the oven's length and belt speed, and the related utilities information, be it electricity or fuel usage. This is all the information that is needed to determine cycle time and calculate an oven's utility costs. However, if this information is not available, detailed material and oven information must be known to be able to determine the heating conditions and utilities information.

Oven information necessary includes the length of the oven, number of heating zones, and max heating temperatures for each zone. Material information necessary includes the starting temperature, final temperature desired, and the Fourier Number, F_0, and the subsequent variables that define it, as shown in Equation 66.

$$F_0 = \frac{k \cdot t}{\rho \cdot C_p \cdot x_m^2}$$

Equation 66

Where k is the thermal conductivity, t is the time, ρ is the solid density, C_p is the heat capacity, and x_m is the distance from the surface to the mid-plane for a flat plate or the radius for a cylinder.

Determining the temperature settings for a given number of zones within an oven requires transitioning from the Fourier Number and the desired mid-point/mid-plane temperature to determine the time required within each zone. This transitioning may be completed via differential equations, but for certain geometries, the solutions are plotted in specialized charts. Two useful geometries for composites are that of a flat plate and that of a cylinder. Charts for these two geometries from *Vlachopoulos et al.* may be found in Figure 57 and Figure 58 in APPENDIX C. In these figures, the x-axis is the Fourier Number and the y-axis is the temperature variation. The temperature variation, Y, is composed of the mid-point/mid-plane temperature, T_m, the initial temperature of the material entering into the given zone, T_i, and the temperature of the zone, T_0, as given in Equation 67.

$$Y = \frac{T_m - T_0}{T_i - T_0}$$

Equation 67

Transitioning from the Fourier Number to the temperature number for the mid-plane temperature of a flat plate, Equation 68 and Equation 69 may be utilized. For the equations of the lines, *x* represents the Fourier Number and *Y* represents the temperature variation. The extracted points and the charts they are extracted from may be found in APPENDIX C.

$$Y = -2.9787x^6 + 14.014x^5 - 25.581x^4 + 22.35x^3 - 8.512x^2 - 0.1961x + 1$$

Equation 68

$$x = 48.794Y^6 - 169.34Y^5 + 230.66Y^4 - 157.33Y^3 + 57.377Y^2 - 11.874Y + 1.1392$$

Equation 69

Transitioning from the Fourier Number to the temperature number for the midpoint temperature of a cylinder plate, Equation 70 and Equation 71 may be utilized. For the equations of the lines, *x* represents the Fourier Number and *Y* represents the temperature variation. The extracted points and the graphs may be found in APPENDIX C.

$$Y = -188.92x^6 + 499.4x^5 - 508.47x^4 + 245.28x^3 - 52.34x^2 - 1.3498x + 0.9896$$

Equation 70

$$x = 18.998Y^6 - 68.799Y^5 + 97.313Y^4 - 69.062Y^3 + 26.585Y^2 - 5.9295Y + 0.9027$$

Equation 71

There are potentially two unknowns within these equations, the temperature setting of the heating zone, T_0, or the time spent in each zone, t. Depending on how or where the heating is located, the scenario may alter how the ultimate energy usage is determined. A decision tree from a hybrid molding process is shown in Figure 33 as an example of what decision need to be made and their subsequent calculation paths.

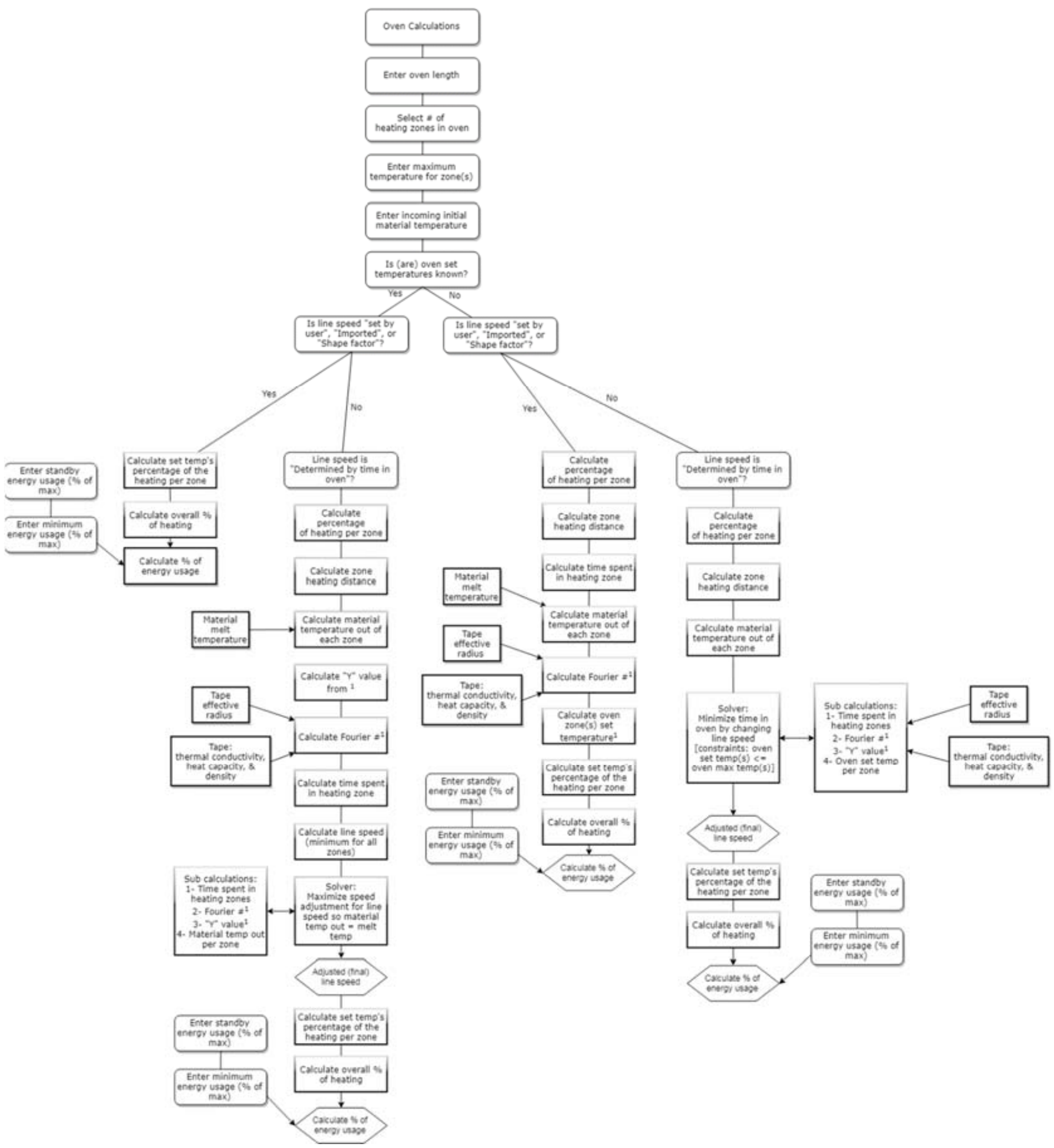

Figure 33. Oven calculations decision tree from hybrid molding process ([1] references equation derived from [43]).

4.4.1.4.5 When bobbin ends, is mechanical bond used?

When the bobbin ends, it must be replaced. The QTC works by pulling the tape through the oven by clamping the tape at the layup table. This keeps tension on the tape to ensure proper consolidation. On dry fiber machines, the ends of the fiber would be tied together and the processing continued. However, with a thermoplastic tape, this is not possible to do. The first thought may be to fuse the tape ends together by applying heat, but this bond would not survive the travel through the oven. Instead, either the bobbin must be replaced, along with the length of tape from the layup head to the creel, or a joint must be formed with a mechanical bond. If a mechanical joint is utilized, the decision tree shown in Figure 34 is followed. If a mechanical joint is not utilized, the decision tree shown in Figure 35 is followed.

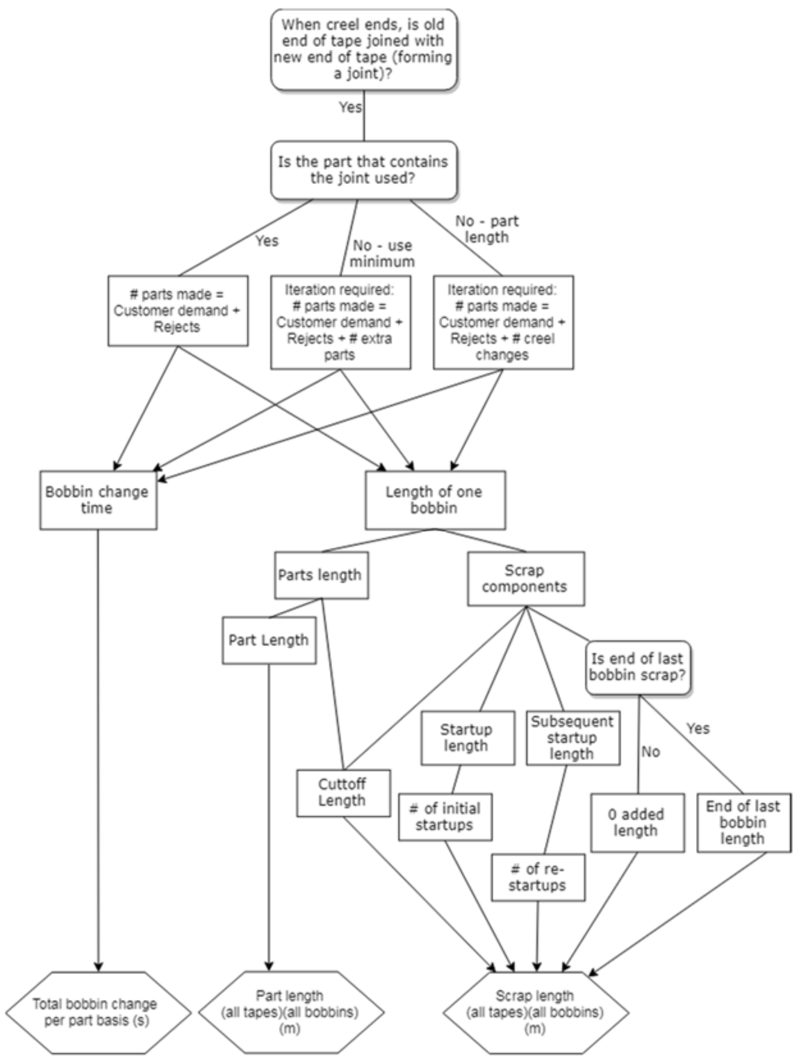

Figure 34. Decision tree dictating calculations for estimating material usage when a mechanical bond is utilized.

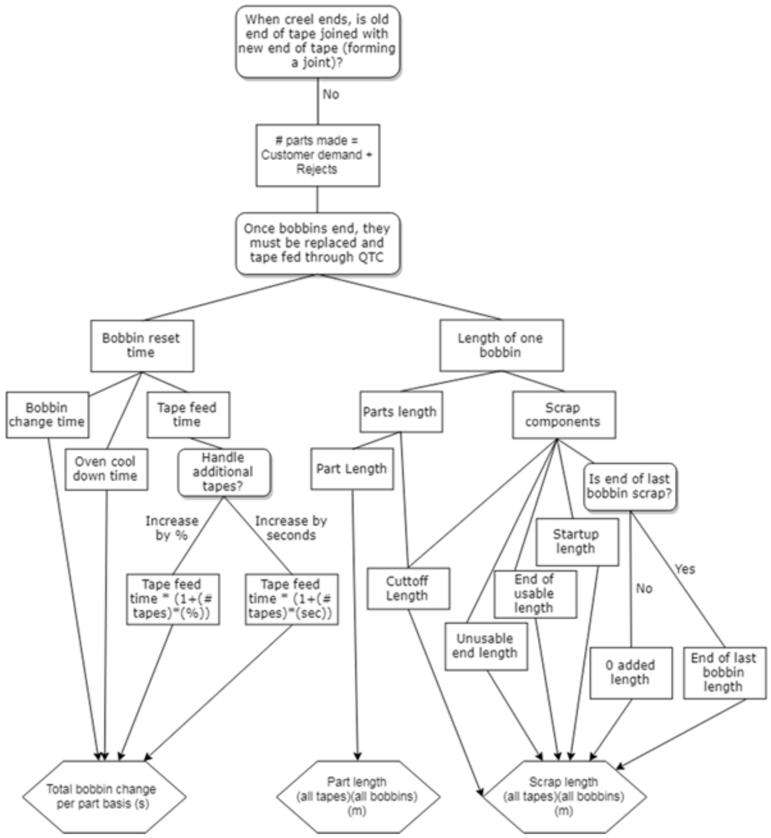

Figure 35. Decision tree dictating calculations for estimating material usage when a mechanical bond is not utilized.

For the models presented within this chapter, the mechanical bond, if utilized, uses a four inch (101.6mm) overlap.

4.4.1.4.6 Are oven temperatures known?

The oven temperature settings can potentially be used to more accurately estimate the amount of energy utilized. It is also important if the layup speed needs to be calculated based on the time required to be spent in the oven. The decision tree shown in Figure 36 is to be followed when oven temperatures must be known.

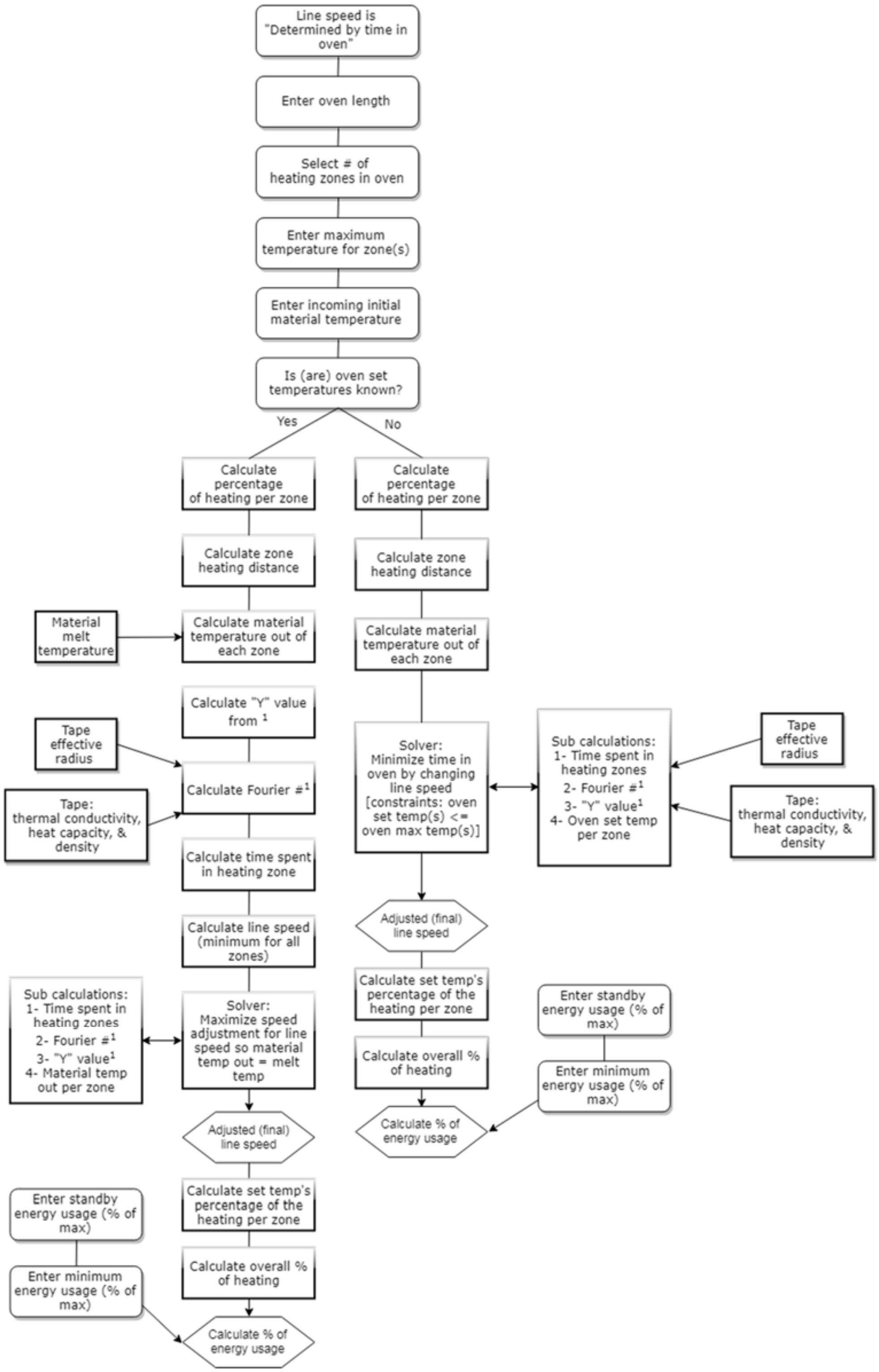

Figure 36. Decision tree dictating calculations when oven temperatures must be known.

4.4.1.5 Injection molding cooling

Cooling is a necessary aspect of injection molding. Selection of coolant and the cooling system utilized is important for the life of the mold and also for the capital cost involved in equipment selection. There are a variety of coolant options, all with their individual pros and cons. Coolant selection is not investigated in this work, but cooling systems are, briefly.

There are three general categories of cooling systems that may be utilized for injection molding systems. These are: once-through cooling systems, open recirculation cooling systems, and closed recirculation cooling systems [44]. System selection plays a role in utilities costs, capital expenditure, and plant operations costs.

4.4.1.5.1 Once-through cooling systems

Once-through cooling systems operate as they sound. Cooling fluid, water in this work's case, comes from the municipality source, is fed through the process to absorb heat, and discharged. A pump may be the only equipment required so long as the municipality source is of an adequate supplied temperature. The volume of water required for one part, V_{water}, if the flow rate is known, $\dot{V}_{IM}$, which Moldex3D provides, is found via Equation 72.

$$V_{water} = \left(t_{cycle,IM} - t_{fill}\right) \cdot \dot{V}_{IM}$$

Equation 72

Where $t_{cycle,IM}$ is the total cycle time of the injection overmolding process and t_{fill} is the fill time portion of the injection overmolding process. If flowrate is unknown, but the heat required to be removed is known, Q, the volume of water can be found through Equation 73.

$$\dot{V}_{IM} = \frac{Q}{\rho \cdot C_p \cdot \Delta T}$$

Equation 73

Where ρ is the cooling fluid density, C_p is the cooling fluid specific heat, and ΔT is the change in temperature. A 4°F temperature change is often considered the maximum temperature change the cooling fluid should experience [45]. Moldex3D provides a cooling liquid efficiency for each cooling channel, applying the mean cooling efficiency to the 4°F max ΔT would provide the actual change.

4.4.1.5.2 Open and closed recirculation cooling systems

Open recirculation and closed recirculation cooling systems operate similarly with one main difference. Both systems recycle the cooling liquid, running it through a heat exchanger and to a storage tank to provide cooling fluid at the needed temperature. However, the open recirculation system re-cools the cooling fluid by means of cascading the cooling fluid against an air flow open to the atmosphere, while the closed recirculation system utilizes cooling equipment where the cooling fluid is never exposed to the atmosphere. Thus, the amount of cooling liquid in the storage tank is needed to be known along with the number of maintenance flushes per year the system undergoes to determine how much cooling fluid is needed on a per part basis. The open recirculation system also loses a portion of its cooling fluid to evaporation, and that portion needs to be replaced.

Determining the volume of cooling fluid required is done by converting the heat removed per part to refrigeration tons. If the flowrate is known, Q can be found via rearranging Equation 73. 1 refrigeration ton is equal to 3,516.85 J/s or 12,000 BTU/hr. For every 1 refrigeration ton required, 1 ton of cooling water is required as a rule of thumb [46]. These conversions allow us to determine the required amount of cooling liquid, which may then be multiplied by a safety factor and one plus the number of flushes to determine how much cooling liquid is used throughout the year. The open recirculation system requires the volume of cooling liquid evaporated, V_{evap}, to be accounted for and can be found via Equation 74.

$$V_{evap} = \dot{V}_{IM} \cdot \Delta T \cdot \frac{0.01}{10°\text{F}}$$

Equation 74

This is a rule of thumb applied throughout the industry [47]. This volume evaporated is added to the volume of cooling liquid required before the safety factor is applied.

For the scenarios presented in this chapter, water is used as the cooling liquid. Utility costs are highest when utilizing a once-through cooling system and near zero when utilizing the open or closed recirculation cooling systems. The once-through cooling system is utilized in the *Domestic vs Global* cost comparisons to add the water utility portion to the cost of the part.

4.5 MDLab test coupon engineering estimates TCM

This section shall present three manufacturing cost analyses for the manufacturing of the test coupon as shown in Figure 26 and discussed in *Section 4.2 MDLab test coupon*. The desired part production volume invested is 100,000 parts per year. The three analyses consist of: 1- *engineering estimates* based, 2- *pre-production* based, and 3- *production adjusted* based.

The *engineering estimates* based analysis utilizes common industry unloading and transfer times along with CAE extracted processing parameters for the additive molding and estimated preform layup time based on the shape factor. This is first used to test the tape management strategies and then to compare 5 additional manufacturing scenarios.

The *pre-production* based analysis utilizes times extracted from a demonstration run of the equipment installed at the MDLab. The same 5 additional manufacturing scenarios are investigated as well.

The *production adjusted* based analysis uses times extracted from the demonstration run, but adjusts any transfer robot movements from the current speed setting to the maximum speed setting. The same 5 additional manufacturing scenarios are investigated as well.

4.5.1 Physical thread inputs

The injection molding machine cost can be estimated from Equation 50 while the tooling costs for the injection mold, QTC jig, and transfer robot EOAT can be estimated utilizing Equation 52 through Equation 55. The cost of the QTC, robots, trimming system, and QC scanning system are unable to be estimated at this time and are based off of quotes received for this estimate. Costs for equipment and tooling for each process step is listed in Table 17.

Table 17. Equipment and tooling cost for the hybrid molding line based on *engineering estimates*.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trimming	6. Quality Control
Equipment Cost	$452,000	$75,000	$203,000	$0	$15,000	$265,000
Tool Cost	$20,200	$17,500	$60,000	$0	$1,500	$0
Operators	0.5	0	0.5	0	0	0

Each process step must be broken out into the steps that form the cycle time. There are some times that are commonly utilized by the industry such as:

- unloading time: 5 seconds [37, 39]
- transfer time: 5 seconds [22]

An additional time used in each process step for the hybrid molding line, loading, was set to 5 seconds. The layup table moves away from the layup head for loading of the bushings and unloading of the preform, both these were set at 3 seconds. Bushing loading was assumed to be 3 seconds as well. Not utilized, by a good time estimation to note is that a preheating oven is typically set to the same cycle time as what the part shall go into after the preheat. [37, 39]

Table 18 breaks out where the contributions to cycle times come from for each process step.

Table 18. Cycle time contribution to *engineering estimates* base case scenario for the hybrid molding line.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trimming	6. Quality Control
Estimated Times Contribution	14	15	12	50	30	20
Calculated/Imported Times Contribution	63.17		95			
Total Cycle Time	77.17	15	107	50	30	20

It should be noted that process step 4 is composed of one unload (5 sec), two transfers (10 sec) one load (5 sec), and trimming (30 sec) totaling 50 seconds. For the scenario where workers replace robots, the unloading, loading, and transfer times incur a 50% handicap to account for a worker's speed efficiency. Since the quality control scan involves multiple movements, this is given a 225% handicap. These handicaps are arbitrarily assigned and have not been tested nor confirmed.

4.5.2 Digital thread inputs

The digital thread inputs do not change for the engineering estimates. They may be found in *Section 4.4.1.2 TCM inputs: Performance Design processing parameter extraction*.

4.5.3 Operational decision: tape management

The first operational decision to be made beyond those governing any physical thread decisions, is whether or not to use a mechanical bond for the preforming process. Essentially, this decision shall dictate possible additional tape scrap that must be accounted for. If mechanical bonding is not utilized, each bobbin has startup waste and end of bobbin waste along with the layup waste. If a mechanical bond is utilized, there is initial startup waste, last bobbin waste, and layup waste, along with a part length layup waste if the part with the joint cannot be used. These scenarios are illustrated in Figure 37 and the resulting tape length to scrap verses part is given in Table 19.

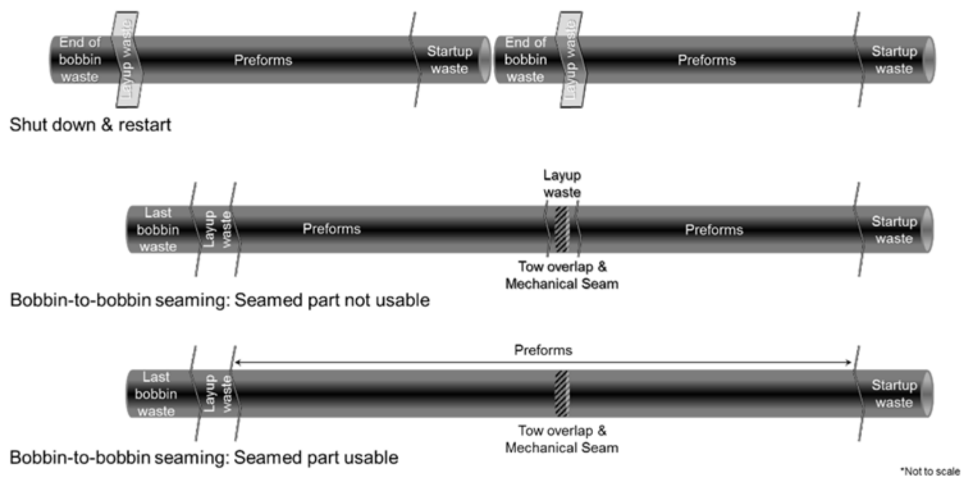

Figure 37. Sources of scrap waste across tape bobbin utilization schemes.

Table 19. Bobbin utilization schemes scrap amounts and bobbin change time estimates.

		Seam Used	Seam NOT Used	Bobbins NOT Seamed
Total Tow Length Required (m)	To Part	362,712	362,712	362,712
	To Scrap	62,928	63,151	65,105
Bobbin seam/change time per part (sec)		0.25	0.25	0.42
Lengthwise No. of parts made		117,321	117,382	117,921
Part length (m)		0.907		
Number of part desired		100,000		

This decision also affects the cycle time of the layup process, since bobbin changeovers have to halt the system. That changeover time has to be accounted for, and is disbursed across all the parts produced. When the bobbins are not mechanically bonded, additional time is necessary since the tape has to be threaded through the QTC equipment. Since this process step is not the rate bottleneck process step, it does not ultimately contribute much for this part, but larger, more complex parts may be a different story. The costs affected are labor and the TP tape material, and are given in Table 20.

Table 20. Affected cost drivers for bobbin utilization schemes.

	Seam Used	Seam NOT Used	Bobbins NOT Seamed
TP Tape ($/p)	0.1634	0.1635	0.1642
Direct Labor cost ($/p)	0.9949	0.9949	0.9977
Total Cost ($/p)	3.9448	3.9449	3.9486

Going forward, the operational decision of operating the preforming system with the bobbins mechanical bonded and that part being utilized shall be referred to as the *Base Case*.

4.5.4 Operational management: production scenarios for the *engineering estimates* case

Managers may want to investigate alternate manufacturing scenarios in order to determine what is best for their particular business. TCM provides the flexibility of having inputs that may be readily altered. Four different cases shall be presented to demonstrate this flexibility beyond the base case scenario: bottleneck increase in cycle time of 50%, QC rejects 10% of parts, and person transfer instead of robot.

Table 21. 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

The equipment and tooling costs remain the same as presented in Table 22. For Scenario 5 where workers replace robots, trimming is conducted by the worker transferring the part from the injection molding machine to the quality control station jig. The operator time is accounted for in the transfer operation and the jig cost is accounted for in the trimming operation. The cycle times for each process step are given in Table 23. A detailed breakout of the cycle times may be found in APPENDIX D.

Table 22. Equipment and tooling costs for the *engineering estimates* case for the hybrid molding line.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trimming	6. Quality Control
Scenarios 1, 3, & 4.						
Equipment Cost	$452,000	$75,000	$203,000	$0	$15,000	$265,000
Tool Cost	$20,200	$17,500	$60,000	$0	$1,500	$0
Operators	0.5	0	0.5	0	0	0
Scenario 2: 25% Increase in Equipment Cost (Tool Cost & Operators same as above)						
Equipment Cost	$565,000	$93,750	$253,750	$0	$18,750	$331,250
Scenario 5: Workers Replace Robots						
Equipment Cost	$452,000	$0	$203,000	$0	$0	$215,000
Tool Cost	$20,200	$0	$60,000	$0	$1,500	$0
Operators	0.5	1	0.5	1	0	1

Table 23. Cycle times for each processing step in the five scenarios for the *engineering estimates* case.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trim-ming	6. Quality Control
Scenario 1, 2, & 4 Cycle Time	77.17	15	107	50	30	20
3: 50% Increase of Injection Cycle Time	77.17	15	160.5	50	30	20
5: Workers Replace Robots Cycle Time	81.17	22.5	112	60	30	45
Sub-process Step Changes	Bushing load & unload	Unload, transfer, & load	Load & unload	Unload, transfer, & load		Physical move-ments

The cost segmentation for 100,000 parts per year production volume is illustrated in Figure 38. The bottleneck process through each scenario remains the injection molding process. At a 100,000 parts per year production rate, the additional time does not necessitate an additional line in any scenario. In scenario 2, the equipment cost increase only affects the machine amortization and the anticipated equipment maintenance. In scenario 3, the additional time in injection molding increases the electricity usage, labor required, and water and sewage usage. This is best captured in Figure 39, as the shift usage time jumps up vastly, from 1.72 shifts required with one manufacturing line required in the base case to 2.58 shifts with one manufacturing line required. In scenario 4, a 10% rejection rate means that the 10,000 extra parts must be made, resulting in slight increases for all cost drivers other than machine amortization and equipment maintenance. A table of values used to create Figure 38 is available in APPENDIX F.

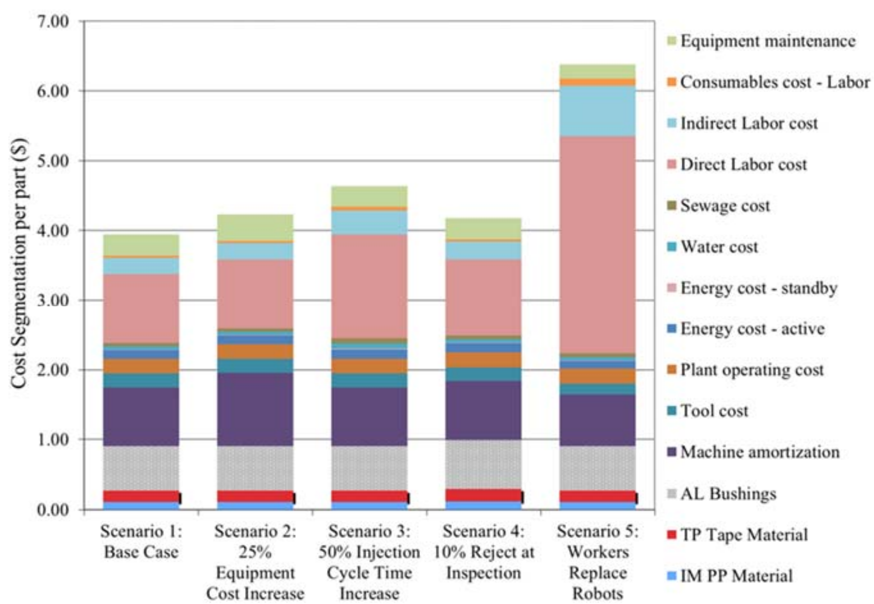

Figure 38. Cost segmentation for the *enginering estimates* base case and four alternate scenarios at 100,000 ppy.

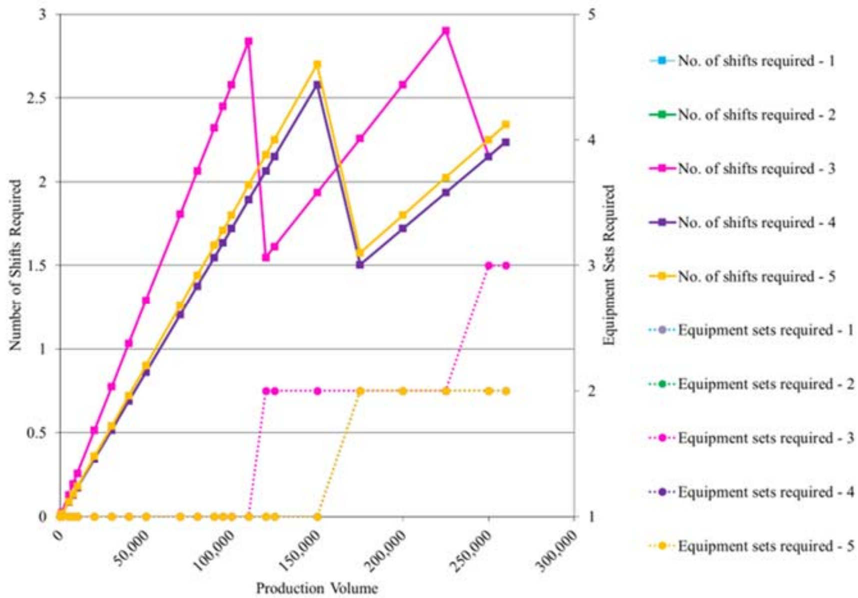

Figure 39. Equipment and shifts required for the five alternate scenarios at varying production volumes based on *engineering estimates* case.

One thing to note, with how the model is currently set up, no recycle is used and the parts are rejected at the quality control process at the end of manufacturing. Thus, in scenario 4, material that is made into a part that is rejected simply becomes scrap. In reality, with the aluminum bushings being ~5 times more expensive than any other material in the part, and with the benefit that the bushings are completely reusable, it would benefit the bottom line to recycle these components. The tow and PP could be shredded and reused in the additive molding process step. Material values for each scenario are given in Table 24

Table 24. Material value earmarked to part or scrap. Values are $/part.

		Scenario 1: Base Case	Scenario 2: 25% Equipment Cost Increase	Scenario 3: 50% Injection Cycle Time Increase	Scenario 4: 10% Reject at Inspection	Scenario 5: Workers Replace Robots
TP Tape	To Part	0.14	0.14	0.14	0.14	0.14
	To Scrap	0.02	0.02	0.02	0.03	0.02
PP	To Part	0.09	0.09	0.09	0.09	0.09
	To Scrap	0.012	0.012	0.012	0.023	0.012
AL Bushings	To Part	0.63	0.63	0.63	0.63	0.63
	To Scrap	0.00	0.00	0.00	0.06	0.00

4.5.5 Operational management: production scenarios for the *pre-production* case

Engineering estimates are referred to as estimates as they present the "best guess" based on previous knowledge, anticipated equipment, and operating procedures. The *pre-production* cycle times, equipment costs, and tooling costs varied from the *engineering estimates* case, primarily in the cost of the injection molding machine. These costs are shown in Table 25. Table 26 breaks out the cycle times for each of the 5 scenarios as found in Table 21. Cycle times were determined based on a trail run conducted on June 26th, 2019. This trial run does not represent the actual operating times that would be experienced at the full production rate, as much of the automation was conducted at significantly reduced speeds and the order of operations was not optimized. The process step times are broken out in APPENDIX E.

Table 25. Equipment and tooling costs for the *pre-production* case for the hybrid molding line.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trimming	6. Quality Control
Scenarios 1-4						
Equipment Cost	$451,690	$75,000	$505,500	$0	$15,000	$265,000
Tool Cost	$20,000	$17,500	$60,000	$0	$1,500	$0
Scenario 2: 25% Increase in Equipment Cost (Tool Cost & Operators same as above)						
Equipment Cost	$564,613	$93,750	$631,875	$0	$18,750	$331,250
Scenario 5: Workers Replace Robots						
Equipment Cost	$451,690	$0	$505,500	$0	$0	$215,000
Tool Cost	$20,000	$0	$60,000	$0	$1,500	$0
Operators	0.5	1	0.5	1	0	1

Table 26. Cycle times for each processing step in the five scenarios for the *pre-production* case.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trim-ming	6. Quality Control
Scenario 1, 2, & 4 Cycle Time	138.25	68	135	90	29	20
3: 50% Increase of Injection Cycle Time	138.25	68	202.5	90	29	20
5: Workers Replace Robots Cycle Time	156.75	102	153	120.5	29	45
Sub-process Step Changes	Bushing load & unload	Unload, transfer, & load	Load & unload	Unload, transfer, & load		Physical move-ments

For Scenario 5 where workers replace robots, trimming is conducted by the worker transferring the part from the injection molding machine to the quality control station jig. The operator time is accounted for in the transfer operation and the jig cost is accounted for in the trimming operation.

One main point not captured in these numbers is that the injection molding cycle time, the only time extracted from CAE tools, was accurate. The opening, fill, pack, and cooling times were identical in both the *engineering estimates* and *pre-production* cases. The discrepancy seen in the cycle times came in the estimated loading, closing, and unloading times. Besides the closing time, the loading and unloading was conducted via the transfer robot that was operating at reduced speeds due to the trials.

The cost segmentation and shifts required and equipment sets required are shown in Figure 40 and Figure 41, respectively. With the slow movements and delay times seen in this case, the injection molding process step is not the bottleneck. Instead, it is the transfer robot followed by the preforming and bushing insert. These increased times lead to increased utilities usage across the board and increased labor costs. The increased cycle times shall lead to the purchase of an additional line sooner, since each line is capable of producing less per shift. Optimizing the process steps time management shall go a long way to reducing the cost per part. This is partially completed in the following section. A table of values used to create Figure 40 is available in APPENDIX F.

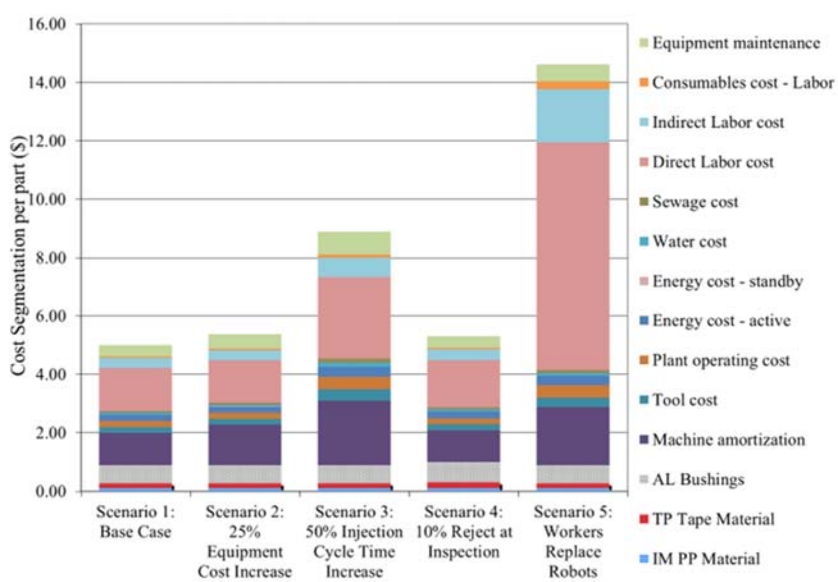

Figure 40. Cost segmentation for the *pre-production* base case and four alternate scenarios at 100,000 ppy.

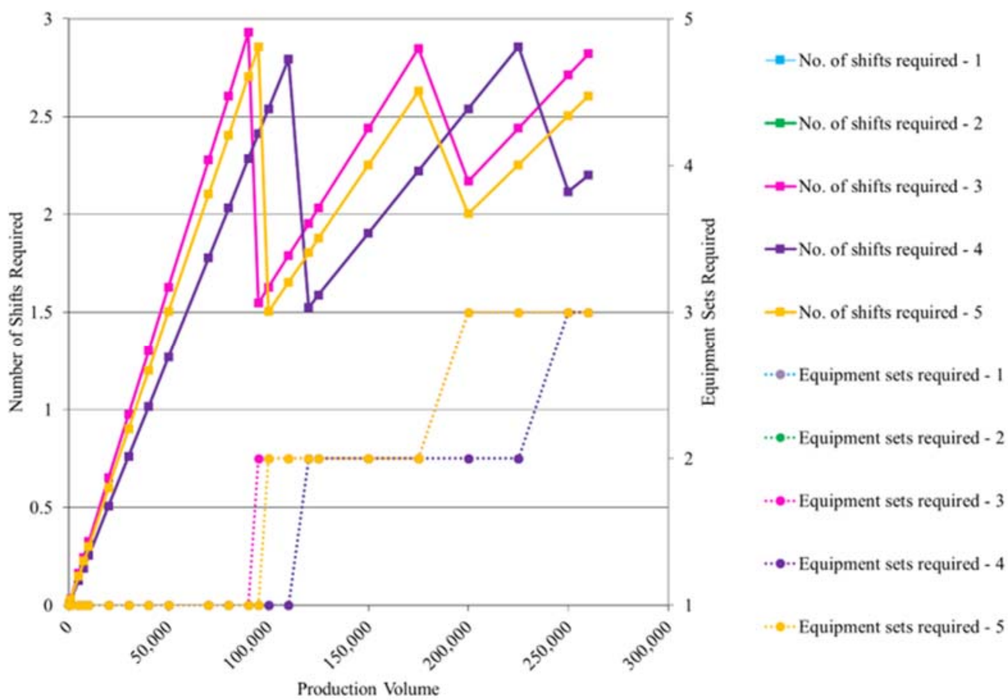

Figure 41. Equipment and shifts required for the five scenarios at varying production volumes based on *pre-production* case.

4.5.6 Operational management: production scenarios for the *production adjusted* case

Knowing that the *pre-production* case was not an optimized manufacturing representation, we can adjust portions to better represent reality in an actual manufacturing plant. The *production adjusted* case brings all transfer robot movements to their maximum speed setting. In the *pre-production* case, the fastest movement speed was 20% of the maximum. Adjusting all speeds evenly so the fastest speed is now set to 100% of the maximum and removing portions of the processing times that could be conducted during concurrent operations, such as the layup head reset, the adjusted cycle times are shown in Table 27 for the five scenarios as found in Table 21. Equipment costs, and tooling costs remained the same as the *pre-production* case and are shown in Table 25. Table 26. The process step times are broken out in APPENDIX E.

Table 27. Cycle times for each processing step in the five scenarios for the *production adjusted* case.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trim-ming	6. Quality Control
Scenario 1, 2, & 4 Cycle Time	92.59	14.3	107.4	44.7	29	20
3: 50% Increase of Injection Cycle Time	92.59	14.3	161.1	44.7	29	20
5: Workers Replace Robots Cycle Time	97.77	21.5	110.8	67.1	29	45
Sub-process Step Changes	Bushing load & unload	Unload, transfer, & load	Load & unload	Unload, transfer, & load		Physical move-ments

Every process step besides trimming and quality control was effected by the transfer robot speed adjustment. This effected loading times, unloading times, and transfer times. All times that are involved throughout each process step.

The cost segmentation and shifts required and equipment sets required are shown in Figure 42 and Figure 43 respectively. The cost trends line up well with the *engineering* estimates case with the adjusted cycle times. The injection molding process is once again the bottleneck. This shows how time management and proper sequencing is vital to minimizing the manufacturing time. A table of values used to create Figure 42 is available in APPENDIX F.

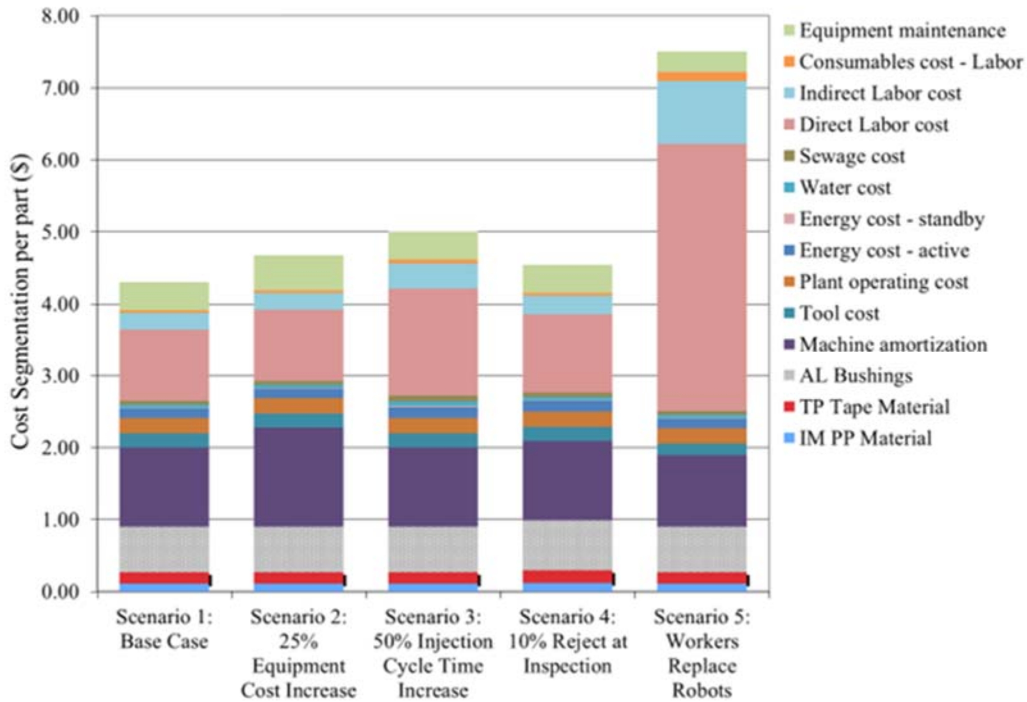

Figure 42. Cost segmentation for the *production adjusted* base case and four alternate scenarios at 100,000 ppy.

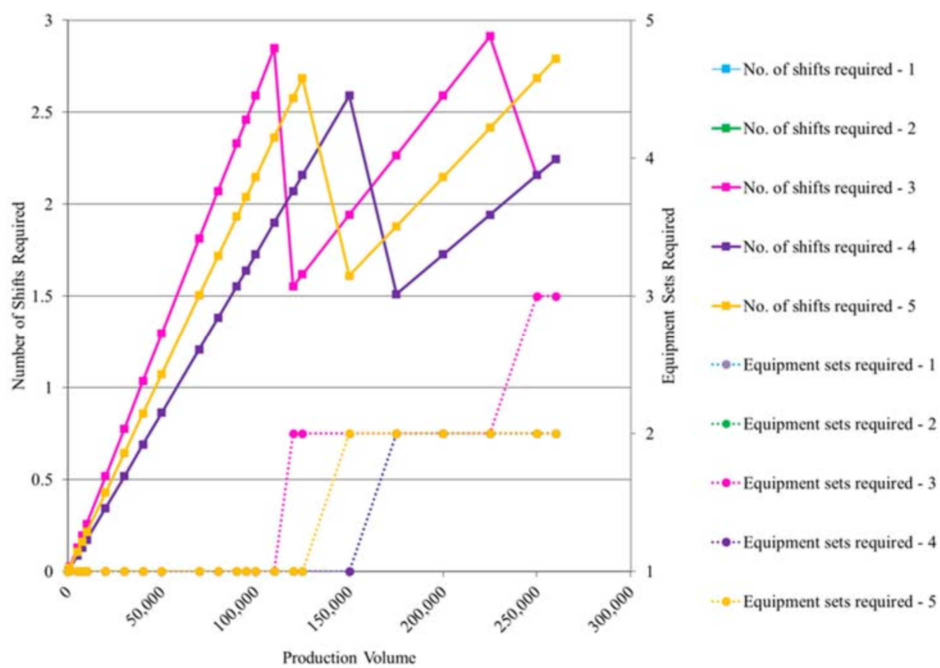

Figure 43. Equipment and shifts required for the five scenarios at varying production volumes based on *production adjusted* case.

4.5.7 Operational management: three case comparison

It is clear that the *pre-production* case is the worst option in terms of operations procedures. Cycle times remained unchanged in *scenarios 1, 2*, and *4*, resulting in a 60.5% difference in manufacturing residence time between the *engineering estimates* case and the *pre-production* case. When looking at *scenario 3: 50% injection cycle time increase*, was a difference of 55.3%, while *scenario 5: workers replace robots* was a difference of 73.9%.

The *engineering estimates* case and the *production adjusted* case came much closer to being representative of the process. Cycle times remained unchanged in *scenarios 1, 2*, and *4*, resulting in a 2.9% difference in manufacturing residence time between the *engineering estimates* case and the *pre-production* case. When looking at *scenario 3: 50% injection cycle time increase*, was a difference of 2.6%, while *scenario 5: workers replace robots* was a difference of 5.8%.

The cycle time differences are given in Table 28 and details of each cycle time for each process step may be found in APPENDIX D and APPENDIX E. A negative time difference represents the *engineering estimates* case being slower than the compared-to case. A positive time difference represents the *engineering estimates* case being faster that the compared-to case.

Table 28. Process step cycle time difference between different cases and scenarios.

Process Step	1. Preforming and Bushing Insert	2. Transfer to Injection Molding	3. Injection Molding	4. Transfer to Trim & QC	5. Trimming	6. Quality Control	Total Difference	Total Percent Difference
Scenarios 1, 2, & 4 Cycle Time								
EE vs *Pre-production*	-61.1	-53.0	-28.0	-40.0	1.0	0.0	-181.1	60.5%
EE vs *Production adjusted*	-15.4	0.7	-0.4	5.3	1.0	0.0	-8.8	2.9%
3: 50% Increase of Injection Cycle Time								
EE vs *Pre-production*	-61.1	-53.0	-42.0	-40.0	1.0	0.0	-195.1	55.3%
EE vs *Production adjusted*	-15.4	0.7	-0.6	5.3	1.0	0.0	-9.0	2.6%
5: Workers Replace Robots Cycle Time								
EE vs *Pre-production*	-75.6	-79.5	-41.0	-60.5	1.0	0.0	-255.6	72.9%
EE vs *Production adjusted*	-16.6	1.0	1.2	-7.1	1.0	0.0	-20.5	5.8%

Cost per part for the three cases and across the five scenarios is broken out in Table 29. Additionally, the manufacturing cost for an adjusted *engineering estimates* case has been included. In this case, the injection molding machine cost has been altered to match that of the *pre-production* case. This new case is referred to as *engineering estimates-IM adjusted*. The most variation is seen in scenario 5: workers replace robots. Within this case, the additional time and labor costs greatly affect the manufacturing costs. This is due to the high variations of 72.9% for the cycle times for the *engineering estimates* vs *pre-production* cases and 5.8% for the cycle times for the *engineering estimates* vs *production adjusted* cases as detailed in Table 28.

Table 29. Manufacturing cost per part for the five scenarios across the different cases.

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
Pre-production	$5.00	$5.37	$8.89	$5.30	$14.61
Production adjusted	$4.31	$4.68	$5.01	$4.55	$7.51
Engineering Estimates	$3.94	$4.23	$4.64	$4.18	$6.38
Engineering Estimates-IM actual	$4.29	$4.66	$4.99	$4.53	$6.73

4.5.8 Composite to aluminum test coupon cost comparison

Composites are often adopted due to their weight reduction capabilities. The manufactured test coupon described in *Section 4.2* weighs 0.43 pounds. A true manufacturing cost for an aluminum test coupon version is not available, but can be calculated utilizing *Joshi et al.'s* cost factor estimate method detailed in *Section 4.4.1.2* Equation 52 through Equation 55 and utilizing the following cost conversion equation for the new part cost, C_B, Equation 75.

$$C_B = C_A \cdot \left(\frac{V_B}{V_A}\right)^{CF_{estimate,B}/CF_{estimate,A}}$$

Equation 75

Where C_B is the cost of the old part, V_B is the volume of the new part, V_A the volume of the old part, $CF_{estimate,i}$ is the cost factor estimate from Equation 52. Equation 75 is an adaptation of the equipment purchase cost relationship to capacity attribute from *Turton et al.* [48] The old part, a bushing in this case, cost $0.31 per bushing and was made of aluminum. It is important to note that a composite performance equivalent test coupon in aluminum is going to be dimensionally different, but is not for this analysis. The inputs for calculating the cost factor estimate for the bushing and the aluminum test coupon are given in Table 30 and Table 31, respectively. This resulted in an estimated manufacturing cost of $4.72 per aluminum test coupon with a weight of 0.8 pounds.

Table 30. Inputs for the cost factor estimate equation for the aluminum bushing.

Part Volume	Part Surface Area	No. of Cores	Core Volume	Min Thickness	Max Thickness	Total Length	Total Width	Total Height	Draw Distance
12,160	4,143	1	12,160	14	14	31.75	31.75	14	14

Table 31. Inputs for the cost factor estimate equation for the aluminum test coupon.

Part Volume	Part Surface Area	No. of Cores	Core Volume	Min Thickness	Max Thickness	Total Length	Total Width	Total Height	Draw Distance
144,790	40,440	1	144,790	2	20	313	47	20	20

The composite test coupon reduces the weight by 0.37 pounds, or 46.25%. From the *engineering estimates* base case, this weight savings comes at a price of -$0.29 per pound saved, but the low automation case comes at a price of $4.30 per pound saved. The aluminum test coupon would require a minimum of 10 CNC machining operations to achieve the approximate shape of the composite test coupon. Additional machining operations would be necessary to achieve similar surface finish smoothness and lettering as found on the composite test coupon, which would further increase its manufacturing cost.

4.6 Conclusions

Extracting processing parameters from CAE tools enables a cost estimator to enhance the accuracy of the manufacturing cost estimates is a viable means to reducing the reliance upon engineering estimates. The extracted cycle time components for the injection molding process step were the same as the real processing conditions. Variations came in the cycle time components that are not within MoldEx3D, such as loading and unloading times. These times were dictated by the transfer robot, which, in actual operation, was extremely slow due to the trial manner of the operation. To best estimate near actual layup time, an adjustment factor of 3.37 must be applied to the shape complexity to account for acceleration and deceleration of the layup table compared to the available layup speeds.

The base case scenario would deliver test coupon parts at $5.00, $4.31 and $3.94 for the *pre-production*, *production adjusted* and *engineering estimates* cases, respectively. The cost discrepancy comes from the cycle time components estimated or calculated compared to the actual processing times and the "optimized" processing times as found in the *pre-production* adjusted case. The residence time through the processes for each case were 480 seconds, 308 seconds, and 299 seconds for the base case of the *pre-production*, *production adjusted* and *engineering estimates* cases, respectively. The estimated cost of the injection molding machine compared to the *pre-production* cost influenced the manufacturing cost. Adjusting the equipment costs to reflect the *pre-production* case brought the estimate within 1.2% across scenarios 1-5. Automating the process is a must, as the manufacturing cost increased anywhere from 55% to 192% when comparing the base case costs across all cases to the low automation transfer scenario. Overall, the *engineering estimates* case showed that the accepted industry and literature times estimates and that the CAE extracted processing parameters are representative of actual processing steps.

Compared to a similar shaped test coupon made fully of aluminum, the composite test coupon reduced the weight by 0.37 pounds, or 46.25%, from 0.8lbs to 0.43lbs. From the *engineering estimates* base case, this weight savings comes at a price of $10.65 per pound saved. Without having a target cost, determining if hybrid molding would be a viable method for producing a lighter part is not possible at this time.

4.7 Summary

This chapter expanded on the test coupon cost model presented in Chapter 2 to look into in-house manufacturing management. Simulation tools utilized to simulate the hybrid molding process had processing parameters extracted from them that provided precise contributions to cycle times and other aspects of the technical cost model, addressing the research question directly on how these tools can be integrated. Models were created to simulate the layup of TP tow from a specific layup process where TP tape is consolidated and laid up in one step. It was found that beyond a part shape complexity factor, a speed correction factor had to be accounted for to capture the ancillary processes required during layup. Cost estimation tools were presented for some aspects of the manufacturing process, such as end of arm tooling costs, injection molding equipment costs, and mold costs.

The completed model allowed for various estimation cases to be explored: engineering estimates, pre-production, and production adjusted/optimized. The engineering estimates case utilized the cost estimation tools costs for equipment and tooling and cycle times imported from the simulation tools to give a pre-installation cost estimate. The pre-production case explored a start-up production run where the times of various process steps were not running at full speeds and the process steps were not fully optimized. The production adjusted/optimized case adjusted the process steps from the pre-production case to run at full speed and removed any process steps that could be conducted simultaneously. Further management cases were investigated that explored raw material management, high automation cases, and low automation cases.

5. TECHNICAL COST MODELING FOR GLOBAL MANUFACTURING MANAGEMENT

Selecting a location for a new manufacturing line comes with a high level of risk. Locating the factors that influence the manufacturing cost at various locations is extremely time consuming, yet necessary to aid in the selection process. These factors include, but are not limited to; utilities, wages, and rent costs. Unfortunately, there is no single consolidated publicly available database that can be accessed to pull these factors from. However, it is possible to assemble a database of current cost parameters to use for comparison analysis of locations, both domestic and global, from publically available datasets if one knows where to look and how to assemble the data properly.

The manufacturing cost is composed of the costs directly related to manufacturing operations and does not include business overhead or environment costs which are highly business specific. The manufacturing cost is often broken down into costs that are treated as fixed or variable costs by accountants. Fixed costs often include equipment, maintenance, construction and installation, and plant operations costs such as rent and insurance. Variable costs often include labor, utilities, tooling, and materials. However, when comparing locations, costs become either location driven or part driven. This breakdown of the manufacturing cost is detailed in Figure 44.

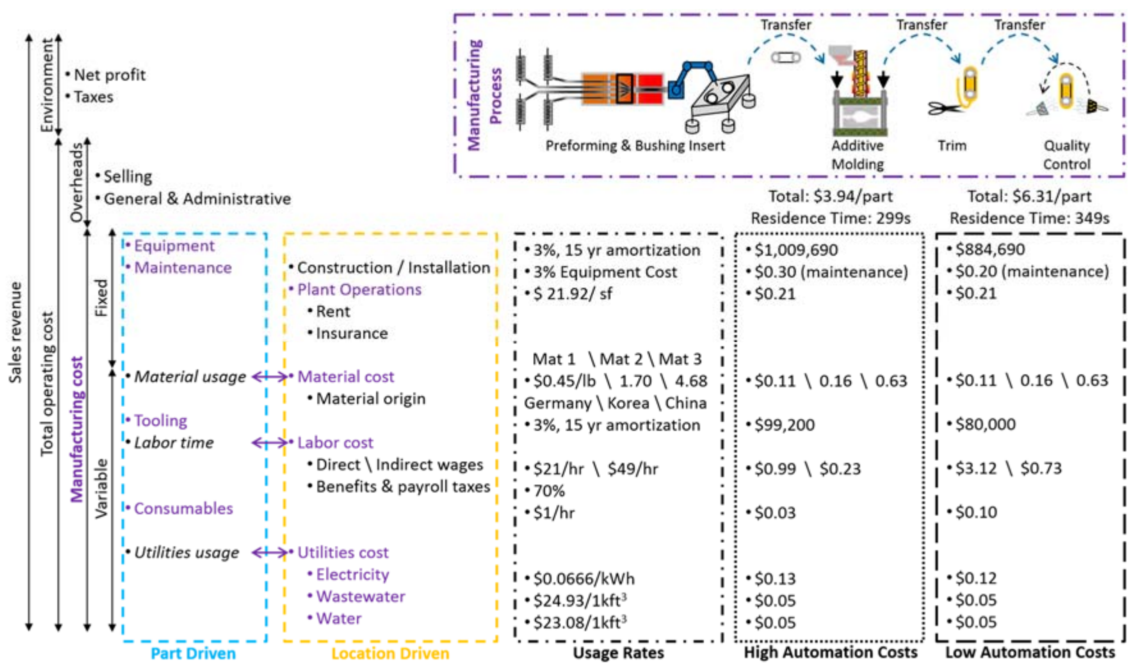

Figure 44. Manufacturing cost breakout for a highly automated and low-automated hybrid molding manufacturing scenario.

The values utilized for this comparison are based on the *engineering estimates* base case for a hybrid molding manufacturing line that creates a thermoplastic tow based structural preform around two aluminum bushings that is then additive molded to create a test coupon. The base case estimate is based on a production rate of 100,000 parts per year.

This work shall describe a method to gather the cost rates that vary by location through publically available datasets for the United States. Furthermore, this work shall describe how to use global cost indexes to compare the cost to manufacture in the US to other countries. This shall enable conducting manufacturing cost estimates across a variety of locations with reduced effort and time compared to locating individual rates for multiple locations.

5.1 Converting costs and base case

To compare manufacturing costs across a variety of locations, a base case is required as a starting point. For this work, the base case values are based on manufacturing a composite test coupon in West Lafayette, Indiana U.S. through a hybrid molding process. The test coupon is composed of two aluminum bushings procured from a Chinese manufacturer, a thermoplastic tow preform structure procured from a Korean manufacturer, and polypropylene overmolding material procured from a German manufacturer. This process is detailed in *Section 4.5 MDLab test coupon engineering estimates TCM.* The usage rates and the cost per part for the various manufacturing costs are broken out in Figure 44.

Two variations of the base case shall be investigated. The first case utilizes a high automation manufacturing line, meaning that the transfers between processes are completed via robot. Also, the trimming operation and quality control scanning is completed via robot. The second case utilizes a low automation manufacturing line, meaning that the transfers between process, the trimming operation, and the quality control scanning is completed via person. These process steps are shown in Figure 44.

Once the base case costs have been established, the comparative analysis can be conducted. A cost rate is needed for each manufacturing cost for each location desired for the comparison. Assembling these cost rates shall be discussed in detail in the following sections. The new location manufacturing cost, C_{NL}, is found via Equation 76 where C_{BL} is the base location cost and CR_{NL} and CR_{BL} are the new and base location cost rates for the cost being converted, respectively.

$$C_{NL} = C_{BL} \cdot \frac{CR_{NL}}{CR_{BL}}$$

Equation 76

5.2 Domestic Standard Federal Regions

Publicly available datasets, especially pertaining to utility related rates, are often grouped into some form of regional state groupings. Four different regional state groupings were found to be used throughout the datasets utilized throughout this study. These regional state groupings are: 1) Standard Federal (SF) Regions, 2) Energy Information Administration (EIA) Regions, 3) Department of Energy (DOE) Regions, and 4) Census Bureau (Census) Regions. Comparison of these regional state groupings are illustrated in Figure 45.

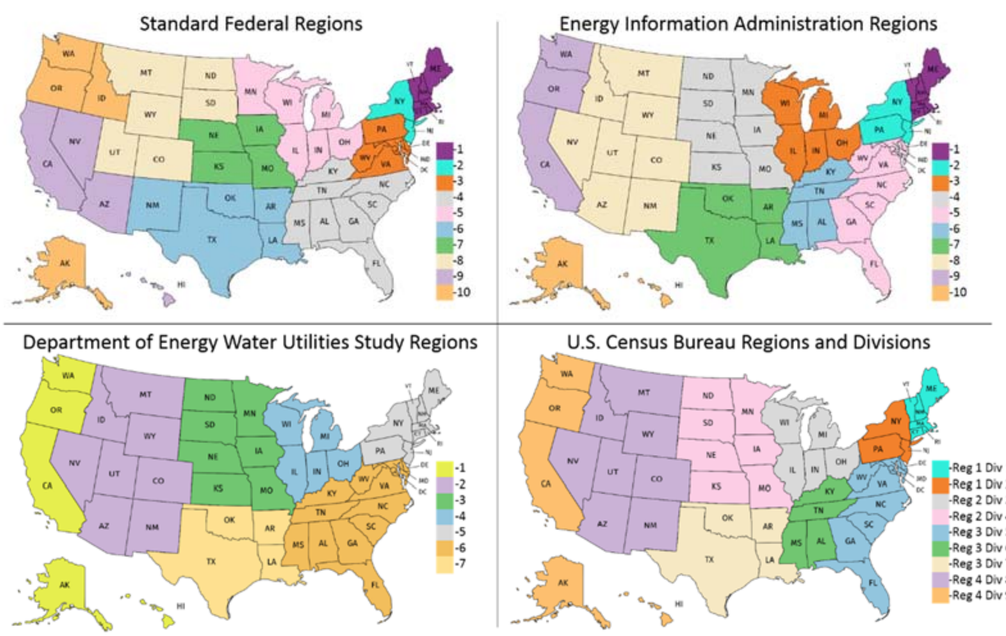

Figure 45. The four domestic regional state groupings employed throughout the government and business datasets utilized within this investigation.

The SF Regions are defined by the Office of Management and Budget. They are comprised of 10 regions and are the only regional state grouping that includes the four U.S. territories. Puerto Rico (PR) and the U.S. Virgin Islands (VI) are grouped into SF Region 2. Guam and American Samoa (AS) are grouped into SF Region 9 [49].

The EIA Regions are defined by the U.S. Energy Information Administration and are comprised of 10 regions [50]. Though not included by the EIA, for comparative purposes PR and the VI have been included in EIA Region 2 to align with their similar placement in the SF Regions while Guam and AS have been included in EIA region 10 to align with their similar remoteness to Hawaii.

The DOE Regions are defined by U.S. Department of Energy and are comprised of 7 regions [51]. Though not included by the DOE, for comparative purposes PR and the VI have been included in DOE Region 5 while Guam and AS have been included in DOE Region 1.

The Census regions are defined by the U.S. Census Bureau and are comprised of four primary regions that are further broken down into a total of nine divisions [52]. Though not included by the DOE, for comparative purposes PR and the VI have been included in Census Division 2 while Guam and AS have been included in Census Division 9.

Though similar, each regional state grouping varies slightly by what states are included in which regions and how many regions there are altogether. These groupings are important because they shall alter the central tendency of the consolidated data depending on which regional state grouping is followed. Which regional state grouping is utilized for each rate determination shall be discussed within each rate determination section.

5.3 Domestic wage rates

The total cost of labor to an employer is comprised of three components; the wages the worker receives, employer provided benefits, and payroll taxes. To accurately contrast worker pay amongst direct and indirect laborers, two things must be known for different locations: the wage percentage of employer cost for employee compensation and the going rate for the job that is being performed.

The Bureau of Labor Statistics (BLS), a part of the Department of Labor, tracks both of these on an annual basis. The BLS has 23 major occupational groups that they track for both metropolitan and non-metropolitan areas for each state. Each major occupational group is broken into minor occupational groups that further group the 967 detailed occupations the BLS tracks. When a state does not report the detailed occupation rate, the minor occupational group rate was used. America Samoa is the only territory that BLS does not track and their labor rates were then determined by the mean of the other states within Census Region 9 [53].

Though the BLS provides the wage percentage of employer cost for employee compensation, it does not provide it for each state as it does for the employee compensation itself. Instead, they break this information down via Census Regions and Divisions [54]. The total cost to the employer for labor on an hourly basis, C_{Labor}, can now be found via Equation 77.

$$C_{Labor} = \frac{C_{IDL} + C_{DL}}{W}$$

Equation 77

Where C_{IDL} is the indirect labor wage, C_{DL} is the direct labor wage, both on an hourly basis, and W is the wage percentage of employer costs.

For the hybrid manufacturing line used for this study, the direct labor came from detailed occupation *51-4011 Computer-controlled machine tool operators*. This comes from the minor occupational group *51-4000 Metal Workers and Plastic Workers* and the major occupational group *51-0000 Production Occupations*. The indirect labor came from the detailed occupational group *11-3051 Industrial Production Managers*, minor occupational group *11-3000 Operations Specialties Managers*, and major occupational group *11-0000 Management Occupations*. The direct and indirect occupations chosen for this study may be seen in Table 32 for a sampling of states. Also noted within the table is the state's Census Region and Division and the wage percentage of employer costs for that state [55]. Direct and indirect labor costs along with the wage percentage of total compensation are compared out via heat maps in Figure 46. Complete data for each state is provided in APPENDIX G.

Table 32. Bureau of Labor Statistics composite manufacturing direct and indirect mean labor rates and the wage percentage of total employer costs for select states for May 2018.

State	Census Region / Division	Wage Percentage of Employer Costs (%)	Indirect Labor Wage: 11-3051 Industrial Production Managers ($/hr)	Direct Labor Wage: 51-4011 Computer-controlled Machine Tool Operators, Metal and Plastic ($/hr)
Alaska – AK	4 / 9	70.1	58.55	22.49[1]
California – CA	4 / 9	70.1	59.19	20.64
Georgia – GA	3 / 5	71.0	50.06	18.08
Illinois – IL	2 / 3	69.2	50.26	19.02
Kansas – KS	2 / 4	69.6	47.73	20.51
Massachusetts – MA	1 / 1	68.4	60.88	24.59
New Mexico – NM	4 / 8	71.4	52.48	17.48
Pennsylvania – PA	1 / 2	68.4	53.61	19.17
Tennessee – TN	3 / 6	70.2	48.88	18.82
Texas – TX	3 / 7	72.2	59.04	19.98
National Avg. – U.S.		70.0	54.51	20.17

Note: [1]Wage rate based on 51-4000 Metal Workers and Plastic Workers since 51-4011 not available for that state.

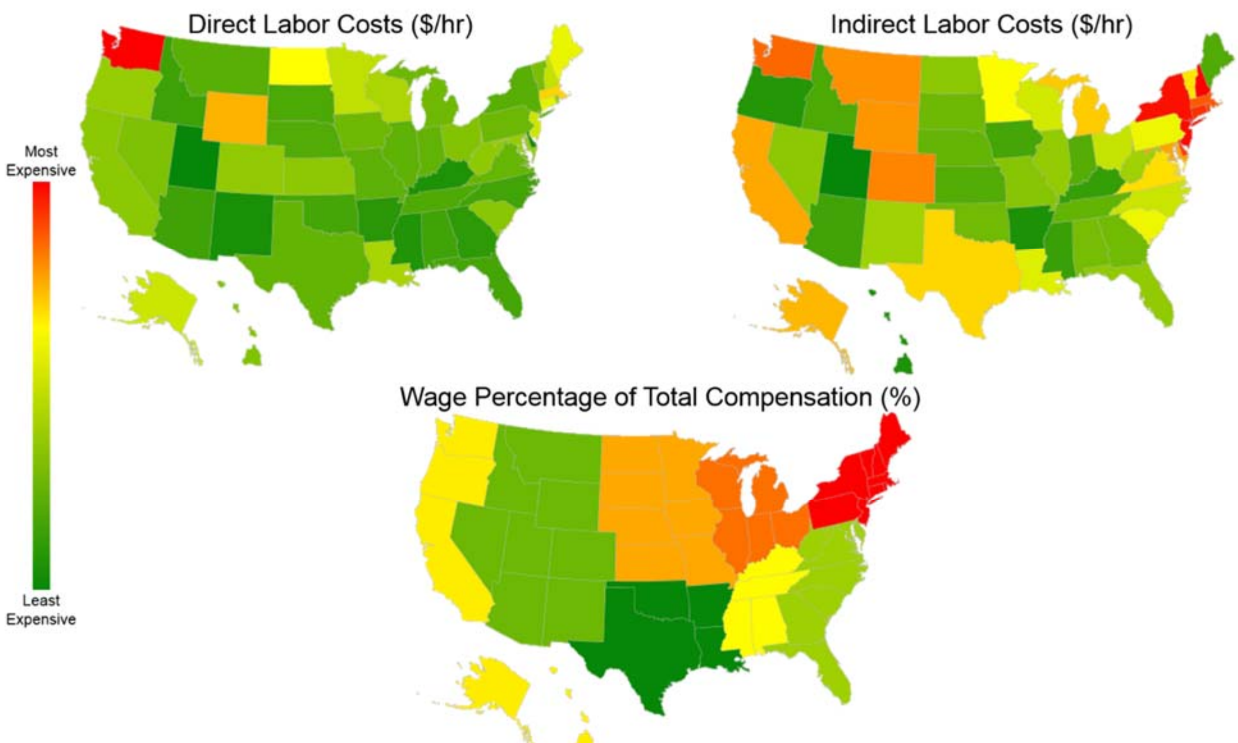

Figure 46. Labor cost component heat maps for the U.S.

It is important to note that payroll taxes do vary region to region, and further still, vary state by state. Though not broken out by individual state, these variations do get captured in the wage percentage of employer costs. These costs are typically less than 1% of the employer costs, varying 0.4% from lowest to highest regions, so obtaining them for each state would not provide a substantial benefit to the analysis. Also, these wage rates would be applicable to full-time employees. It would be expected that part-time employees would receive less employer provided benefits, and thus their overall employer costs would be reduced. Part-time employees are not taken into account in this work.

5.4 Domestic utilities - Electricity

The U.S. Energy Information Administration (EIA) tracks electricity costs by end-use sector. Monthly updates are posted to EIA's *Average price of electricity to ultimate customers by end-use sector* and are broken out into residential, commercial, industrial, transportation, and all sectors. Most manufacturing facilities are located in industrial areas, thus the industrial sector electrical rates were chosen for this analysis. Rates for select states are listed in Table 33 [50]. Complete data for each state is provided in APPENDIX G and compared via heat map in Figure 47.

Table 33. U.S. Energy Information Administration industrial sector electricity rates for select states. Rates as of January 2019.

State	AK	CA	GA	IL	KS	MA	NM	PA	TN	TX	U.S.
Industrial Electricity Rate (¢/kWh)	16.91	11.43	5.37	6.7	7.22	14.74	5.21	6.8	6.04	5.25	6.58

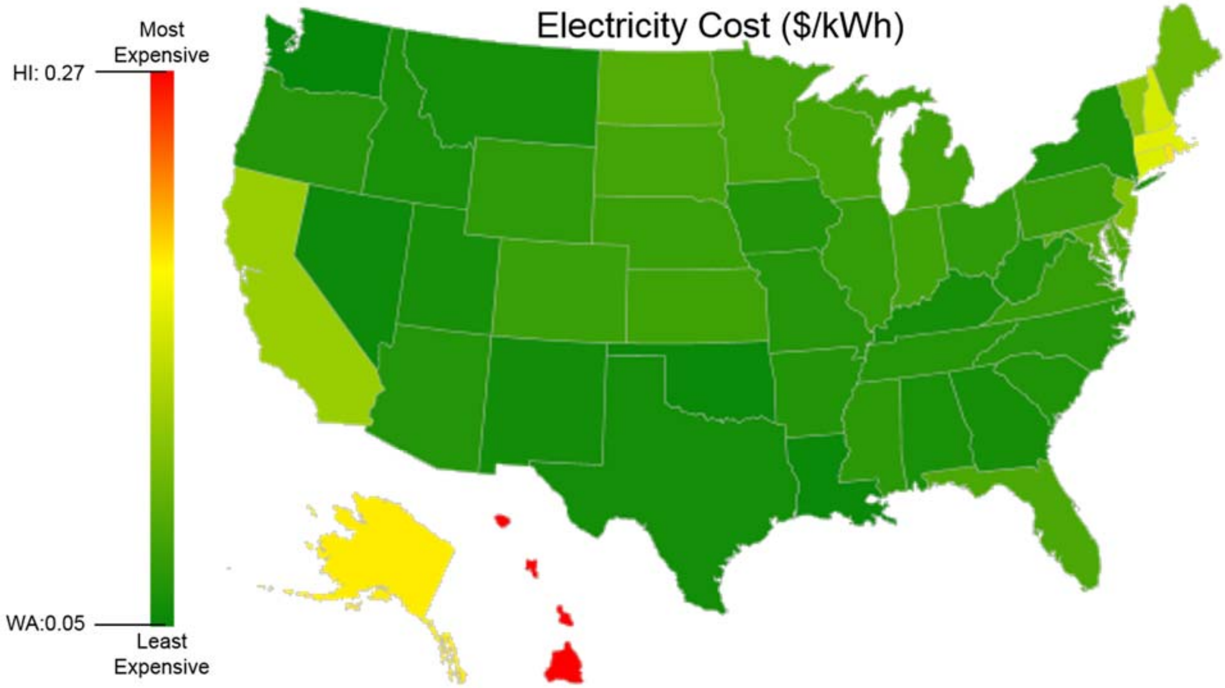

Figure 47. Industrial electricity rate comparison of the U.S.

EIA does not track the U.S. Territories, however. The Office of Energy Efficiency & Renewable Energy (OEERE) provides "Island Energy Snapshots" that list the industrial or commercial electrical rates. At least one of these values is always listed, along with the residential rate. If provided, the industrial rate was utilized for this analysis, if not, then the commercial rate was utilized. The latest OEERE rate update was in 2015 [56]. Fortunately, the EIA publishes the average price of electricity to ultimate customers by end-use sectors on a year-to-year basis. These values can be used to calculate the yearly change in industrial electrical rates and apply them to the U.S. Territories information as needed. See Table 34 for yearly rate changes from 2015 to 2018 [57].

Table 34. Converting Office of Energy & Renewable Energy "Island Energy Snapshots" of U.S. Territories via U.S. Energy Information Administration annual average price of electricity year-to-year changes.

U.S. Territory	2015 Industrial Electricity Rate (¢/kWh)	EIA Rate Change by year			Adjusted 2018 Industrial Electricity Rate (¢/kWh)
		2015→2016	2016→2017	2017→2018	
Guam	29.0	-2.17%	1.78%	0.73%	29.08
Puerto Rico	24.0				24.07
U.S. Virgin Islands	51.7				51.85
American Samoa	26.0				26.08

5.5 Domestic utilities - Water & wastewater

Many manufacturing operations require water in some aspect of their operation, be it for cooling or machining, and subsequently, sewage is required. The hybrid molding case studied here utilizes water for cooling in a once-through cooling system. Unfortunately, a comprehensive, publically available list of water and sewage rates for each state was not found.

One great resource for water and wastewater rates is the Environmental Finance Center, a part of the University of North Carolina (UNC). UNC maintains utility "dashboards" that track water and wastewater rates for seven states: Connecticut, Alabama, Arizona, Georgia, North Carolina, New Hampshire, and Wisconsin. The dashboards provide a state median value, but do not provide the mean. Given UNC's sample size encompasses all providers within a state, the mean would be a better representation of the state's rates than the median value [58]. Gathering all the providers' rates to determine the median becomes time intensive. Ultimately, UNC's values are current, but are too limited in their scope of states that they track, that another path to water and wastewater rates is needed. The closest assemblage of rates for a large enough sample size are from surveys of various cities.

The DOE's Office of Energy Efficiency & Renewable Energy previously published annual water and wastewater rate survey for select cities, but stopped in 2017 with their rates as of 2016 [51]. There are various private industry rate surveys that exist, but the most current versions are not freely accessible. However, old versions of these rate surveys may be found, such as Black & Veatch's (B&V) 2012/2013 rate survey for the 50 largest U.S. cities [59].

The DOE and B&V surveys provide values from a diverse set of states, but need to be updated to current year values, as the cost for water and wastewater is not stagnant. Fortunately, the National Association of Clean Water Agencies (NACWA) tracks annual wastewater rates in their annual "*Cost of Clean Water Index*." They also project wastewater cost changes out through the next five years, which can allow for flexibility in producing cost estimates in future years. The NACWA reports their information by Standard Federal Regions and also provide current average wastewater rates for each region [60].

Assuming the water rate is directly relatable to the wastewater rate, means a conversion rate can be determined for each state from the DOE and B&V rate surveys. To accomplish this, both rate surveys were first brought to a consistent time point via yearly rate changes tracked by NACWA and converted to the same rate basis of $/1,000 gallons. The conversion rate, $R_{convert}$, was then found for each city via Equation 78.

$$R_{convert} = \frac{C_{water}}{C_{sewage}}$$

Equation 78

Where C_{water} and C_{sewage} are the cost of water and sewage, respectively. The conversion rates were then averaged by each regional state grouping to determine regional conversion rates. The combined water and wastewater rates calculated from each regional conversion rate was compared to the combined rates in the surveys, with the conversion rate that gave the smallest percent difference being chosen as the conversion rate utilized within this study. For states without any known combined rates from the DOE and B&V surveys, the utilized conversion rate is the mean of all the utilized conversion rates across all regional state groupings that that the unknown state is part of. The conversion rates by regional state grouping, conversion rate utilized, percent difference between the known combined water and wastewater rates and the calculated water and wastewater rates using the regional state grouping conversion rate, NACWA wastewater rate, and calculated water rate for select states are shown in Table 35. Complete data for each state is provided in APPENDIX G and compared via heat map in Figure 48.

Table 35. Wastewater to water conversion rate (CR) determination from regional state groupings' wastewater to water CR for select states.

State	AK	CA	GA	IL	KS	MA	NM	PA	TN	TX	U.S.
Census Div.	9	9	5	3	4	1	8	2	6	7	
EIA Region	10	9	5	3	4	1	8	2	6	7	
DOE Region	1	1	6	4	3	5	2	5	6	7	
SF Region	10	9	4	5	7	1	6	3	4	6	
Census CR	1.03	1.03	0.61	0.91	0.88	0.80	1.09	0.94	0.59	1.01	
EIA CR	0.72	1.05	0.61	0.91	0.88	0.80	1.09	0.94	0.59	1.01	
DOE CR	1.03	1.03	0.61	0.91	0.88	0.91	1.09	0.91	0.61	1.01	
SF CR	0.50	1.28	0.56	0.93	0.85	0.80	1.01	0.82	0.56	1.01	
Census % Diff	-12.93	-12.93	-1.78	-6.17	-3.14	0.00	-4.25	-1.52	-1.34	-7.42	
EIA % Diff	0.00	-13.95	-1.78	-6.17%	-3.14	0.00	-4.25	-1.52	-1.34	-7.42	
DOE % Diff	-12.93	-12.93	-1.69	-6.17	-3.14	-1.23	-4.25	-1.23	-1.69	-7.42	
SF % Diff	-0.70	-9.72	-1.76	-5.61	-3.56	0.00	-6.68	-1.09	-1.76	-6.68	
CR Utilized	0.72	1.28	0.61	0.93	0.88	0.80	1.09	0.82	0.59	1.01	0.73
Wastewater Rate ($/kgal)	32.40	24.29	29.28	24.93	29.62	48.31	21.92	31.20	29.28	21.92	27.35
Calc. Water Rate ($/kgal)	23.45	31.13	17.76	23.08	26.00	38.74	23.90	25.51	17.37	22.18	19.95

Note: % *Diff* is the percent difference between the known combined water and wastewater rates and the calculated water and wastewater rates using the regional state grouping CR. Wastewater rates from NACWA.

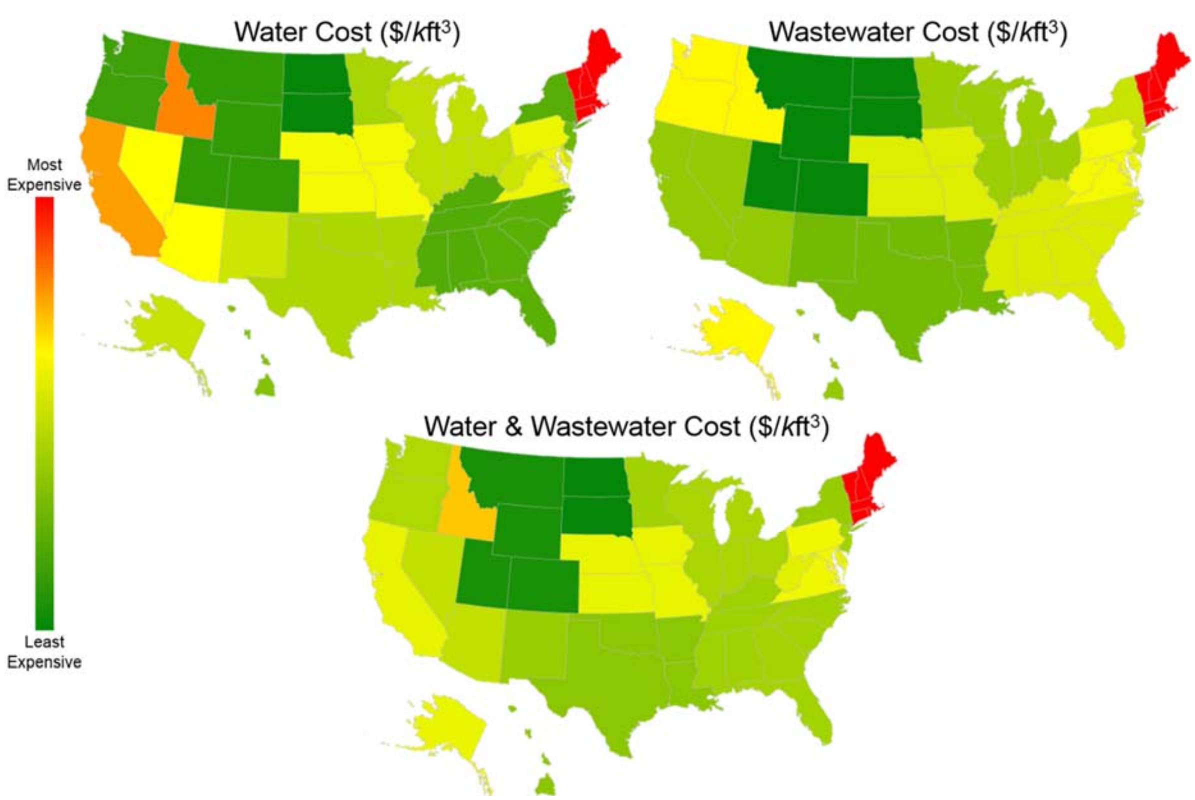

Figure 48. Wate, wastewater, and combined rate comparison of the U.S.

5.6 Domestic Plant Operations

Plant operations include all the miscellaneous costs that directly affect the manufacturing environment. These include, but are not limited to space costs, insurance, janitorial services, etc. The only consistent cost which is lumped into plant operations that is tracked via publically available datasets is the space cost. Manufacturing space is either rented or purchased. For this study, only rented space has been investigated.

Cushman & Wakefield (C&W), a commercial real estate services company, publishes a quarterly *U.S. Industrial Marketbeat* for their investors. Real estate factors, such as asking rents for the manufacturing sector for select U.S. cities in $ per square foot, are part of this publication. Their publication does not cover every state across the U.S., so a strategy to provide values for states without available data is required [61].

To set a value for states that do not have data available for them, the mean asking rent price is found for each regional state grouping. The average of the four regional state groupings is the rent rate utilized within this study. The regional state grouping industrial sector rental rates and utilized rental rates for select states are listed in Table 36. Complete data for each state is provided in APPENDIX G and compared via heat map in Figure 49.

The plant operations cost, calculated on a $ per square foot basis, has been found to be five times that of the space cost from various case studies.

Table 36. Regional state grouping industrial sector rental rates and the utilized industrial sector rental rates for select states. Rates are in $/sf.

State	AK	CA	GA	IL	KS	MA	NM	PA	TN	TX	U.S.
Census Rent	11.16	11.16	6.63	4.38	5.30	6.06	6.48	5.59	3.08	5.47	11.16
EIA Rent	11.16	11.16	6.63	4.38	5.30	6.06	6.48	5.59	3.08	5.47	11.16
DOE Rent	11.16	11.16	6.12	4.38	5.30	5.72	6.48	5.72	6.12	5.47	11.16
SF Rent	7.77	10.40	6.22	4.38	5.30	6.06	5.47	5.27	6.22	5.47	7.77
Rent Utilized	10.31	10.97	6.40	4.38	5.30	5.97	6.23	5.54	4.62	5.47	10.31

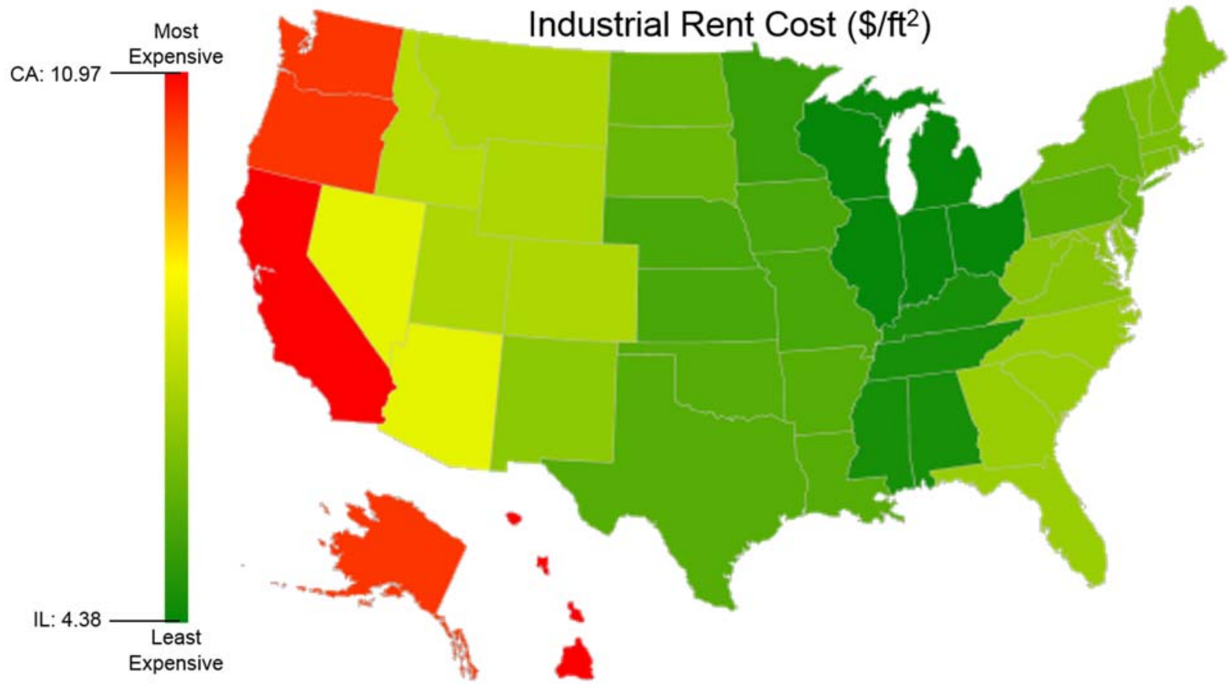

Figure 49. Industrial rent rate comparison of the U.S.

Cities, however, do not cover the full extent of possible manufacturing locations, as there is a difference in metropolitan verse non-metropolitan rental prices. C&W's publication does not address this, but the U.S. Department of Housing and Urban Development (HUD) issues residential Fair Market Rental rates (FMR) for each fiscal year that provides metropolitan and non-metropolitan rates for each state [62]. Assuming the rates for industrial zoned areas follow the same trends as residential areas, a conversion from metropolitan to non-metropolitan rental rates can be determined.

HUD issues FMRs in five different categories of housing. The locations were sorted for each of the categories by state and metropolitan or non-metropolitan designation. The mean is found for each state and designation, and the conversion rate for metropolitan to non-metropolitan rate is then found using Equation 79.

$$R_{RR} = \frac{\overline{C_{nmRR}}}{\overline{C_{mRR}}}$$

Equation 79

Where R_{RR} is the conversion rate for a state's metropolitan rental rate to non-metropolitan rental rate and C_{nmRR} and C_{mRR} are a state's average non-metropolitan and metropolitan residential rent rates, respectively.

The conversion rate utilized within this study for a state is the average of the five HUD category conversion rates for that state, for states that have available data. The national conversion rate was found via the same method, but utilized all of the raw data instead of grouping by state. These rates for FY2019 are broken out in Table 37. Complete data for each state is provided in APPENDIX G.

Table 37. Conversion rates from metropolitan to non-metropolitan regions for each HUD FY19 Fair Market Rents (FMR) areas and the conversion rate utilized for select states.

State	AK	CA	GA	IL	KS	MA	NM	PA	TN	TX	U.S.
FMR 0 CR	1.01	0.61	0.74	0.77	0.87	0.83	0.98	0.79	0.77	0.82	0.73
FMR 1 CR	1.03	0.60	0.72	0.79	0.82	0.81	0.88	0.74	0.73	0.76	0.71
FMR 2 CR	0.98	0.61	0.76	0.80	0.82	0.80	0.91	0.74	0.74	0.77	0.72
FMR 3 CR	0.89	0.61	0.77	0.80	0.80	0.83	0.89	0.75	0.75	0.77	0.72
FMR 4 CR	0.83	0.60	0.74	0.77	0.75	0.82	0.90	0.76	0.72	0.73	0.71
CR Utilized	0.95	0.61	0.75	0.78	0.81	0.82	0.91	0.76	0.74	0.77	0.73

The average of the four regional areas' conversion rates for a state is used for states that are not included in the HUD database: Delaware, New Jersey, Rhode Island, Washington D.C. Guam, Virgin Islands, and American Samoa. These areas' conversion rates are given in Table 38. Each of the four regional area's conversion rates is broken out by region/division in Table 39.

Table 38. Metropolitan to non-metropolitan conversion rates for areas not included in the HUD FMR database.

State	DE	NJ	RI	DC	Guam	VI	AS
CR	0.76	0.74	0.78	0.76	0.78	0.74	0.73

Table 39. Regional state grouping metropolitan to non-metropolitan conversion rates from HUD FMR data.

Region #	1	2	3	4	5	6	7	8	9	10
Census Division CR	0.79	0.71	0.83	0.83	0.77	0.79	0.82	0.85	0.76	
EIA Region CR	0.79	0.71	0.83	0.83	0.77	0.79	0.82	0.85	0.68	0.85
DOE Region CR	0.75	0.85	0.83	0.83	0.77	0.78	0.82			
EPA Region CR	0.79	0.75	0.75	0.78	0.81	0.84	0.83	0.85	0.75	0.83

5.7 Materials

Composite materials are produced world-wide and often purchased on a per pound basis. The material cost to the manufacturing location is comprised of the supplier's sale price plus the delivery cost. Thus, different manufacturing locations vary by the delivery cost.

Delivery methods vary by material handling requirements, time requirements, and shipping and destination locations. For this study, the delivery cost is broken into two components: ground-based and intercontinental. Ground-based shipping is defined as the shipping from one location to another that is completed via vehicle. Intercontinental shipping is defined as either shipping from one country to another, or shipping to or from the continental U.S. to non-continental U.S. locations. The goal is for a comparative delivery cost, not an exact delivery price. Knowing the origin of the material allows the delivery costs to be determined to compare how manufacturing location affects material costs. This does, however, require the base case material cost quotes to be broken into material and delivery costs and for the shipping location to be known.

The supplier's sale price, or the base material cost, BMC, provides a basis to determine a new material cost, NMC, for different manufacturing locations. The NMC is found via Equation 80.

$$NMC = \alpha \cdot \left[BMC \cdot \left(1 + \frac{SF}{10{,}000}\right) + \frac{ZC}{70}\right]$$

$$\alpha = \frac{MC_{known}}{MC_{calc}}$$

Equation 80

Where SF is the intercontinental shipping factor, ZC is the ground-based zone cost, and α is an adjustment factor. MC_{known} is the known material cost that includes the supplier's sale price plus the delivery cost. MC_{calc} is the value of NMC calculated using Equation RR with α set to 1 for the base case scenario. This scales the price to meet the actual cost of delivered goods; i.e. if the actual material cost is \$0.45/lb delivered from Germany to Indiana with a supplier's sale price of \$0.40/lb for the base case scenario, MC_{calc} is \$1.08/lb, resulting in an adjustment α of 0.416 being required to match the actual material cost as delivered. The adjustment α of 0.416 then gets applied for different delivery locations to scale the delivery cost appropriately.

Ground-based shipping is determined for this work based on the United States Postal Service (USPS) Retail Ground zone rates for a package up to 70 pounds [63]. The USPS defines shipping zones based on the distance from one location to the next, with 9 zones in total [64]. Only zones 1-8 are utilized for this work, as zone 9 is for Exceptional Network Circumstances; essentially any unusual packages. For locations within the continental U.S., the distance between locations is found via straight line distance calculated from their latitude and longitude. The maximum mileage and associated cost for each zone is in Table 40.

Table 40. USPS shipping zones with associated maximum mileage and rates to ship 70lbs via retail ground.

USPS Zone	1	2	3	4	5	6	7	8
Max Mileage	50	150	300	600	1,000	1,400	1,800	>1,800
Cost	$27.46	$27.46	$33.03	$42.10	$52.75	$62.89	$72.87	$83.21
ZC/70 value	0.39	0.39	0.47	0.60	0.75	0.90	1.04	1.19

The ground-based shipping portion for non-continental U.S. locations was found by one of two manners. If shipping from foreign country to foreign country, the difference in the distance of each country to a respective U.S. port location is used to determine the zone category. If shipped from the U.S. to a foreign country, the distance of the state to the appropriate U.S. port is used to determine the zone category. Values of $ZC/70$ for select states and countries are shown in Table 41. Complete data for each state is provided in APPENDIX G.

Table 41. Ground based shipping factors of ZC/70 for select states and countries to be used in the formula for NMC.

To \ From	AK	CA	GA	Australia	China	Germany
AK	0	0.47	1.19	1.19	1.19	1.04
CA	0.47	0	1.19	0.47	0.47	1.19
GA	1.19	1.19	0	1.19	1.19	0.60
Australia	1.19	0.47	1.19	0	0.90	1.19
China	1.19	0.47	1.19	0.90	0	1.19
Germany	1.04	1.19	0.60	1.19	1.19	0

Intercontinental shipping to or from the U.S. is based on the freight shipping cost of sending a container from U.S. port to foreign country port. Freight costs were found for a country's port to Los Angeles, CA and Baltimore, MD ports. The less expensive U.S. port was used. The freight cost was based on a full 40-foot container load of auto parts with a $10,000 commodity value and was obtained from World Freight Rates, a logistics company that provides estimated market rates for a variety of freight shipping methods. The foreign country port was chosen at random from the available options, and may or may not be the actual port that the material would transfer through. This gives us a shipping cost per $10,000 material value that can be easily converted to a shipping cost per pound value since the material sale's price is known on a per pound basis.

Intercontinental to intercontinental shipping are determined by comparing the country-to-U.S. shipping costs and the ground-based costs based on the country-to-U.S. distances discussed prior. The intercontinental shipping factor, SF, is found via Equation 81.

$$SF = \left|C_{frieght,A} - C_{freight,B}\right| \cdot F_{port}$$

Equation 81

$C_{frieght,A}$ is the cost of shipping from the origin foreign port to the less expensive of the two U.S. ports. $C_{frieght,B}$ is the cost of shipping from the destination foreign port to the less expensive of the two U.S. ports. F_{port} is a correction value based on port city shipping cost variation.

F_{port} was determined by first finding the cost of shipping for countries within one world region to another world region. Country regions are from the International Telecommunications Union, with the exception that Asia and Pacific countries were separated, creating seven regions [65]. The metric utilized to determine countries within the "Pacific" region was that the country is an island nation such as Australia, Philippines, or New Zealand. Second, the absolute value of the difference in the cost of shipping from origin-to-U.S. and destination-to-U.S. was found. Third, a multiplier was determined to convert the cost of shipping difference to the actual cost of shipping for the countries in question. An average of these multipliers across the sampling of countries gathered forms F_{port}. Values for F_{port} for country region 1 to the 7 country regions along with the port-to-port values are given in Table 42. Values of $SF/_{10,000}$ for select states and countries are shown in Table 43. A complete table for F_{port} and which countries belong in which world region is provided in APPENDIX G.

Table 42. Values for F_{port} for select country regions.

Country Region Origin	Country Region Destination	F_{port}	Same US Ports (Baltimore to Baltimore) F_{port}	Same US Ports (Los Angeles to Los Angeles) F_{port}	Different US Ports (Baltimore to Los Angeles) F_{port}	Different US Ports (Los Angeles to Baltimore) F_{port}
1	1	2.944	2.944	2.944	2.316	3.571
1	2	1.965	1.278	1.965	1.965	2.652
1	3	4.138	4.138	5.841	2.434	4.138
1	4	2.256	1.343	2.256	2.256	3.169
1	5	2.734	2.734	3.432	2.037	2.734
1	6	11.025	11.025	7.522	14.528	11.025
1	7	0.943	0.943	1.086	0.799	0.943

Table 43. Intercontinental based shipping factors of SF⁄10,000 for select states and countries to be used in the formula for NMC.

From / To	AK	CA	GA	Australia	China	Germany
AK	0	0.115	0.115	0.612	0.314	0.608
CA	0.115	0	0	0.256	0.104	0.204
GA	0.115	0	0	0.256	0.104	0.204
Australia	0.378	0.256	0.256	0	0.254	0.264
China	0.216	0.104	0.104	0.205	0	0.223
Germany	0.648	0.204	0.204	0.368	0.305	0

5.8 Domestic Miscellaneous Costs

To induce a location variation for other miscellaneous costs that aren't covered in the categories already discussed, a Cost Of Living Allowance, COLA, is established for each state. The raw COLA value is based off of 1 hour of labor for both direct and indirect workers, 1,000 kWh of electricity used, 1 ft^3 of water used, 1 ft^3 of wastewater produced, and 100 ft^2 of space rented. The raw values are then divided by the highest value, giving the most expensive state a COLA value of 1. Locations for determining COLA were the 50 U.S. States, four U.S. Territories, and Washington D.C. The highest raw COLA value belonged to Guam (Raw: 1,508, COLA: 1) and the lowest belonged to Illinois (Raw: 654, COLA: 0.43). Raw COLA and COLA values for select states are in Table 44. Complete data for each state is provided in APPENDIX G and compared via heat map in Figure 50.

Table 44. Cost of living allowance (COLA) for select states.

State	AK	CA	GA	IL	KS	MA	NM	PA	TN	TX	U.S.
Raw COLA	1,372	1,380	836	654	756	957	819	785	666	753	856
COLA	0.909	0.904	0.555	0.433	0.501	0.634	0.543	0.521	0.441	0.500	0.568

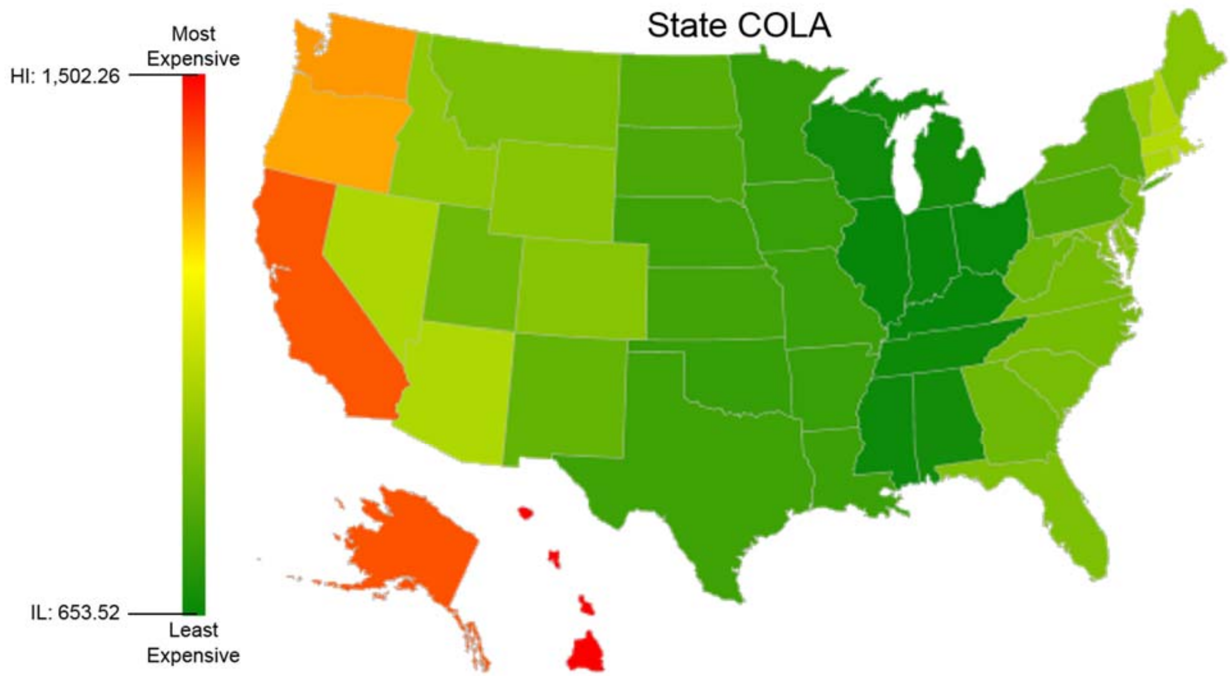

Figure 50. COLA comparison of the U.S.

5.9 Global Costs

Besides shipping and material costs, costs in foreign countries have not been discussed in detail. To assemble the databases used in the U.S. domestic comparisons for each country that one wants to investigate is unreasonable. Instead, there are organizations that establish country COLA and wage indexes that can be used to convert U.S. costs to equivalent foreign country costs. COLA and wage indexes from WorldData were used for this study [66, 67].

To convert a U.S. based manufacturing cost to a foreign country based manufacturing cost, the base case, which takes place in a specific U.S. state, is indexed via the COLA value found for *Miscellaneous Costs* to the U.S. average for every manufacturing cost component described except for wages. Wages are indexed separately, as a country wage index is available via WorldData. Once the manufacturing cost has been converted to the U.S. average cost, they can be indexed to the foreign country in question. The wage index and COLA index for select countries along with the country's regional classification and their subsequent regional averages are in Table 45. Complete data for each country is provided in APPENDIX G.

Table 45. The wage and Cost of Living Allowance (COLA) indexes for select countries and the country's regional classification and their subsequent regional averages.

Country	Wage Index	COLA	Region	Region Wage Index	Region COLA
Australia	0.88	1.08	Pacific	0.77	0.93
China	0.15	0.55	Asia	0.24	0.56
Chile	0.23	0.68	South/Latin America	0.22	0.64
Germany	0.75	0.92	Europe	0.45	0.75
Saudi Arabia	0.34	0.62	Arab States	0.30	0.54
South Africa	0.09	0.53	Africa	0.05	0.67
U.S.	1	1	North America	1.11	1.17

5.10 Comparing domestic and global manufacturing cost of a high automation hybrid molding manufacturing line

The hybrid manufacturing process described in the *Section 5.1 Converting costs and base case* with the highly automated manufacturing cost values broken out in Figure 44 provides the base manufacturing cost that can now be used to find the manufacturing cost across the U.S. This base case occurs in West Lafayette, Indiana U.S. Table 46 breaks out the total manufacturing costs for the select U.S. states we've been following throughout this study. Figure 51 shows a heat map of the U.S. with green being low manufacturing costs and red being high.

Table 46. The segmented manufacturing cost for select U.S. states and the national mean, as calculated from the highly automated case (HAC) scenario. All costs are $/part.

State	HAC	AK	CA	GA	IL	KS	MA	NM	PA	TN	TX	U.S.
IM Mat.	0.11	0.17	0.17	0.11	0.12	0.14	0.11	0.15	0.09	0.11	0.14	0.12
Tow	0.16	0.18	0.11	0.16	0.15	0.14	0.16	0.13	0.16	0.16	0.14	0.15
Bushing	0.63	0.72	0.55	0.63	0.61	0.60	0.63	0.58	0.63	0.63	0.60	0.62
Equip.	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Tooling	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Plant Ops.	0.21	0.50	0.53	0.31	0.21	0.26	0.29	0.30	0.27	0.22	0.26	0.31
Energy	0.13	0.30	0.20	0.10	0.12	0.13	0.26	0.09	0.12	0.11	0.09	0.12
Water	0.05	0.05	0.06	0.04	0.05	0.05	0.08	0.05	0.05	0.04	0.04	0.04
Waste-water	0.05	0.07	0.05	0.06	0.05	0.06	0.10	0.04	0.06	0.06	0.04	0.06
Direct Labor	0.99	1.17	1.08	0.94	0.99	1.07	1.28	0.91	1.00	0.98	1.04	1.05
Indirect Labor	0.23	0.28	0.29	0.24	0.24	0.23	0.30	0.26	0.26	0.24	0.29	0.27
Labor Consum-ables	0.03	0.07	0.07	0.04	0.03	0.04	0.05	0.04	0.04	0.03	0.04	0.04
Equip. Maint.	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total Manufacturing Cost	3.94	4.86	4.45	3.97	3.93	4.06	4.60	3.91	4.03	3.93	4.04	4.12

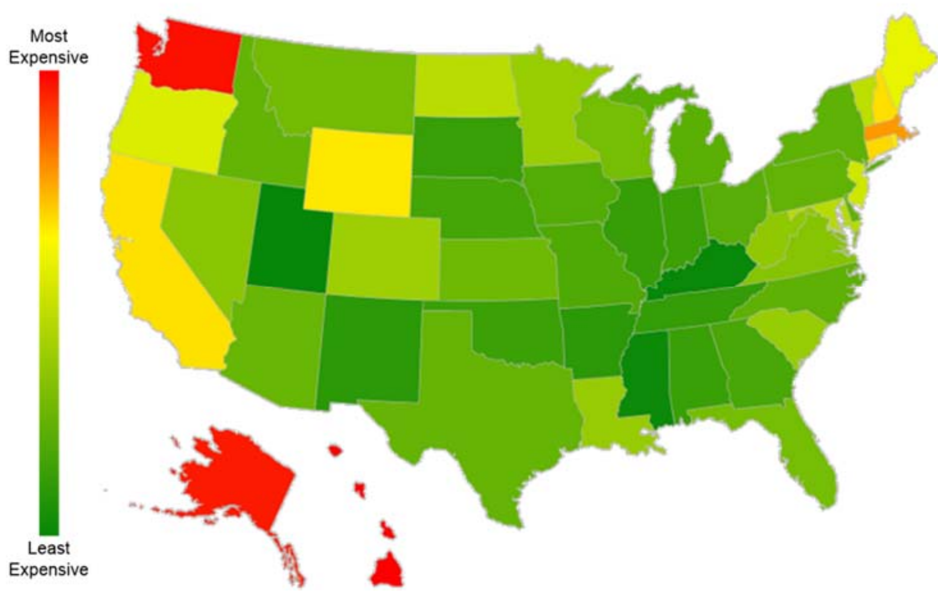

Figure 51. U.S. heat map of manufacturing costs for manufacturing a test coupon via high auotmation hybrid manufacturing.

The most expensive state to manufacture in is Hawaii with a manufacturing cost of $4.91, followed by Alaska at $4.86. These states have the two highest costs of livings, at 0.996 for HI and 0.909 for AK and shipping costs to them are high. Note, the four territories are included in the COLA calculations, with Guam being the highest at 1.000.

The least expensive state to manufacture in is Utah with a manufacturing cost of $3.82. It had the benefit of a much lower cost of livings at 0.55.

It is difficult to generalize regional manufacturing unless the regional grouping are defined. A breakdown according to the regional state groupings shown in Figure 45 is given in Table 47. For each regional state grouping, the region manufacturing costs are highlighted green-to-yellow-to-red to represent low-to-mid-to-high manufacturing cost. Speaking very generally, the Midwest is the least expensive area to manufacture in, followed by the mountain states, the south east, the north east, and finally the west coast. The majority of manufacturing is located in the Midwest currently, so the trends fit reality.

Table 47. Manufacturing costs broken out by regional state groupings for highly automated hybrid manufacturing.

Region	SF Region	EAI Region	DOE Region	Census Region
1	$4.42	$4.42	$4.73	$4.42
2	$4.29	$4.22	$4.08	$4.22
3	$4.19	$4.00	$4.05	$4.00
4	$3.97	$4.05	$4.00	$4.05
5	$4.02	$4.15	$4.37	$4.15
6	$3.99	$3.88	$4.07	$3.88
7	$4.00	$4.01	$4.01	$4.01
8	$4.11	$4.08		$4.08
9	$4.44	$4.55		$4.73
10	$4.52	$4.90		

Expanding the investigation to the global stage via the international wage and COLA indexes, Figure 52 shows an international heat map with green representing low manufacturing costs and red representing high. Table 48 lists the manufacturing costs for select countries.

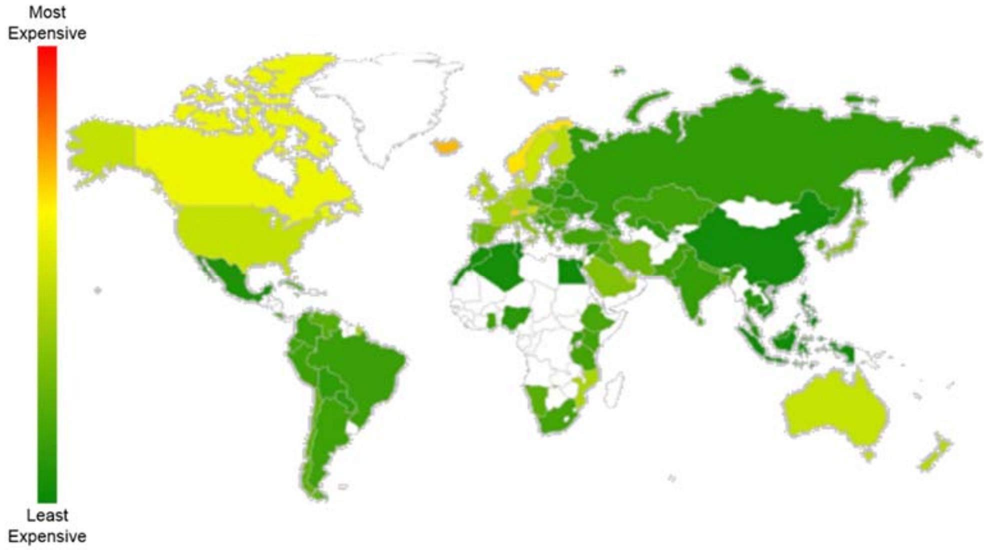

Figure 52. Global heat map of manufacturing costs for manufacturing a test coupon via high automation hybrid manufacturing.

Table 48. The manufacturing cost for select countries as calculated for highly automated hybrid manufacturing.

Country	Manufacturing Cost ($/part)	Region	Manufacturing Cost ($/part)
Australia	4.11	Pacific	3.88
China	2.66	Asia	3.07
Chile	3.17	South/Latin America	3.09
Germany	3.84	Europe	3.47
Saudi Arabia	3.43	Arab States	3.07
South Africa	2.94	Africa	3.05
U.S.	4.12	North America	4.67

The most expensive country to manufacture in is Bermuda with a manufacturing cost of $6.35. The least expensive country to manufacture in is the Philippines with a manufacturing cost of $2.55. China is generally the focus for inexpensive manufacturing. However, China ranks higher in wage index at 0.149 vs 0.063 and COLA at 0.551 vs 0.443 compared to the Philippines. Looking regionally, Asia is calculated to be the least expensive to manufacture in, which agrees with current manufacturing trends. North America followed by Europe are the most expensive, which may be contributing to the trend of manufacturing moving out of these areas to better the bottom line of companies.

State and country values for every location investigated is available in APPENDIX H.

5.11 Comparing domestic and global manufacturing cost of a low automation hybrid molding manufacturing line

The hybrid manufacturing process described in the *Section 5.1 Converting costs and base case* with the low automation manufacturing cost values broken out in Figure 44 provides the base manufacturing cost that can now be used to find the manufacturing cost across the U.S. This base case occurs in West Lafayette, Indiana U.S. In this low automation case, workers conduct all the transfers, loading, unloading, trimming, and quality control scanning, resulting in a labor intensive manufacturing scenario.

Table 49 breaks out the total manufacturing costs for the select U.S. states we've been following throughout this study. Figure 53 shows a heat map of the U.S. with green representing low manufacturing costs and red high.

Table 49. The segmented manufacturing cost for select U.S. states and the national mean, as calculated from the low automation case (LAC) scenario. All costs are $/part.

State	LAC	AK	CA	GA	IL	KS	MA	NM	PA	TN	TX	U.S.
IM Mat.	0.11	0.17	0.17	0.11	0.12	0.14	0.11	0.15	0.09	0.11	0.14	0.12
Tow	0.16	0.18	0.11	0.16	0.15	0.14	0.16	0.13	0.16	0.16	0.14	0.15
Bushing	0.63	0.72	0.55	0.63	0.61	0.60	0.63	0.58	0.63	0.63	0.60	0.62
Equip.	0.85	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Tooling	0.20	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Plant Ops.	0.21	0.50	0.53	0.31	0.21	0.26	0.29	0.30	0.27	0.22	0.26	0.31
Energy	0.13	0.28	0.19	0.09	0.11	0.12	0.24	0.09	0.11	0.10	0.09	0.11
Water	0.05	0.05	0.07	0.04	0.05	0.05	0.08	0.05	0.05	0.04	0.05	0.04
Waste-water	0.05	0.07	0.05	0.06	0.05	0.06	0.10	0.05	0.07	0.06	0.05	0.06
Direct Labor	0.99	3.67	3.37	2.94	3.10	3.35	4.01	2.85	3.13	3.07	3.26	3.29
Indirect Labor	0.23	0.89	0.90	0.76	0.77	0.73	0.93	0.80	0.82	0.75	0.90	0.83
Labor Consum-ables	0.03	0.22	0.22	0.13	0.10	0.12	0.15	0.13	0.12	0.11	0.12	0.14
Equip. Maint.	0.30	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Total Manufacturing Cost	3.94	7.85	7.25	6.34	6.39	6.67	7.81	6.24	6.55	6.35	6.71	6.77

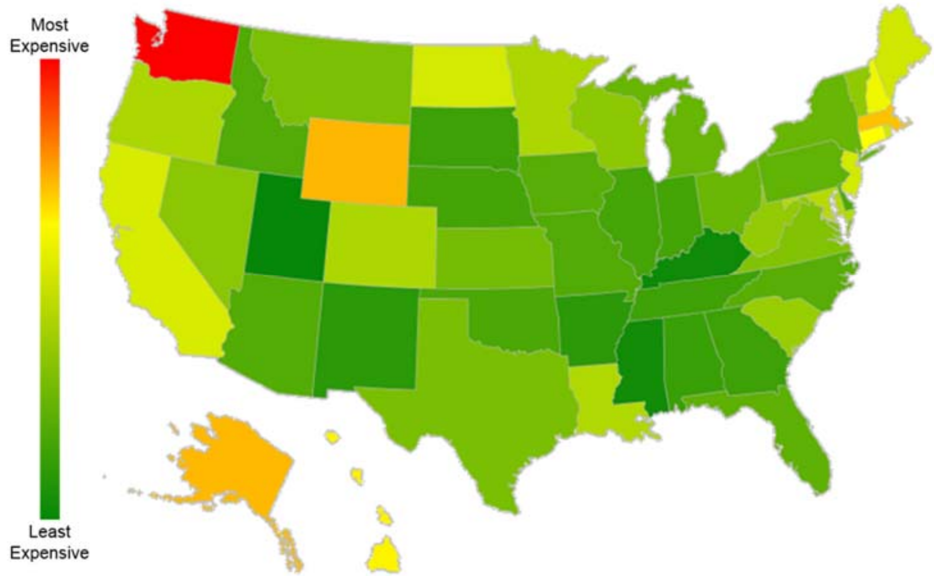

Figure 53. U.S. heat map of manufacturing costs for manufacturing a test coupon via low automation hybrid manufacturing.

When labor dominates, the most expensive state to manufacture in is Washington with a manufacturing cost of \$8.85, an increase of 81.27% compared to its highly automated manufacturing cost. Washington has the highest combined direct and indirect labor costs to employers, at \$132.30 per hour for one worker in each category. The least expensive state to manufacture in is still Utah with a manufacturing cost of \$6.02. Utah's combined labor costs total only \$87.41 per hour. The general regional state grouping trends remain the same, as seen in Table 50. Interestingly, Hawaii, which had the highest highly automated manufacturing cost, has the smallest manufacturing cost increase of 53.32%. This is due to HI's low wages but high utility costs. On average, the U.S. experiences a 64.37% increase in manufacturing costs in the labor dominated scenario.

Table 50. Manufacturing costs broken out by regional state groupings for low automation hybrid manufacturing.

Region	SF Region	EAI Region	DOE Region	Census Region
1	$7.33	$7.33	$7.74	$7.33
2	$7.04	$6.90	$6.70	$6.90
3	$6.97	$6.56	$6.66	$6.56
4	$6.39	$6.66	$6.56	$6.66
5	$6.63	$6.84	$7.19	$6.84
6	$6.53	$6.21	$6.64	$6.21
7	$6.50	$6.60	$6.60	$6.60
8	$6.86	$6.70		$6.70
9	$7.08	$7.70		$7.74
10	$7.54	$7.70		

Expanding the investigation to the global stage via the international wage and COLA indexes, Figure 54 shows an international heat map with green representing low manufacturing costs and red representing high. Table 51 lists the manufacturing costs for select countries.

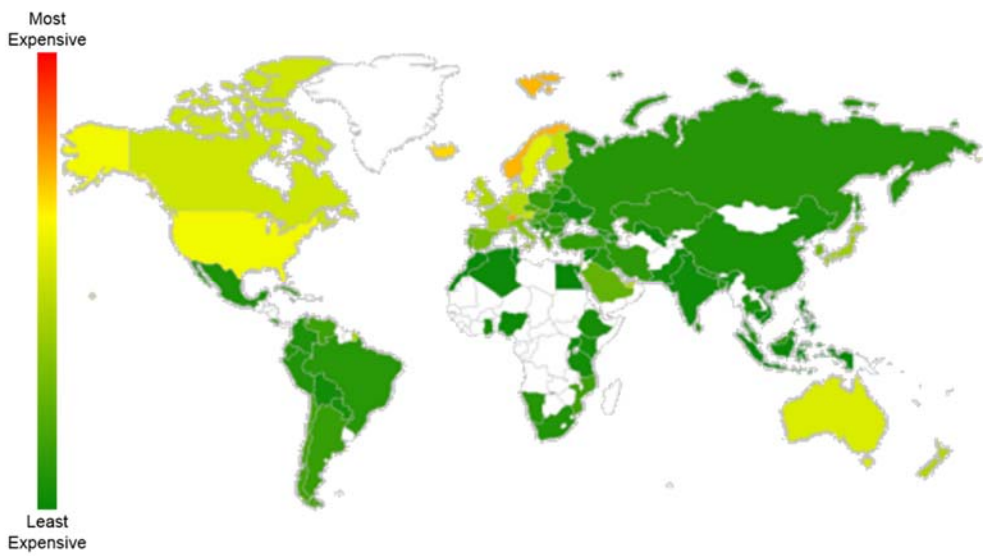

Figure 54. Global heat map of manufacturing costs for manufacturing a test coupon via low automation hybrid manufacturing.

Table 51. The manufacturing cost for select countries as calculated for low automation hybrid manufacturing.

Country	Manufacturing Cost ($/part)	Region	Manufacturing Cost ($/part)
Australia	6.44	Pacific	5.88
China	2.89	Asia	3.53
Chile	3.64	South/Latin America	3.51
Germany	5.77	Europe	4.56
Saudi Arabia	4.21	Arab States	3.71
South Africa	3.01	Africa	3.00
U.S.	6.77	North America	7.65

The most expensive and inexpensive country to manufacture remains Bermuda and the Philippines, with a manufacturing cost of $11.38 and $2.52, respectively. North America saw the highest increase when switching to the labor dominated low automation manufacturing, with a 63.89% increase. In decreasing order by region, the increases when switching to low automation manufacturing are: North America at 63.89%, Pacific at 51.49%, Europe at 31.36%, Arab States at 20.71%, Asia at 15.13%, South/Latin America at 13.64%, and Africa at -1.73%.

State and country values for every location investigated is available in APPENDIX H.

5.12 Conclusions

Assembling all the requisite components to execute a manufacturing cost estimation for one location is a daunting task in and of itself. If tasked for comparing multiple locations, it becomes overwhelming quickly. Methods to assemble location indexes for the primary cost drivers of the manufacturing cost were shown utilizing U.S. Government and privately assembled, yet freely available resources. Further, the means to account for material costs based on material production location and shipping fees was presented. These indexes could be annually updated and integrated into the cost estimation process to quickly provide location comparisons to guide future investment planning.

Ultimately, more factors must be investigated before a decision is made about placing a manufacturing line in a particular country. Ease of access, political stability, a ready and available workforce, and taxes are just a few of these factors. Within the U.S., high-automation manufacturing costs in the West Coast/Pacific are 20.1% greater compared to the Midwest and similarly, low-automation costs are 21.2% greater. Globally, high-automation manufacturing costs in North America are 52.1% greater compared to Asia while low-automation costs are 116.5% greater. It is understandable why companies are relocating their manufacturing out of these high cost areas.

5.13 Summary

This chapter focused on global manufacturing management, or the decision-making process governing manufacturing location. Various manufacturing cost drivers are location dependent, thus a dataset was developed to alter these parameters for the U.S. states. Global comparisons were accomplished through indexing of global cost of living allowances and labor rates. Heat maps provide visually striking and easily identifiable differences between locations, thus are the best tool to visualize these results. These variations highlight why we see geographically clustered manufacturing centers within the states and major manufacturing relocations due to cost sensitive and labor sensitive production.

6. MANUFACTURING INTELLIGENCE

Manufacturing intelligence is the coalescing of the digital and physical threads. Physical elements, such as equipment, are more and more frequently being outfitted with sensors that output data continuously or at set time intervals. Additionally, enhanced tracking capabilities through the use of scanners and RFID tagging can track material through a manufacturing process from start to finish. These elements are providing digitization to what was once an analogue world of manufacturing, bringing it into *Industry 4.0*.

These physical thread elements can be coupled with data obtained through CAE design simulations to provide the baseline operating procedures for a manufacturing line. Together, these physical and digital threads may be useful to conduct data analytics upon to determine cost, manage time, and ensure quality. This flow is visualized in Figure 55.

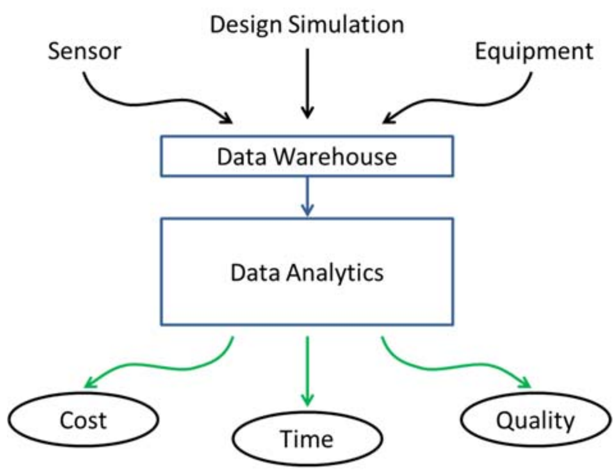

Figure 55. Visulaization of physical and digital thread elements coalescing to deliver desired business outcomes.

The technical cost modeling methods presented in the previous chapters is one data analytics business outcome that can provide an economic indicator for how efficient an instrumented manufacturing line can operate compared to its estimated operational capabilities. For instance, if a piece of equipment is instrumented with a temperature setting, and the temperature setting is known from the CAE simulation, the TCM equipment module can provide the base line operating cost at that temperature. It is assumed here that for this equipment, temperature dictates a process step time, influencing cycle time and electricity usage. If the temperature changes, the cost would change as the cycle time would be altered and since the heating temperature has been reduced or risen, this should mean that the heating element is drawing either more or less power to be at that temperature. A high temperature may result in the equipment or operator compensating and increasing the speed through the process, resulting in an overall lower cost due to reduced cycle time. A low temperature may result in more time being spent in the process, resulting in an overall increase in cost due to the increased cycle time. A visualization of this is represented in Figure 56.

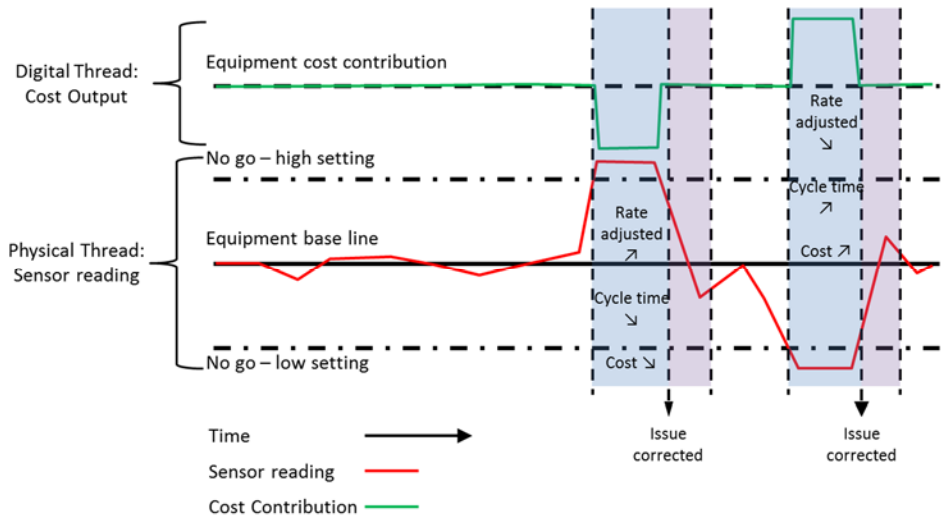

Figure 56. Physical thread input to economic indicator.

Managing the integration of physical sensor data into real time economic indicators shall come in subsequent work. The real time monitoring of manufacturing floor activities and how it directly relates to cost is where the industry is headed.

In addition to creating an operational manufacturing execution system in the MDLab, refinements to estimation calculations relating temperature to electrical usage, part geometrical parameters to mold cost, EOAT cost, and jig cost, and additional equipment estimation cells are necessary to further enhance the accuracy of the cost estimate and to be able to implement other manufacturing methods within the framework besides hybrid molding. An interactive user interface is under development to allow users to drag and drop equipment into custom designed manufacturing lines and determine manufacturing costs based on user inputs or the CAE produced processing parameters from the chosen manufacturing performance design application.

APPENDIX A. T1P PROJECT COST MODELING INPUTS

The inputs listed below are were under development when the project was terminated. Where a "?" is shown is where information requests had been made for more detailed information. Provided by [35-38].

Category	Units	Notes	Equipment								
Equipment			Seamer	Layup / Consolidation System	Patch System	Slitter	Multi-Layer System	Consolidation Unit	Transfer Robot - Blank Form→F.C.	Net-Shape Trimmer	
					Exclude for now	Mohamed			Purdue	Mohamed - Water Jet	J
Make			Globe	Globe	Globe	Fill	Fill	Fill	6-axis	?	
Model			Seamer	Consolidator	?				Generic	?	
Lifespan	Years	Delete this?	?	20	?	?	?	?	7	?	
Cost	$		$800,000.00	$2,500,000.00	?	$233,500.00	$1,233,000.00	$1,105,600.00	-small: $86,000 - large: $117,000 (weight based)	$350,200.00	
Cost Converted	Date		N/A	N/A	N/A	7/12/2018	7/12/2018	7/12/2018	N/A	7/13/2018	
Processing / Movement / rate			Continuos, weld time based	120IPM / 127.5 blanks/hr	?	? - will use water jet cutting rates, assume all slits done at once	max 2 m/s	Load time, closing time, lift up time, heating time, cooling time, lift down time, conveyor time, opening time, unload time		IMI water jet: max (200 in/min), slowest (0.04 in/min), avg range (1.35-27.59 in/min)	
Cycle Time	s		12 sec weld (for 58") (290 in/min)		?	? - how many rolls can be slit concurrently? - how many slits can be done to roll concurrently?	111s for 6 sheets (5 June 2018)	60s	HS: 5s, MS: 9s, LS: 10s	Calculated from	
Scrap		If known, or avg %	Cut offs of new input rolls (also end of seamed roll length accounted for)	Ends of seamed rolls from Seamer (accounted for in Seamer)	?	excess tape width	None	N/A			
Tooling		Jig, mold, end effector, etc.							End Effector	Jig, router bits (for router cutting if used)	
Lifespan	# of parts		?	?	?	?	?	?	?	?	
Cost	$		?	?	?	?	?	?	?	?	
Plant Operation											
Footprint	sf		208	427.5 (57' x 7'6")	?	100m^2 (1,076.39 ft^2)	245	473.612	~20	Water Jet (Mohammed) - 120m^2 (1291.67ft^2)	
Safety Standoff	sf		+~5ft	793 (61' x 13')	None used	None used	None used	None used	None used	None used	
Energy											
In-use	kW		~60kW (estimated)	~400kW ($50/hr operating burden rate)	?	3	60	450	0.67-30 (use 15)	Water Jet (Mohammed) - 40 kW/hr	
Standby	kW		?	?	?	?	?	?	?	?	
Water Utilities											
Machine Usage	ft^3/hr		N/A	N/A	N/A	N/A	N/A	N/A	N/A	Water Jet (Mohammed) - 0.5m^3/hr (132.09gal/hr) (17.6573 ft^3/hr)	
Water Cost	$/gal	[Detroit- $23.76/Mcf for water, $52.73/Mcf for sewage (Mcf=1000 ft^3)]			N/A					[Water Jet (Mohammed) - 0.05€/m^3 (0.059$/m^3) (0.000223$/gal)]	
Compressed Air Utilities											
Machine Usage	ft^3/hr	0.00510 €/Nm^3 ($0.00016/SCF)	N/A	N/A	N/A	Water Jet (Mohammed) - 5.0Nm^3/hr (3.110 SCFM --> 186.6 SCFH)	N/A	N/A	N/A	Water Jet (Mohammed) - 5.0Nm^3/hr (3.110 SCFM --> 186.6 SCFH)	
Labor											
Direct # Involved			1 or 0.5	0.5	0.5	0.5	0.5	0.5	0	0.5	
Indirect # Involved			0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
Consumables											
Cost per Direct Person	$/hr	Labor related consumables	?	?	?	?	?	?	0	?	
Cost per output lb	$/lb	Equipment related consumables	?	$0.0020 / lb	?	?	?	?	0	?	
Maintenance											
Known Expense	$/yr		?	$10,000.00	?	?	?	?		$11,675.00	
Maintenance/Repair Rate	%		?	?	?	3%	?	?	?	2%	
Material											
In		New material IN	Yes	No	Yes	Yes	Yes	No	No	No	
Out		Material Out (Scrap)	Yes	No	Maybe	Yes	No	No	No	Yes	

Category	Units	Notes	Equipment			
Equipment			Net-Shape Trimmer	IR Oven	Injection Molder	Final Inspection
			Jim - Dynamic Robotic Solutions Trimmer	Purdue	Kipp and Jim	
Make			?	IR Oven	?	Person
Model			?	Generic	?	Person
Lifespan	Years	Delete this?	?	?	?	?
Cost	$		?	$85,000.00	$2,500,000.00	Hourly Labor
Cost Converted	Date		N/A	7/13/2018	N/A	N/A
Processing / Movement / rate			?		?	
Cycle Time	s		?	Entered or Internal Temp TP-P4 based (Jespersen)	60s used	60s used
Scrap		If known, or avg %		N/A	?	Reject rate ?
Tooling		Jig, mold, end effector, etc.			Mold	?
Lifespan	# of parts		?	N/A	1,000,000 shots used	?
Cost	$		?	N/A	$250k - $300k ($275k used)	?
Plant Operation						
Footprint	sf		?	162	?	? - 25sf used
Safety Standoff	sf		None used	None used	None used	None used
Energy						
In-use	kW			150		
Standby	kW		?	?	?	?
Water Utilities						
Machine Usage	ft^3/hr		N/A	N/A	N/A	N/A
Water Cost	$/gal	[Detroit- $23.76/Mcf for water, $52.73/Mcf for sewage (Mcf=1000 ft^3)]				
Compressed Air Utilities						
Machine Usage	ft^3/hr	0.00510 €/Nm^3 ($0.00016/SCF)	N/A	N/A	N/A	N/A
Labor						
Direct # Involved			0.5	0	0.5	1
Indirect # Involved			0.1	0.1	0.1	0.1
Consumables						
Cost per Direct Person	$/hr	Labor related consumables		0		
Cost per output lb	$/lb	Equipment related consumables		0		
Maintenance						
Known Expense	$/yr		?	?	?	?
Maintenance/Repair Rate	%		?	?	?	?
Material						
In		New material IN	No	No	Yes	No
Out		Material Out (Scrap)	Yes	No	No	No

APPENDIX B. SHAPE FACTOR DETERMINATION

The following tables break down the shape complexity, speed correction factor, and the shape complexity for various parts of the test coupon. The known run times are from the trial run recorded 26 June 2019, file GOPR0319.

Table 52. Shape factor determinationfor total test coupon.

Component	Total test coupon			
Known run time (sec)	60			
Lengths (mm)	Straight	508	Curve	399
Curve length factors	Radius (mm)	15.875	# of curves	16
QTC speed setting (mm/min)	Straight	8,000	Curve	4,000
QTC table max speed (mm/min)	20,000			
Shape complexity	1.79			
Layup time (QTC speed based, sec)	Straight	3.81	Curve	5.985
Layup time (SC based, sec)	Straight	6.8025	Curve	10.68582
Speed correction factor (calc)	3.60			
Shape factor	6.43			
Estimated layup time (sec)	62.95			
Percent difference	-4.92%			

Table 53. Shape factor determination for test coupon bushings.

Component	First bushing length				Second bushing length			
Known run time (sec)	36				15			
Lengths (mm)	Straight	0	Curve	249.375	Straight	0	Curve	149.625
Curve length factors	Radius (mm)	15.875	# of curves	10	Radius (mm)	15.875	# of curves	6
QTC speed setting (mm/min)	Straight	8,000	Curve	4,000	Straight	8,000	Curve	4,000
QTC table max table speed (mm/min)	20,000				20,000			
Shape complexity	1.64				1.64			
Layup time (QTC speed based, sec)	Straight	0	Curve	3.74	Straight	0	Curve	2.24

Layup time (SC based, sec)	Straight	0	Curve	6.12	Straight	0	Curve	3.67
Speed correction factor (calc)	5.00				5.00			
Shape factor	8.18				8.18			
Estimated layup time (sec)	30.61				18.37			
Percent difference	14.97%				-22.44%			

Table 54. Shape factor determination for test coupon straight lengths.

Component	Left side straight length				Right side straight length			
Known run time (sec)	4				5			
Lengths (mm)	Straight	254	Curve	0	Straight	254	Curve	0
Curve length factors	Radius (mm)	0	# of curves	0	Radius (mm)	0	# of curves	0
QTC speed setting (mm/min)	Straight	8,000	Curve	4,000	Straight	8,000	Curve	4,000
QTC table max table speed (mm/min)	20,000				20,000			
Shape complexity	1.00				1.00			
Layup time (QTC speed based, sec)	Straight	1.905	Curve	0	Straight	1.905	Curve	0
Layup time (SC based, sec)	Straight	1.905	Curve	0	Straight	1.905	Curve	0
Speed correction factor (calc)	2.50				2.50			
Shape factor	2.50				2.50			
Estimated layup time (sec)	4.76				4.76			
Percent difference	-19.06%				4.75%			

APPENDIX C. UNSTEADY HEAT CONDUCTION PLOT EXTRACTION

In order to be useful in computations, the equations for the lines within Figure 57 and Figure 58 were extracted; Equation 68 and Equation 70 respectively. The extracted points from the plots were also plotted in an inverse fashion and their equations for the lines extracted as well; Equation 69 and Equation 71 respectively. This allows for easily transitioning from the Fourier Number to the temperature number shown on the y-axis in Figure 57 and Figure 58. For the equations of the lines, *x* represents the Fourier Number and *Y* represents the temperature variation.

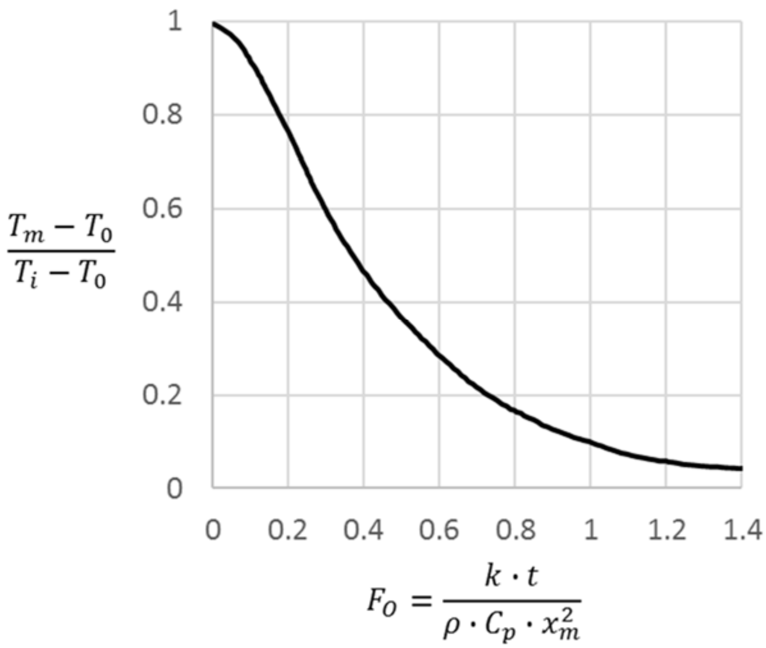

Figure 57. Plot to calculate the mid-plane temperature of a flat plate [43].

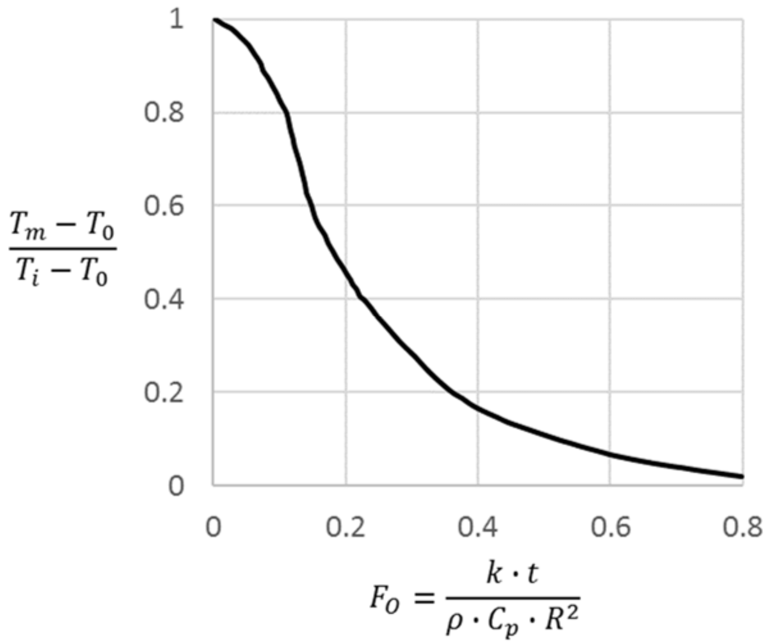

Figure 58. Plot to calculate the midpoint temperature of a cylinder [43].

The data points extracted from the plots in Figure 57 and Figure 58 are given in Table 56. Plots of the extracted points and the inverse of the extracted points used to find Equation 68 and Equation 69 for a flat plate follow Table 55. Plots of the extracted points and the inverse of the extracted points used to find Equation 70 and Equation 71 for a cylinder follow Table 56.

Table 55. Data points extracted from Figure 57: mid-plane for a flat plate.

x	y		x	y		x	y		x	y
0.004105	0.995336		0.257697	0.666611		0.552531	0.320114		0.955557	0.10812
0.014101	0.991157		0.26141	0.65717		0.563522	0.314294		0.969315	0.105204
0.024183	0.986449		0.265933	0.65019		0.572797	0.305006		0.981955	0.102039
0.035362	0.980223		0.271433	0.64079		0.583443	0.297537		0.994139	0.100006
0.049186	0.972611		0.276474	0.634125		0.593414	0.28747		1.003227	0.096734
0.058452	0.964865		0.281681	0.625859		0.606194	0.279763		1.013986	0.093229
0.068559	0.957266		0.287375	0.617824		0.617598	0.271208		1.027519	0.090072
0.076432	0.948733		0.294168	0.605483		0.628239	0.264527		1.040858	0.085585
0.084762	0.939564		0.299475	0.598308		0.63751	0.256046		1.052769	0.082649
0.090527	0.929594		0.305956	0.586676		0.648146	0.250341		1.065674	0.079124
0.096696	0.923817		0.313566	0.576573		0.657417	0.241706		1.079642	0.075031
0.101076	0.914512		0.320778	0.567632		0.668052	0.236156		1.09362	0.072903
0.109877	0.905477		0.326651	0.556039		0.676427	0.22813		1.108845	0.0694
0.117379	0.895252		0.333081	0.548087		0.687952	0.223086		1.123727	0.066848
0.122402	0.886406		0.341004	0.536654		0.697025	0.216577		1.138606	0.064708
0.128271	0.88053		0.3491	0.526537		0.708191	0.211135		1.153488	0.062054
0.132407	0.870565		0.356444	0.519545		0.717105	0.20455		1.168365	0.060325
0.137387	0.864012		0.364003	0.508453		0.727986	0.199156		1.184239	0.057515

0.142409	0.855341		0.372881	0.49791		0.739909	0.194149		1.198112	0.058
0.14882	0.846652		0.385358	0.483077		0.752834	0.187407		1.204318	0.055982
0.153845	0.838914		0.397279	0.466982		0.764666	0.179885		1.213985	0.055292
0.160616	0.826509		0.407947	0.458452		0.777434	0.175563		1.22821	0.053367
0.167604	0.816808		0.418532	0.444362		0.787386	0.16865		1.242754	0.050756
0.174275	0.804685		0.428334	0.434134		0.79745	0.167023		1.257626	0.049851
0.183327	0.791367		0.43787	0.426605		0.802835	0.162945		1.272499	0.048739
0.192749	0.776412		0.446571	0.415372		0.814689	0.160681		1.287373	0.047422
0.200322	0.765585		0.455759	0.405633		0.82305	0.154815		1.302245	0.046516
0.207423	0.753423		0.467441	0.397136		0.834819	0.15054		1.317118	0.045405
0.215343	0.739704		0.478897	0.386843		0.847627	0.146897		1.330992	0.045766
0.222396	0.727553		0.488378	0.376165		0.859649	0.14161		1.347355	0.04405
0.226617	0.718828		0.500339	0.364784		0.871585	0.134426		1.36173	0.043305
0.232474	0.709853		0.508901	0.358162		0.884917	0.131214		1.376599	0.042913
0.238432	0.699159		0.518556	0.350349		0.898465	0.125715		1.391473	0.041699
0.243233	0.691029		0.528123	0.342979		0.912791	0.121888		1.403857	0.042419
0.248027	0.684157		0.535994	0.334614		0.927686	0.117073			
0.251657	0.67471		0.545557	0.327958		0.942014	0.112946			

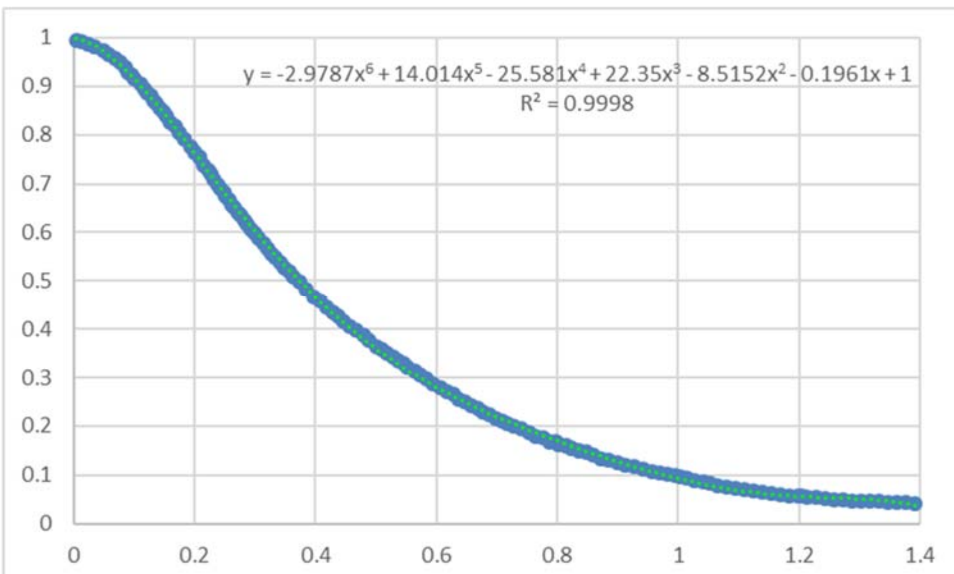

Figure 59. Plot of extracted points from Table 55 to determine equation of the line: mid-plane of a plate.

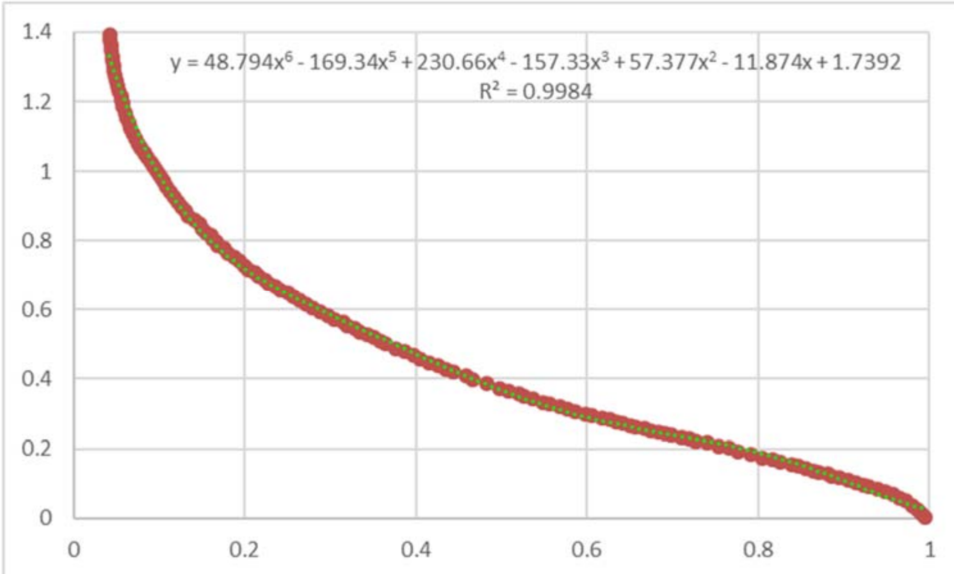

Figure 60. Plot of inverse of extracted points from Table 55 to determine equation of the line: mid-plane of a plate.

Table 56. Data points extracted from line of Figure 58: mid-point of a cylinder.

x	y		x	y		x	y
0.002851	0.998205		0.168153	0.537816		0.416246	0.154575
0.014502	0.987674		0.173117	0.520182		0.429288	0.146496
0.027658	0.977868		0.180037	0.503595		0.444149	0.136561
0.040879	0.960168		0.187079	0.485545		0.461225	0.127922
0.052712	0.943584		0.194402	0.470313		0.476298	0.120536
0.061942	0.923615		0.201438	0.453889		0.49147	0.113012
0.070728	0.905453		0.206975	0.441879		0.507747	0.105386
0.074665	0.888784		0.210105	0.431924		0.524344	0.097583
0.081595	0.874932		0.216162	0.421735		0.539889	0.091282
0.088636	0.857196		0.221269	0.406516		0.554737	0.084787
0.095865	0.838504		0.228927	0.397157		0.570806	0.078417
0.101265	0.821714		0.239815	0.378314		0.586524	0.072559
0.110275	0.798611		0.249028	0.360174		0.599704	0.066926
0.114103	0.776661		0.259393	0.344025		0.616212	0.061877
0.116604	0.760223		0.26992	0.326947		0.631925	0.057278
0.119934	0.744007		0.280716	0.309532		0.647638	0.052889
0.12195	0.729197		0.292718	0.292738		0.663349	0.04892
0.12566	0.711898		0.304717	0.276514		0.679059	0.045266
0.130522	0.690166		0.315511	0.259608		0.694768	0.041717
0.134385	0.667225		0.326034	0.243789		0.710477	0.038482
0.137867	0.647904		0.338287	0.227367		0.726186	0.034828
0.140487	0.627898		0.351016	0.211412		0.741896	0.031383
0.144145	0.614996		0.36404	0.197038		0.757603	0.028464
0.148724	0.59806		0.37577	0.187645		0.773312	0.025124

0.153029	0.576356		0.388132	0.175006		0.789717	0.021937
0.159746	0.555421		0.400735	0.164945		0.798902	0.01999

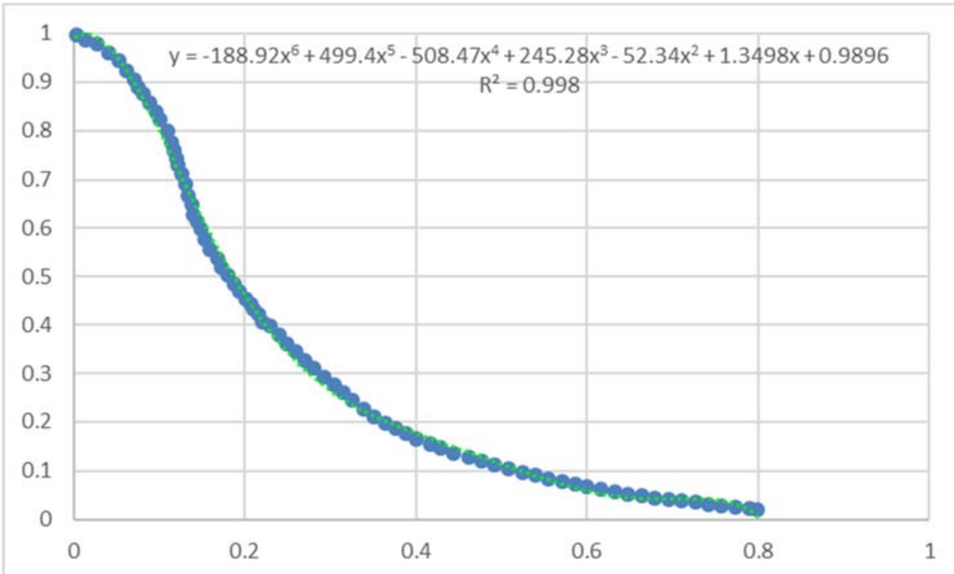

Figure 61. Plot of extracted points from Table 56 to determine equation of the line: mid-point of a cylinder.

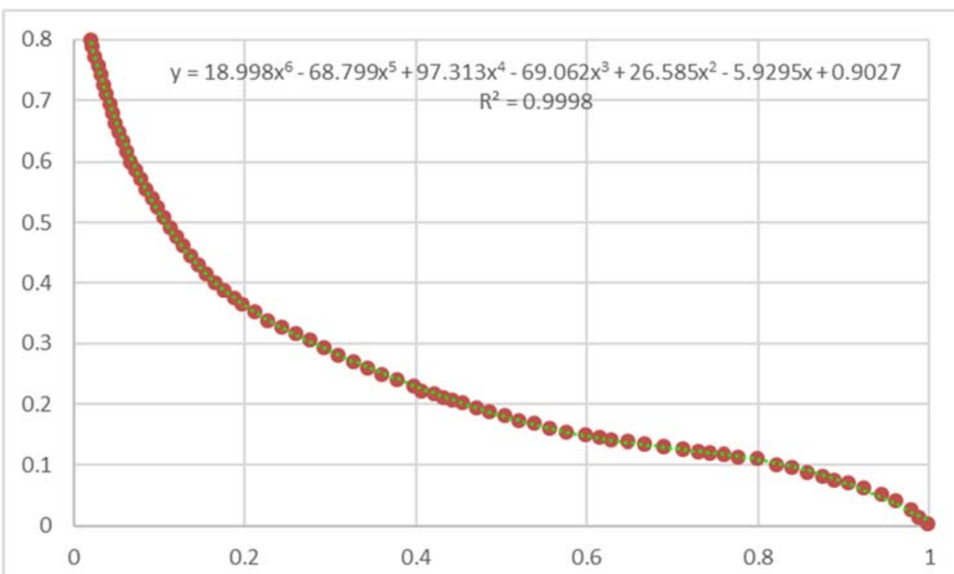

Figure 62. Plot of inverse of extracted points from Table 56 to determine equation of the line: mid-point of a cylinder.

APPENDIX D. ENGINEERING ESTIMATES CYCLE TIME BREAKOUT

Table 57. Cycle time breakout for each process step in the five scenarios for the *engineering estimates*.

Process Step / Sub-process steps	Scenarios		
1. Preforming and Bushing Insert	1, 2, & 4 Cycle Time	3: 50% Increase of Injection Cycle Time	5: Workers Replace Robots Cycle Time
Bushing loading time (per bushing)(s)	3.00	3.00	4.50
Start time (s)	3.00	3.00	3.00
Layup time (s)	62.92	62.92	62.92
Finish time (s)	3.00	3.00	3.00
Unload time (s)	5.00	5.00	7.50
Creel change time (s)	0.25	0.25	0.25
Total time (s)	77.17	77.17	81.17
Process Step / Sub-process steps	Scenarios		
2. Transfer to Injection Molding	1, 2, & 4 Cycle Time	3: 50% Increase of Injection Cycle Time	5: Workers Replace Robots Cycle Time
Unload (s)	5.00	5.00	7.50
Transfer (s)	5.00	5.00	7.50
Load (s)	5.00	5.00	7.50
Total time (s)	15.00	15.00	22.50
Process Step / Sub-process steps	Scenarios		
3. Injection Molding	1, 2, & 4 Cycle Time	3: 50% Increase of Injection Cycle Time	5: Workers Replace Robots Cycle Time
Load mold	5.00	7.50	7.50
Close mold	2.00	3.00	2.00
Inject cycle	90.00	135.00	90.00
Fill	0.55	0.82	0.55
Pack	2.45	3.68	2.45
Cool	87.00	130.50	87.00
Open mold	5.00	7.50	5.00
Eject part	5.00	7.50	7.50
Total cycle time (s):	107.00	160.50	112.00
Process Step / Sub-process steps	Scenarios		

4. Transfer to Trim & QC	1, 2, & 4 Cycle Time	3: 50% Increase of Injection Cycle Time	5: Workers Replace Robots Cycle Time
Unload IM (s)	5	5	7.5
Transfer (s)	5	5	7.5
Trim (s)	30	30	30
Transfer (s)	5	5	7.5
Load (s)	5	5	7.5
Total time (s)	50	50	60
Process Step / Sub-process steps	Scenarios		
5. Trimming	1, 2, & 4 Cycle Time	3: 50% Increase of Injection Cycle Time	5: Workers Replace Robots Cycle Time
Trim (s)	30	30	30
Process Step / Sub-process steps	Scenarios		
6. Quality Control	1, 2, & 4 Cycle Time	3: 50% Increase of Injection Cycle Time	5: Workers Replace Robots Cycle Time
Scanning (s)	20	20	45

APPENDIX E. AS-INSTALLED AND AS-INSTALLED ADJUSTED CYCLE TIME BREAKOUTS

The numbers from these tables come from the test coupon trial run conducted on 26 June 2019 and recorded under the file name GOPR0319. The 4x adjustment and delay time comes from the transfer robot movement program NAME COUPON_AUTO-2, see Table 62*. The maximum relative speed setting was 20%, so adjusting that to 100% is four times faster. The delays come from averaging the total delays observed in the program (20) and adjusting them to fit the number of robot process steps kept (14).*

Table 58. Injection molding machine cycle time breakout for the *pre-production* and *production adjusted* cases.

Injection Molding Machine Cycle				
Process Step Time (sec)	Process step Description	Adjusted Movement Times (4 faster with 0.736 delay per step)	Person transferring (actual)	Person transferring (adjusted)
5	Close mold	5	5	5
90	Injection cycle	90	90	90
4	Open mold	4	4	4
20	Demold (robot movement from IM delay through IM part pickup)	4.59	30.00	6.52
16	Load mold (prefrom loading into IM plus movement till robot is clear of IM)	3.79	24.00	5.32
135	Total used	107.38	153.00	110.83

Table 59. Trimming cycle time breakout for the *pre-production* and *production adjusted* cases.

Trimming				
Process Step Time (sec)	Process step Description	Adjusted Movement Times (4 faster with 0.736 delay per step)	Person transferring (actual)	Person transferring (adjusted)
29	Trimming	29	Trimming	29

Table 60. QTC preform layup cycle time breakout for *pre-production* and *production adjusted* cases.

QTC Preform Layup						
Model Cycle Step	Process Step Time (sec)	Process step Description	Adjusted Movement Times (4x faster with 0.736 delay per step)	Person transferring (actual)	Person transferring (adjusted)	Notes
Start time (s)	19	Layup Head recovery twist	19	19	19	
Start time (s)	10	Table moves from pickup location to layup position	10	10	10	
Layup time (s)	60	Layup	60	60	60	
Finish time (s)	10	Table moves from layup location to pickup position	10	10	10	
Bushing loading time (per bushing)(s) & Unload time (s)	39	Table paused for preform pickup and bushing loading	12.34	57.5	17.516	*Transfer Robot Process Step # 1, 2, 3, 4, and 5 altered for this adjustment
	138	Total Used	13	156.5		
	119	Total needed (w/ no robot speed changes) (Layup head recovery twist can be done elsewhere)	92.344		97.516	

Table 61. Transfer robot cycle time breakouts for the *pre-production* and *production adjusted* cases.

Transfer Robot							
Process Step #	Process Step Time (sec)	Process step Description	Adjusted Mvmt Time (4x faster with 0.736 delay per step)(sec)	Used for QTC --> IM Transfer	Used for IM --> Cut & Inspection Transfer		
1	3	Mvmt (SP to bushing pickup)	1.19	X			Actual
2	7	Bushing pickup	1.99	X			
3	12	Mvmt (bushing pickup to preform pickup)	2.99	X			Adjusted
4	6	Preform pickup	1.79	X			
5	9	Bushing placement	2.39	X			
6	17	Mvmt (preform pickup to IM pickup point)	3.99	X			
7	14	Delay (impact previous Mvmt due to stop and start of robot)	14.00	X			
8	15	IM part pickup	3.59		X		
9	12	Preform load into IM	2.99		X		
10	12	Mvmt (IM pickup point to trimming)	2.99		X		
11	29	Trim (~1 sec w/ snip tool)(Robot does not dictate this time)	29.00		X		
12	9	Mvmt (trim to QC jig)	2.39		X		
13	4	Part loading into QC jig	1.39		X		
14	9	Mvmt (Robot return to start point)	2.39		X		
						Person transfer	
	62	Total movement time	15.93	32	30	48	45
	53	Pickup & loading time	14.13	22	31	33	46.5
	29	Trimming	29.00		29	0	29
	14	Delay	14.00	14		21	0
	158	Total Used	73.07	68	90	102	120.5
	144	Total needed (remove delay time)	59.07	54	90		
		Total needed (remove delay time, use adjusted times)	59.07	14.33	44.73	21.50	67.10

Table 62. Relative speeds and delay times for transfer robot from movement program.

Robot Movement: NAME COUPON_AUTO-2							
Coordinate	Relative speed (%)	Coordinate	Relative speed (%)	Delays	Delay time		
0	15.00	28	10.00	1	0.4		
1	5.00	29	1.50	2	0.25	Max delay	
2	0.20	30	0.07	3	0.25	3	
3	0.20	31	0.78	4	0.25	Min delay	
4	7.00	32	0.25	5	0.25	0.25	
5	10.00	33	0.20	6	0.25	Average delay	
6	5.00	34	1.00	7	0.25	0.515	
7	4.00	35	5.00	8	0.4	Total Delay	
8	2.00	36	10.00	9	0.25	10.3	
9	0.20	37	8.00	10	0.25		
10	0.20	38	7.00	11	0.25	Observed Robot Process Steps	
11	2.00	39	0.03	12	0.25	14	
12	10.00	40	6.00	13	0.25		
13	2.00	41	15.00	14	0.25	Average time delay per step	
14	0.20	42	20.00	15	0.25	0.735714	
15	0.75	43	10.00	16	0.25		
16	15.00	44	1.50	17	3		
17	20.00	45	5.00	18	0.25		
18	20.00	46	5.00	19	0.25		
19	20.00	47	15.00	20	2.5		
20	20.00						
21	20.00						
22	3.00	Max speed	20.00				
23	3.00						
24	1.50						
25	0.20						
26	0.20						
27	1.50						

APPENDIX F. COST SEGMENTATION CHART BREAKDOWNS

The following tables were used to create the cost segmentation bar charts found in Sections 4.5.4, 4.5.5, and 4.5.6.

Table 63. *Engineering estimates* cost segmentaion values for Figure 38.

	Scenario 1: Base Case	Scenario 2: 25% Equipment Cost Increase	Scenario 3: 50% Injection Cycle Time Increase	Scenario 4: 10% Reject at Inspection	Scenario 5: Workers Replace Robots
IM PP Material	0.11	0.11	0.11	0.12	0.11
TP Tape Material	0.16	0.16	0.16	0.18	0.16
AL Bushings	0.63	0.63	0.63	0.69	0.63
Machine amortization	0.85	1.06	0.85	0.85	0.74
Tool cost	0.20	0.20	0.20	0.20	0.16
Plant operating cost	0.21	0.21	0.21	0.21	0.21
Energy cost - active	0.12	0.12	0.13	0.13	0.12
Energy cost - standby	0.01	0.01	0.02	0.01	0.01
Water cost	0.05	0.05	0.07	0.05	0.05
Sewage cost	0.05	0.05	0.08	0.06	0.05
Direct Labor cost	0.99	0.99	1.49	1.09	3.12
Indirect Labor cost	0.23	0.23	0.35	0.25	0.73
Consumables cost - Labor	0.03	0.03	0.05	0.04	0.10
Equipment maintenance	0.30	0.38	0.30	0.30	0.20
Total Cost	3.94	4.23	4.64	4.18	6.38

Table 64. *Pre-production* cost segmentation values for Figure 40.

	Scenario 1: Base Case	Scenario 2: 25% Equipment Cost Increase	Scenario 3: 50% Injection Cycle Time Increase	Scenario 4: 10% Reject at Inspection	Scenario 5: Workers Replace Robots
IM PP Material	0.11	0.11	0.11	0.12	0.11
TP Tape Material	0.16	0.16	0.16	0.18	0.16
AL Bushings	0.63	0.63	0.63	0.69	0.63
Machine amortization	1.10	1.37	2.20	1.10	1.99
Tool cost	0.20	0.20	0.40	0.20	0.32
Plant operating cost	0.21	0.21	0.42	0.21	0.42
Energy cost - active	0.20	0.20	0.33	0.23	0.31
Energy cost - standby	0.01	0.01	0.01	0.01	0.00
Water cost	0.06	0.06	0.13	0.06	0.10
Sewage cost	0.06	0.06	0.14	0.07	0.11
Direct Labor cost	1.47	1.47	2.82	1.61	7.80
Indirect Labor cost	0.34	0.34	0.66	0.38	1.82
Consumables cost - Labor	0.05	0.05	0.09	0.05	0.26
Equipment maintenance	0.39	0.49	0.79	0.39	0.58
Total Cost	5.00	5.37	8.89	5.30	14.61

Table 65. *Production adjusted* cost segmentation values for Figure 42.

	Scenario 1: Base Case	Scenario 2: 25% Equipment Cost Increase	Scenario 3: 50% Injection Cycle Time Increase	Scenario 4: 10% Reject at Inspection	Scenario 5: Workers Replace Robots
IM PP Material	0.11	0.11	0.11	0.12	0.11
TP Tape Material	0.16	0.16	0.16	0.18	0.16
AL Bushings	0.63	0.63	0.63	0.69	0.63
Machine amortization	1.10	1.37	1.10	1.10	0.99
Tool cost	0.20	0.20	0.20	0.20	0.16
Plant operating cost	0.21	0.21	0.21	0.21	0.21
Energy cost - active	0.14	0.14	0.15	0.15	0.13
Energy cost - standby	0.01	0.01	0.01	0.00	0.01
Water cost	0.05	0.05	0.07	0.05	0.05
Sewage cost	0.05	0.05	0.08	0.06	0.05
Direct Labor cost	1.00	1.00	1.50	1.10	3.72
Indirect Labor cost	0.23	0.23	0.35	0.26	0.87
Consumables cost - Labor	0.03	0.03	0.05	0.04	0.12
Equipment maintenance	0.39	0.49	0.39	0.39	0.29
Total Cost	4.31	4.68	5.01	4.55	7.51

APPENDIX G. DOMESTIC AND GLOBAL INPUTS

This section provides the database assembled for the domestic and global manufacturing cost comparisons. These include, but are not limited to: latitude, longitude, indirect/direct labor rate, wage percentage of total compensation, electric rates, water rates, sewer rates, rent rates, and COLA rates.

Table 66. U.S. State location and wage related inputs (1 of 2).

Census Region	EAI Region	DOE Region	SF Region	State	Latitude	Longitude	Wage % of total compensation	IDL Cost ($/hr)	DL Cost ($/hr)	IDL & DL Notes
6	6	6	4	AL	32.992	-86.753	70.2%	$49.73	$18.35	1
9	10	1	10	AK	62.983	-151.194	70.1%	$58.55	$22.49	2
8	8	2	9	AZ	33.258	-111.727	71.4%	$48.10	$18.66	1
7	7	7	6	AR	34.690	-92.622	72.2%	$47.00	$18.16	1
9	9	1	9	CA	36.014	-119.789	70.1%	$59.19	$20.64	1
8	8	2	8	CO	39.005	-105.282	71.4%	$61.72	$21.15	1
1	1	5	1	CT	41.469	-72.885	68.4%	$62.41	$22.71	1
5	5	6	3	DE	38.951	-75.476	71.0%	$64.31	$17.16	1
5	5	6	4	FL	28.083	-81.942	71.0%	$51.52	$18.73	1
5	5	6	4	GA	32.745	-83.546	71.0%	$50.06	$18.04	1
9	10	1	9	HI	20.888	-157.200	70.1%	$45.69	$20.29	2
8	8	2	10	ID	44.326	-115.093	71.4%	$48.63	$18.62	1
3	3	4	5	IL	40.736	-88.980	69.2%	$50.26	$19.02	1
3	3	4	5	IN	40.101	-86.237	69.2%	$47.52	$19.09	1
4	4	3	7	IA	41.833	-92.792	69.6%	$47.14	$19.59	1
4	4	3	7	KS	38.293	-97.846	69.6%	$47.73	$20.51	1
6	6	6	4	KY	37.553	-85.920	70.2%	$46.80	$17.36	1
7	7	7	6	LA	31.080	-91.971	72.2%	$55.91	$22.08	1
1	1	5	1	ME	44.836	-69.369	68.4%	$46.83	$22.85	1
5	5	6	3	MD	39.269	-77.083	71.0%	$60.04	$21.19	1
1	1	5	1	MA	42.249	-71.556	68.4%	$60.88	$24.59	1
3	3	4	5	MI	43.401	-84.812	69.2%	$57.10	$19.47	1
4	4	3	5	MN	45.640	-93.723	69.6%	$55.19	$21.96	1
6	6	6	4	MS	32.485	-89.819	70.2%	$47.01	$17.43	1

Table 67. U.S. State location and wage related inputs (2 of 2).

Census Region	EAI Region	DOE Region	SF Region	State	Latitude	Longitude	Wage % of total compensatio	IDL Cost ($/hr)	DL Cost ($/hr)	IDL & DL Notes
4	4	3	7	MO	38.359	-91.897	69.6%	$50.01	$19.10	1
8	8	2	8	MT	47.055	-110.215	71.4%	$61.24	$19.44	1
4	4	3	7	NE	41.205	-99.108	69.6%	$48.51	$18.74	1
8	8	2	9	NV	39.267	-117.619	71.4%	$51.60	$20.60	1
1	1	5	1	NH	43.179	-71.448	68.4%	$64.35	$21.74	1
2	2	5	2	NJ	40.271	-74.519	68.4%	$63.95	$22.00	1
8	8	2	6	NM	34.357	-106.216	71.4%	$52.48	$17.48	1
2	2	5	2	NY	42.610	-75.885	68.4%	$63.69	$18.61	1
5	5	6	4	NC	35.522	-78.884	71.0%	$54.04	$18.64	1
4	4	3	8	ND	47.502	-100.033	69.6%	$50.22	$23.84	1
3	3	4	5	OH	40.479	-82.762	69.2%	$52.50	$20.08	1
7	7	7	6	OK	35.533	-97.241	72.2%	$50.86	$19.10	1
9	9	1	10	OR	44.388	-122.150	70.1%	$46.00	$20.94	1
2	2	5	3	PA	40.645	-77.887	68.4%	$53.61	$19.17	1
1	1	5	1	RI	41.690	-71.502	68.4%	$61.81	$20.53	1
5	5	6	4	SC	34.019	-80.947	71.0%	$55.66	$20.78	1
4	4	3	8	SD	44.502	-100.247	69.6%	$48.95	$18.57	1
6	6	6	4	TN	35.700	-86.227	70.2%	$48.88	$18.82	1
7	7	7	6	TX	31.098	-98.190	72.2%	$59.04	$19.98	1
8	8	2	8	UT	39.610	-111.617	71.4%	$45.48	$16.93	1
1	1	5	1	VT	44.089	-72.878	68.4%	$55.38	$19.57	2
5	5	6	3	VA	37.732	-78.318	71.0%	$57.73	$19.76	1
9	9	1	10	WA	47.254	-121.421	70.1%	$61.83	$30.91	1
5	5	6	3	WV	38.845	-80.680	71.0%	$52.16	$20.96	1
3	3	4	5	WI	44.032	-88.952	69.2%	$53.01	$21.25	1
8	8	2	8	WY	42.556	-107.029	71.4%	$61.02	$26.61	2
5	5	6	3	DC	38.917	-77.033	71.0%	$71.96	$27.00	3
9	10	1	9	GU	13.445	144.768	70.1%	$39.17	$14.98	4
2	2	5	2	PR	18.208	-66.502	68.4%	$53.05	$11.65	4
2	2	5	2	VI	17.728	-64.768	68.4%	$39.81	$21.05	5
9	10	1	9	AS	-14.329	-170.714	70.1%	$51.74	$21.71	5
				U.S.	39.828	-98.580	70.0%	$54.51	$20.17	1

Table 68. U.S. State utilities related inputs (1 of 2).

State	Electric - Industrial ($/kWh)	Water - Commercial ($/1000ft^3)	Water Notes	Wastewater ($/1000ft^3)	Wastewater Notes	Wastewater to water rate conversion (%)				
						Best Fit Utilized	EIA	DOE	SF	Census
AL	0.056	34.78	A1	25.36	A	59.32	59.32	60.65	56.10	59.32
AK	0.169	23.45	B1	32.40	B	72.36	72.36	102.85	49.85	102.85
AZ	0.060	29.67	B1	32.30	C	109.03	109.03	109.03	128.16	109.03
AR	0.059	22.18	B1	21.92	B	101.19	101.05	101.05	101.19	101.05
CA	0.114	31.13	B1	24.29	B	128.16	105.39	102.85	128.16	102.85
CO	0.070	15.54	B1	14.25	B	109.03	109.03	109.03	84.45	109.03
CT	0.145	51.85	D1	23.68	B	80.19	80.19	90.91	80.19	80.19
DE	0.081	23.76	B1	31.20	B	76.17	61.03	60.65	81.79	61.03
FL	0.078	17.76	B1	29.28	B	60.65	61.03	60.65	56.10	61.03
GA	0.054	17.76	B1	29.28	B	60.65	61.03	60.65	56.10	61.03
HI	0.267	19.80	B1	24.29	B	81.53	72.36	102.85	128.16	102.85
ID	0.055	32.36	B1	32.40	B	99.86	109.03	109.03	49.85	109.03
IL	0.067	23.08	B1	24.93	B	92.57	91.45	91.45	92.57	91.45
IN	0.073	23.08	B1	24.93	B	92.57	91.45	91.45	92.57	91.45
IA	0.059	26.00	B1	29.62	B	87.77	87.77	87.77	84.78	87.77
KS	0.072	26.00	B1	29.62	B	87.77	87.77	87.77	84.78	87.77
KY	0.054	17.37	B1	29.28	B	59.32	59.32	60.65	56.10	59.32
LA	0.049	22.18	B1	21.92	B	101.19	101.05	101.05	101.19	101.05
ME	0.093	38.74	B1	48.31	B	80.19	80.19	90.91	80.19	80.19
MD	0.081	25.51	B1	31.20	B	81.79	61.03	60.65	81.79	61.03
MA	0.147	38.74	B1	48.31	B	80.19	80.19	90.91	80.19	80.19
MI	0.074	23.08	B1	24.93	B	92.57	91.45	91.45	92.57	91.45
MN	0.074	21.88	B1	24.93	B	87.77	87.77	87.77	92.57	87.77
MS	0.063	17.37	B1	29.28	B	59.32	59.32	60.65	56.10	59.32

Table 69. U.S. State utilities related inputs (2 of 2).

State	Electric - Industrial ($/kWh)	Water - Commercial ($/1000ft^3)	Water Notes	Wastewater ($/1000ft^3)	Wastewater Notes	Wastewater to water rate conversion (%)				
						Best Fit Utilized	EIA	DOE	SF	Census
MO	0.060	26.00	B1	29.62	B	87.77	87.77	87.77	84.78	87.77
MT	0.053	15.54	B1	14.25	B	109.03	109.03	109.03	84.45	109.03
NE	0.070	26.00	B1	29.62	B	87.77	87.77	87.77	84.78	87.77
NV	0.049	26.48	B1	24.29	B	109.03	109.03	109.03	128.16	109.03
NH	0.141	38.74	B1	48.31	B	80.19	80.19	90.91	80.19	80.19
NJ	0.102	18.81	B1	27.98	B	67.22	94.49	90.91	62.89	94.49
NM	0.052	23.90	B1	21.92	B	109.03	109.03	109.03	101.19	109.03
NY	0.057	17.60	B1	27.98	B	62.89	94.49	90.91	62.89	94.49
NC	0.060	17.76	B1	29.28	B	60.65	61.03	60.65	56.10	61.03
ND	0.082	13.27	B1	14.25	B	93.08	87.77	87.77	84.45	87.77
OH	0.066	23.08	B1	24.93	B	92.57	91.45	91.45	92.57	91.45
OK	0.049	22.18	B1	21.92	B	101.19	101.05	101.05	101.19	101.05
OR	0.060	16.15	B1	32.40	B	49.85	105.39	102.85	49.85	102.85
PA	0.068	25.51	B1	31.20	B	81.79	94.49	90.91	81.79	94.49
RI	0.171	38.74	B1	48.31	B	80.19	80.19	90.91	80.19	80.19
SC	0.058	17.76	B1	29.28	B	60.65	61.03	60.65	56.10	61.03
SD	0.075	13.27	B1	14.25	B	93.08	87.77	87.77	84.45	87.77
TN	0.060	17.37	B1	29.28	B	59.32	59.32	60.65	56.10	59.32
TX	0.053	22.18	B1	21.92	B	101.19	101.05	101.05	101.19	101.05
UT	0.055	15.54	B1	14.25	B	109.03	109.03	109.03	84.45	109.03
VT	0.107	38.74	B1	48.31	B	80.19	80.19	90.91	80.19	80.19
VA	0.067	25.51	B1	31.20	B	81.79	61.03	60.65	81.79	61.03
WA	0.047	16.15	B1	32.40	B	49.85	105.39	102.85	49.85	102.85
WV	0.058	23.76	B1	31.20	B	76.17	61.03	60.65	81.79	61.03
WI	0.075	23.08	B1	24.93	B	92.57	91.45	91.45	92.57	91.45
WY	0.065	15.54	B1	14.25	B	109.03	109.03	109.03	84.45	109.03
DC	0.084	25.51	B1	31.20	B	81.79	61.03	60.65	81.79	61.03
GU	0.291	19.80	B1	24.29	B	81.53	72.36	102.85	128.16	102.85
PR	0.241	20.13	B1	27.98	B	71.95	94.49	90.91	62.89	94.49
VI	0.519	17.35	B1	27.98	B	62.00	94.49	90.91	62.89	94.49
AS	0.261	18.65	B1	24.29	B	76.79	72.36	102.85	128.16	102.85
U.S.	0.066	19.95	B1	27.35	B	72.94	72.94	72.94	72.94	72.94

IDL & DL Notes (Table 66 and Table 67):

1 – IDL is 11-3051 Industrial Production Managers & DL is 51-4011 Computer-Controlled Machine Tool Operators, Metal and Plastic; May 2018 BLS data

2 – IDL is 11-3051 Industrial Production Managers & DL is 51-0000 Production Ocupations for 51-4011 in place of 51-4011 Computer-Controlled Machine Tool Operators, Metal and Plastic used; May 2018 BLS data

3 – IDL is 11-0000 Management Occupations for 11-3051 in place of IDL is 11-3051 Industrial Production Managers & DL is 51-0000 Production Ocupations for 51-4011 in place of 51-4011 Computer-Controlled Machine Tool Operators, Metal and Plastic used; May 2018 BLS data

4 – IDL is 11-3051 Industrial Production Managers & DL is 51-0000 Production Ocupations for 51-4011 in place of 51-4011 Computer-Controlled Machine Tool Operators, Metal and Plastic used; May 2018 BLS data. Wage percentage of total compensation based on average of the state means from the Census state regional grouping since that is how BLS groups the states for the wage percentage

5 – IDL is 11-0000 Management Occupations for 11-3051 in place of IDL is 11-3051 Industrial Production Managers & DL is 51-0000 Production Ocupations for 51-4011 in place of 51-4011 Computer-Controlled Machine Tool Operators, Metal and Plastic used; May 2018 BLS data. Wage percentage of total compensation based on average of the state means from the Census state regional grouping since that is how BLS groups the states for the wage percentage

Water Note (Table 68 and Table 69):

A1 – Rate is as of Jan 2019. From: https://efc.sog.unc.edu/resource/alabama-water-and-wastewater-rates-dashboard

B1 – Value calculated using Best Fit Sewer to Water rate conversion %

C1 – Rates as of July 2017, adjusted for 3.05% 2018 and 3.0% 2019 projections according to https://www.nacwa.org/docs/default-source/news-publications/White-Papers/2017index.pdf?sfvrsn=4, rates from: https://efc.sog.unc.edu/resource/arizona-water-and-wastewater-rates-dashboard

D1 – Rate as of Aug 2018, industrial year round commodity charge all consumption, adjusted for 3.0% 2019 projections according to https://www.nacwa.org/docs/default-source/news-publications/White-Papers/2017index.pdf?sfvrsn=4, rates from https://www.ctwater.com/media/2016/s-1-pa-associate-rate-schedules-2018-cwc-09-2018-new-header.pdf

Wastewater Notes (Table 68 and Table 69):

A – Rate is as of Jan 2019. From: https://efc.sog.unc.edu/resource/alabama-water-and-wastewater-rates-dashboard

B – Projected average annual service charge per 1,000ft^3 by EPA region; from: https://www.nacwa.org/docs/default-source/news-publications/White-Papers/2017index.pdf?sfvrsn=4

C – Rates as of July 2017, adjusted for 3.05% 2018 and 3.0% 2019 projections according to https://www.nacwa.org/docs/default-source/news-publications/White-Papers/2017index.pdf?sfvrsn=4, rates from: https://efc.sog.unc.edu/resource/arizona-water-and-wastewater-rates-dashboard

Regional state groupings are averages of the state means that are included in a particular region and are not included in this appendix. Nor are the metropolitan and non-metropolitan state means and regional state grouping data.

The following two tables are the conversion rates from HUD to determine metropolitan or non-metropolitan rental rates.

Table 70. Conversion rates from metropolitan to non-metropolitan regions for each HUD FY19 Fair Market Rents (FMR) areas and the conversion rate utilized for all U.S. states (1 of 2).

State	FMR 0 CR	FMR 1 CR	FMR 2 CR	FMR 3 CR	FMR 4 CR	FMR CR Utilized
AL	0.84	0.82	0.83	0.85	0.79	0.83
AK	1.01	1.03	0.98	0.89	0.83	0.95
AZ	0.86	0.82	0.83	0.78	0.75	0.81
AR	0.87	0.85	0.87	0.86	0.83	0.86
CA	0.61	0.60	0.61	0.61	0.60	0.61
CO	0.74	0.67	0.67	0.64	0.62	0.67
CT	0.86	0.87	0.90	0.89	0.82	0.87
DE	*0.76*	*0.76*	*0.76*	*0.76*	*0.76*	*0.76*
FL	0.78	0.74	0.73	0.73	0.70	0.74
GA	0.74	0.72	0.76	0.77	0.74	0.75
HI	0.74	0.79	0.80	0.72	0.69	0.74
ID	1.01	0.92	0.93	0.89	0.90	0.93
IL	0.77	0.79	0.80	0.80	0.77	0.78
IN	0.84	0.83	0.84	0.84	0.83	0.84
IA	0.87	0.80	0.82	0.81	0.78	0.81
KS	0.87	0.82	0.82	0.80	0.75	0.81
KY	0.80	0.79	0.78	0.74	0.69	0.76
LA	0.82	0.74	0.77	0.79	0.77	0.78
ME	0.86	0.85	0.80	0.83	0.79	0.83
MD	0.76	0.69	0.73	0.74	0.74	0.73
MA	0.83	0.81	0.80	0.83	0.82	0.82
MI	0.85	0.84	0.83	0.82	0.83	0.83
MN	0.75	0.74	0.74	0.70	0.65	0.72
MS	0.82	0.82	0.87	0.86	0.83	0.84
MO	0.77	0.80	0.81	0.80	0.81	0.80
MT	0.88	0.88	0.85	0.80	0.79	0.84
NE	0.87	0.91	0.90	0.86	0.85	0.88
NV	0.87	0.87	0.87	0.83	0.77	0.84

Table 71. Conversion rates from metropolitan to non-metropolitan regions for each HUD FY19 Fair Market Rents (FMR) areas and the conversion rate utilized for all U.S. states.

State	FMR 0 CR	FMR 1 CR	FMR 2 CR	FMR 3 CR	FMR 4 CR	FMR CR Utilized
NH	0.77	0.78	0.78	0.76	0.79	0.78
NJ	0.74	0.74	0.74	0.74	0.74	-
NM	0.98	0.88	0.91	0.89	0.90	0.91
NY	0.66	0.64	0.65	0.67	0.68	0.66
NC	0.85	0.83	0.86	0.85	0.83	0.84
ND	1.00	0.96	0.92	0.92	0.84	0.93
OH	0.92	0.87	0.86	0.85	0.85	0.87
OK	*0.90*	*0.90*	*0.90*	*0.88*	*0.85*	*0.89*
OR	0.61	0.66	0.68	0.66	0.63	0.65
PA	0.79	0.74	0.74	0.75	0.76	0.76
RI	0.78	0.78	0.78	0.78	0.78	0.78
SC	0.80	0.75	0.80	0.80	0.73	0.78
SD	0.82	0.83	0.84	0.84	0.81	0.83
TN	0.77	0.73	0.74	0.75	0.72	0.74
TX	0.82	0.76	0.77	0.77	0.73	0.77
UT	0.89	0.88	0.90	0.84	0.84	0.87
VT	0.71	0.64	0.60	0.60	0.65	0.64
VA	0.61	0.68	0.71	0.70	0.67	0.67
WA	0.78	0.80	0.80	0.79	0.78	0.79
WV	0.91	0.85	0.84	0.83	0.83	0.85
WI	0.84	0.83	0.84	0.82	0.80	0.83
WY	0.96	0.96	0.97	0.93	0.91	0.95
DC	0.76	0.76	0.76	0.76	0.76	0.76
GU	0.78	0.78	0.78	0.78	0.78	0.78
PR	0.86	0.83	0.86	0.86	0.83	0.85
VI	0.74	0.74	0.74	0.74	0.74	0.74
AS	0.73	0.73	0.73	0.73	0.73	0.73
U.S.	0.73	0.71	0.72	0.72	0.71	0.73

The following portion covers U.S. states and territories zone cost shipping values (ZC) and intercontinental shipping factors, SF.

Table 72. Ground based shipping factors of ZC⁄70 for U.S. states and territories to be used in the formula for NMC, Equation 80 (1 of 4).

Start \ End	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD	MA	MI	MN	MS	MO	MT	NE
AL	0	1.189	1.041	0.601	1.189	0.898	0.754	0.754	0.601	0.472	1.189	1.041	0.601	0.601	0.754	0.754	0.601	0.601	0.898	0.754	0.898	0.754	0.754	0.472	0.601	1.041	0.754
AK	1.189	0	0.601	1.041	0.472	0.754	1.189	1.189	1.189	1.189	0.472	0.754	1.041	1.189	1.041	0.898	1.189	1.041	1.189	1.189	1.189	1.189	1.041	1.041	1.041	0.898	0.898
AZ	1.041	0.601	0	0.898	0.601	0.601	1.189	1.189	1.041	1.041	0.601	0.754	0.898	1.041	0.898	0.754	1.041	0.898	1.189	1.189	1.189	1.041	0.898	0.898	0.898	0.754	0.754
AR	0.601	1.041	0.898	0	1.041	0.754	0.898	0.754	0.754	0.601	1.041	0.898	0.601	0.601	0.601	0.601	0.601	0.472	1.041	0.754	0.898	0.754	0.754	0.472	0.472	0.898	0.601
CA	1.189	0.472	0.601	1.041	0	0.754	1.189	1.189	1.189	1.189	0.472	0.754	1.041	1.189	1.041	0.898	1.189	1.041	1.189	1.189	1.189	1.189	1.041	1.041	1.041	0.754	0.898
CO	0.898	0.754	0.601	0.754	0.754	0	1.041	1.041	1.041	0.898	0.754	0.754	0.754	0.898	0.754	0.601	0.898	0.754	1.189	1.041	1.041	0.898	0.754	0.754	0.754	0.754	0.601
CT	0.754	1.189	1.189	0.898	1.189	1.041	0	0.472	0.898	0.754	1.189	1.189	0.754	0.754	0.898	0.898	0.754	0.898	0.472	0.472	0.392	0.754	0.898	0.898	0.898	1.189	0.898
DE	0.754	1.189	1.189	0.754	1.189	1.041	0.472	0	0.754	0.754	1.189	1.189	0.754	0.601	0.754	0.898	0.601	0.898	0.601	0.392	0.601	0.601	0.898	0.754	0.754	1.189	0.898
FL	0.601	1.189	1.041	0.754	1.189	1.041	0.898	0.754	0	0.601	1.189	1.189	0.754	0.754	0.898	0.898	0.754	0.754	0.898	0.754	0.898	0.898	0.898	0.601	0.754	1.189	0.898
GA	0.472	1.189	1.041	0.601	1.189	0.898	0.754	0.754	0.601	0	1.189	1.189	0.754	0.601	0.754	0.754	0.601	0.601	0.898	0.601	0.754	0.754	0.898	0.601	0.754	1.041	0.898
HI	1.189	0.472	0.601	1.041	0.472	0.754	1.189	1.189	1.189	1.189	0	0.754	1.041	1.189	1.041	0.898	1.189	1.041	1.189	1.189	1.189	1.189	1.041	1.041	1.041	0.898	0.898
ID	1.041	0.754	0.754	0.898	0.754	0.754	1.189	1.189	1.189	1.189	0.754	0	0.898	1.041	0.898	0.754	1.041	1.041	1.189	1.189	1.189	1.041	0.898	1.041	0.898	0.601	0.754
IL	0.601	1.041	0.898	0.601	1.041	0.754	0.754	0.754	0.754	0.754	1.041	0.898	0	0.472	0.472	0.601	0.472	0.754	0.898	0.754	0.754	0.472	0.601	0.601	0.472	0.898	0.601
IN	0.601	1.189	1.041	0.601	1.189	0.898	0.754	0.601	0.754	0.601	1.189	1.041	0.472	0	0.601	0.754	0.472	0.754	0.754	0.601	0.754	0.472	0.601	0.601	0.601	0.898	0.754
IA	0.754	1.041	0.898	0.601	1.041	0.754	0.898	0.754	0.898	0.754	1.041	0.898	0.472	0.601	0	0.601	0.601	0.754	0.898	0.754	0.898	0.601	0.472	0.754	0.472	0.754	0.601
KS	0.754	0.898	0.754	0.601	0.898	0.601	0.898	0.898	0.898	0.754	0.898	0.754	0.601	0.754	0.601	0	0.754	0.601	1.041	0.898	1.041	0.754	0.601	0.754	0.601	0.754	0.472
KY	0.601	1.189	1.041	0.601	1.189	0.898	0.754	0.601	0.754	0.601	1.189	1.041	0.472	0.472	0.601	0.754	0	0.601	0.754	0.601	0.754	0.601	0.754	0.601	0.601	0.898	0.754
LA	0.601	1.041	0.898	0.472	1.041	0.754	0.898	0.898	0.754	0.601	1.041	1.041	0.754	0.754	0.754	0.601	0.601	0	1.041	0.898	0.898	0.754	0.898	0.472	0.601	1.041	0.754
ME	0.898	1.189	1.189	1.041	1.189	1.189	0.472	0.601	0.898	0.898	1.189	1.189	0.898	0.754	0.898	1.041	0.754	1.041	0	0.601	0.472	0.754	0.898	0.898	0.898	1.189	1.041
MD	0.754	1.189	1.189	0.754	1.189	1.041	0.472	0.392	0.754	0.601	1.189	1.189	0.754	0.601	0.754	0.898	0.601	0.898	0.601	0	0.601	0.601	0.754	0.754	0.754	1.041	0.898
MA	0.898	1.189	1.189	0.898	1.189	1.041	0.392	0.601	0.898	0.754	1.189	1.189	0.754	0.754	0.898	1.041	0.754	0.898	0.472	0.601	0	0.754	0.898	0.898	0.898	1.189	1.041
MI	0.754	1.189	1.041	0.754	1.189	0.898	0.754	0.601	0.898	0.754	1.189	1.041	0.472	0.472	0.601	0.754	0.601	0.754	0.754	0.601	0.754	0	0.601	0.754	0.601	0.898	0.754
MN	0.754	1.041	0.898	0.754	1.041	0.754	0.898	0.898	0.898	0.898	1.041	0.898	0.601	0.601	0.472	0.601	0.754	0.898	0.898	0.754	0.898	0.601	0	0.754	0.601	0.754	0.601
MS	0.472	1.041	0.898	0.472	1.041	0.754	0.898	0.754	0.601	0.601	1.041	1.041	0.601	0.601	0.754	0.754	0.601	0.472	0.898	0.754	0.898	0.754	0.754	0	0.601	1.041	0.754
MO	0.601	1.041	0.898	0.472	1.041	0.754	0.898	0.754	0.754	0.754	1.041	0.898	0.472	0.601	0.472	0.601	0.601	0.601	0.898	0.754	0.898	0.601	0.601	0.601	0	0.898	0.601
MT	1.041	0.898	0.754	0.898	0.754	0.754	1.189	1.189	1.189	1.041	0.898	0.601	0.898	0.898	0.754	0.754	0.898	1.041	1.189	1.041	1.189	0.898	0.754	1.041	0.898	0	0.754
NE	0.754	0.898	0.754	0.601	0.898	0.601	0.898	0.898	0.898	0.898	0.898	0.754	0.601	0.754	0.601	0.472	0.754	0.754	1.041	0.898	1.041	0.754	0.601	0.754	0.601	0.754	0

Table 73. Ground based shipping factors of ZC/70 for U.S. states and territories to be used in the formula for NMC, Equation 80 (2 of 4).

Start \ End	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD	MA	MI	MN	MS	MO	MT	NE
NV	1.041	0.601	0.601	1.041	0.472	0.754	1.189	1.189	1.189	1.189	0.601	0.601	1.041	1.041	0.898	0.898	1.041	1.041	1.189	1.189	1.189	1.041	0.898	1.041	0.898	0.754	0.754
NH	0.898	1.189	1.189	0.898	1.189	1.041	0.392	0.601	0.898	0.754	1.189	1.189	0.754	0.754	0.898	1.041	0.754	0.898	0.472	0.601	0.392	0.754	0.898	0.898	0.898	1.189	1.041
NJ	0.754	1.189	1.189	0.898	1.189	1.041	0.392	0.392	0.754	0.754	1.189	1.189	0.754	0.754	0.754	0.898	0.754	0.898	0.601	0.472	0.472	0.601	0.898	0.898	0.754	1.189	0.898
NM	0.898	0.754	0.601	0.754	0.754	0.601	1.189	1.041	1.041	0.898	0.754	0.754	0.898	0.898	0.754	0.601	0.898	0.754	1.189	1.041	1.189	0.898	0.898	0.754	0.754	0.754	0.754
NY	0.754	1.189	1.189	0.898	1.189	1.041	0.472	0.472	0.898	0.754	1.189	1.189	0.754	0.601	0.754	0.898	0.754	0.898	0.601	0.472	0.472	0.601	0.754	0.898	0.754	1.041	0.898
NC	0.601	1.189	1.189	0.754	1.189	1.041	0.601	0.601	0.601	0.601	1.189	1.189	0.754	0.601	0.754	0.898	0.601	0.754	0.754	0.472	0.754	0.754	0.898	0.754	0.754	1.041	0.898
ND	0.898	0.898	0.898	0.754	0.898	0.754	0.898	0.898	1.041	0.898	0.898	0.754	0.754	0.754	0.601	0.754	0.754	0.898	1.041	0.898	1.041	0.754	0.601	0.898	0.754	0.601	0.601
OH	0.601	1.189	1.041	0.754	1.189	0.898	0.601	0.601	0.754	0.601	1.189	1.041	0.601	0.472	0.601	0.754	0.472	0.754	0.754	0.601	0.601	0.472	0.754	0.754	0.601	1.041	0.754
OK	0.754	0.898	0.754	0.472	0.898	0.601	0.898	0.898	0.898	0.754	0.898	0.898	0.601	0.754	0.601	0.472	0.754	0.601	1.041	0.898	1.041	0.754	0.754	0.601	0.601	0.898	0.601
OR	1.189	0.754	0.754	1.041	0.601	0.754	1.189	1.189	1.189	1.189	0.754	0.601	1.041	1.189	1.041	0.898	1.189	1.189	1.189	1.189	1.189	1.189	0.898	1.189	1.041	0.754	0.898
PA	0.754	1.189	1.189	0.754	1.189	1.041	0.472	0.472	0.754	0.754	1.189	1.189	0.601	0.601	0.754	0.898	0.601	0.898	0.601	0.392	0.601	0.601	0.754	0.754	0.754	1.041	0.898
RI	0.898	1.189	1.189	0.898	1.189	1.041	0.392	0.472	0.898	0.754	1.189	1.189	0.754	0.754	0.898	1.041	0.754	0.898	0.472	0.601	0.392	0.754	0.898	0.898	0.898	1.189	1.041
SC	0.601	1.189	1.041	0.754	1.189	0.898	0.754	0.601	0.601	0.472	1.189	1.189	0.754	0.601	0.754	0.754	0.601	0.754	0.754	0.601	0.754	0.754	0.898	0.601	0.754	1.041	0.898
SD	0.898	0.898	0.754	0.754	0.898	0.601	0.898	0.898	1.041	0.898	0.898	0.754	0.754	0.754	0.601	0.601	0.754	0.898	1.041	0.898	1.041	0.754	0.601	0.898	0.754	0.601	0.472
TN	0.472	1.189	1.041	0.601	1.189	0.898	0.754	0.754	0.601	0.472	1.189	1.041	0.601	0.601	0.601	0.754	0.392	0.601	0.898	0.601	0.754	0.601	0.754	0.601	0.601	1.041	0.754
TX	0.754	0.898	0.754	0.601	0.898	0.754	1.041	0.898	0.754	0.754	0.898	0.898	0.754	0.754	0.754	0.601	0.754	0.601	1.189	0.898	1.041	0.898	0.898	0.601	0.754	0.898	0.754
UT	1.041	0.601	0.601	0.898	0.601	0.601	1.189	1.189	1.189	1.041	0.601	0.601	0.898	0.898	0.754	0.754	0.898	0.898	1.189	1.189	1.189	1.041	0.754	0.898	0.898	0.601	0.754
VT	0.898	1.189	1.189	0.898	1.189	1.041	0.472	0.601	0.898	0.754	1.189	1.189	0.754	0.754	0.898	0.898	0.754	0.898	0.472	0.601	0.392	0.601	0.898	0.898	0.898	1.189	0.898
VA	0.601	1.189	1.189	0.754	1.189	1.041	0.601	0.472	0.754	0.601	1.189	1.189	0.754	0.601	0.754	0.898	0.601	0.754	0.754	0.392	0.601	0.601	0.754	0.754	0.754	1.041	0.898
WA	1.189	0.754	0.898	1.041	0.754	0.754	1.189	1.189	1.189	1.189	0.754	0.601	1.041	1.189	1.041	0.898	1.189	1.189	1.189	1.189	1.189	1.041	0.898	1.189	1.041	0.601	0.898
WV	0.601	1.189	1.041	0.754	1.189	0.898	0.601	0.472	0.754	0.601	1.189	1.189	0.601	0.601	0.754	0.754	0.472	0.754	0.754	0.472	0.601	0.601	0.754	0.754	0.754	1.041	0.754
WI	0.754	1.041	1.041	0.754	1.041	0.754	0.754	0.754	0.898	0.754	1.041	0.898	0.472	0.601	0.472	0.754	0.601	0.754	0.754	0.754	0.754	0.472	0.472	0.754	0.601	0.898	0.601
WY	0.898	0.754	0.754	0.754	0.754	0.472	1.041	1.041	1.041	1.041	0.754	0.601	0.754	0.898	0.754	0.601	0.898	0.898	1.189	1.041	1.041	0.898	0.754	0.898	0.754	0.601	0.601
DC	0.754	1.189	1.189	0.754	1.189	1.041	0.472	0.392	0.754	0.601	1.189	1.189	0.754	0.601	0.754	0.898	0.601	0.898	0.601	0.392	0.601	0.601	0.754	0.754	0.754	1.041	0.898
GU	1.189	1.189	0.601	1.041	0.472	0.754	1.189	1.189	1.189	1.189	1.189	0.754	1.041	1.189	1.041	0.898	1.189	1.041	1.189	1.189	1.189	1.189	1.041	1.041	1.041	0.898	0.898
PR	1.189	0.898	0.601	1.041	0.472	0.754	1.189	1.189	1.189	1.189	0.754	0.754	1.041	1.189	1.041	0.898	1.189	1.041	1.189	1.189	1.189	1.189	1.041	1.041	1.041	0.898	0.898
VI	1.189	0.898	0.601	1.041	0.472	0.754	1.189	1.189	1.189	1.189	0.754	0.754	1.041	1.189	1.041	0.898	1.189	1.041	1.189	1.189	1.189	1.189	1.041	1.041	1.041	0.898	0.898
AS	1.189	1.189	0.601	1.041	0.472	0.754	1.189	1.189	1.189	1.189	1.189	0.754	1.041	1.189	1.041	0.898	1.189	1.041	1.189	1.189	1.189	1.189	1.041	1.041	1.041	0.898	0.898

Table 74. Ground based shipping factors of ZC⁄70 for U.S. states and territories to be used in the formula for NMC, Equation 80 (3 of 4).

Start \ End	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY	DC	GU	PR	VI	AS
AL	1.041	0.898	0.754	0.898	0.754	0.601	0.898	0.601	0.754	1.189	0.754	0.898	0.601	0.898	0.472	0.754	1.041	0.898	0.601	1.189	0.601	0.754	0.898	0.754	1.189	1.189	1.189	1.189
AK	0.601	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.754	1.189	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	0.754	1.189	1.041	0.754	1.189	1.189	0.898	0.898	1.189
AZ	0.601	1.189	1.189	0.601	1.189	1.189	0.898	1.041	0.754	0.754	1.189	1.189	1.041	0.754	1.041	0.754	0.601	1.189	1.189	0.898	1.041	1.041	0.754	1.189	0.601	0.601	0.601	0.601
AR	1.041	0.898	0.898	0.754	0.898	0.754	0.754	0.754	0.472	1.041	0.754	0.898	0.754	0.754	0.601	0.601	0.898	0.898	0.754	1.041	0.754	0.754	0.754	0.754	1.041	1.041	1.041	1.041
CA	0.472	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	0.754	1.189	1.041	0.754	1.189	0.472	0.472	0.472	0.472
CO	0.754	1.041	1.041	0.601	1.041	1.041	0.754	0.898	0.601	0.754	1.041	1.041	0.898	0.601	0.898	0.754	0.601	1.041	1.041	0.754	0.898	0.754	0.472	1.041	0.754	0.754	0.754	0.754
CT	1.189	0.392	0.392	1.189	0.472	0.601	0.898	0.601	0.898	1.189	0.472	0.392	0.754	0.898	0.754	1.041	1.189	0.472	0.601	1.189	0.601	0.754	1.041	0.472	1.189	1.189	1.189	1.189
DE	1.189	0.601	0.392	1.041	0.472	0.601	0.898	0.601	0.898	1.189	0.472	0.472	0.601	0.898	0.754	0.898	1.189	0.601	0.472	1.189	0.472	0.754	1.041	0.392	1.189	1.189	1.189	1.189
FL	1.189	0.898	0.754	1.041	0.898	0.601	1.041	0.754	0.898	1.189	0.754	0.898	0.601	1.041	0.601	0.754	1.189	0.898	0.754	1.189	0.754	0.898	1.041	0.754	1.189	1.189	1.189	1.189
GA	1.189	0.754	0.754	0.898	0.754	0.601	0.898	0.601	0.754	1.189	0.754	0.754	0.472	0.898	0.472	0.754	1.041	0.754	0.601	1.189	0.601	0.754	1.041	0.601	1.189	1.189	1.189	1.189
HI	0.601	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.754	1.189	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	0.754	1.189	1.041	0.754	1.189	1.189	0.754	0.754	1.189
ID	0.601	1.189	1.189	0.754	1.189	1.189	0.754	1.041	0.898	0.601	1.189	1.189	1.189	0.754	1.041	0.898	0.601	1.189	1.189	0.601	1.189	0.898	0.601	1.189	0.754	0.754	0.754	0.754
IL	1.041	0.754	0.754	0.898	0.754	0.754	0.754	0.601	0.601	1.041	0.601	0.754	0.754	0.754	0.601	0.754	0.898	0.754	0.754	1.041	0.601	0.472	0.754	0.754	1.041	1.041	1.041	1.041
IN	1.041	0.754	0.754	0.898	0.601	0.601	0.754	0.472	0.754	1.189	0.601	0.754	0.601	0.754	0.601	0.754	0.898	0.754	0.601	1.189	0.601	0.601	0.898	0.601	1.189	1.189	1.189	1.189
IA	0.898	0.898	0.754	0.754	0.754	0.754	0.601	0.601	0.601	1.041	0.754	0.898	0.754	0.601	0.601	0.754	0.754	0.898	0.754	1.041	0.754	0.472	0.754	0.754	1.041	1.041	1.041	1.041
KS	0.898	1.041	0.898	0.601	0.898	0.898	0.754	0.754	0.472	0.898	0.898	1.041	0.754	0.601	0.754	0.601	0.754	0.898	0.898	0.898	0.754	0.754	0.601	0.898	0.898	0.898	0.898	0.898
KY	1.041	0.754	0.754	0.898	0.754	0.601	0.754	0.472	0.754	1.189	0.601	0.754	0.601	0.754	0.392	0.754	0.898	0.754	0.601	1.189	0.472	0.601	0.898	0.601	1.189	1.189	1.189	1.189
LA	1.041	0.898	0.898	0.754	0.898	0.754	0.898	0.754	0.601	1.189	0.898	0.898	0.754	0.898	0.601	0.601	0.898	0.898	0.754	1.189	0.754	0.754	0.898	0.898	1.041	1.041	1.041	1.041
ME	1.189	0.472	0.601	1.189	0.601	0.754	1.041	0.754	1.041	1.189	0.601	0.472	0.754	1.041	0.898	1.189	1.189	0.472	0.754	1.189	0.754	0.754	1.189	0.601	1.189	1.189	1.189	1.189
MD	1.189	0.601	0.472	1.041	0.472	0.472	0.898	0.601	0.898	1.189	0.392	0.601	0.601	0.898	0.601	0.898	1.189	0.601	0.392	1.189	0.472	0.754	1.041	0.392	1.189	1.189	1.189	1.189
MA	1.189	0.392	0.472	1.189	0.472	0.754	1.041	0.601	1.041	1.189	0.601	0.392	0.754	1.041	0.754	1.041	1.189	0.392	0.601	1.189	0.601	0.754	1.041	0.601	1.189	1.189	1.189	1.189
MI	1.041	0.754	0.601	0.898	0.601	0.754	0.754	0.472	0.754	1.189	0.601	0.754	0.754	0.754	0.601	0.898	1.041	0.601	0.601	1.041	0.601	0.472	0.898	0.601	1.189	1.189	1.189	1.189
MN	0.898	0.898	0.898	0.898	0.754	0.898	0.601	0.754	0.754	0.898	0.754	0.898	0.898	0.601	0.754	0.898	0.754	0.898	0.754	0.898	0.754	0.472	0.754	0.754	1.041	1.041	1.041	1.041
MS	1.041	0.898	0.898	0.754	0.898	0.754	0.898	0.754	0.601	1.189	0.754	0.898	0.601	0.898	0.601	0.601	0.898	0.898	0.754	1.189	0.754	0.754	0.898	0.754	1.041	1.041	1.041	1.041
MO	0.898	0.898	0.754	0.754	0.754	0.754	0.754	0.601	0.601	1.041	0.754	0.898	0.754	0.754	0.601	0.754	0.898	0.898	0.754	1.041	0.754	0.601	0.754	0.754	1.041	1.041	1.041	1.041
MT	0.754	1.189	1.189	0.754	1.041	1.041	0.601	1.041	0.898	0.754	1.041	1.189	1.041	0.601	1.041	0.898	0.601	1.189	1.041	0.601	1.041	0.898	0.601	1.041	0.898	0.898	0.898	0.898
NE	0.754	1.041	0.898	0.754	0.898	0.898	0.601	0.754	0.601	0.898	0.898	1.041	0.898	0.472	0.754	0.754	0.754	0.898	0.898	0.898	0.754	0.601	0.601	0.898	0.898	0.898	0.898	0.898

Table 75. Ground based shipping factors of ZC⁄70 for U.S. states and territories to be used in the formula for NMC, Equation 80 (4 of 4).

End / Start	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY	DC	GU	PR	VI	AS
NV	0	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	1.189	0.754	1.041	0.898	0.601	1.189	1.189	0.601	1.189	1.041	0.601	1.189	0.601	0.601	0.601	0.601
NH	1.189	0	0.472	1.189	0.472	0.754	1.041	0.754	1.041	1.189	0.601	0.392	0.754	1.041	0.754	1.041	1.189	0.392	0.601	1.189	0.601	0.754	1.041	0.601	1.189	1.189	1.189	1.189
NJ	1.189	0.472	0	1.041	0.472	0.601	0.898	0.601	0.898	1.189	0.472	0.472	0.601	0.898	0.754	1.041	1.189	0.472	0.472	1.189	0.601	0.754	1.041	0.472	1.189	1.189	1.189	1.189
NM	0.754	1.189	1.041	0	1.041	1.041	0.754	0.898	0.601	0.898	1.041	1.189	1.041	0.754	0.898	0.601	0.601	1.189	1.041	0.898	1.041	0.898	0.601	1.041	0.754	0.754	0.754	0.754
NY	1.189	0.472	0.472	1.041	0	0.601	0.898	0.601	0.898	1.189	0.472	0.472	0.754	0.898	0.754	1.041	1.189	0.472	0.601	1.189	0.601	0.754	1.041	0.472	1.189	1.189	1.189	1.189
NC	1.189	0.754	0.601	1.041	0.601	0	0.898	0.601	0.898	1.189	0.601	0.601	0.472	0.898	0.601	0.898	1.189	0.754	0.472	1.189	0.472	0.754	1.041	0.472	1.189	1.189	1.189	1.189
ND	0.898	1.041	0.898	0.754	0.898	0.898	0	0.754	0.754	0.898	0.898	1.041	0.898	0.472	0.898	0.898	0.754	0.898	0.898	0.754	0.898	0.601	0.601	0.898	0.898	0.898	0.898	0.898
OH	1.189	0.754	0.601	0.898	0.601	0.601	0.754	0	0.754	1.189	0.472	0.601	0.601	0.754	0.601	0.898	1.041	0.601	0.601	1.189	0.472	0.601	0.898	0.601	1.189	1.189	1.189	1.189
OK	0.898	1.041	0.898	0.601	0.898	0.898	0.754	0.754	0	1.041	0.898	1.041	0.754	0.754	0.754	0.601	0.754	1.041	0.898	1.041	0.754	0.754	0.754	0.898	0.898	0.898	0.898	0.898
OR	0.601	1.189	1.189	0.898	1.189	1.189	0.898	1.189	1.041	0	1.189	1.189	1.189	0.898	1.189	1.041	0.754	1.189	1.189	0.472	1.189	1.041	0.754	1.189	0.754	0.754	0.754	0.754
PA	1.189	0.601	0.472	1.041	0.472	0.601	0.898	0.472	0.898	1.189	0	0.601	0.601	0.898	0.601	0.898	1.041	0.601	0.472	1.189	0.472	0.754	1.041	0.392	1.189	1.189	1.189	1.189
RI	1.189	0.392	0.472	1.189	0.472	0.601	1.041	0.601	1.041	1.189	0.601	0	0.754	1.041	0.754	1.041	1.189	0.472	0.601	1.189	0.601	0.754	1.189	0.601	1.189	1.189	1.189	1.189
SC	1.189	0.754	0.601	1.041	0.754	0.472	0.898	0.601	0.754	1.189	0.601	0.754	0	0.898	0.601	0.898	1.041	0.754	0.472	1.189	0.601	0.754	1.041	0.601	1.189	1.189	1.189	1.189
SD	0.754	1.041	0.898	0.754	0.898	0.898	0.472	0.754	0.754	0.898	0.898	1.041	0.898	0	0.754	0.754	0.754	0.898	0.898	0.898	0.898	0.601	0.601	0.898	0.898	0.898	0.898	0.898
TN	1.041	0.754	0.754	0.898	0.754	0.601	0.898	0.601	0.754	1.189	0.601	0.754	0.601	0.754	0	0.754	1.041	0.754	0.601	1.189	0.601	0.601	0.898	0.601	1.189	1.189	1.189	1.189
TX	0.898	1.041	1.041	0.601	1.041	0.898	0.898	0.898	0.601	1.041	0.898	1.041	0.898	0.754	0.754	0	0.754	1.041	0.898	1.041	0.898	0.898	0.754	0.898	0.898	0.898	0.898	0.898
UT	0.601	1.189	1.189	0.601	1.189	1.189	0.754	1.041	0.754	0.754	1.041	1.189	1.041	0.754	1.041	0.754	0	1.189	1.041	0.754	1.041	0.898	0.601	1.189	0.601	0.601	0.601	0.601
VT	1.189	0.392	0.472	1.189	0.472	0.754	0.898	0.601	1.041	1.189	0.601	0.472	0.754	0.898	0.754	1.041	1.189	0	0.601	1.189	0.601	0.754	1.041	0.601	1.189	1.189	1.189	1.189
VA	1.189	0.601	0.472	1.041	0.601	0.472	0.898	0.601	0.898	1.189	0.472	0.601	0.472	0.898	0.601	0.898	1.041	0.601	0	1.189	0.392	0.754	1.041	0.392	1.189	1.189	1.189	1.189
WA	0.601	1.189	1.189	0.898	1.189	1.189	0.754	1.189	1.041	0.472	1.189	1.189	1.189	0.898	1.189	1.041	0.754	1.189	1.189	0	1.189	1.041	0.754	1.189	0.754	0.754	0.754	0.754
WV	1.189	0.601	0.601	1.041	0.601	0.472	0.898	0.472	0.754	1.189	0.472	0.601	0.601	0.898	0.601	0.898	1.041	0.601	0.392	1.189	0	0.601	0.898	0.472	1.189	1.189	1.189	1.189
WI	1.041	0.754	0.754	0.898	0.754	0.754	0.601	0.601	0.754	1.041	0.754	0.754	0.754	0.601	0.601	0.898	0.898	0.754	0.754	1.041	0.601	0	0.754	0.754	1.041	1.041	1.041	1.041
WY	0.601	1.041	1.041	0.601	1.041	1.041	0.601	0.898	0.754	0.754	1.041	1.189	1.041	0.601	0.898	0.754	0.601	1.041	1.041	0.754	0.898	0.754	0	1.041	0.754	0.754	0.754	0.754
DC	1.189	0.601	0.472	1.041	0.472	0.472	0.898	0.601	0.898	1.189	0.392	0.601	0.601	0.898	0.601	0.898	1.189	0.601	0.392	1.189	0.472	0.754	1.041	0	1.189	1.189	1.189	1.189
GU	0.601	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.754	1.189	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	0.754	1.189	1.041	0.754	1.189	0	1.189	1.189	0.898
PR	0.601	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.754	1.189	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	0.754	1.189	1.041	0.754	1.189	1.189	0	0.392	1.041
VI	0.601	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.754	1.189	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	0.754	1.189	1.041	0.754	1.189	1.189	0.392	0	0.898
AS	0.601	1.189	1.189	0.754	1.189	1.189	0.898	1.189	0.898	0.754	1.189	1.189	1.189	0.898	1.189	0.898	0.601	1.189	1.189	0.754	1.189	1.041	0.754	1.189	0.898	1.041	0.898	0

Table 76. Intercontinental based shipping factors of SF/10,000 for U.S. states and countries to be used in the formula for NMC, Equation 80 (1 of 6).

Start \ End	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD	MA	MI	MN	MS	MO	MT	NE
Albania	0.335	1.602	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.058	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335
Algeria	0.248	0.755	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	1.501	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248
Argentina	0.509	0.655	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.390	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509
Armenia	0.326	1.538	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.120	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326
Australia	0.256	0.378	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.146	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256
Austria	0.293	1.301	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.349	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293
Azerbaijan	0.326	4.485	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.023	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326
Bahamas	0.139	0.040	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.480	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139
Bangladesh	0.447	7.056	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.141	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447
Belarus	0.240	0.912	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.724	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240
Belgium	0.202	0.633	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.992	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202
Bermuda	0.142	0.491	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.868	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142
Bolivia	0.633	0.861	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.681	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633
Bosnia & Herzegovina	0.313	1.447	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.207	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313
Brazil	0.491	0.624	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.346	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491
Bulgaria	0.328	1.550	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.109	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328
Burma	0.311	4.179	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.043	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311
Cambodia	0.145	0.646	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.268	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145
Canada	0.136	0.374	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.896	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136
Chile	0.661	0.908	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.747	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661
China	0.104	0.216	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.322	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104
Colombia	0.589	0.788	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.578	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589
Costa Rica	0.461	0.575	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.276	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461
Croatia	0.302	1.360	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.291	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302
Cuba	0.595	0.797	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.590	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595
Czech Republic	0.293	1.301	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.349	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293
Denmark	0.206	0.662	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.965	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206
Ecuador	0.605	0.815	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.615	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605
Egypt	0.304	1.077	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.609	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304
Estonia	0.235	0.879	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.755	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235
Ethiopia	0.598	1.019	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	1.470	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598
Finland	0.235	0.879	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.755	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235
France	0.229	0.836	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.797	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229
Georgia	0.334	1.595	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.065	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334
Germany	0.204	0.648	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.979	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204
Ghana	0.692	1.286	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.770	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692
Greece	0.296	1.320	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.330	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296
Hong Kong	0.098	0.360	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.332	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098
Hungary	0.293	1.301	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.349	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293

Table 77. Intercontinental based shipping factors of SF/10,000 for U.S. states and countries to be used in the formula for NMC, Equation 80 (2 of 6).

Start \ End	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD	MA	MI	MN	MS	MO	MT	NE
Iceland	0.449	2.434	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.744	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449
India	0.316	4.272	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.037	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316
Indonesia	0.128	0.287	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.290	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128
Iran	0.424	6.568	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.109	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424
Iraq	0.417	1.715	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	1.157	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417
Ireland	0.217	0.747	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.883	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217
Israel	0.299	1.340	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.311	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299
Italy	0.241	0.919	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.717	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241
Jamaica	0.568	0.753	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.528	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568
Japan	0.102	0.257	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.325	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
Kazakhstan	0.322	4.396	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.029	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322
Kenya	0.599	1.023	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	1.480	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599
Kosovo	0.315	1.458	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.197	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315
Latvia	0.240	0.912	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.724	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240
Lithuania	0.240	0.912	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.724	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240
Luxembourg	0.211	0.701	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.927	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211
Macao	0.098	0.360	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.332	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098
Malaysia	0.123	0.185	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.297	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123
Mauritius	0.626	1.079	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	1.633	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626
Mexico - land	0.154	0.065	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.444	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154
Mexico -sea	0.274	0.265	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.161	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274
Moldova	0.332	1.584	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.076	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332
Morocco	0.241	0.717	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	1.608	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241
Mozambique	0.689	1.213	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	2.001	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689
Namibia	0.683	1.200	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	1.966	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683
Nepal	0.381	5.664	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.052	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381
Netherlands	0.202	0.633	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.992	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202
New Zealand	0.408	0.782	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.109	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408
Nigeria	0.698	1.300	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.784	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698
North Macedonia	0.315	1.458	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.197	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315
Norway	0.209	0.690	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.937	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209
Pakistan	0.353	5.053	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.013	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353
Paraguay	0.592	0.793	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.584	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592
Peru	0.605	0.815	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.615	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605
Philippines	0.110	0.012	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.392	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110
Poland	0.240	0.912	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.724	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240
Portugal	0.243	0.935	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.701	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243
Qatar	0.372	1.461	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.455	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372
Romania	0.328	1.550	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.109	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328
Russia	0.240	0.912	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.724	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240

Table 78. Intercontinental based shipping factors of SF⁄10,000 for U.S. states and countries to be used in the formula for NMC, Equation 80 (3 of 6).

End / Start	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD	MA	MI	MN	MS	MO	MT	NE
Saudi Arabia	0.433	1.808	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	1.416	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433
Serbia	0.277	1.179	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.466	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277
Singapore	0.127	0.262	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.292	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127
Slovakia	0.293	1.301	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.349	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293
Slovenia	0.304	1.380	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.272	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304
South Africa	0.504	0.821	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.928	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504
South Korea	0.102	0.257	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.325	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102
Spain	0.209	0.690	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.937	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209
Sri Lanka	0.356	5.118	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.017	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356
Sweden	0.235	0.879	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.755	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235
Switzerland	0.219	0.759	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.871	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219
Syria	0.343	4.848	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.000	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343
Tanzania	0.605	1.034	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	1.511	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605
Thailand	0.132	0.364	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.286	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132
Tunisia	0.245	0.743	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	1.536	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245
Turkey	0.307	1.401	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.252	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307
Uganda	0.598	1.019	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	1.470	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598
Ukraine	0.337	1.618	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.043	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337
United Arab Emirates	0.387	1.546	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.689	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387
United Kingdom	0.211	0.704	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.924	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211
Uzbekistan	0.322	4.396	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.029	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322
Venezuela	0.793	1.126	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	1.055	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793
Vietnam	0.147	0.697	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.264	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147
Africa Region	0.629	1.086	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	1.652	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629
Arab States Region	0.331	1.228	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.192	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331
Pacific Region	0.327	0.568	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.027	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327
Europe Region	0.271	1.137	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.506	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271
North America Region	0.122	0.115	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.957	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122
South/Latin America Region	0.523	0.678	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.421	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523
Asia Region	0.237	2.592	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.144	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237

Table 79. Intercontinental based shipping factors of SF/10,000 for U.S. states and countries to be used in the formula for NMC, Equation 80 (4 of 6).

End / Start	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY	DC	GU	PR	VI	AS
Albania	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.335	0.622	0.406	0.504	0.622
Algeria	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	0.248	2.764	0.521	0.614	2.764
Argentina	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.509	0.201	0.831	1.535	0.201
Armenia	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.684	0.421	0.519	0.684
Australia	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.282	0.854	1.010	0.282
Austria	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.913	0.475	0.573	0.913
Azerbaijan	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.132	0.221	0.272	0.132
Bahamas	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.668	5.259	5.963	0.668
Bangladesh	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.032	0.115	0.166	0.032
Belarus	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	1.287	0.564	0.662	1.287
Belgium	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	1.556	0.628	0.726	1.556
Bermuda	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	1.215	0.714	0.810	1.215
Bolivia	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.633	0.493	0.654	0.050	0.493
Bosnia & Herzegovina	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.771	0.441	0.539	0.771
Brazil	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.158	1.052	1.756	0.158
Bulgaria	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.672	0.418	0.516	0.672
Burma	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.151	0.233	0.285	0.151
Cambodia	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.376	0.378	0.430	0.376
Canada	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	0.136	1.244	0.725	0.821	1.244
Chile	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.661	0.558	0.989	0.285	0.558
China	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.431	0.414	0.465	0.431
Colombia	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.589	0.389	0.128	0.576	0.389
Costa Rica	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.461	0.088	1.408	2.112	0.088
Croatia	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.302	0.855	0.461	0.559	0.855
Cuba	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.402	0.192	0.512	0.402
Czech Republic	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.913	0.475	0.573	0.913
Denmark	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	0.206	1.529	0.621	0.719	1.529
Ecuador	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.427	0.319	0.385	0.427
Egypt	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	1.873	0.432	0.525	1.873
Estonia	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	1.319	0.571	0.670	1.319
Ethiopia	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	1.006	0.096	0.203	1.006
Finland	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	1.319	0.571	0.670	1.319
France	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	1.360	0.581	0.679	1.360
Georgia	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.334	0.629	0.408	0.506	0.629
Germany	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	0.204	1.542	0.624	0.723	1.542
Ghana	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.692	0.593	1.850	0.886	0.593
Greece	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.296	0.894	0.471	0.569	0.894
Hong Kong	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.440	0.420	0.471	0.440
Hungary	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.913	0.475	0.573	0.913

Table 80. Intercontinental based shipping factors of SF/10,000 for U.S. states and countries to be used in the formula for NMC, Equation 80 (5 of 6).

End / Start	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY	DC	GU	PR	VI	AS
Iceland	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.449	0.180	0.216	0.314	0.180
India	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.145	0.229	0.281	0.145
Indonesia	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.399	0.393	0.445	0.399
Iran	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.001	0.135	0.186	0.001
Iraq	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.417	0.106	0.255	0.348	0.106
Ireland	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	0.217	1.446	0.602	0.700	1.446
Israel	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.874	0.466	0.564	0.874
Italy	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	1.281	0.562	0.660	1.281
Jamaica	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.568	0.339	0.128	0.832	0.339
Japan	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.434	0.416	0.467	0.434
Kazakhstan	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.137	0.224	0.276	0.137
Kenya	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	0.599	1.016	0.105	0.194	1.016
Kosovo	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.761	0.439	0.537	0.761
Latvia	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	1.287	0.564	0.662	1.287
Lithuania	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	1.287	0.564	0.662	1.287
Luxembourg	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	1.491	0.612	0.710	1.491
Macao	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.440	0.420	0.471	0.440
Malaysia	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.405	0.397	0.449	0.405
Mauritius	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	0.626	1.169	0.239	0.059	1.169
Mexico - land	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.154	0.632	5.075	5.779	0.632
Mexico -sea	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.274	0.350	3.637	4.341	0.350
Moldova	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.640	0.410	0.508	0.640
Morocco	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	0.241	2.871	0.532	0.625	2.871
Mozambique	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	0.689	1.537	0.562	0.263	1.537
Namibia	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	0.683	1.502	0.532	0.233	1.502
Nepal	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.381	0.057	0.172	0.223	0.057
Netherlands	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	1.556	0.628	0.726	1.556
New Zealand	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.027	0.453	0.609	0.027
Nigeria	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.698	0.607	1.952	0.988	0.607
North Macedonia	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.761	0.439	0.537	0.761
Norway	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	1.501	0.615	0.713	1.501
Pakistan	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.353	0.096	0.197	0.249	0.096
Paraguay	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.592	0.395	0.159	0.545	0.395
Peru	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.427	0.319	0.385	0.427
Philippines	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.527	1.240	1.396	0.527
Poland	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	1.287	0.564	0.662	1.287
Portugal	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	0.243	1.265	0.559	0.657	1.265
Qatar	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.808	0.325	0.418	0.808
Romania	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.328	0.672	0.418	0.516	0.672
Russia	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	1.287	0.564	0.662	1.287

Table 81. Intercontinental based shipping factors of SF/10,000 for U.S. states and countries to be used in the formula for NMC, Equation 80 (6 of 6).

Start \ End	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY	DC	GU	PR	VI	AS
Saudi Arabia	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.153	0.229	0.322	0.153
Serbia	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	0.277	1.030	0.503	0.601	1.030
Singapore	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.401	0.394	0.446	0.401
Slovakia	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.293	0.913	0.475	0.573	0.913
Slovenia	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.836	0.457	0.555	0.836
South Africa	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.504	0.465	0.379	0.678	0.465
South Korea	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.434	0.416	0.467	0.434
Spain	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	0.209	1.501	0.615	0.713	1.501
Sri Lanka	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.356	0.091	0.195	0.246	0.091
Sweden	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	0.235	1.319	0.571	0.670	1.319
Switzerland	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	0.219	1.435	0.599	0.697	1.435
Syria	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.343	0.109	0.206	0.257	0.109
Tanzania	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	0.605	1.047	0.132	0.167	1.047
Thailand	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.394	0.390	0.441	0.394
Tunisia	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	0.245	2.800	0.525	0.618	2.800
Turkey	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.307	0.816	0.452	0.550	0.816
Uganda	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	1.006	0.096	0.203	1.006
Ukraine	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.337	0.607	0.402	0.501	0.607
United Arab Emirates	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.574	0.302	0.395	0.574
United Kingdom	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	0.211	1.487	0.611	0.709	1.487
Uzbekistan	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.322	0.137	0.224	0.276	0.137
Venezuela	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.793	0.867	2.560	1.856	0.867
Vietnam	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.373	0.376	0.428	0.373
Africa Region	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	1.188	0.256	0.043	1.188
Arab States Region	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	0.331	1.455	0.390	0.483	1.455
Pacific Region	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.162	0.666	0.822	0.162
Europe Region	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	1.070	0.512	0.610	1.070
North America Region	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	0.122	1.304	0.748	0.844	1.304
South/Latin America Region	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.523	0.233	0.668	1.373	0.233
Asia Region	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.252	0.298	0.350	0.252

Table 82. Country wage index, COLA, regional groupings, and shipping information (1 of 3).

Country	Wage Index (US=1)	Cost of living index (US = 1)	Wage percentage of total compensation	World Regional Grouping	Shipping cost, low	Shipping cost, high	Date aquired	Port Shipped to/from:	Shipping rate, low average	US Port City that provides lowest average	US port city to City Shipped to distance (straight line distance) (mile)	Notes
United States - USA	1.000	1.000	70.00%	5	1,026.47	1,134.52	15-Apr-19		1,080.50	Baltimore	2,319	Truck frieght from Los Angeles, CA to Baltimore, MD and vice versa. Cost is for a container with same conditions, but via truck. Driving distance is 2,662 miles.
Albania	0.074	0.460	61.99%	4	3,179.48	3,514.16	11-Apr-19	Vlore	3,346.82	Baltimore	4,807	
Algeria	0.068	0.405	61.99%	2	2,352.40	2,600.02	11-Apr-19	Oran	2,476.21	Baltimore	4,043	
American Samoa - AS	1.000	1.000	61.99%	3	4,021.71	4,445.05	12-Apr-19	Pago-Pago	4,233.38	Los Angeles	4,782	
Argentina	0.224	0.540	68.60%	6	4,836.13	5,345.20	11-Apr-19	Rio Grande	5,090.67	Baltimore	6,448	
Armenia	0.069	0.433	61.99%	4	0.00	0.00	*11-Apr-19*		3,258.88	Baltimore	5,264	average of Turkey, Georgia, and Ukraine
Australia	0.881	1.077	71.30%	3	2,432.14	2,688.15	11-Apr-19	Sydney	2,560.15	Los Angeles	7,486	
Austria	0.780	0.973	52.50%	4	0.00	0.00	*11-Apr-19*		2,932.91	Baltimore	4,489	average of Slovenia, Poland, Croatia, and Romania
Azerbaijan	0.070	0.389	61.99%	7	0.00	0.00	*11-Apr-19*		3,258.88	Baltimore	5,264	average of Turkey, Georgia, and Ukraine
Bahamas	0.501	1.268	61.99%	6	1,316.44	1,455.01	11-Apr-19	Nassau	1,385.73	Baltimore	984	
Bangladesh	0.025	0.412	61.99%	7	4,246.85	4,693.88	11-Apr-19	Chittagong	4,470.37	Los Angeles	8,081	
Belarus	0.091	0.435	61.99%	4	0.00	0.00	*11-Apr-19*		2,398.74	Baltimore	4,253	average of Poland and Latvia
Belgium	0.717	0.991	48.50%	4	1,915.16	2,116.75	11-Apr-19	Bruges	2,015.96	Baltimore	3,771	
Bermuda	1.821	1.903	61.99%	5	1,352.97	1,495.39	11-Apr-19	Hamilton	1,424.18	Baltimore	819	
Bolivia	0.054	0.456	61.99%	6	0.00	0.00	*11-Apr-19*		6,333.05	Los Angeles	4,566	average of Peru and Chile
Bosnia & Herzegovina	0.084	0.473	61.99%	4	0.00	0.00	*11-Apr-19*		3,134.85	Baltimore	4,528	average of Croatia, Albania, and Slovenia
Brazil	0.148	0.571	54.30%	6	4,660.32	5,150.88	11-Apr-19	Santos	4,905.60	Baltimore	4,782	
Bulgaria	0.135	0.475	61.99%	4	3,111.44	3,438.96	11-Apr-19	Varna	3,275.20	Baltimore	5,042	
Burma	0.021	0.688	61.99%	7	0.00	0.00	*11-Apr-19*		3,114.84	Los Angeles	8,579	average of Bangladesh and Thailand and Sri Lanka
Cambodia	0.021	0.600	61.99%	7	1,377.41	1,522.40	11-Apr-19	Sihanoukville	1,449.91	Los Angeles	8,298	
Canada	0.736	0.959	69.90%	5	1,289.95	1,425.74	15-Apr-19	Regina	1,357.85	Los Angeles	1,327	Cost is for a container with same conditions, but via truck. Driving distance is 1,691 miles.
Chile	0.234	0.676	61.99%	6	6,282.75	6,944.09	11-Apr-19	Valparaiso	6,613.42	Los Angeles	5,516	
China	0.149	0.551	61.99%	7	991.71	1,096.10	11-Apr-19	Yantai	1,043.91	Los Angeles	6,195	
Colombia	0.101	0.429	61.99%	6	5,598.27	6,187.56	11-Apr-19	Cartagena	5,892.92	Los Angeles	3,144	
Costa Rica	0.191	0.700	61.99%	6	4,377.69	4,838.50	11-Apr-19	Caldera	4,608.10	Los Angeles	3,509	**via car
Croatia	0.216	0.634	61.99%	4	2,864.28	3,165.79	11-Apr-19	Rijeka	3,015.04	Baltimore	4,411	
Cuba	0.123	0.564	61.99%	6	5,649.15	6,243.80	11-Apr-19	Havana	5,946.48	Los Angeles	2,286	
Czech Republic	0.312	0.605	60.40%	4	0.00	0.00	*11-Apr-19*		2,932.91		4,489	average of Slovenia, Poland, Croatia, and Romania
Denmark	0.948	1.188	72.70%	4	1,952.32	2,157.83	11-Apr-19	Copenhagen	2,055.08	Baltimore	4,008	
Ecuador	0.102	0.563	61.99%	6	5,750.04	6,355.30	11-Apr-19	Manta	6,052.67	Los Angeles	3,416	
Egypt	0.052	0.336	61.99%	2	2,890.55	3,194.82	11-Apr-19	Port Said	3,042.69	Baltimore	5,762	
Estonia	0.312	0.697	64.30%	4	2,236.23	2,471.62	11-Apr-19	Parnu	2,353.93	Baltimore	4,318	
Ethiopia	0.013	0.608	61.99%	1	0.00	0.00	*11-Apr-19*		5,975.17	Los Angeles	10,259	average of Kenya, Mozambique, and South Africa
Finland	0.765	1.051	58.90%	4	2,236.23	2,471.62	11-Apr-19	Helsinki	2,353.93	Baltimore	4,269	
France	0.652	0.983	56.40%	4	2,179.83	2,409.29	11-Apr-19	Marseilles	2,294.56	Baltimore	4,084	2063.81 to 2281.05 using Rouen
Georgia	0.065	0.388	61.99%	4	3,170.68	3,504.43	11-Apr-19	Poti	3,337.56	Baltimore	5,606	
Germany	0.746	0.919	57.50%	4	1,933.74	2,137.29	11-Apr-19	Hamburg	2,035.52	Baltimore	3,974	
Ghana	0.032	0.722	61.99%	1	6,570.30	7,261.91	11-Apr-19	tema	6,916.11	Baltimore	5,251	
Greece	0.311	0.756	58.40%	4	2,811.75	3,107.73	11-Apr-19	Corinth	2,959.74	Baltimore	5,058	

Table 83. Country wage index, COLA, regional groupings, and shipping information (2 of 3).

Country	Wage Index (US=1)	Cost of living index (US = 1)	Wage percentage of total compensation	World Regional Grouping	Shipping cost, low	Shipping cost, high	Date aquired	Port Shipped to/from:	Shipping rate, low average	US Port City that provides lowest average	US port city to City Shipped to distance (straight line distance) (mile)	Notes
Guam - GU	1.000	1.000	61.99%	3	4,021.71	4,445.05	12-Apr-19	Jose D. Leon Gu	4,233.38	Los Angeles	6,098	
Alaska - AK	1.000	1.000	70.10%	5	1,088.27	1,202.82	16-Apr-19	Anchorage	1,145.55	Los Angeles	2,361	
Hawaii - HI	1.000	1.000	70.10%	3	3,258.64	3,601.65	12-Apr-19	Honolulu	3,430.15	Los Angeles	2,554	
Hong Kong	0.795	0.951	61.99%	7	926.91	1,024.48	11-Apr-19	Hong Kong	975.70	Los Angeles	7,247	
Hungary	0.221	0.559	56.80%	4	0.00	0.00	*11-Apr-19*		2,932.91	Baltimore	4,489	average of Slovenia, Poland, Croatia, and Romania
Iceland	1.044	1.409	61.99%	4	4,265.96	4,715.00	11-Apr-19	Reykjavik	4,490.48	Baltimore	2,771	
India	0.031	0.313	61.99%	7	3,000.63	3,316.48	11-Apr-19	Mumbai	3,158.56	Los Angeles	8,709	
Indonesia	0.061	0.447	61.99%	7	1,216.86	1,344.95	11-Apr-19	Jakarta	1,280.91	Los Angeles	8,980	
Iran	0.093	0.443	61.99%	7	4,028.17	4,452.19	11-Apr-19	Bushehr	4,240.18	Los Angeles	8,044	
Iraq	0.079	0.545	61.99%	2	3,957.52	4,374.10	11-Apr-19	Um Qasr	4,165.81	Los Angeles	7,934	
Ireland	0.949	1.073	61.60%	4	2,063.81	2,281.05	11-Apr-19	Dublin	2,172.43	Baltimore	3,345	
Israel	0.640	1.081	61.99%	4	2,838.02	3,136.76	11-Apr-19	Haifa	2,987.39	Baltimore	5,805	
Italy	0.532	0.905	52.60%	4	2,287.68	2,528.49	11-Apr-19	Napoli	2,408.09	Baltimore	4,564	
Jamaica	0.082	0.766	61.99%	6	5,394.74	5,962.61	11-Apr-19	Montego Bay	5,678.68	Los Angeles	2,694	
Japan	0.662	0.996	56.00%	7	973.20	1,075.64	11-Apr-19	Kawasaki	1,024.42	Los Angeles	5,492	
Kazakhstan	0.137	0.422	61.99%	7	0.00	0.00	*11-Apr-19*		3,216.95	Baltimore	6,592	average of Iran, India, Turkey, and Russia
Kenya	0.025	0.505	61.99%	1	5,693.42	6,292.73	11-Apr-19	Mombasa	5,993.08	Los Angeles	9,936	
Kosovo	0.067	0.410	61.99%	4	0.00	0.00	*11-Apr-19*		3,149.20	Baltimore	4,830	average of Greece, Albania, Bulgaria, and Croatia
Latvia	0.253	0.655	61.99%	4	2,278.80	2,518.67	11-Apr-19	Riga	2,398.74	Baltimore	4,358	
Lithuania	0.261	0.608	61.99%	4	0.00	0.00	*11-Apr-19*		2,398.74	Baltimore	4,253	average of Poland and Latvia
Los Angeles, CA	1.000	1.000	61.99%	5	1,026.47	1,134.52	15-Apr-19	Baltimore, MD	1,080.50	Baltimore	2,319	Driving distance is 2,662 miles
Luxembourg	1.206	1.135	61.99%	4	0.00	0.00	*11-Apr-19*		2,108.82	Baltimore	3,886	average of France, Belgium, and Netherlands
Macao	1.236	0.816	61.99%	7	0.00	0.00	*11-Apr-19*		975.70	Los Angeles	7,247	equal to Hong Kong
Malaysia	0.166	0.506	61.99%	7	1,170.99	1,294.25	11-Apr-19	Port Kelang	1,232.62	Los Angeles	8,812	
Mauritius	0.174	0.691	61.99%	1	5,945.29	6,571.11	11-Apr-19	Port Louis	6,258.20	Los Angeles	11,456	
Mexico - land	0.148	0.474	61.99%	6	1,462.28	1,616.20	15-Apr-19	Altamira	1,539.24	Los Angeles	1,473	Cost is for a container with same conditions, but via truck. Driving distance is 1,904 miles.
Mexico -sea	0.148	0.474	61.99%	6	2,605.80	2,880.10	11-Apr-19	Altamira	2,742.95	Los Angeles	1,473	
Moldova	0.038	0.433	61.99%	4	0.00	0.00	*11-Apr-19*		3,321.97	Baltimore	5,018	average of Romania and Ukraine
Morocco	0.049	0.459	61.99%	2	2,287.68	2,528.49	11-Apr-19	Casablanca	2,408.09	Baltimore	3,762	
Mozambique	0.007	1.681	61.99%	1	6,549.76	7,239.21	11-Apr-19	Pemba	6,894.49	Los Angeles	10,472	
Namibia	0.078	0.583	61.99%	1	6,492.52	7,175.95	11-Apr-19	Walvis Bay	6,834.24	Los Angeles	9,490	
Nepal	0.014	0.402	61.99%	7	0.00	0.00	*11-Apr-19*		3,814.46	Los Angeles	8,395	average of India and Bangladesh
Netherlands	0.792	0.994	58.60%	4	1,915.16	2,116.75	11-Apr-19	Rotterdam	2,015.96	Baltimore	3,803	
New Zealand	0.669	1.051	83.90%	3	3,871.41	4,278.93	11-Apr-19	Wellington	4,075.17	Los Angeles	6,698	
Nigeria	0.036	0.430	61.99%	1	6,629.48	7,327.32	11-Apr-19	Onne	6,978.40	Baltimore	5,668	
North Macedonia	0.084	0.429	61.99%	4	0.00	0.00	*11-Apr-19*		3,149.20	Baltimore	4,830	average of Greece, Albania, Bulgaria, and Croatia
Norway	1.304	1.319	61.99%	4	1,989.48	2,198.90	11-Apr-19	Bergen	2,094.19	Baltimore	3,648	
Pakistan	0.027	0.296	61.99%	7	3,350.07	3,702.71	11-Apr-19	Karachi	3,526.39	Los Angeles	8,368	
Paraguay	0.094	0.424	61.99%	6	0.00	0.00	*11-Apr-19*		5,918.92	Los Angeles	5,193	average of Peru, Chile, and Argentina
Peru	0.102	0.505	61.99%	6	5,750.04	6,355.30	11-Apr-19	Paita	6,052.67	Los Angeles	3,615	

Table 84. Country wage index, COLA, regional groupings, and shipping information (3 of 3).

Country	Wage Index (US=1)	Cost of living index (US = 1)	Wage percentage of total compensation	World Regional Grouping	Shipping cost, low	Shipping cost, high	Date aquired	Port Shipped to/from:	Shipping rate, low average	US Port City that provides lowest average	US port city to City Shipped to distance (straight line distance) (mile)	Notes
Philippines	0.063	0.443	75.00%	3	1,047.25	1,157.48	11-Apr-19	Cebu	1,102.37	Los Angeles	7,349	
Poland	0.218	0.509	58.90%	4	2,278.80	2,518.67	11-Apr-19	Szczecin	2,398.74	Baltimore	4,147	
Portugal	0.340	0.730	60.00%	4	2,309.26	2,552.33	11-Apr-19	Lisbon	2,430.80	Baltimore	3,531	
Puerto Rico - PR	1.000	1.000	70.00%	6	5,496.51	6,075.09	12-Apr-19	San Juan	5,785.80	Los Angeles	3,364	
Qatar	1.039	0.819	61.99%	2	3,533.64	3,905.60	11-Apr-19	Doha	3,719.62	Los Angeles	8,299	
Romania	0.172	0.482	61.99%	4	3,111.44	3,438.96	11-Apr-19	Constantza	3,275.20	Baltimore	5,029	
Russia	0.158	0.480	61.99%	4	2,278.80	2,518.67	11-Apr-19	St. Petersburg	2,398.74	Baltimore	4,434	
Saudi Arabia	0.345	0.622	61.99%	2	4,113.93	4,546.97	11-Apr-19	Jeddah	4,330.45	Los Angeles	8,337	
Serbia	0.089	0.473	61.99%	4	2,627.89	2,904.51	11-Apr-19	Bar	2,766.20	Baltimore	4,678	
Singapore	0.936	0.958	63.60%	7	1,205.39	1,332.28	11-Apr-19	Singapore	1,268.84	Los Angeles	8,780	
Slovakia	0.285	0.617	53.40%	4	0.00	0.00	*11-Apr-19*		2,932.91	Baltimore	4,489	average of Slovenia, Poland, Croatia, and Romania
Slovenia	0.377	0.733	61.99%	4	2,890.55	3,194.82	11-Apr-19	Piran	3,042.69	Baltimore	4,367	
South Africa	0.093	0.533	61.99%	1	4,786.04	5,289.83	11-Apr-19	Port Elizabeth	5,037.94	Los Angeles	10,368	
South Korea	0.487	0.940	61.99%	7	973.20	1,075.64	11-Apr-19	Incheon	1,024.42	Los Angeles	5,983	
Spain	0.466	0.794	54.80%	4	1,989.48	2,198.90	11-Apr-19	Bilbao	2,094.19	Baltimore	3,706	
Sri Lanka	0.066	0.431	61.99%	7	3,379.19	3,734.89	11-Apr-19	Colombo	3,557.04	Los Angeles	9,381	
Sweden	0.903	1.052	58.40%	4	2,236.23	2,471.62	11-Apr-19	Stockholm	2,353.93	Baltimore	4,086	
Switzerland	1.382	1.468	62.70%	4	0.00	0.00	*11-Apr-19*		2,188.53	Baltimore	4,098	average of Italy, Belgium, France, and Germany
Syria	0.032	0.366	61.99%	7	3,258.28	3,601.26	11-Apr-19	Tartous	3,429.77	Baltimore	5,741	
Tanzania	0.016	0.522	61.99%	1	5,743.79	6,348.40	11-Apr-19	Tanga	6,046.10	Los Angeles	9,975	
Thailand	0.102	0.618	61.99%	7	1,251.27	1,382.98	11-Apr-19	Bangkok	1,317.13	Los Angeles	8,276	
Tunisia	0.060	0.333	61.99%	2	2,330.83	2,576.18	11-Apr-19	Rades	2,453.51	Baltimore	4,531	
Turkey	0.188	0.447	67.70%	4	2,916.82	3,223.85	11-Apr-19	Istanbul	3,070.34	Baltimore	5,180	
Uganda	0.010	0.403	61.99%	1	0.00	0.00	*11-Apr-19*		5,975.17	Los Angeles	10,259	average of Kenya, Mozambique, and South Africa
Ukraine	0.041	0.355	61.99%	4	3,200.30	3,537.17	11-Apr-19	Odessa	3,368.74	Baltimore	5,007	
United Arab Emirates	0.672	0.779	61.99%	2	3,674.93	4,061.77	11-Apr-19	Port Rashid	3,868.35	Los Angeles	8,331	
United Kingdom	0.696	0.996	71.90%	4	2,008.07	2,219.44	11-Apr-19	London	2,113.76	Baltimore	3,628	
Uzbekistan	0.034	0.357	61.99%	7	0.00	0.00	*11-Apr-19*		3,216.95	Baltimore	6,592	average of Iran, India, Turkey, and Russia
Venezuela	0.219	0.375	61.99%	6	7,531.79	8,324.61	11-Apr-19	Puerto Sucre	7,928.20	Los Angeles	3,763	
Vietnam	0.037	0.499	61.99%	7	1,400.35	1,547.75	11-Apr-19	Saigon	1,474.05	Los Angeles	8,170	
Virgin Islands - VI	0.239	1.111	70.00%	6	6,056.21	6,693.70	11-Apr-19	Port Alcuroix	6,374.96	Los Angeles	3,433	
Africa Region	0.048	0.668	61.99%	1					6,290.89	Los Angeles	9,313	Port city most often shipped to was used
Arab States Region	0.295	0.537	61.99%	2					3,308.09	Baltimore	6,375	Port city most often shipped to was used
Pacific Region	0.769	0.929	70.71%	3					3,272.43	Los Angeles	5,828	Port city most often shipped to was used
Europe Region	0.452	0.753	60.68%	4					2,708.68	Baltimore	4,389	Port city most often shipped to was used
North America Region	1.111	1.172	66.79%	5					1,217.71	Baltimore	1,829	Port city most often shipped to was used
South/Latin America Regic	0.218	0.641	62.87%	6					5,226.47	Los Angeles	3,509	Port city most often shipped to was used
Asia Region	0.236	0.564	61.79%	7					2,366.91	Los Angeles	7,601	Port city most often shipped to was used

Table 85. Country region port city shipping correction value, F_{port} (1 of 2).

Country Region Origin	Country Region Destination	F_{port}	Same US Ports (Baltimore to Baltimore) F_{port}	Same US Ports (Los Angeles to Los Angeles) F_{port}	Different US Ports (Baltimore to Los Angeles) F_{port}	Different US Ports (Los Angeles to Baltimore) F_{port}
1	1	2.944	2.944	2.944	2.316	3.571
1	2	1.965	1.278	1.965	1.965	2.652
1	3	4.138	4.138	5.841	2.434	4.138
1	4	2.256	1.343	2.256	2.256	3.169
1	5	2.734	2.734	3.432	2.037	2.734
1	6	11.025	11.025	7.522	14.528	11.025
1	7	0.943	0.943	1.086	0.799	0.943
2	1	1.304	1.212	1.304	1.396	1.304
2	2	3.772	3.772	3.772	3.772	3.772
2	3	11.618	11.618	11.618	11.618	11.618
2	4	3.766	3.766	3.766	3.766	3.766
2	5	5.473	5.473	5.473	5.473	5.473
2	6	1.288	1.288	1.288	1.288	1.288
2	7	0.863	0.863	0.863	0.863	0.863
3	1	3.992	3.992	5.775	3.992	2.210
3	2	15.730	15.730	15.730	15.730	15.730
3	3	1.683	1.683	1.683	1.683	1.683
3	4	7.017	7.017	7.017	7.017	7.017
3	5	4.326	4.326	4.326	4.326	4.326
3	6	2.346	2.346	2.346	2.346	2.346
3	7	1.351	1.351	1.351	1.351	1.351
4	1	1.507	1.383	1.507	1.631	1.507
4	2	3.643	3.643	3.643	3.643	3.643
4	3	5.041	5.041	5.041	5.041	5.041
4	4	2.103	2.103	2.103	2.103	2.103
4	5	6.835	6.835	6.835	6.835	6.835
4	6	1.344	1.344	1.344	1.344	1.344
4	7	2.245	2.245	2.245	2.245	2.245

Table 86. Country region port city shipping correction value, F_{port} (2 of 2).

Country Region Origin	Country Region Destination	F_{port}	Same US Ports (Baltimore to Baltimore) F_{port}	Same US Ports (Los Angeles to Los Angeles) F_{port}	Different US Ports (Baltimore to Los Angeles) F_{port}	Different US Ports (Los Angeles to Baltimore) F_{port}
5	1	2.169	2.169	2.110	2.169	2.228
5	2	5.677	5.677	5.677	5.677	5.677
5	3	2.670	2.670	2.670	2.670	2.670
5	4	7.276	7.276	7.276	7.276	7.276
5	5	17.610	17.610	17.610	17.610	17.610
5	6	1.660	1.660	1.660	1.660	1.660
5	7	21.223	21.223	21.223	21.223	21.223
6	1	10.718	10.718	5.070	10.718	16.367
6	2	1.575	1.575	1.575	1.575	1.575
6	3	2.648	2.648	2.648	2.648	2.648
6	4	1.665	1.665	1.665	1.665	1.665
6	5	1.636	1.636	1.636	1.636	1.636
6	6	11.951	11.951	11.951	11.951	11.951
6	7	0.873	0.873	0.873	0.873	0.873
7	1	1.130	1.130	1.225	1.130	1.035
7	2	2.053	2.053	2.053	2.053	2.053
7	3	1.673	1.673	1.673	1.673	1.673
7	4	3.080	3.080	3.080	3.080	3.080
7	5	30.872	30.872	30.872	30.872	30.872
7	6	1.083	1.083	1.083	1.083	1.083
7	7	3.140	3.140	3.140	3.140	3.140

APPENDIX H. HEAT MAP MANUFACTURING COST VALUES

This section has the tables for the heat map values from Section 5.10 and Section 5.11.

Table 87. State and country manufacturing costs for the high automated case heat maps (1 of 2).

Location	Cost	Location	Cost	Location	Cost
AL	3.94	NJ	4.28	Argentina	2.96
AK	4.86	NM	3.91	Armenia	2.84
AZ	4.04	NY	4.02	Australia	4.11
AR	3.91	NC	4.02	Austria	4.04
CA	4.45	ND	4.23	Azerbaijan	2.82
CO	4.17	OH	4.01	Bahamas	3.64
CT	4.47	OK	3.94	Bangladesh	3.09
DE	4.03	OR	4.31	Belarus	2.75
FL	4.08	PA	4.03	Belgium	3.83
GA	3.97	RI	4.44	Bermuda	6.35
HI	4.91	SC	4.15	Bolivia	2.81
ID	4.04	SD	3.94	Bosnia & Herzegovina	2.88
IL	3.93	TN	3.93	Brazil	2.91
IN	3.94	TX	4.04	Bulgaria	2.97
IA	4.00	UT	3.82	Burma	3.01
KS	4.06	VT	4.24	Cambodia	2.68
KY	3.83	VA	4.11	Canada	4.28
LA	4.15	WA	4.88	Chile	3.17
ME	4.34	WV	4.14	China	2.66
MD	4.22	WI	4.08	Colombia	2.87
MA	4.60	WY	4.44	Costa Rica	3.05
MI	4.01	DC	4.59	Croatia	3.12
MN	4.16	U.S.	4.12	Cuba	3.01
MS	3.84	GU	4.60	Czech Republic	3.22
MO	3.99	PR	4.35	Denmark	4.24
MT	4.07	VI	5.15	Ecuador	2.94
NE	3.97	AS	4.88	Egypt	2.60
NV	4.12	Albania	2.89	Estonia	3.19
NH	4.46	Algeria	2.64	Ethiopia	2.94

Table 88. State and country manufacturing costs for the high automated case heat maps (2 of 2).

Location	Cost	Location	Cost	Location	Cost
Finland	3.97	Macao	4.30	Saudi Arabia	3.43
France	3.78	Malaysia	2.79	Serbia	2.83
Georgia	2.80	Mauritius	3.22	Singapore	4.06
Germany	3.84	Mexico - land	2.74	Slovakia	3.19
Ghana	2.93	Mexico -sea	2.81	Slovenia	3.41
Greece	3.30	Moldova	2.82	South Africa	2.94
Hong Kong	3.79	Morocco	2.65	South Korea	3.29
Hungary	3.08	Mozambique	3.60	Spain	3.40
Iceland	4.96	Namibia	3.08	Sri Lanka	3.00
India	2.82	Nepal	2.96	Sweden	4.16
Indonesia	2.62	Netherlands	3.93	Switzerland	5.00
Iran	3.16	New Zealand	3.92	Syria	2.76
Iraq	3.00	Nigeria	2.76	Tanzania	2.90
Ireland	4.24	North Macedonia	2.85	Thailand	2.78
Israel	3.90	Norway	4.81	Tunisia	2.58
Italy	3.59	Pakistan	2.87	Turkey	2.98
Jamaica	3.04	Paraguay	2.81	Uganda	2.82
Japan	3.58	Peru	2.91	Ukraine	2.79
Kazakhstan	2.93	Philippines	2.55	United Arab Emirates	3.90
Kenya	2.90	Poland	2.97	United Kingdom	3.84
Kosovo	2.81	Portugal	3.27	Uzbekistan	2.76
Latvia	3.10	Qatar	4.38	Venezuela	3.09
Lithuania	3.07	Romania	3.02	Vietnam	2.65
Luxembourg	4.56	Russia	2.86		

Table 89. State and country manufacturing costs for the low automated case heat maps (1 of 2).

Location	Cost	Location	Cost	Location	Cost
AL	6.32	NJ	7.23	Argentina	3.40
AK	7.85	NM	6.24	Armenia	2.82
AZ	6.47	NY	6.59	Australia	6.44
AR	6.25	NC	6.50	Austria	6.08
CA	7.25	ND	7.23	Azerbaijan	2.81
CO	7.00	OH	6.61	Bahamas	4.91
CT	7.49	OK	6.43	Bangladesh	2.95
DE	6.45	OR	7.00	Belarus	2.80
FL	6.54	PA	6.55	Belgium	5.69
GA	6.34	RI	7.21	Bermuda	11.38
HI	7.53	SC	6.88	Bolivia	2.75
ID	6.46	SD	6.34	Bosnia & Herzegovina	2.91
IL	6.39	TN	6.35	Brazil	3.13
IN	6.38	TX	6.71	Bulgaria	3.14
IA	6.50	UT	6.02	Burma	2.88
KS	6.67	VT	6.84	Cambodia	2.55
KY	6.07	VA	6.75	Canada	6.19
LA	7.02	WA	8.85	Chile	3.64
ME	7.21	WV	6.85	China	2.89
MD	7.05	WI	6.81	Colombia	2.95
MA	7.81	WY	7.87	Costa Rica	3.40
MI	6.59	DC	8.19	Croatia	3.54
MN	7.00	U.S.	6.77	Cuba	3.16
MS	6.09	GU	6.56	Czech Republic	3.90
MO	6.46	PR	6.06	Denmark	6.77
MT	6.71	VI	7.73	Ecuador	3.03
NE	6.39	AS	7.69	Egypt	2.53
NV	6.80	Albania	2.89	Estonia	3.89
NH	7.39	Algeria	2.62	Ethiopia	2.79

Table 90. State and country manufacturing costs for the low automated case heat maps (2 of 2).

Location	Cost	Location	Cost	Location	Cost
Finland	5.97	Macao	7.60	Saudi Arabia	4.21
France	5.45	Malaysia	3.05	Serbia	2.88
Georgia	2.78	Mauritius	3.53	Singapore	6.53
Germany	5.77	Mexico - land	2.95	Slovakia	3.80
Ghana	2.84	Mexico -sea	3.02	Slovenia	4.29
Greece	4.00	Moldova	2.72	South Africa	3.01
Hong Kong	5.86	Morocco	2.58	South Korea	4.49
Hungary	3.50	Mozambique	3.53	Spain	4.54
Iceland	7.77	Namibia	3.10	Sri Lanka	2.98
India	2.69	Nepal	2.79	Sweden	6.54
Indonesia	2.59	Netherlands	6.00	Switzerland	8.76
Iran	3.22	New Zealand	5.65	Syria	2.64
Iraq	3.03	Nigeria	2.65	Tanzania	2.75
Ireland	6.75	North Macedonia	2.88	Thailand	2.88
Israel	5.55	Norway	8.35	Tunisia	2.54
Italy	4.92	Pakistan	2.72	Turkey	3.31
Jamaica	3.09	Paraguay	2.87	Uganda	2.64
Japan	5.28	Peru	3.00	Ukraine	2.69
Kazakhstan	3.11	Philippines	2.52	United Arab Emirates	5.61
Kenya	2.77	Poland	3.38	United Kingdom	5.63
Kosovo	2.79	Portugal	4.05	Uzbekistan	2.64
Latvia	3.62	Qatar	7.13	Venezuela	3.50
Lithuania	3.61	Romania	3.30	Vietnam	2.55
Luxembourg	7.81	Russia	3.10		

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