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REAL-TIME GEOMETRY-BASED FEEDBACK FOR DESIGN ENGINEERS ON THE
ENVIRONMENTAL IMPACT OF MANUFACTURING

BY

AMANDA BLIGH

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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IN
INDUSTRIAL AND SYSTEMS ENGINEERING

UNIVERSITY OF RHODE ISLAND

2019

DOCTOR OF PHILOSOPHY DISSERTATION
OF
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UNIVERSITY OF RHODE ISLAND
2019

ABSTRACT

In this dissertation study, the concept of an energy shadow, which represents all the work done by the interacting systems back to the earth-based inputs needed to produce a product, is used as a metric to investigate the development of a real-time, geometry-based software tool to assist design engineers in evaluating the environmental impact of manufacturing. A literature review of the energy metrics of consumed energy, exergy, and emergy was conducted to evaluate which may best serve as the thermodynamic framework for representing an energy shadow. Following the comparison and evaluation of the possible metrics emergy was selected as it best covers the entire energy shadow of a product. The framework was developed for manufacturing using emergy accounting as an analog to cost. Modular emergy models were generated as analogues to the major manufacturing cost accounting areas, and the framework was applied to an example assembly using data from a design for manufacturing (DFM) cost analysis as input. This framework greatly expanded the detail and coverage of existing emergy models regarding manufacturing areas. The models in the framework were implemented as a prototype extension in a commercially available manufacturing costing software that provides cost estimates based on 3D CAD files. Sensitivity analyses of the model were conducted based on changing input values for emergy and varying the CAD geometry, which identified areas for model refinement and characterized the influence of the design parameters. The software extension was tested with a group of 19 engineering students including both graduates and undergraduates to understand if the use of emergy as a sustainability metric enabled better ranking of a set of design alternatives. It was found that performance on the ranking exercise improved in a statistically significant manner after exposure to the concept of emergy and the software extension. The participants were able to constructively provide feedback for further improvement on the best designs, despite limited exposure to the newly introduced concept of emergy.

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The work contained herein is not the work of a few months or years, but part of an ongoing cycle of gaining and applying knowledge. With that in mind, I would like to thank my dad and mom—James Bligh and Joanna Bligh—for encouraging my curiosity and determination throughout my childhood with special thanks to my mom for her assistance in reviewing this material and helping me get most of the commas and hyphens into the right places.

Thanks to my major professor Dr. Manbir Sodhi for posing the initial question and keeping a bug in my ear about engaging in a Ph.D. after I completed my Master's work. Additionally, I want to thank him for his support and regular intellectual exercises to ensure I was in the position to talk about my work cogently both at my defense and more broadly.

I am very much indebted to Dr. Daniel Campbell for his support in working with emergy. His knowledge, guidance, and collaboration were instrumental in producing the work that follows. Hopefully, the proposals I have added to the emergy space will be helpful in developing it further in the disciplines of engineering and manufacturing.

Thanks also go to my remaining committee members—Dr. Carl-Ernst Rousseau and Dr. Mercedes Rivero—and those students and professors in the ISE department at URI who I have engaged with over the years in classes and other activities.

I would not have had the mental space to complete this dissertation if it was not for those I work with, particularly MK and SF. Their willingness to support my further education with both time and software is notable and shows the value they place on supporting the development of their teams. Also many thanks to MD for providing comments for improvements on my user interfaces.

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GLOSSARY

activity-based costing A method for defining costs within a company based on the number of activities or cost-driving units consumed. Commonly used within manufacturing facilities.

aPriori Software A physics-based manufacturing costing software that creates costs estimates based on 3D models.

Design for X Abbreviated as DFX or DfX. A group of methodologies for ensuring the consideration of various topics during the development of a product.

exergy A thermodynamic value representing the work available within a system as it is brought into equilibrium with its environment.

modeFRONTIER Software A process integration and design optimization (PIDO) software for conducting optimization and statistical analysis studies.

R² A statistical measure of how close a set of data is to a fitted regression line.

rough mass Mass of a part including scrap material from the sheet and internal holes.

solar emergy Available solar energy used directly and indirectly to make a service or a product.

solar emjoules Abbreviated as sej. Unit for solar emergy denoting the past use of available energy or exergy within a system.

unit emergy value Abbreviated as UEV. A value for converting a unit of a material, service, or other quantity into emergy units of sejs. For example, a material might have a UEV in the form of $\frac{\text{sej}}{\text{kg}}$ and also be, in some cases, noted as a transformity or specific emergy.

virtual production environment Abbreviated as VPE. A model of a factory as used in aPiori costing software, which includes cycle time and cost models plus supporting data.

SYMBOLS

Variable	Description	Unit
A_{gap}	Area of gap around the machine	m^2
A_{mach}	Area taken by machine on factory floor	m^2
A_{space}	Other non-production space attributed to a machine	m^2
C_j	Impact of emissions on human health	sej
C_m	Total cost of material from DFM analysis	USD
$C_{L\&S}$	Cost of labor and services on a part within a piece of manufacturing equipment	USD
C_{OH}	Total cost of direct overhead at the machine	USD
C_{board}	Retail price of circuit board	$\frac{USD}{hr}$
C_{cal}	Average cost per calorie	$\frac{USD}{cal}$
C_l	Total cost of direct labor at the machine	USD
C_{part}	Retail cost of a part within a piece of manufacturing equipment	USD
E_{Gibbs}	Emergy of dilution of emissions	sej
$E_{m_{info}}$	Emergy for independent information learned by worker	$\frac{sej}{yr}$
$E_{m_{age}}$	Emergy lost by worker due to age	$\frac{sej}{yr}$
$E_{m_{assy}}$	Emergy contained in the assembly of a piece of manufacturing equipment	sej
$E_{m_{build}}$	Emergy contribution in the factory building	sej
$E_{m_{cars}}$	Emergy attributed to a worker per year for car	$\frac{sej}{yr}$
E_{m_d}	Total emergy for disposal of waste	sej
$E_{m_{ed}}$	Emergy for worker education	$\frac{sej}{yr}$
$E_{m_{equip}}$	Emergy in a part provided by manufacturing equipment	sej

Variable	Description	Unit
Em_{exp}	Emergy for worker experience	$\frac{sej}{yr}$
$Em_{facility}$	Emergy contribution in the operation of the facility housing manufacturing	sej
Em_{im}	Total emergy for impact of waste on the environment	sej
$Em_{l, fact}$	Emergy contribution from the facility labor	sej
Em_l	Emergy for labor	$\frac{sej}{yr}$
Em_{mach}	Emergy in a piece of manufacturing equipment	sej
$Em_{mat, part}$	Emergy for a part within a piece of manufacturing equipment	sej
Em_{mat}	Emergy contribution from material in factory building	sej
Em_{met}	Emergy for metabolic processes of a worker	$\frac{sej}{yr}$
Em_{parts}	Emergy contained in the parts that make up a piece of manufacturing equipment	sej
Em_{power}	Emergy in power used in running manufacturing equipment	sej
Em_{raw}	Emergy in raw material	sej
Em_{res}	Emergy attributed to a worker per year for residential energy use	$\frac{sej}{yr}$
Em_{serv}	Emergy for services consumed by the worker	$\frac{sej}{yr}$
Em_{set}	Emergy contribution from setup of manufacturing processes	sej
Em_{supp}	Emergy contained in supplies to support manufacturing process	sej
Em_{train}	Emergy for on-the-job training of a worker	$\frac{sej}{yr}$
Em_{util}	Emergy contribution from the building utilities	sej

Variable	Description	Unit
$Em_{waste,const}$	Emergy of waste due to factory construction	sej
Em_{waste}	Total emergy for disposal, remediation and impact of waste	sej
$Em_{worker,adj}$	Adjusted total emergy for a worker	$\frac{sej}{yr}$
Em_{worker}	Total emergy for a worker	$\frac{sej}{yr}$
F_{day}	Calories consumed per day	$\frac{cal}{day}$
P_{PU}	Price of polyurethane on board per mass	$\frac{USD}{kg}$
P_{board}	Price of board per mass based on material makeup	$\frac{USD}{kg}$
P_{mat2}	Price of second material on a part within a piece of manufacturing equipment	$\frac{USD}{kg}$
P_{mat1}	Price of first material on a part within a piece of manufacturing equipment	$\frac{USD}{kg}$
P_m	Market commodity price for material	$\frac{sej}{mass}$
P_{part}	Retail price of a part in manufacturing equipment	USD
P_{part}	Retail price of a part in a piece of manufacturing equipment	USD
P_{retail}	Retail price of manufacturing equipment	USD
R_A	Yearly rent rate for building	$\frac{USD}{m^2 \cdot yr}$
R_{sup}	Rate of supply use	$\frac{kg}{sec}$
T_A	UEV for factory building by area	$\frac{sej}{m^2}$
$T_{\$}$	UEV for money in the United States	$\frac{sej}{USD}$
$T_{concrete}$	UEV of concrete	$\frac{sej}{kg}$
$T_{ed,b}$	UEV for workers with a bachelors degree	$\frac{sej}{hr}$
$T_{ed,h}$	UEV for workers with only a high school diploma	$\frac{sej}{hr}$
$T_{ed,m}$	UEV for workers with a masters degree	$\frac{sej}{hr}$
$T_{ed,n}$	UEV for workers with a no high school diploma	$\frac{sej}{hr}$

Variable	Description	Unit
$T_{ed,p}$	UEV for workers with a PhD degree	$\frac{sej}{hr}$
$T_{ed,sc}$	UEV for workers with some college but no diploma, with a certificate degree, or an associates degree	$\frac{sej}{hr}$
T_{elec}	UEV for electricity	$\frac{sej}{kWh}$
T_l	UEV per time for labor	$\frac{sej}{hr}$
T_{mat1}	UEV of first material on a part within a piece of manufacturing equipment	kg
T_{mat2}	UEV of second material on a part within a piece of manufacturing equipment	kg
T_{mat}	UEV for material	$\frac{sej}{mass}$
T_{steel}	UEV of steel for supporting construction	$\frac{sej}{kg}$
W_{cap}	Total yearly capacity of the facility	hr
Z	Z-score for sample size estimation	
α	The p-value for sample size estimation	
c_{dis}	Cost of disposal	USD
c_{int}	Cost of interest on machine	USD
c_{kg}	Material cost per kilogram	$\frac{USD}{kg}$
c_{mach}	Cost of a production machine	USD
c_{mat}	Cost of commodity material to make a manufacturing supply	USD
c_{rem}	Cost of remediation	USD
c_{rent}	Yearly cost of rent attributed to machine	USD
c_{sup}	Cost of supplies	USD
d_{avg}	Average distance between rank by study participant and emergy ranking for design alternatives	ranking positions
d	The margin of error for sample size estimation	
f_{elec}	Facility electricity factor	
f_{fire}	Building fire insurance factor	

Variable	Description	Unit
f_g	Facility gas factor	
f_{inst}	Machine installation factor	
f_{liab}	Building liability insurance factor	
f_{loss}	Building loss insurance factor	
f_{maint}	Machine maintenance factor	
f_{markup}	Estimated retail markup for parts within a piece of manufacturing equipment	USD
f_{mat2}	Fraction of second material on a part within a piece of manufacturing equipment	
f_{mat1}	Fraction of first material on a part within a piece of manufacturing equipment	
f_w	Facility water factor	
h_d	Number of hours in a day	$\frac{\text{hrs}}{\text{day}}$
h_{assy}	Hourly rate for a machine assembler	$\frac{\text{USD}}{\text{hr}}$
h_{eng}	Electricity rate	$\frac{\text{USD}}{\text{kWh}}$
h_{eng}	Hourly wage for facility engineering worker	$\frac{\text{USD}}{\text{hr}}$
h_{fm}	Hourly wage for facility maintenance worker	$\frac{\text{USD}}{\text{hr}}$
h_{pur}	Hourly wage for facility purchasing worker	$\frac{\text{USD}}{\text{hr}}$
h_p	Hourly wage for machine worker	$\frac{\text{USD}}{\text{hr}}$
h_q	Hourly wage for facility quality control worker	$\frac{\text{USD}}{\text{hr}}$
h_{tc}	Hourly wage for facility tool crib worker	$\frac{\text{USD}}{\text{hr}}$
h_y	Number of hours per year	$\frac{\text{hr}}{\text{yr}}$
m_{PU}	Mass of PU on board	kg
m_{board}	Mass of curcuit board	kg
$m_{concrete}$	Mass of concrete in factory building	kg
m_{part}	Mass of a part within a piece of manufacturing equipment	kg

Variable	Description	Unit
m_{part}	Mass of a part in a piece of manufacturing equipment	kg
m_{rough}	Part rough mass, includes attributable scrap	kg
m_{steel}	Mass of steel in factory building	kg
n_{alts}	Number of design alternatives	
n_p	Number of workers at a machine	people
p_{act}	Emergy ranking for a design alternative	ranking position
p_{mach}	Machine power	kW
p_{par}	Participant ranking for a design alternative	ranking position
p_{rand}	Probability of correct ranking occurring randomly	
s_{as}	Fraction of workers in an occupation with an associates degree	
s_b	Fraction of workers in an occupation with a bachelors degree	
s_{cert}	Fraction of workers in an occupation with a certificate degree	
s_{eng}	Facility engineering worker factor	
s_{fm}	Facility maintenance worker factor	
s_{hs}	Fraction of workers in an occupation with only high school diploma	
s_m	Fraction of workers in an occupation with a masters degree	
s_n	Fraction of workers in an occupation with no high school diploma	
s_{pur}	Facility purchasing worker factor	
s_p	Fraction of workers in an occupation with a PhD degree	
s_q	Facility quality control worker factor	

Variable	Description	Unit
s_{sc}	Fraction of workers in an occupation with only some collage, but no college diploma	
s_{tc}	Facility tool crib worker factor	
s	Sample size estimation	people
t_{assy}	Time to complete assembly of a product	sec
t_{assy}	Time to assemble the manufacturing equipment	hr
t_c	Operation time attributed to machine	sec
t_{earn}	Machine earned hours	hr
t_{exp}	Expected factory building life	yr
t_h	Part handling time	sec
t_{life}	Life of production machine	yr
t_l	Time attributed to labor	sec
t_{set}	Time to setup the machine	hr

ABBREVIATIONS

ABC Activity-Based Costing

ABS Acrylonitrile Butadiene Styrene

BLS Bureau of Labor Statistics

BOF Basic Oxygen Furnace

BOM Bill of Materials

CAD Computer Added Design

CR Cold Rolled

CSL Cost Scripting Language

D Double Sided Impact Forming

DALY Disability-Adjusted Life Years

DFA Design for Assembly

DfE Design for Environment; also DFE

DFM Design for Manufacturing

DFX Design for X

EAF Electric Arc Furnace

EEA Extended Exergy Analysis

EIA Energy Information Administration

EmA Emergy Analysis

EMR Emergy to Money Ratio

EPA Environmental Protection Agency

EPWH Energy use Per Worker-Hour

EREF Environmental Research Education Foundation

ESL Energy Systems Language

ETU Effluent Treatment Unit

F Imported Resource

GEB Geobiosphere Emergy Baseline

GUI Graphical User Interface

HDPE High-Density Polyethylene

HVAC Heating, Ventilation, and Air Condition

IF Impact Forming

IFC Industrial Final Consumption

IPCC The Intergovernmental Panel on Climate Change

LCA Life Cycle Analysis

LCD Liquid Crystal Display

LCI Life Cycle Inventory

LCI/A Life Cycle Inventory and Analysis

LH Left Hand

LIST Luxembourg Institute of Science and Technology

LPG Liquefied Petroleum Gas

MEP Maximum Empower Principle

MIG Metal Inert Gas

OOH Occupational Outlook Handbook

PC Polycarbonate

PDP Product Development Process

PIDO Process Integration and Design Optimization

PP Polypropylene

PU Polyurethane

PVC Polyvinyl Chloride

R Renewable Resource

R and D Research and Development

RH Right Hand

S Single Sided Impact Forming

sej Solar emjoules

TEA Thermo-Ecological cost Analysis

TFC Total Final Consumption

TPES Primary Energy Supply

UEV Unit Emergy Value

US BLS United States Bureau of Labor Statistics

VPE Virtual Production Environment

XML eXtensible Markup Language

Y System Yield

CHAPTER 1

Introduction

Every person we encounter, every organization, every animal, garden, tree, and forest is a complex system.

—Meadows and Wright [1]

It is our belief...that many, if not all, of the systems we care about can be interpreted as thermodynamic interactions.

—Bakshi, Gutowski and Sekulic [2]

Nature consists of animals, plants, microorganisms, earth processes and human societies working together...joined by invisible pathways over which pass chemical materials that cycle around and around, being used and reused, and through which flow potential energies that cannot be reused.

—H.T. Odum [3]

The Earth is composed of systems that transfer thermodynamic energy from one element to the other. Some of this energy is combined and transformed by natural and industrial systems from one form to another to perform what the inhabitants of the Anthropocene epoch see as useful work. The development of a product includes inputs of energy from multiple sources, which are, in turn, dependent on further upstream energy contributions. Figure 1.1 shows the energy inputs for a simple USB drive.

The drive is made of a selection of parts assembled together. One assembly step (1) is the gluing of the circuit board to the plastic housing. This step is completed by workers using glue guns, which require electricity to operate. The workers operating the glue guns require energy to support their lives: gasoline to drive to work and natural gas or other fuels

Figure 1.1. A diagram showing the energy inputs within the manufacturing of a product.

to heat their homes. The glue gun is a manufactured product, which was assembled using a manufacturing process infused with energy.

Turning to the manufacture of the metal part (2) that makes up the decoration on the USB drive, it is created through a metal stamping process that requires the input of energy and is supported by workers. These workers, much like the glue gun operators, are supported by energy in their daily lives. Additionally, the part is made using a stamping die, which was also manufactured by processes requiring energy inputs.

The metal of the part was rolled from steel ingots at a rolling mill (3) using a process that required the input of energy and was attended to by workers. The ingots were created in further upstream processes, also requiring energy. Ultimately, ore was mined from the ground by a collaboration of workers and machines all infused with energy from a selection of sources, such as diesel fuel, food, and electricity.

All of the manufacturing processes occurred within a factory (4) that was built by workers and machines with energy input, from materials created from earth-based processes. Once the factory is constructed, the lights and heat are supported by energy from electricity and directly from fossil fuels. Factory maintenance and other activities supporting

manufacturing are completed by factory workers. The factory also outputs effluent that is either treated with industrial systems to reach nontoxic levels and requires energy input or processed by natural systems requiring their energy input from earth-related cycles.

Looking at each of these manufacturing steps, all can be traced back to energetic work done by or to the earth (5). Ores are collected into mineable deposits by the tectonic work from the deep heat of the earth. Oil and gas used in power and material generation are formed from long buried plant matter originally created by energy extracted via photosynthesis from the sun and supported by the nitrogen cycle. The same energy transformations by plants support the calories workers consume. Industrial systems or environmental organisms process, dilute, or segregate toxic materials through the input of energy. Even renewable forms of power—solar, tidal, hydro, and wind—can be traced back to the interaction of the sun, the gravitation pull of the moon and sun, and other earth-based cycles and processes.

Considering all of these energy inputs, the sum of this result is an *energy shadow*, representing all the energetic work done by all the interacting systems back to the earth-based inputs to create a product. The energy shadow is the total collection of all inputs and impacts of a system within the environment.

In this dissertation study, the concept of an energy shadow is used as a metric to investigate the development of a real-time, geometry-based software tool to aid design engineers in evaluating the environmental impact of manufacturing. This investigation was completed through a literature review of the energy metrics of consumed energy, exergy, and emergy to serve as a suitable thermodynamic framework for representing an energy shadow. Following a comparison and evaluation process, a model for the selected metric, emergy, is developed for manufacturing using an analogy to cost.

The set of equations representing the model are evaluated with an example assembly. The equations are then coded into a physics and geometry-based, manufacturing costing tool where the sensitivity of the model to variations of inputs and geometry are investigated.

This software-based model is then evaluated for its ability to support the improvement of sustainable design recommendations by engineering students.

The dissertation study concludes with a review of areas where this investigation has expanded on the existing literature. Opportunities for future work are identified, as is the potential impact on relevant areas of research.

CHAPTER 2

Literature Review

2.1 Engineering Decision-Making in Product Development

A product development process (PDP) is the procedure by which companies bring a product from concept to market. Many approaches have been described throughout the last 30 years [4–8]. Ulrich and Eppinger’s process [8] shown in Figure 2.1 is representative. Most researchers recommend that products be developed by a cross-functional team, including marketing and engineering at a minimum, but optimally the product development team includes representatives from sales, manufacturing, finance, and a selection of other disciplines depending on the company, product, and other requirements. Decisions related to the development of the product occur regularly in the process at various levels and are made by various participants [4–8]. The end-of-stage review—shown by the diamonds between phases in Figure 2.1—are crucial steps [4]. The decisions driving critical aspects of a product design are made within PDP stages by engineers. These decisions determine how well a design performs against a selection of downstream metrics based on the product’s final embodiment. As an example, more than 70% of a product’s total cost is driven by choices made by designers early in product development [9]. To combat surprises later in the design cycle, a series of methodologies was proposed in the early 1980s, known as “Design for X” (DFX). Two critical DFX methodologies are design for manufacturing (DFM) and design for environment (DFE, interchangeably known as eco-design outside the United States [10]).

2.1.1 DFM and Its Metrics

Design for manufacturability (or DFM) is a strategy for guiding a product’s design in the early stages of concept development in an effort to avoid difficulties later in man-

Figure 2.1. PDP adapted from Ulrich and Eppinger [8].

ufacturing [8, 9, 11]. Difficulties in manufacturing lead to longer cycle times, different process selections, and lack of product quality [8]. These elements are important to a business as longer cycle times mean less throughput, different processes may mean higher costs, and poorer product quality lead to more scrap in the process or more returns by customers [8, 12]. Each of these results in higher cost to the company as a whole. As a result, the principal metric for determining if one design is more manufacturable than another is cost. Cost serves as a metric for comparing two alternative manufacturing methods for making the same part, two different designs satisfying the same function with the same manufacturing process, or a combination of both.

The cost of a product or a manufactured component within the scope of a DFM assessment is allocated using an activity-based costing (ABC) structure [8]. ABC is well suited as a framework for such evaluations because it defines costs “according to the number of activities or cost-[driving] units it consumes” [13]. This is demonstrated in an input-output format, as shown by Ulrich and Eppinger [8] in Figure 2.2, which can be decomposed in an ABC structure by reviewing how the inputs create the output.

Figure 2.2. Simple input-output model of a manufacturing system [8].

The output of finished goods in Figure 2.2 could be a full product, an assembly or a subassembly within the product, or a part within an assembly. An additional output is waste. This may be in the form of scrap material or waste in other supporting materials, such as cutting fluids. Elements directly related to creating the finished goods are inputs

into the manufacturing system: raw materials, labor to operate the machine or complete assembly tasks, equipment altering the raw material to its desired state, supplies and energy to support the equipment, and any tooling required by the process (for example, fixtures and molds). Finally, there are elements supporting the manufacturing environment: information (for example, work completed by design and manufacturing teams) and services (for example, machine maintenance, building heating and management). Bralla outlines a similar set of elements that contribute to assessing the cost of a part for DFM evaluation: material, direct labor (machine operator), indirect labor (factory support services), tooling, supplies, utilities (energy), and capital (equipment and factory) [11].

In an ABC environment, each of these inputs is calculated based on the amount of that activity that is attributed to it, such as the mass of steel for material cost or the amount of time required by an employee on the manufacturing line [11]. For any given implementation of ABC, a company may break down the cost elements in a different manner from other companies based on their business and cost tracking needs [13]. Within the cost accounting of products, though, standard structures are developed for costing to fit most cases.

Figure 2.3 represents a factory with a single production line. Incoming materials are transformed through two sequential processes. Each process is supported by labor, supplies, electricity, and maintenance on the machines. After processing, parts are sent to the assembly line, which also requires labor, supplies, electricity, and maintenance support. Once the products are assembled, they are shipped to their next destination. It is assumed that all wastes—both recycled, reprocessed or remediated—exit the facility.

The machines or work stations included in the boxes represent two processes and the assembly line. The machines are purchased and installed and they take up a known amount of floor space within the factory. The factory itself provides several support services for the production line: labor activities, such as engineering; quality assurance; planning and purchasing; and facility maintenance and utilities (gas, water, etc.). The dashed dark-gray

Figure 2.3. Factory layout with unit manufacturing process shown in gray box.

box around Process A shows the scope of the analysis: a single unit process within the factory.

A selection of software tools are available for assessing design alternatives from a DFM perspective. The specifics of these tools are further discussed in Section 2.1.3. The aPriori (Concord, MA) physics-based costing software [14] uses an ABC model [15] to estimate the cost of part features based on the manufacturing process used to produce them. The cost equations used by aPriori are useful as they capture the major activities involved in manufacturing an individual part in a facility as shown in Figure 2.3. The total cost as presented in the software is:

$$C_{total} = C_m + \sum_i (C_{l,i} + C_{OH,i} + C_{IOH,i} + C_{set,i}) \quad (1)$$

where C_m is the cost of the material for the part and any related scrap, represented by the rough mass (part mass including scrap) multiplied by the cost per unit mass for the material being used (c_{kg}):

$$C_m = m_{rough}c_{kg} \quad (2)$$

The remaining terms in Equation 1 are the sum of the cost elements for each of the unit manufacturing or assembly processes required to make the part from process 1 to i . A single unit manufacturing process is shown by Process 1, with the gray dotted outline in Figure 2.3. Inside the sum, C_l is the cost of labor involved in making the part. This is equal to the worker's hourly wage, including benefits (h_p) for the process multiplied by the process cycle time¹ (t_c) plus any handling time (t_h , which includes loading, unloading, and other manipulation of a part in a workcenter) and the number of workers at the station (n_p , which can be less than one if a worker operates more than one station simultaneously):

$$C_l = (t_c + t_h)n_ph_p \quad (3)$$

C_{OH} is the direct overhead cost related to running the machine for a given amount of time. This can be built up from constituent factors:

$$C_{OH} = \frac{\frac{c_{mach}(1+f_{inst})}{t_{life}} + h_{eng}p_{mach}t_{earn} + c_{mach}f_{maint} + c_{int} + c_{sup}}{t_{earn}}t_c \quad (4)$$

where the purchase cost of the machine (c_{mach}) and installation cost (a fraction of the machine cost [f_{inst}]) are depreciated over its life (t_{life}) in years. The energy cost per hour (h_{eng}) times the power of the machine p_{mach} and the earned hours t_{earn} gives the yearly energy usage. The maintenance cost for the machine is a fraction of the machine cost (f_{maint}). Finally, there are the yearly imputed interest cost (c_{int}) and the cost of any supplies

¹See Appendix A for an example of how manufacturing cycle time is estimated in physics-based costing of geometric features.

for running the machine (c_{sup}). These are summed, then divided by the earned hours t_{earn} attributed to the machine for the year.

C_{IOH} is the indirect overhead cost, related to the factory and its support services for the machine and related activities:

$$C_{IOH} = \frac{c_{rent} + c_{util} + c_{ins} + c_{sup}}{t_{earn}} t_c \quad (5)$$

$$c_{rent} = (A_{mach} + A_{gap} + A_{space})(R_A) \quad (6)$$

$$c_{util} = c_{rent}(f_w + f_{gas} + f_{elec}) \quad (7)$$

$$c_{ins} = c_{rent}(f_{fire} + f_{loss} + f_{liab}) \quad (8)$$

$$c_{sup} = W_{cap}(h_q s_q + h_{pur} s_{pur} + h_{eng} s_{eng} + h_{tc} s_{tc} + h_{fm} s_{fm}) \quad (9)$$

where c_{rent} is the cost per area of the floor space allocated to the machine, A_{mach} is the floor area the machine takes up in the factory, A_{gap} is the nonproductive area around the machine, A_{space} is amount of nonproduction space in the rest of the factory (for example, walkways) attributed to the machine, and R_A is the rent cost per area per year. The cost of utilities (c_{util}) is calculated based on a fraction of the rent cost for the building with a factor for water (f_w), gas (f_{gas}), and electricity (f_{elec}). Insurance cost (c_{ins}) is similar with a factor each for fire f_{fire} , loss f_{loss} , and liability f_{liab} . For the support services (c_{sup}), each of the roles has an hourly rate (h_i) and a support fraction (s_i), which represents the number of workcenters an individual in that role covers. There are five roles in total: quality, purchasing, engineering, tool crib, and facility maintenance. These costs are multiplied by

the total hourly capacity for the facility (W_{cap}) in a year. These are summed and divided by the total number of earned hours for the workcenter.

The setup cost (C_{set}) is the cost for setting up the machine to running a batch of parts (n_b), which is calculated as:

$$C_{set} = \frac{(\frac{C_{OH}+C_L}{t_c})t_{set}}{n_b} \quad (10)$$

where C_{OH} is the overhead rate at the machine as defined in Equation 4; C_L , the labor cost as defined in Equation 3; and t_{set} is the time it takes to set up the machine. This may be as short as 15 minutes or as long as multiple days depending on the complexity of the machine. In Equations 3 and 4 the value for t_c would be set equal to t_{set} for calculating the setup cost.

These cost equations ignore any tooling,² fixturing, packaging, assembly, or in-plant handling, but can be expanded to include these factors and others. The goal for estimating manufacturing cost in DFM is to capture the cost drivers for a part, which in most cases will be found in the elements above.

It should be noted there are many possible cost taxonomies depending on the needs of the evaluation at hand. Additionally, some costs are susceptible to regional variation. For example, materials and initial machine purchase costs can be assumed to be sourced from a global market with similar costs worldwide, but labor, rent, and utility costs can vary widely within and between countries. For that reason, it is important when completing an assessment to have a clear understanding regarding regional cost assumptions.

As can be noted in Equations 4 and 7, energy is considered at two levels in the model. The first is related to the direct overhead, and the second is related to the utility costs within the indirect overhead. With direct overhead, it is calculated based on the average energy usage for a machine in the total earned hours in one year. This is calculated in reference to the published power for the machine and the run time of the machine to make the required

²See Appendix B.

features on the part being analyzed. C_{OH} is also used in Equation 10 as an element of setup cost, where the machine may be running in an idle mode while it is being setup for the next batch.

Within the indirect costs, the yearly cost of gas and electricity is calculated as a factor of rent in Equation 7. These energy costs are then averaged over the earned hours and multiplied by the run time of the machine to make the required features on the part being analyzed. With these in mind, the energy cost per part can be calculated as:

$$C_{eng} = \left(\frac{c_{rent}(f_{gas} + f_{elec})}{t_{earn}} + h_{eng}p_{mach} \right) t_c + \frac{h_{eng}p_{mach}}{n_b} t_{set} \quad (11)$$

Equation 11 enables the assessment of how energy costs will be impacted by a change in geometry for the same machine and what elements are constant if the machine is not changed. The factors related to the machine cycle time (t_c) can further be identified as those directly related to the machine running—the cost of energy (h_{eng}) and the power of the machine (p_{mach})—and the overall costs related to running the facility.

It should be noted that while the energy terms were fundamentally easy to extract from the equations above, they are not used on their own as a metric in standard DFM analyses, despite the growing concern about energy costs within manufacturing [16]. In a standard DFM analysis, as defined in Equation 1, cost is the most common metric, and is relevant for evaluating a single part in multiple manufacturing processes for comparison purposes. If the design of a part but not its manufacturing process is changed, the cycle time for each of the steps in the processes (t_c) can be compared [9]. Finally, in the case where cycle time might be fixed, such in as a stamping process, only the material cost, as given in Equation 2, may be tracked. This is common for efforts in improving nesting of parts on a progressive die or other stamping process in the automotive and other high volume, weight-sensitive industries [11, 12].

DFM, as outlined in this Section, is a common tool used by engineers to improve their products. In practice, engineers use guidelines for improving the manufacturability of their

designs. The most common metric for developing the guidelines and assessing resulting designs is manufacturing cost, usually approached using ABC [9, 11]. Software tools exist for aiding engineers in completing these assessments while they are working directly on their CAD (computer aided design) files. These tools are further discussed in Section 2.1.3. aPriori software is one of these tools and offers a standardized set of equations for understanding the cost of product manufacture, and captures the major activities contributing to the resulting part or product. Such a structure, as demonstrated later in this study, can serve as a strong analogy for other evaluations of manufacturing including environmental impact.

2.1.2 Eco-Design and Its Metrics

Eco-design is a product design and development methodology, for integrating environmental principles into a product's life-cycle, defined in ISO 14006. The term eco-design is interchangeable with design for environment (DFE), most commonly used in the United States [10].

Like other DFX methods, eco-design is integrated into existing development processes. During the planning stage, the goals are defined, and performance criteria or metrics are established [17]. Fiksel [17] defines 44 high level areas for performance criteria and Kim et al. [18] provide 28 for unit part manufacture within the scope of DFM. Companies often select multiple criteria for use by engineers when designing products [8, 18]. Examples of metrics related to energy include:

- “Total energy consumed during the product life cycle” [17]
- “Renewable energy consumed during the life cycle” [17]
- “Power used during operation” of a product [17]
- “Energy consumption” during production [8]
- Energy “required to extract. . . materials” used in the product [8]

From concept development through detail design, the performance criteria selected are used to determine guidelines for the design engineers and others on the team to use in decision-making. For example, if the performance metric of energy “required to extract... materials” is used, then a guideline to the engineers might be to “specify renewable and abundant resources” [8]. For each design embodiment the environmental impacts are assessed and compared against the goals and to each other. The data from the environmental portion of the assessment are used with other design criteria, such as performance or DFM values, to determine a design direction.

Life-cycle assessment (LCA) methods are some of the most common tools used for environmental evaluation [8, 17]. LCA is a well developed methodology, defined by ISO 14040:2006 [19,20] and supported by a wide variety of tools to enable analysis. More than 80 tools are listed as of February 2019 by the European Platform on Life Cycle Assessment [21].

Completing an LCA requires first developing a life cycle inventory (LCI) for each of the elements in the life cycle. For manufacturing processes, an effort known as the Cooperative Effort on Process Emission in Manufacturing (CO₂PE!) has been developing unit process manufacturing processes with an objective to study “the environmental footprint of manufacturing processes with energy consumption/CO₂ emission as first priority” [22]. As of 2018, 31 unit process have been completed as part of the CO₂PE! effort and the results have been tested on development of a fuel nozzle [23]. The structure of the LCIs for this effort are focused on energy consumption and CO₂ emissions and the methodology for developing these models for energy consumption is detailed in Section 2.2.1. At this time, there is no commercial software that implements the CO₂PE! effort, although some models have been built into SimaPro® [22].

Overall, using LCA can be difficult for design engineers because they require substantial training to productively use the methodology since multiple attributes need to be balanced [8, 17]. For eco-design more generally, a study by Sihvonen and Partanen [24] found

through surveys of product development professionals that environmental considerations are rarely applied during early product development phases at the micro or individual level, despite there being wide-spread policies or objectives within companies at the macro level. This is reinforced by a study from Zetterland et al. [25], regarding tools for eco-design. The authors found that “methods/tools with an explicit and original purpose to support sustainability considerations in product development often have a low level of implementation for this purpose” [25].

Further lack of commitment by the development teams in including sustainability concepts is demonstrated in a study by Jakobsen and Clausen [26], who looked at the interaction between what a company’s high level statements are and how environmentally friendly their products are. The authors note that companies with high environmental innovation spend less on internal research and development (R&D), concluding that this “may imply that the emphasis on external knowledge in environmental innovation processes act[s] as a substitute for internal environmental knowledge” demonstrating a lack of internal commitment toward structural adoption of environmental considerations [26]. Finally, even when designers think they are good at making sustainable design decisions, Telenko and Wood [27] demonstrate that often they are not. The authors performed a survey of 22 designers of various levels of environmental experience and had them rate a selection of products on sustainability. They found that those with “self-perceived expertise in sustainability” were not significantly better at determining product sustainability compared to those who did not self-identify as experts [27].

Overall, while eco-design is commonly included in the development process at an organization level, there is limited accurate application of its tenants by product development professionals, in part due to the difficulty in using environmental assessment methods during product development. The CO₂PE! effort demonstrates how completing assessments of manufacturing processes can be useful with few metrics, but the methodology as of today has limited application beyond academic research. Efforts have been made to broaden the

application of eco-design through the development of software tools intended for application by engineers during early design. These tools are discussed in Section 2.1.3.

2.1.3 Software for DFM and Eco-Design

Since it is often difficult for engineering professionals to have extensive know-how for performing DFX analyses, software tools have been developed to provide decision-making guidance and fill this knowledge gap. These tools are often embedded in or attached to the CAD system, a place engineers work on a daily basis. Commercial software for supporting DFM assessments is well developed. Similar approaches for supporting eco-design assessments by design engineers have much more limited development outside of LCA tools. This section provides background on the current software landscape for both DFM and eco-design.

A selection of software tools are available for assessing design alternatives from a DFM perspective. These include aPriori³, Costimater[®], DFMA[®] (from BDI), HyperLean[®], and DFMPPro[®]. These software packages often look at the cost of manufacturing as the ultimate evaluation for DFM based on the geometry of a design or an assembly, supported by estimated cycle times and material usage values [28]. As outlined by Boothroyd et al. [9], design choices for a part are a fundamental driver of product cost. To capture this geometric information to enable better cost estimates, feature data for a given part will be manually entered, extracted directly from the CAD system, or provided through a combination of both strategies [28]. Such automation removes the need for the design engineer to have comprehensive knowledge regarding manufacturing cost.

The aPriori physics-based costing software [14] uses an activity-based costing model [15] to estimate the cost of part features created by the manufacturing process. Manufacturing physics-based assessment tools, which leverage feature based assessment, such as aPriori, gather the feature set directly from a CAD file or geometrically representative in-

³The author is employed by aPriori Technologies, makers of aPriori costing software.

formation (such as representative dimensions) to drive the calculation of a cost [29–34]. While specific models vary between software packages, in general, the geometric data is used in combination with representative data for process capabilities, such as cut speeds, industry standard time estimates, and other commonly available data sets to estimate a cycle time and apply hourly rates to determine manufacturing cost [28]. Some tools include features such as unfolding and nesting algorithms [14], the ability to build custom manufacturing models [14, 35], and application of manufacturing rules [14, 35, 36]. A detailed example of physics-based costing including feature assessment is given in Appendix A.

Eco-design software tied to the CAD system has been explored in the literature [37–42], but has few commercially available products. SolidWorks Sustainability™ [43] is the primary commercial example. The software provides LCA results based on the part geometry integrated into the CAD interface.

The solutions in the research literature are similar to the SolidWorks product in output. The *ecologiCAD* project from Leibrecht [41], work by Tao et al. [39], and the *ecoDesign* workbench from Pfouga et al. [42] allow a design engineer to change the design of a CAD model and understand the environmental impact. In each case, the impact assessment is completed using LCI/A, and a custom geometry assessment tool for understanding environmental drivers is constructed. The work done by Tao et al. [39] is representative of these efforts. Their tool output a selection of impact areas representing major emission categories, with a CO₂ equivalent output from the LCI and a selection of impact categories output from the LCIA. Pfouga et al. [42] used the geometric information to conduct an LCIA, but completed a fuzzy-logic interpretation of a verbal weighting system (e.g., very high, high, medium, and low) for each of the impact categories to calculate an Eco-Index for the overall product relative to global warming potential.

While the currently commercially available DFE solutions reduce the difficulty in completing the data gathering stage of LCIA evaluations, they do not reduce the difficulty in comparing two designs against each other. For example, a given design may use less water

but generate more CO₂. While an expert in LCI/A use may be able to balance those options, most engineers cannot. Detailed understanding of each metric and which metrics to prioritize over others for decision-making are required. The direction provided by Pfouga et al. [42] is promising since the software user reviews a single metric. The authors note this allows system users without extensive environmental knowledge to estimate results and reach a conclusion. However, this software tool has not seen development beyond the research stage, does not appear to be used within industrial product development, and relies on a nonstandard development of a single metric.

An alternative solution, which will be investigated within this study, is to use the well developed geometry analysis capabilities and manufacturing models with the data of an existing DFM tool and add customizations to the tool for completing an environmental analysis. The goal, much like that described by Pfouga et al. [42] for their ecoDesign Workbench, will be allow an engineer without a detailed environmental background to estimate the impact of a given design.

2.2 Energy as a Metric for Sustainable Manufacturing

The concept of an energy shadow, as described in Chapter 1, holds significant promise for numerically articulating the resources required and the impact resulting from human-built systems. Based on arguments from Bakshi et al. [2], these systems are thermodynamically supported and can be measured, at least in part.

To support the goal of a usable energy shadow metric for engineers in evaluating the manufacturing sustainability of designs, a selection of different methods for measuring energy within natural and human built systems can be found in the literature. The literature for three of the most developed and promising energy metrics—consumed energy, exergy, and emergy—are on the path toward reaching the ideal state of capturing the entire energy shadow as described in the following Sections.

2.2.1 Consumed Energy

Consumed energy, also known as net energy analysis, or embodied energy analysis, is commonly used as a metric within life-cycle inventory and analysis (LCIA) representing the energy consumed by a manufacturing process [19,44–46]. Within the context of a LCIA completed for a manufacturing facility, data are created via an energy audit [47]. Graedel and Allenby [47] give an example of an energy audit for the production of aluminum cans, shown in Figure 2.4. For each stage in can production, the amount of energy, in the form of electricity or other primary inputs such as gasoline for transport, is determined. The audit may be done via direct measurement of the usage by the factory, machines, operations, or fuel involved, thus easing data collection when compared with other types of environmental information [19]. Fiksel [17] notes that energy consumed either during manufacture or the entire product life cycle can serve as an individual metric. Generic references of embodied energy for a variety of common materials, processes, chemicals, and other elements are commonly available within LCIA software [48,49].

Figure 2.4. Energy audit example [47].

In addition to looking at the consumed energy within an entire product life cycle, a control volume of a single unit manufacturing process can be examined from the perspective of energy consumed. Indeed, more than 30 models have been completed as of 2018 as part of the CO₂PE! effort [22,23,44]. Duflou et al. [44] discuss two different methods to

support the building of these models. The first is a theoretical approach from Feickert and Abele [50], where the total energy needed for manufacturing a part is equal to:

$$E_{total} = E_{th} + E_{additional} + E_{periphery} \quad (12)$$

where E_{th} is the amount of energy to theoretically produce the effect of the process (for example, a bend in sheet steel), $E_{additional}$ is the amount of energy to support other machine functions (for example, computer controls) or losses in the process, and $E_{periphery}$ is the energy required to power peripherals (for example, ventilation systems) [44, 50]. Duflou et al. [44] note that such an approach can be useful for screening processes for improvement opportunities, with the benefit that data for this are based either on theoretical or otherwise publicly available materials.

Zhang and Zhao [51] used this approach to estimate the amount of energy required for gas metal arc welding. They estimated the total energy (E_{total}) as:

$$E_{total} = P_{basic}t_{basic} + P_{idle}t_{idle} + P_{tip}t_{tip} \quad (13)$$

where P_{basic} , P_{idle} , and P_{tip} are the power consumptions during: loading / unloading of the workpiece, time between the previous and next workpiece, and welding of the workpiece, respectively. Correspondingly, t_{basic} , t_{idle} , and t_{tip} are the times spent in each of those manufacturing steps. Similar to Duflou et al. [44], Zhang and Zhao [51] use publicly available data (for P_{basic} , and P_{idle}) and derive an equation for estimating power based on the physics of the process and expected losses. The work of the authors is part of a broader effort to build a selection of life cycle inventory models for unit manufacturing processes. This research is part of the CO₂PE! initiative described in Section 2.1.2 [51]⁴.

The second approach Duflou et al. [44] report is the active measurement of machines, based on time and power consumption studies. They cite more than 30 different studies

⁴A more detailed review of E_{th} for three processes is covered in Appendix C.

that use such an approach for a wide variety of processes from additive manufacturing to air bending [44]. A more recent article from Ingarao [52] catalogs more than 30 studies from between 2010 and 2015 that use energy as a metric to improve process efficiency.

Figure 2.5. Power profile for a 1.85 kW diode laser [53].

An illustrative example of the output of time and power data gathering efforts was given by Kellens et al. [53] for a selection of laser cut machines. Figure 2.5 shows an example of the power profile for a 1.85 kW diode laser. In the profile, the main activities performed by the machine are highlighted. From their experiments, the authors were able to determine average electrical energy requirements for various stages within the laser cut process. Additionally, by analyzing these outputs, they were able to recommend possible improvements to energy efficiency. As an example, they recommended reducing the power requirements for the stand-by mode, shown in Figure 2.5 as the steady-state loading, which pulled under 4000 W and 2000 W with the cooling drive on and off, respectively. The authors completed similar analyses for a number of laser cut machines, varying both by power and technology. This allowed them to compare the energy requirements and overall environmental impact for a specific part nesting layout.

Figure 2.6. Control volume for energy analysis [54].

Unit manufacturing analysis can be expanded to evaluate the consumed energy for a larger portion of the supply chain for a process. Cooper et al. [54] completed a cradle-to-gate embodied energy analysis of five forming processes across a selection of piece-parts, as diagrammed in Figure 2.6. The red lines represent input of energy in the form of electricity into the various steps in the process. Green lines represent the inputs of materials and embodied energy from sources outside the analysis. The blue lines are material movement through the elements. As can be seen, the elements included are the forming processes and the activities upstream, particularly electricity generation, die set manufacture, lubrication manufacture, and sheet manufacture.

Table 2.1. General Sources for Consumed Energy Data in Cooper et al. [54]

Item	Gathered	Theoretical	Referenced
Electricity Generation			✓
Aluminum Sheet		✓	✓
Galv. Steel Sheet		✓	✓
Forming Processes	✓		
Lubricants		✓	✓
Die Set Material			✓
Die Set Casting		✓	
Die Set Machining		✓	

A selection of methods, listed in Table 2.1, were used for estimating the energy usage for each of the supporting processes within the overall manufacturing of the parts. Data for

the consumption of the forming processes were gathered directly from sensors on the machines. Values for electricity generation and die set material were gathered from reference data from ecoinvent [49]. The method for estimating the energy for casting and machining of the die set was based on previous research by the authors [55,56]. Finally, the energy data for the lubricants and sheet metal were derived from reference data within the context of equations and methods from previous research.

Figure 2.7. Energy analysis results for four sheet metal processes [54].

Figures 2.7 and 2.8 show per-part consumed energy results for each of the processes. Two points should be noted regarding these results: (1) each graph represents a different part and a different manufacturing process and (2) the energy related to the die sets was straight-line amortized over the number of parts made per die.

Zhang and Dornfeld [57] note that earlier estimates of the energy of labor, such as suggested by Boustead and Hancock [58], include the caloric energy consumed by a worker per day. Zhang, in her PhD dissertation [59], notes that while there have been some eco-

Figure 2.8. Energy analysis results for stretch forming process [54].

nomic evaluations trading-off energy, capital, and labor, these styles of calculations have not commonly found their way into standard LCA analysis.

In both works, the authors note that the model from Boustead and Hancock [58] significantly undercounts the energy required for a worker, as it does not include the energy used to support the worker through their daily life. As such, it should be considered the lower bound of energy required for a worker. As an upper bound, they propose using a top-down method based on the primary energy supply used by a country divided by the working population to account for a full life-cycle of the worker, including childhood and old age when they may not be productive. Zhang [59] cites a calculation from Odum [60] of fuel-use per capita, as a similar approach. She notes that such estimates are attractive because they include losses through transmission, which are not accounted for in consumption numbers. Such a metric, though, is not a strong candidate for use in LCA, as it will result in double-counting of industrial energy.

A third metric, which falls between these two bounds and helps avoid double-counting is the use of the nonindustrial energy supply per worker, which functionally amounts to distributing the commercial and residential primary energy use over the working population. For this, in both works, [57, 59] the authors suggest the use of the following equation to calculate energy use per worker-hour (EPWH):

$$EPWH = \frac{TPES(1 - \frac{IFC}{TFC})}{n_{pop}h_y} \quad (14)$$

where TPES is the total primary energy supply, IFC is the industrial final consumption, and TFC is the total final consumption for a given country. The working population is given by n_{pop} and h_y is the working hours per year. It should be noted that the IFC and TFC are used in a ratio here to take the place of the total primary energy supply for industry, which is a harder value to find within current data sources. The authors note that each of these factors can be easily found through either the International Energy Agency (IEA) or the International Labor Organization (ILO). Zhang [59] notes that one disadvantage with this approach is that energy supporting industrial transportation is included in these estimates, which, again, will mean double-counting if LCA includes a transportation component.

In considering the amount of energy to allocate per worker-hour, Zhang [59] and Zhang and Dornfeld [57] suggest that employers gain advantage during work hours from the energy workers consume outside of work hours. As such, they conclude that any energy consumed during non-working hours should be split only over the hours worked instead of using a broader approach of splitting the energy consumed over the total number of hours in a year.

With this metric in mind, Zhang [59] notes that determining an hourly energy rate for workers provides substantial opportunity to evaluate the real impact of a variety of industrial decisions involving labor. The examples presented include the evaluation of labor-intensive industries, decisions regarding the ratio of labor to automation, location-based decisions, and trade-offs in the pricing of labor in comparison to other forms of energy.

Overall, the theoretical unit process models described by Zhang and Zhao [51], the run time data collected by Kellens et al. [53], and the models more generally compiled as part of the CO₂PE! effort provide a framework for design-time evaluation of the net energy impact for a given part. The final results of the study by Cooper et al. [54] in Figures 2.7

and 2.8 show how these data could be used to drive design decisions. Although the work Cooper et al. completed for estimating total energy used for their alternative processes was based on different products, it is an easy extrapolation to see the application of their combination of gathered, theoretical, and referenced data to evaluate the energy needed for any given design during the development process. To give a more complete picture, the work of Zhang and Dornfeld [57] could be added to the evaluation to include the impact of the energy that workers consume.

The SolidWorks Sustainability™ product [43] includes the calculation of a consumed energy metric for the design of parts. The metric includes “the net calorific value of primary energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.)” [43]. Such a split of renewable and non-renewable energy is common within the structure of LCIA [19] but is not commonly considered in manufacturing analyses. This methodological choice is demonstrated in the CO₂PE! project with its preference for evaluating only total energy consumption.

When looking at the the complete list of manufacturing inputs, shown in Table 2.2, the literature demonstrates frequently that the estimate of consumed energy is only a portion of the energy shadow of a product. In particular, the impact of the factory-level elements (buildings, utilities, and support labor) and manufacturing equipment is not considered in favor of direct consumption of electricity by the processes and embedded energy in the materials. Based on this assessment, a broader method for understanding the energy in production is required to cover all common inputs into manufacturing.

2.2.2 Exergy

Exergy analysis, also known as availability analysis, is a thermodynamic approach for understanding the work available within a system as it is brought into equilibrium with its environment [61–64]. A simple example of this analysis was given by Bejan [61]. Shown in the left side of Figure 2.9 is a closed system, with energy E , entropy S , and volume V .

Table 2.2. Coverage by Consumed Energy of Elements Included in Cost Accounting

Manufacturing Accounting	Net Energy*
Material of Part(s)	✓
Direct Labor	✓
Manuf. Equipment	
Factory	
Process Power	✓
Process Supplies	✓
Tooling (Dies)	✓
Building Utilities	
Support Labor	
Machine Setup	✓

*For all checked elements, only energy consumed is included.

Figure 2.9. Exergy example [61].

This closed system exists in an environment with pressure P_0 and temperature T_0 . Work and heat interactions are possible between the system and environment. Over time this closed system reaches a *dead state* with its properties equal to those of its environment [62]. This is shown in the right-side of the diagram, with energy E_0 , entropy S_0 , and volume V_0 .

This interaction is represented by:

$$\Xi = E - E_0 - T_0(S - S_0) + P_0(V - V_0) \quad (15)$$

where Ξ is the exergy in Joules available in the system. It should be noted that the equilibrium described above is considered by the authors to be in a restricted dead state as though the thermal and mechanical equilibrium have been reached relative to the environment, the system is not necessarily in chemical equilibrium [61]. Bejan [61] notes that this equation can be interpreted as the system accumulating $E - T_0S$ as potential work, moving through time as shown in Figure 2.9, and thus the work potential changes from $E - T_0S$ before the transformation to $E_0 - T_0S_0$ after. The difference demonstrated in first two terms in Equation 15 represents the sum of all work possibly produced during the process. The final set of terms, $P_0(V - V_0)$, reduces this quantity by the work completed by the system against the environment or lost work.

Figure 2.10. Manufacturing exergy example [63].

Exergy analysis has been used within the context of manufacturing for understanding the thermodynamic efficiency by evaluating how effectively a task is completed by a process [63,65]. Gyftopoulos [63] gives the example of an energy conversion system linked to a material processing system. Figure 2.10 shows such a system, where power is generated and transferred via a shaft. The system is designed to operate at steady state with the work produced by the power plant equal to that required by the material processing step. With this system in mind, the rate of work from Energy-conversion system B is:

$$\dot{W}_s^{B \rightarrow} = [\dot{H}_1^{f+a} - \dot{H}_{0*}^{f+a} - T_{R*}(\dot{S}_a^{f+a} - \dot{S}_{0*}^{f+a})] - T_{R*}\dot{S}_{irr*}^B \quad (16)$$

and the rate of work in Materials-processing system A is:

$$\dot{W}_s^{A \leftarrow} = [\dot{H}_1^m - \dot{H}_2^m - T_{R*}(\dot{S}_1^m - \dot{S}_2^m)] + T_{R*}\dot{S}_{irr*}^A \quad (17)$$

where $\dot{H}_1^{f+a}$ and $\dot{H}_1^m$ are the enthalpy (total heat content of a system) rates of the incoming fuel and air mixture for the power plant and materials, respectively and $\dot{H}_{0*}^{f+a}$ and $\dot{H}_2^m$ are the corresponding enthalpy rates of the outputs of each process. The incoming entropy rates for the incoming fuel and air mixture for the power plant and materials are $\dot{S}_a^{f+a}$ and $\dot{S}_1^m$, respectively, with the corresponding output entropy rates being $\dot{S}_{0*}^{f+a}$ and $\dot{S}_2^m$. Each process has interactions with the environment of $T_{R*}\dot{S}_{irr*}^B$ for the power plant and $T_{R*}\dot{S}_{irr*}^A$ for the material processing system, with the entropy terms $\dot{S}$ representing the irreversibly in the processes. In the case of the power plant, this is a loss of heat to the environment, occurring at a rate of $\dot{Q}_{R*}^{B \leftarrow}$, whereas for material processing, the transfer of heat to the environment occurs at a rate of $\dot{Q}_{R*}^{A \leftarrow}$. If no entropy is generated in these processes, the exergy rates for each of the processes is based on the primary enthalpy and entropy flows.

Gyftopoulos [63] notes that since $\dot{W}_s^{B \rightarrow} = \dot{W}_s^{A \leftarrow}$, the equations can be rearranged to:

$$\begin{aligned} & [\dot{H}_1^{f+a} - \dot{H}_{0*}^{f+a} - T_{R*}(\dot{S}_a^{f+a} - \dot{S}_{0*}^{f+a})] = \\ & [\dot{H}_1^m - \dot{H}_2^m - T_{R*}(\dot{S}_1^m - \dot{S}_2^m)] + T_{R*}\dot{S}_{irr} \end{aligned} \quad (18)$$

where the entropy terms from the power plant and processing system are summed to the single term $\dot{S}_{irr}$.

Equation 18 provides opportunity to see the elements involved in an efficiency analysis, showing how effectively resources are used [62]. Gyftopoulos [63] describes that the left side of the equation is the maximum rate work could be done by the power plant ($\dot{W}_{largest}^{\rightarrow}$)

and the right side of the equation in the brackets is the minimum work rate for completing the processing task ($\dot{W}_{least}^{\leftarrow}$)—or exergy rates. The entropy term represents the entropy generation rate due to irreversibility. This occurs because the processes are not the best achievable, with the energy transformed to entropy becoming unusable. This demonstrates that exergy, unlike energy, is not conserved.

The efficiency (ε) of a system within such an analysis is found by the ratio of the used energy to the total energy [62]. This leads us to the efficiency equation [63]:

$$\varepsilon = \frac{\dot{W}_{least}^{\leftarrow}}{\dot{W}_{largest}^{\rightarrow}} = 1 - \frac{T_{R*}\dot{S}_{irr}}{\dot{W}_{largest}^{\rightarrow}} \quad (19)$$

Exergenic efficiency analysis can be used to evaluate various levels of manufacturing processes from the operational steps, such as chip cutting or material melting to the overall efficacy of the manufacturing process [65]. In this application, exergy is focused on the efficiency of a given process and allows for comparison of the energy efficiency for two methods for making the same part or product [66].

From a practical perspective, energy values within the exergenic equations are either calculated or gathered in a similar manner as given in Section 2.2.1 for consumed energy (e.g., energy audits and sensors on machines), or are sourced from a selection of pre-calculated values, such as reported in Gutowski and Sekulić [65] and Szarsgut et al. [67]. Exergy values exist for a selection of materials, chemicals, and other common inputs into manufacturing processes [68]. This is an advantage when comparing exergy to consumed energy analysis, as there is the possibility of capturing the useful work from the material, heat, and energy streams in manufacturing [68].

Beyond an efficiency analysis, input exergy can be summed, much like seen in Section 2.2.1 for consumed energy, to give a single numeric exergenic value to the system being analyzed [45]. This provides a way to compare a selection of manufacturing methods for a product. Dittrich et al. [68] completed exergy analysis comparing prototype annual volume sheet metal forming processes in this manner. The initial analysis looked at a

control volume around the unit production processes. The options of processes included conventional forming with die sets from two types (cast iron and plastic), hydroforming with a plastic die set, and two types of incremental forming (single and double-sided) where no custom die set is required. In addition, two raw materials were compared, aluminum and steel sheet.

Table 2.3. General Sources for Exergy Data from Dittrich et al. [68] and Per-Part Input Exergy, Including both Single (S) and Double-Sided (D) Impact Forming.

Item	Gathered	Theoretical	Referenced	Input Exergy ($\frac{MJ}{part}$)
Aluminum sheet			✓	43
Steel sheet			✓	27
Conventional forming			✓	0.35 - 0.8
Hydroforming		✓		3.0 - 5.0
Lubricants for IF			✓	1.4 - 1.5 (S); 1.7 (D)
Die Sets		✓	✓	amortized
Incremental forming	✓			2.7 (S); 5.3 (D)

For each option, the authors either gathered data or calculated data based on theoretical equations, as summarized in Table 2.3. For all the materials and chemicals, referenced values for exergy were used. Additionally, for the conventional forming process, other research was referenced. In the case of die sets, the exergenic values for materials were referenced, then a set of theoretical calculations were applied to estimate the additional work done to the materials for the die set creation. Similar approaches were used for both the plastic and cast iron sets, with a recycle rate of 80% used for cast iron and 0% used for plastic molds, allowing for some recovery of the exergy embodied in the part from its manufacturing. Finally, in the case of incremental forming, energy data were gathered directly from the machines by measuring the input electricity and the force applied to the workpiece.

The final column in Table 2.3 reports the per-part values or ranges found for each of the elements. To evaluate the per-part input exergy for the die sets, the total exergy calculated for the die sets was amortized over the number of parts that will be made. The estimated

ranges calculated by Dittrich et al. [68] for the various die sets are shown in Table 2.4. The final two columns in Table 2.4 provide the straight-line amortization of the exergy in the die sets at prototyping part volumes of 50 and 350 parts. The assessment found that for higher part volumes (above approximately 500 parts), conventional forming process with a cast iron die have a lower exergy value than either of the incremental forming processes. For the plastic molds, the exergenic sum crosses over double-sided incremental forming at about 850 parts for conventional forming, but not at all for hydroforming.

Table 2.4. Calculated Values for Input Exergy in Die Sets from Dittrich et al. [68], Including Totals, with Recycling Included and Per-Part Based on Straight-Line Amortization at Prototype Volumes of 50 and 350 Parts

Die Set Type	Input Exergy (MJ)	w/Recycle (MJ)	50 ($\frac{MJ}{part}$)	350 ($\frac{MJ}{part}$)
Conv. Cast Iron	6,945 - 8,487	1,389 - 1,697	28 - 34	4 - 5
Conv. Plastic	4,323 - 5,313	Same	86 - 106	12 - 15
Hydro. Plastic	2,162 - 2,657	Same	43 - 53	6 - 8

In the second part of the analysis, the authors expand the control volume beyond the streams related directly to forming to the material supply chain and systems providing power for die set and aluminum sheet manufacturing [68]. The authors focused this analysis on primary energy resources within these subsystems, and did not conduct a full exergy analysis based on these inputs accounting for “nearly all” exergy in the system [68]. Based on this new control volume, neither the conventional nor the hydroforming ranges crossed the calculated values for either the single or double incremental forming for any volume of parts manufactured. Additionally, within the conventional forming evaluation, the exergy range for the plastic die set is much closer to that of cast iron. This comparison shows how simple changes in the control volume and number of parts produced for a single part can drive very different conclusions in the direction recommended by the analysis, even without a full exergenic assessment of each step in the production supply chain.

Two additional types of exergy analysis have been identified in a review by Sciubba [69]: thermo-ecological cost analysis (TEA) and extended exergy accounting (EEA). In

TEA, the monetary cost of the harmfulness due to the ‘production line emissions is converted to an equivalent exergy based on the final products used in the domestic sector of the country where the production occurs, and any non-renewable exergy resources in the immediate vicinity of the production processes [69]. This method has difficulties related to data availability [69]. No studies covering unit manufacturing processes using this method could be identified in a literature search.

EEA is a method for including externalities, such as human labor, environmental impact, and related activities as part of exergy analysis with the goal of including all exergy transfers through the entire chain of the production of a product [45, 69]. Sciubba [69] presents eight considerations required to complete EEA analysis:

1. Inflows for exergy include all resources—renewable and non-renewable, material and immaterial, and local and imported.
2. Extended exergy for any given factor is defined as the equivalent exergy flow to that factor.
3. The local population uses a portion of the total exergy in an area, which is calculated using an economic coefficient derived from a country’s global exergy budget.
4. Monetary circulation is also converted into an exergy flux and is calculated based on the labor data for the country.
5. All terms in an EEA are summed.
6. From the above, J/hour and J/currency factors can be determined for labor and capital, respectively.
7. A country is divided into seven sectors which exchange extended energy through flux interactions plus an abroad category accounting for inputs through imports and exports.

8. Influxes to the process in question may come from any of the above sectors.

While EEA can be outlined and structured with specific unit processes in mind, there has been limited work completed in the area of manufacturing assessment [70–73]. The direction appears promising, but data and methodologies are not well developed for unit manufacturing, services, or environmental impact.

Standard exergy analysis offers the ability to cover more of the life cycle of a product than consumed energy analysis because it is possible to give an exergetic value to both materials and processes within unit manufacturing [45]. Standard exergy analysis is also well suited for determining inefficiencies and areas for improvement related to energy use within manufacturing processes, as it is better at capturing losses than consumed energy analysis [63]. As such, it is a common analysis applied to manufacturing systems, with work completed on a large selection of processes. Gutowski and Sekulić [74] analyzed 26 manufacturing processes in this manner. With these models in mind, similar comparisons of designs, as those described in Section 2.2.1 for consumed energy analysis, could be completed. Though the application to manufacturing processes has been thorough, the work on including exergy in LCI/A analyses has been weak [17, 75]. While exergy does provide a strong indicator for both resource use and depletion and is thermodynamically valid, as Finnveden et al. [75] note, it has had limited application within the LCI/A structure. Based on a review of current engineering tools, applications beyond individual studies have not been found, and no current software tools exist to enable engineers to assess the exergy within a designed part.

Table 2.5 summarizes the coverage of cost accounting elements within the context of standard exergy analysis—excluding EEA and TEA due to lack of examples and methodology development. As shown in the literature, standard exergy analysis has no approach for handling the exergy of labor. Additionally, much like consumed energy, exergy analysis is focused on direct energy, ignoring the impact from manufacturing equipment and the plant (factory building, utilities, and support labor). While exergy analysis does pro-

vide a method to cover more than the consumed energy—thus making it a more complete assessment of the energy in a product—it does not capture the complete energy shadow.

Table 2.5. Coverage by Exergy of Elements Included in Cost Accounting

Manufacturing Accounting	Exergy
Material of Part(s)	✓
Direct Labor	
Manuf. Equipment	
Factory	
Process Power	✓
Process Supplies	✓
Tooling (Dies)	✓
Building Utilities	
Support Labor	
Machine Setup	✓*

*Only includes energy consumed.

2.2.3 Emergy

The concept of emergy, principally developed by Howard Odum [3, 76] during the 1960s through to his death in 2002, was initially developed as a metric for use by environmental and ecosystem scientists. Emergy can be described as the memory of energetic work held in the output of a system converted into solar emergy units. This includes energetic work done by the environment through solar, wind, water, and other earth-based forces as well as work completed by human-, animal-, plant- and industrial-based processes. All energy added to a product via these processes is converted to solar energy equivalents through the use of *transformities*, which give quality to the energy being added to a product via work. Transformities have been developed for materials, labor, and economic elements within systems [76–79]. With this in mind, emergy is calculated [45, 76] as:

$$Em = T\Upsilon \quad (20)$$

where Em is the emenergy, T is the solar transformity in units of solar emjoules per joule (sej/J), and Y is the available energy in joules, which, is equivalent to exergy. A simple example demonstrating transformities is provided by Odum [60] and shown in Figure 2.11, using the energy systems language (ESL) [76].

$$\text{Solar transformity of Logs} = \frac{\text{Solar EMERGY flow}}{\text{Energy flow}} = \frac{30,000 \text{ E10 sej/yr}}{7.8 \text{ E10 J/yr}} = 3846 \text{ solar emjoules per Joule}$$

Figure 2.11. Emenergy and solar transformity example from Odum [60].

The overall system of one hectare of Swedish forest is represented by the large box, noted as the *system window* [60]. On the left are the natural energy inputs into the system—sunlight, rain, wind, and earth. Some of the energy is not used and flows outside the system, with the remainder used to produce trees in the forest. Within the forest production process, some amount of the inflow energy is not transformed into logs and is considered to be degraded in quality and not usable within this system. Other systems may be able to recover this energy through the use of additional energy inputs. To find the transformity for this system, the input emenergy value in solar emjoules (sej) is divided by the output energy in joules embodied in the logs.

Beyond transformities, the simple example shown in Figure 2.11 introduces a few additional aspects of emenergy analysis. First, the ESL, a systems diagramming language, which serves as the primary tool in understanding a system from an emenergy perspective. In this diagramming language, developed by Odum and documented in detail in his book *Ecological and General Systems: An Introduction to Systems Ecology* [76], energy inputs, outputs, and transformations for a system are described. The ESL diagrams themselves provide,

in Odum's estimation, a better way for reviewing systems. Equations can obscure critical details, especially when they are put into simplest terms.

A number of symbols are used to represent various aspects of a systems model. The most common, as noted by Odum [76], are shown in Figure 2.12. The most relevant for further discussion are: pathways, storage, boundaries, sources, production, interaction, and transaction (used for money).

The pathways between elements visualize the flow of energy, materials, or information. It should be noted that a path always has some amount of energy along with the flow. The pathways do not perform any storage function and therefore do not create delays. If a lag is required, an appropriate symbol is added. The pathways between two elements can be thought of as a force balance, where there is flow from a source to an unknown downstream location. The force X from the source is balanced against the flow resistance R , and the rate of flow J results in the following equation:

$$X = RJ \quad (21)$$

which can be rewritten in a form similar to Ohm's law:

$$J = \frac{X}{R} \quad (22)$$

Odum [76] notes that outflows crossing system boundaries can be described as *sinks*. *Heat sinks*, in the model Odum [76] developed, must accompany all real processes and storages. This loss of energy is based on the energy degradation law: as energy turns into heat, energy becomes less useful, reflecting the modeling connection to exergy and emphasizing the concept that some energy flows are of better quality and more useful than others [45,80].

Boundaries are another important component of a system. Odum [76] suggests setting boundaries so the model represents a larger system than that being modeled to ensure that

Figure 2.12. Common energy systems language symbols [76].

all the interactions between the desired system and its environment are captured . External influences from outside the system in question are referred to as *forcing functions* and

are represented by circles [76]. These outside sources must have an energy component. They can vary with time and require a function (equation or time series) for full definition. These are placed around the edge of the diagram in order of increasing transformity and can include inputs from other systems or the biosphere [60, 76].

A *production* symbol represents a subsystem that uses higher quality energy flows to convert lower quality energy into more a useful energy of increased quality [76]. An example of a producer is the forest in Figure 2.11. The forest takes in the higher quality energies found in biomass and rain to convert the lower quality energy of sun into a higher quality biomass product found in logs. Related and often embedded within a producer is an interaction, represented by an arrow symbol, as shown in Figure 2.12. An *interaction* represents the intersection of two or more flows that combine into one outflow through a function or relationship. An example is the input of land being transformed with asphalt, cement, steel, and fuel through construction into a highway [60].

Money is often included in the systems modeling as it controls or releases the flow of other energy through a system [76]. The symbol for a *transaction*—a diamond—may contain a heat sink to represent the cost of the transaction. Money flows as a counter-current to energy flows and depending on the needs of the system modeler, may be symbolized separately from the energy flows. The emergy value of money within a given economy or sector has been calculated using input-output analysis by a number of researchers, as summarized by Barval and Bakshi [81].

A second important concept shown in Figure 2.11 is the source of energy from the sun, tides, and internal heat of the earth known as the geobiosphere emergy baseline (GEB) [60, 82–86]. The current calculations methods for each can be summarized as follows:

- Sun: Based on the surface of the Earth turned toward the sun, percent of the energy absorbed by the earth system, and the amount of energy in sunlight [60]
- Tides: Based on kinetic energy imparted by the gravity of the moon and sun [85, 86]

- Heat of earth: Based on equating the energy of tectonic uplift to that of erosion, with the work of erosion being the result of solar energy additions and the equivalent uplift value being due exclusively to deep heat [86]

The global values are used for downstream applications. Brown and Uligati [84] used the most recent calculations of a GEB to calculate values for secondary and tertiary earth processes. These processes include rain, wind, and currents and serve as inputs into other systems, such as the forest shown in Figure 2.11.

Emergy's theoretical background is based on the Maximum Empower Principle (MEP), which states that “all self-organizing systems tend to maximize their rate of emergy use or empower” [87]. The principle takes a donor-based perspective, where value is defined by what is put into an item rather than what an external player is willing to pay for it. It is important to note, the principle specifies that systems tend to reach this state over time—any given behavior of a system due to chance events may not reflect the MEP, but given enough time, the systems will tend toward maximizing their rate of emergy use [88]. Put in another way, Odum described that designs “that process more useful energy, will prevail in competition with alternate designs because more available energy provides contingency needs and better adaptation to surrounding conditions” [60].

While there is continued interest in the MEP in the space of systems ecology and biology [89–91], there is controversy regarding its use within emergy analysis [87]. Work, though, by Hau and Bakshi [87] notes that for use in engineering analysis, such an assumption is not important due to “emergy analysis [being] equivalent to exergy analysis if the analysis boundary includes ecosystems” [87]. Indeed, work has been completed to demonstrate that emergy is proportional to exergy when the following are consistent [45, 92]:

1. The control volume of the analysis
2. The allocation method
3. How global energy inputs are combined

Point (1) has been discussed above and is noted to be important within any systems analysis activity [76]. Point (3) refers to the use of a common unit for summing values, such as sej. Point (2) refers to emergy algebra, the rules of which are represented in Figure 2.13. Emergy algebra is slightly different to that usually applied in other thermodynamic situations, in that emergy paths do not strictly sum [45, 76]. These behaviors are summarized in Figure 2.13.

Figure 2.13. Rules of emergy algebra [45].

Figure 2.13a represents the division of a single emergy stream into two streams of the same quality of energy, though they are in different proportions. Figure 2.13b represents an emergy transformation where two coproducts are produced. In this case, each coproduct has the same emergy value since each cannot be produced on its own. Care must be taken, as shown in Figure 2.13c, if these streams are recombined to avoid double-counting, since both streams originally came from the same production process. If, though, two independent streams are combined, no matter the energy type, they are added, as shown in Figure 2.13d.

With these rules and this structure in mind, emergy can be used to analyze a wide selection of systems that includes both industrial and environmental elements. While the

application within industrial systems is not as well developed as for exergy or consumed energy analysis, there has been work related to a range of industrial applications. In construction, the dominant applications of emergy include buildings [79,93,94] and wind-farm construction [95, 96]. Within manufacturing, assessments have included the comparison of manufacturing alternatives [97–99] and product manufacturing assessments [100–102]. Labor assessments include determination of transformities based on data from the U.S. Bureau of Labor Statistics (US BLS) [103, 104] and calculations of both direct and indirect labor within a system [105, 106]. When looking at economic efficiency, research has been done within the agricultural sector showing that when comparing emergy analysis versus economic analysis, each can lead to different decisions [107]. Additionally, emergy provides a way to quantify ecosystem services, an area that is difficult to capture in any other type of analysis, including consumed energy and exergy [99, 108–112].

The general approach to the application of emergy analysis for eco-design cases is captured by a series of studies around manufacturing processes led by Almeida [97–99]. The case of comparing two fastener coating processes, as described in Almeida et al. (2018) [99] is particularly instructive of the methodology they employed.

The authors follow an analysis procedure for comparing a zinc coating process to an organo-metallic coating process for fasteners [99]:

1. Define the system to to set boundaries for analysis
2. Understand the context of the system and complete a mass balance
3. Create an energy flow diagram
4. Modify the energy flow diagram with collected data
5. Calculate emergy indicators
6. Review for driving management activities and other decision-making

Item numbers (1), (2), and (3) are satisfied by the ESL diagrams, shown in Figures 2.14 and 2.15. Each shows a selection of sources from the larger economy above the boundary of the analysis area and the renewable resources input from the left on both diagrams, with the yield of the system exiting out the right of the diagram. The path of water from the effluent treatment units (ETU) in Figure 2.14, traces both back to the environment and to the zinc coating process. This differs from the similar path in Figure 2.15 where all the water is sent back to the environmental system for the organo-metallic process. It should be noted that the output to the environment from the zinc coating process is water that includes a hexavalent chromium. An additional difference is the requirement of an LPG (liquid petroleum gas) input for the organo-metallic process, which is not present in the zinc process.

Figure 2.14. ESL diagram for zinc coating of fasteners [113].

Figure 2.15. ESL diagram for organo-metallic coating of fasteners [113].

For item (4) in the analysis procedure, data were either gathered or calculated and presented in a table for each of the processes. These tables are reproduced in Figures 2.16 and 2.17 in a format common for presenting emergy results. These results include the following columns:

- **Description:** Element in the emergy flow
- **Unit:** Unit for the data collected for the element
- **Class:** If the element is renewable (R), purchased / imported (F), or a system yield (Y)
- **Value:** Value collected or calculated for the element
- **UEV⁵:** $\frac{sej}{unit}$, the universal emergy value for the item listed in the description
- **Emergy:** Emergy total for the line-item
- **%:** The last two columns represent percentages for the total emergy related to the process and the product. These are not standard columns in an emergy table

Description	Unit	Class	Value	UEV (sej/unit)	Emergy (sej/year)	% (sej/sej) ^a	% (sej/sej) ^b
<i>Implantation</i>							
1 Concrete	g	F	5.94×10^6	1.54×10^9	9.15×10^{15}	5.55%	0.42%
2 Steel	g	F	1.60×10^6	2.77×10^9	4.43×10^{15}	2.68%	0.21%
3 Polypropylene	g	F	1.37×10^5	5.87×10^9	8.04×10^{14}	0.49%	<0.10%
4 Equipment	g	F	5.30×10^4	4.10×10^9	2.17×10^{14}	0.13%	<0.10%
5 Labor	J	F	5.02×10^7	4.30×10^6	2.16×10^{14}	0.13%	<0.10%
6 Machinery	g	F	2.22×10^4	4.10×10^9	9.10×10^{13}	<0.10%	<0.10%
7 PVC	g	F	1.15×10^4	5.87×10^9	6.75×10^{13}	<0.10%	<0.10%
8 Water	g	N	2.70×10^7	2.25×10^5	6.08×10^{12}	<0.10%	<0.10%
9 Rubber	g	F	1.00×10^3	4.30×10^9	4.30×10^{12}	<0.10%	<0.10%
<i>Operation</i>							
10 Electricity	J	F	4.95×10^{11}	1.65×10^5	8.17×10^{16}	49.52%	3.78%
11 Labor	J	F	9.80×10^9	4.30×10^6	4.21×10^{16}	25.52%	1.95%
12 Chemicals	g	F	2.55×10^7	1.00×10^9	2.55×10^{16}	15.45%	1.18%
13 Water	g	N	3.67×10^9	2.25×10^5	8.26×10^{14}	0.50%	<0.10%
Emergy (process)	kg	Y1	7.2×10^3	2.29×10^{13}	1.65×10^{17}	100.00%	—
14 Steel	g	N	7.20×10^8	2.77×10^9	1.99×10^{18}	—	92.13%
Emergy (fasteners)	kg	Y2	7.27×10^5	2.97×10^{12}	2.16×10^{18}	—	100.00%

^a Considering items from 1 to 13.

^b Considering items from 1 to 14.

Figure 2.16. Emergy table for zinc coating of fasteners [113].

⁵It should be noted that Almeida et al. [99] were not following best practices in this table, which recommend including the source for the transformity in the table or as notes [114].

Description	Unit	Class	Value	UEV (sej/un)	Emergy (sej/year)	% (sej/sej) ^a	% (sej/sej) ^b
<i>Implantation</i>							
1 Concrete	g	F	3.50×10^6	1.54×10^9	5.39×10^{15}	0.96%	0.21%
2 Equipment	g	F	5.58×10^5	4.10×10^9	2.29×10^{15}	0.41%	<0.10%
3 Steel	g	F	2.00×10^5	2.77×10^9	5.54×10^{14}	0.10%	<0.10%
4 Machinery	g	F	1.10×10^5	4.10×10^9	4.51×10^{14}	<0.10%	<0.10%
5 Labor	J	F	5.02×10^7	4.30×10^6	2.16×10^{14}	<0.10%	<0.10%
6 Rubber	g	F	5.00×10^4	4.30×10^9	2.15×10^{14}	<0.10%	<0.10%
7 Polypropylene	g	F	2.00×10^4	5.87×10^9	1.17×10^{14}	<0.10%	<0.10%
8 Water	g	N	3.50×10^6	2.25×10^5	7.88×10^{11}	<0.10%	<0.10%
<i>Operation</i>							
9 Electricity	J	F	1.50×10^{12}	1.65×10^5	2.48×10^{17}	43.97%	9.69%
10 LPG	J	F	3.89×10^{12}	4.80×10^4	1.87×10^{17}	33.16%	7.30%
11 Labor	J	F	2.29×10^{10}	4.30×10^6	9.85×10^{16}	17.46%	3.85%
12 Chemicals	g	F	2.20×10^7	1.00×10^9	2.20×10^{16}	3.90%	0.86%
13 Water	g	N	2.64×10^8	2.25×10^5	5.94×10^{13}	<0.10%	<0.10%
Energy (process)	kg	Y1	3.00×10^3	1.88×10^{14}	5.64×10^{17}	100.00%	—
14 Steel	g	N	7.20×10^8	2.77×10^9	1.99×10^{18}	—	77.73%
Energy (fasteners)	kg	Y2	7.23×10^5	3.54×10^{12}	2.56×10^{18}	—	100.00%

^a Considering items from 1 to 13.

^b Considering items from 1 to 14.

Figure 2.17. Emergy table for organo-metallic coating of fasteners from [113].

It should be noted that these tables include all inputs required for building (implementing) the processes within the system, amortized over the life of the factory in years, and the annual operating inputs for running the machinery, but does not include the emergy of human life and the impact to the environment from the outflow of hexavalent chromium [99]. The implementation grouping includes the building of the factory, the machines and supporting materials, and labor for construction and installation. Operation includes the materials and labor for operating the machinery. The materials for the fasteners are broken out separately. In both processes we can note that the majority of the emergy for the entire product comes from the steel fasteners, and when looking at the process only, the majority comes from electricity. Reviewing the totals, though, shows that the zinc process has a lower emergy value per year than that of the organo-metallic process.

As noted, Figure 2.16 does not include the emergy impact of hexavalent chromium. This was calculated separately based on two components: damage to human health and dilution into the environment. Emergy representing the damage to human health (C_j) was calculated from:

$$C_j = m_j \times \text{DALY} \times \tau_{HR} \quad (23)$$

where m_j is the mass of the released substance, the disability adjusted life year (DALY) is the number of years of life lost related to the released substance, and τ_{HR} is the trans-formity for inhabitants of Brazil. Dilution by the environment was calculated based on the Gibbs free energy due to the the gradient of concentration between the effluent and the environment where it was output:

$$E_{Gibbs} = N \times R \times T \times \ln \frac{C_1}{C_2} \quad (24)$$

where E_{Gibbs} is the Gibbs free energy required for dilution, N is number of moles effluent discharged, R is the universal gas constant, T is the average environmental temperature, C_1 is the effluent concentration, and C_2 is the local concentration of the effluent of interest. The sum of these values with the totals for the zinc-coating process is 1.65×10^{17} sej per year versus 5.64×10^{17} for the organo-metallic process, fulfilling our need for item (5) in the analysis procedure.

This result leads to item (6) in the analysis procedure: discussion for future action. The authors concluded that such a result is not intuitive, as the organo-metallic process was introduced to the automotive industry as a more environmentally friendly coating process. Despite this, the authors note that changing the technology, would result in a global decrease of efficiency [99].

Figure 2.18. ESL for a general production system [102].

Liu et al. [102] developed a model for a production system, with a scope shown in Figure 2.18. This is translated into the following equation representing the emergy for the production system (Em_{all}):

$$Em_{all} = Em_{en} + Em_{ma} + Em_{se} + Em_{iw} \quad (25)$$

where Em_{en} is the sum of the energy for the input energy in the form of electricity and other fuel for all subprocesses; Em_{ma} is the sum of the material used to make the product, plus that consumed by each of the production processes (such as cutting fluid and water); Em_{se} is the sum of the services supporting each of the subprocesses including equipment, land, labor, and supporting activities; and Em_{iw} is the emergy value for the environmental pollution caused by any wastes from the system.

The authors [102] applied this model to a truck production system using audits from production data, energy, service, and waste, as well as process routings, the bill of materials, and other available data based on one month of facility statistics. Through this effort they were able to quantify a total emergy for the production system and identify the largest contributors. From this analysis, the authors identified areas of focus within the facility for improvements related to resource and energy savings that would result in an 8.8% reduction in energy input for the production system.

Though emergy as a metric has been primarily applied to ecosystems and large systems analyses, increasing research has been completed around industrial processes [115]. Studies applying emergy to manufacturing, while limited, include full analyses and comparisons of manufacturing processes and assessments of the manufacture of individual products [97–99, 102]. While previously thought to be a thermodynamically invalid concept, research has been completed to confirm emergy is an equivalent concept to that of exergy [45, 87, 92, 116]. Indeed, thermodynamic assumptions included in exergy have been rolled into the general calculations for global baselines [83]. As noted, the inclusion of the ecosystem is a critical advantage of emergy over other consumed energy and exergy analy-

sis. With the consideration of ecosystems, emergy provides a stronger holistic approach for environmentally conscious decision-making as it goes beyond the emissions-centric view of environmental impact seen in LCA and similar comprehensive analyses. With emergy it is possible to define the critical contribution of ecosystems to human-built systems [87].

Table 2.6 summarizes the coverage of manufacturing accounting inputs in two representative emergy studies by Almeida et al. [99] and Liu et al [102]. In addition to the standard manufacturing accounting elements, two additional sources of emergy—waste disposal/remediation and waste impact—have been added since these are directly addressed in both studies. As demonstrated by Table 2.6, between these two studies, all aspects of manufacturing are covered, which is in sharp contrast to the previous two metrics discussed, whose differences will be explored further in Section 2.3.

Table 2.6. Coverage of Manufacturing Accounting Elements in Emergy Analyses

Manufacturing Accounting	Almeida et al. [99]	Liu et al. [102]
Material of Part(s)	✓	✓
Direct Labor	✓	✓
Manuf. Equipment	✓	✓
Factory	✓	✓
Process Power	✓	✓
Process Supplies	✓	✓
Tooling (Dies)		✓
Building Utilities		✓
Support Labor		✓
Machine Setup		✓
Waste Disposal/Remediation*	✓	✓
Waste Impact*	✓	

* Not included in current cost accounting model.

2.3 Selecting an Energy Metric for Supporting Engineers in Eco-Design

In selecting energy metrics first introduced in Sections 2.2.1, 2.2.2, and 2.2.3 for use in product development decision-making and related to manufacturing process choice, the following criteria should be considered

- a. Comprehensiveness: Do the energy metrics capture the industrial-environmental system?
- b. Useful in design decisions: Can the energy metrics be tied to design variables based on current research?
- c. Data availability: Are there data available to calculate the impact on the environment for the energy metrics?
- d. Theoretically backed: Are analyses using the energy metrics backed by physical behaviors and properties?
- e. Established for industrial evaluation: Have the energy metrics been used for evaluating industrial systems and their interactions with the environment?
- f. Standard analysis methodology: Do the energy metrics have standard and well documented approaches to analyses?

Table 2.7. Comparison of Energy Metrics Against Criteria for Use in Product Development

Criteria	Consumed Energy	Exergy	Emergy
(a) Comprehensive	○	⊙	⊕
(b) Useful in design	⊕	⊕	⊙
(c) Data available	⊙	⊙	⊙
(d) Theory	⊕	⊕	⊕
(e) Industrial evaluations	⊙	⊙	⊙
(f) Standardized analysis	⊕	⊙	⊕

○ Does not satisfy criteria

⊙ Partially satisfies criteria

⊕ Satisfies criteria

Table 2.7 summarizes the performance of each energy metric against these criteria. The sections below discuss the ranking of each and how that relates to the advantages, disadvantages, and limitations. A final section discusses the final choice of energy to fill the role of an energy metric for product development decisions.

2.3.1 Comprehensiveness

Industrial and environmental systems are inherently complex and contain many flows of materials, and energies. In determining a single metric for evaluating the environmental impact of industrial systems, a metric that covers as much of that system as possible is desired. To evaluate metric capabilities, Table 2.8 combines Tables 2.2, 2.5, and 2.6, keeping waste disposal/remediation and waste impact. Emergy is broken into two columns. One represents each of the two studies detailed in Section 2.2.3. For the exergy and consumed energy columns, data were also based on the studies detailed in their respective sections.

Table 2.8. Coverage of Manufacturing Accounting Elements in Energy Analyses

Manufacturing Accounting	Cost [117]	Emergy [99]	Emergy [102]	Exergy	Consumed Energy*
Material of part(s)	✓	✓	✓	✓	✓
Direct labor	✓	✓	✓		✓
Manuf. equipment	✓	✓	✓		
Factory	✓	✓	✓		
Process power	✓	✓	✓	✓	✓
Process supplies	✓	✓	✓	✓	✓
Tooling (dies)	✓		✓	✓	✓
Building utilities	✓		✓		
Support labor	✓		✓		
Machine setup	✓		✓	✓*	✓
Waste disposal/remediation [†]		✓	✓		
Waste impact [†]		✓			

*Only energy consumed is included.

[†] Not included in aPriori software cost accounting model.

As can be seen in Table 2.8, in the two emergy columns, all the elements in a complete manufacturing accounting based on aPriori's taxonomy are covered. In the case of both exergy and consumed energy analyses, elements related to labor and equipment are rarely included and standard methodologies for including them have not been developed.

Consumed energy satisfies very few of the accounting elements, and, for those that it does cover, only the consumed energy of the processes is covered. Exergy fares slightly better, with its coverage of supplies. The lack of coverage of the labor and waste impact, in particular, is recognized as a particular deficit within both exergy and consumed energy analyses [45, 78]. With these considerations in mind, energy has the most comprehensive coverage.

2.3.2 Useful in Design Decisions

Based on the examples provided Sections 2.2.1, 2.2.2, and 2.2.3, all three of the energy metrics in question can be used to drive decisions in design and manufacturing. Energy and exergy are ranked slightly better because the literature related to quantifying unit manufacturing processes is much broader than for emergy. Emergy does, though, provide a single metric which captures all energy input into a system, which is a more promising approach than consumed energy and exergy for engineers as those completing an analysis are not asked to balance a set of different environmental criteria.

2.3.3 Data Availability

Data are available for consumed energy, exergy, and emergy. Both consumed energy and exergy have well developed datasets within manufacturing. Although emergy studies and approaches are limited for manufacturing applications, the comprehensiveness of the available industrial analyses demonstrate methods for determining required values. Additionally, emergy data have been more comprehensively developed for the wider ecosystem and economy, an area that is out of scope for consumed energy analysis and has only limited development for exergy analysis.

2.3.4 Theoretically Backed

Consumed energy, exergy, and emergy are all theoretically backed, either based on thermodynamic, other physics mechanisms,⁶ or practical measurements. Many researchers have addressed the validity of emergy as a metric. Criticisms of the emergy approach in the literature have been addressed at various levels, including work completed confirming a relationship between emergy and exergy [45,92]. The common criticisms and their responses are summarized Table 2.9. With resolutions reached for all concerns, these criticisms are not relevant for application within product development analyses.

Table 2.9. Summary of Appraisals of Emergy

Appraisal & Source	Response & Source
Arbitrariness of the values of transformities compared to exergy [118]	The relationship to exergy has been established, and with latest global emergy baseline calculations, the relationship has been reaffirmed [45, 115]
Lack of consensus around the global values for emergy related to earth functions [118]	There is currently consensus around global values as described by Brown et al. [83] versus 2010 when this critique was raised
Provides different ratios of values for key energy contributors (such as the ratio of oil to coal) than exergy analysis [118]	Exergy comparisons have been included in “several researchers’ work. From their research it became clearer that EmA [emergy analysis] should not be seen as a competitor or alternative method to exergy analysis, but rather as a complementary method. Exergy analysis provides a clearer view of the process itself, while EmA is useful to understand context in which the process occurs and its relationship with environmental dynamics” [115].
One dimensional and does not include considerations for other criteria for evaluating an energy source [119]	“Representing global energy flows in solar equivalent. . . does not imply that solar energy is being converted into tidal energy or deep Earth heat. The primary benefit of this approach is that it allows a fair comparison of the concentration, of different kinds of energy.” [87].
Single transformities used for different qualities of the same energy sources [119]	It “has been assumed that generalized transformities do not differ significantly from any specific case. This criticism is also shared by most other approaches” such as LCA [87].
Data used to calculate emergy varies in quality, and there has not been much research completed to understand the statistical variation in values [119]	More recent analyses have been completed covering this area [115].

⁶See expanded discussion in Appendix C.

2.3.5 Established for Industrial Evaluation

All three energy metrics are well established for evaluation of industrial systems. As discussed in Section 2.2.3, the applications of emergy within industrial systems is more limited than with exergy or consumed energy analyses (whose scopes are normally focused on industrial systems) because emergy tends to take a larger view of an ecosystem. Emergy analysis, though, intrinsically includes the interaction with inputs from the environment, which is out of scope for consumed energy analysis and has only limited development for exergy analysis.

2.3.6 Standard Analysis Methodology

Consumed energy analysis relating to the CO₂PE! initiative and its more general role in LCI/A has a well defined structure and control volume for analysis [23, 120]. Emergy, with ESL and presentation tables, also has a well established approach for understanding and comparing analyses [76, 114, 121]. However, emergy requires deliberate definition of a control volume for analysis and accounting for all inputs and output based on the same global baseline values [76,83]. Exergy, on the other hand, while clearly thermodynamically based, does not have a standardized method or notation for completing analyses. Different researchers use different notations, select different control volumes, and make different assumptions regarding the ambient environment. With those differences, it is hard to compare data to each other or use data from one study in another.

2.3.7 Choice of Emergy

Table 2.7 shows that both exergy and emergy have similar levels of overall performance. The comprehensiveness of an emergy analysis approach, though, is critical for including the complete industrial system, including interactions with the economy and the environment. Additionally, the standardized analysis approach used for emergy investigations versus exergy allows for more consistent modeling and the simplified use of existing data. The one

area where exergy performs better than energy is in the application to engineering design decision-making. Nevertheless, energy is a strong choice as a metric for product development application. A more detailed review of the energy literature is provided in Section 2.4.

2.4 Manufacturing Elements in Emergy Research

As noted in Section 2.2.3, direct manufacturing applications of emergy are limited, but there are a selection of analyses that cover adjacent areas, have similar methodological approaches, or contain data that can be used to support manufacturing-related calculations. The following Sections cover these related areas, concluding with Section 2.4.7, which includes Table 2.11 summarizing the mapping of these concepts to manufacturing cost accounting.

2.4.1 Construction

Construction modeling, while not identical to manufacturing, shares many aspects in common, such as dependency on materials and labor and the concept of amortizing an investment. The dominant applications for emergy in this area include building [79, 93, 94] and wind farm construction [95, 96], as well as examples of industrial factories [122]. These projects are all modeled similarly, including the entire life cycle and reflecting impacts for the initial construction phase, use phase, and maintenance phase. For the initial construction phase, the energy inflows are based on the mass of the varied materials used, the supporting labor (except for Li et al. [93]), and land use.

Although Li et al. [93] do not include a labor model, they do quantify the emergy of the initial construction phase (E_B) clearly with three contributing emergy components: the land a building sits on (E_L), the building itself (E_M), and the waste produced during construction (E_W), written as:

$$E_B = E_M + E_L + E_W \quad (26)$$

For the land portion of the equation, the authors use an approach described by Pulselli et al. [94], where the emergy embodied per area of building space through the use of the land under a building is equal to:

$$E_L = \frac{A}{N} \rho_{ground} D_{soil} E_{n_{ground}} T_l \quad (27)$$

where A is the floor space in units of area, N is the number of floors in the building, ρ_{ground} is the density of the ground, D_{soil} is the depth of the soil impacted (estimated by Pulselli et al. [94] to be 3 cm), $E_{n_{ground}}$ is the energy content of the ground, and T_l is the UEV for the land.

Li et al. [93] estimated E_W based on the average amount of solid-state waste for a building. Since most construction waste in China is added to a landfill, the authors calculate the impacts to the ground in a similar manner as the is done for the building in Equation 27. The method Li et al. used for estimating the building materials (E_M) were based on a residential building, where the vertical space is of more importance, and resulted in a UEV in terms of volume.

The impact of landfilled materials was calculated by Franzese et al. [123]. The analysis was completed on a specific landfill in Italy and includes construction of the landfill amortized over its life, collection and disposal of the waste. With the analysis they were able to calculate a UEV for the safe collection and disposal of waste (including labor and services) of 1.15E9 sej/gram of waste.

Saladini et al. [122] evaluated the emergy for a biodiesel manufacturing plant, following a methodology from Cavalet and Ortega [124] to estimate the two principal building materials for a factory: steel and concrete. The method assumed a generic building with a

square footprint, steel reinforced concrete walls, a steel reinforced concrete pad for a floor, and a steel roof. The estimation for the mass of concrete is as follows:

$$m_{concrete} = (4h_{wall}\sqrt{A} + A)w_{avg}\rho_{concrete} \quad (28)$$

where A is the area of the building's footprint, h_{wall} is the height of the wall, w_{avg} is the average width (thickness) of the concrete, and $\rho_{concrete}$ is the density of concrete. Correspondingly, the mass of the required steel is estimated as:

$$m_{steel} = \rho_{rebar}m_{concrete} + \rho_{roof}A \quad (29)$$

where ρ_{rebar} is the mass of steel reinforcement per volume of cement and ρ_{roof} is the surface density of the roof. With these calculations complete, UEVs for each of the materials can be identified and emergies for each material calculated.

In Use phases, inputs are defined as the direct energy required to operate the building or wind farm, and, in the cases of wind farms, the human labor required to support the operation. For Maintenance phases, Pulselli et al. [94] included the emergy cost of materials required for maintenance of the building, while Yang et al. (2013) [96] did the same for the wind farm, but they also included the emergy inputs from labor for this phase. Pulselli et al. [94] and Li et al. [93], each proposed relevant metrics, functionally amortizing the emergy across another value. Pulselli et al. [94] looked at it based on time, volume, cost and emergy per resident benefiting from the construction. Li et al. [93] focused on an emergy-per-area metric.

The contribution to the manufacturing emergy model from construction includes the use of the model by Li et al. [93] for the emergy in a building, supported by the work of Saladini et al. [122], Pulselli et al. [94], and Cavalet and Ortega [124] to allow for a full estimate of the emergy in a factory. The studies reviewing the use phase [93, 94, 96]

are applied to represent the building utilities and the support labor. The details of these applications and the resulting model are discussed in Section 3.3.7.

2.4.2 Products and Manufacturing

While there are limited applications of emergy analyses in product manufacturing, there are a selection of instructive approaches. In particular, Almeida et al. (2010) [98] proposed the use of emergy within the eco-design process, noting the usefulness of a single metric (environmental loading ratio) for comparing design alternatives. Using this framework, they compared the emergy required for manufacturing beverage packaging options in Brazil. An additional study by Almeida et al. [97] in 2013 compared the emergy in the manufacturing processes of lead-free versus tin-lead solders. In this study, the authors included emergy assessments for the infrastructure of each producer and the required services based on the materials that make up that infrastructure. These materials include the components of the factory (e.g. concrete and the roof), the supporting machinery and equipment, materials to support reverse logistics, and the labor to support building the facility.

As discussed in Section 2.2.3, Almeida et al. [99] completed a similar analysis comparing a zinc coating to an organo-metallic coating process. The analysis for each process included the implementation of the system supporting the process, including labor, machinery, electricity, and additional human services. These were divided by the plant lifetime to result in a per-year emergy value for the initial construction of the manufacturing line. Additionally, the running of the coating processes was included in the initial analysis. For operation of the processes, supporting energy (electricity and LPG), input material (e.g. the fasteners, chemicals, and water for effluent treatment), and labor to support the manufacturing line were included.

Assessments of the emergy in a computer were calculated by Di Salvo and Agostinho [100] and Puca et al. [101]. Di Salvo and Agostinho [100], calculated the total emergy required to manufacture a computer based on the input materials, input electricity, services,

labor, and technological research. Since detailed data were not available for these breakdowns, material inputs were estimated based on previous research and the services, labor, and technical research were estimated based on the known cost for a selection of ten laptop computers. This total emergy value was calculated on a per-gram basis for a computer both including and not including indirect services, such as infrastructure, electricity and labor.

Puca et al. [101] completed an emergy assessment of the manufacture of a computer's lifecycle including the acquisition of raw material, manufacturing, and use for both a laptop and desktop computer. These two computers were then assessed with renewable material and power assumptions and a nonrenewable assumption (virgin raw materials with nonrenewable power). For a final metric, the authors included the total emergy per computer for each scenario.

For any given manufactured product, there are labor and services that are part of the production. These are purchased on the open market. Odum [60] described a method for estimating the emergy in labor and services for a product by using an emergy-per-dollar value for the market price of the product. This approach was cited by Raugei et al. [125] in evaluating solar power and by Bargigli and Ulgiati [126] in reviewing steel production. Odum [60] noted that one must be careful not to double-count in these situations. If the emergy is being evaluated for the material included in the product, then the dollar value of the market price must be reduced by the value of the materials to ensure the numerical value only covers the labor and services for the product.

Emergy-per-dollar ratios can be calculated on a selection of scales and are commonly calculated on a national level as described by Odum [60]. Campbell et al. [127] generated emergy-to-dollar ratios based on US GDP values and emergy assessments at the national level. The emergy assessment, based on the ESL shown in Figure 2.19, included the following components: (1) renewable sources of energy; (2) soil erosion; (3) energy consumption by the economy; (4) minerals consumed by the economy; (5) imported goods outside of fuels and minerals; (6) imported services in the forms of goods, fuels, and minerals; (7) other

Figure 2.19. ESL showing national-level energy flows [127].

imported services; and (8) immigrants, bringing knowledge and experience. The resulting analysis included data and energy-to-dollar ratios from 1900 through 2011.

The works led by Almeida [97–99] had the most direct applications to the methods used throughout the energy models in Chapter 3. The work on computers by Di Salvo and Agostinho [100] and Puca et al. [101], was leveraged primarily in calculating the total energy of manufacturing equipment, as it provides a more refined method for estimating the contribution of product constructed from many materials. This is investigated further in Section 3.3.3. Finally, in some cases, labor and services of unknown energy contribution but a known market-cost contribution remains. In these cases, the approach outlined by Odum [60] and supported by Campbell et al. [127] in their energy-to-dollar ratios were used and can be found in Chapter 3.

2.4.3 Labor

In most energy analyses, including those cited in Sections 2.4.1 and 2.4.2, labor is captured based on the an estimate of the money not used for materials. Ideally, labor could be captured more directly based on the requirements of the system instead of using

money as a proxy. Indeed, Kamp and Østergård [106] proposed a method for accounting for direct and indirect labor involved in an economy. To demonstrate this, they evaluated the differences in two different cooking systems in Ghana with the goal of capturing the reality that much of the energy used within a country is dependent on indirect labor from other countries.

This idea was expanded in a later work by Kamp et al. [105] that proposes the use of local labor UEVs for direct labor and forming location specific UEVs for indirect labor, ideally mapping the full labor input chain. While the authors noted that previous work has relied on the use of an emergy-to-money ratio (EMR) for determining the emergy of labor, they did not consider money as a good proxy for labor. As an alternative, the authors suggest the use of time, as it is a more fundamental unit than money, and direct and indirect labor can be summed up using time as a metric. However, with current methods time was not a viable alternative and is left as a future development. Kamp et al. [105] noted that it is easy to double-count energy when using an approach like that of Zhang and Dornfeld [57] who split nonindustrial energy usage across workers because the industrial sector is dependent upon other sectors. While Kamp et al. [105] described that there has been mathematical work completed to address double-counting, they suggested double-counting related to labor inputs is canceled out since it is equally distributed throughout various production systems.

Determining an hourly emergy rate is a less researched area. Bergquist et al. [128] gave a bottom-up proposal, noting:

“...labor contribution should incorporate at least four aspects: calorie intake, quality and quantity of knowledge, how it was generated and acquired (i.e., transferred between individuals and wider society), and in what cultural context the labor is applied.” [128]

Bergquist et al. [128] discussed how knowledge acquisition for labor varies in formal (e.g., university) and less formal (e.g., rural farming) educational situations. Figure 2.20

shows the model by Bergquist et al. [128] for formal education. In this ESL, a university's storage of information was supported by a selection of external nonrenewable resources (N, infrastructure, electricity), external information (research communities) and its own teaching activities. The teaching activities supported the development of professional knowledge for workers, who also gained further knowledge from their own involvement in the labor market. Workers were supported by additional nonrenewable resources, which contributed to society and contributed to the production of the nonrenewable resources.

Figure 2.20. ESL showing a model for formal knowledge acquisition [128].

Bergquist et al. [128] focused on the cultural context and informal knowledge development. For manufacturing activities addressed within this dissertation study, formal education is more relevant. To that end, Campbell et al. [104] used data from the US BLS and energy values computed in earlier work related to formal educational attainment [103]. The goal of the work of Campbell et al. [104] was to test if

“...the money paid to a worker...[is] linearly related to the energy of the knowledge and experience possessed by an individual trained to do the work of that occupation.”

They also noted a secondary goal of producing data on the amount of emergy delivered via the labor of workers in the U.S. for supporting on-going research. With these goals in mind, the authors provided an ESL diagram demonstrating their assumed model, shown on in Figure 2.21. In this model, global society was split into three main subsystems: ecosystems, environmental-economic interface, and human-economic systems. The ecosystem received its primary emergy from the environment, but performed its contribution to larger systems of the Anthropocene. The contribution from the environment was represented by the interaction with human systems and the economic use of the services provided by the ecosystem. The useful services included the production of fuel and minerals. Human knowledge and experience was also treated as a storage distributed to global society through interactions with the economic usage of the environment, the main economy, and teaching interactions. Knowledge and experience were built through learning activities.

Figure 2.21. ESL showing impact of human knowledge and experience on global society [104].

For this dissertation study, the application of knowledge to the main economy was of primary interest. Focusing in on the economic exchange for a product, Campbell et al. [104] suggested the model shown in Figure 2.22. Here, buyers and sellers determined the value

for a product in the economy. In that exchange, they transferred some amount of emergy for a given price. The amount of emergy transferred in this transaction was proposed to be equal to the sum of the emergy within the materials of the product plus the emergy of the knowledge and experience required to create the product.

Figure 2.22. ESL showing impact of human knowledge and experience on exchanges on the economy [104].

Building on this model, the authors proposed a method for estimating the empower held by labor based on education and experience. Due to a lack of available data, on-the-job training and experience were not considered as part of this analysis. Education was assumed to provide a conservative estimate of the emergy transferred by labor. Using US BLS data from the American Community Survey [129], the authors identified the fraction of those in an occupation with a given level of education. To calculate empower values for the education required for 558 occupations, they used the following approach:

$$E_{ed,occ} = \sum_i^n E_{ed-level,i} f_{ed-level,i} \quad (30)$$

where the product between the emergy for bringing an individual to a given education level $E_{ed-level}$ [103] and the percentage of workers at that education level for the occupation in question $f_{ed-level}$ was summed over each of the education levels (i) relevant for an occupation. The result was the emergy of education held by an average person in a given occupation.

To find an hourly emergy value, Campbell et al. [104] needed to determine over what amount of time a given person in an occupation would use the knowledge on their job acquired through their education. Knowledge, unlike other resources, is not used up. The same information can be used many times over a career. Considering this property of knowledge, the authors made the assumption that a worker would draw directly or indirectly on their entire knowledge base, through a year of work in a job. They noted that this is a simplification, but maintained it is not unreasonable given the variety of problems a worker could encounter in a year. The emergy per hour for education was provided in the supplemental materials and was equal to the occupation emergy from education (Em_{ed}) divided by the total number of hours in a year (h_y):

$$Em_h = \frac{Em_{ed}}{h_y} \quad (31)$$

Lupinacci and Bonilla [130] built off of work relating to education from Campbell and Lu [103] to evaluate the emergy provided to students in an English language class in Brazil. They looked at two approaches for calculating the emergy within the school for one year based on different approaches for calculating the emergy held by the teachers. The first method for estimating the emergy of a teacher was based on dividing the emergy of the region for a year by the number of citizens within various educational groups, which is a widely used method for estimating yearly labor estimates. The second method treated the teachers as students at the school and reviews how much emergy they built up by entering as high school graduates and completing their course of studies at the same school. With this second method, teachers accumulated the amortized emergy from the initial construction of

the building, as well as the emergy of operation on a yearly basis, similar to the bottom-up method used by Campbell and Lu [103]. Lupinacci and Bonilla [130] found this gave a three times larger transformity than the first calculation method.

Lupinacci and Bonilla [130] argued that the second method was more appropriate, as it takes into account local considerations, such as the specific school building, versus averaging the values from the top-down over the entire region. Additionally, they more generally argued that human transformities are specific to an activity, time, and place, and required more detailed definitions to produce accurate results. This is very much aligned with the contention from Kamp et al. [105] that more fundamental units are required for labor calculations and solidifying the approach of building a bottom-up model versus the top-down energy calculation approach for labor proposed by Zhang and Dornfeld [57]. This bottom-up approach closely mimics the concepts of ABC and is strongly leveraged in Section 3.3.2 for developing a labor model with an hourly emergy rate for manufacturing.

2.4.4 Power

For most industrial studies, such as led by Almeida [97–99], the electricity used relies on a generic value for electricity. For a given region, a specific emergy value should be calculated to represent the local mix of electricity generation methods. Häyhä et al. [131] completed such a study to determine the total emergy for producing the electricity in Finland. Using data on the national load of electricity production by type, the authors were able to estimate the total emergy cost for the production of electricity in Finland for a base year of 2008, as well as projecting forward to 2025 and 2050 based on the expected future mix of electricity production. The authors referenced earlier estimated values for electricity production via a selection of sources, including coal, natural gas, wind, and hydroelectric power for locations in Europe.

This model reflected common cost-modeling standards of using local rates for labor and other regionally varying quantities. The framework of Häyhä et al. [131] was used

for developing a model within the relevant region for analysis in this study and will be discussed in more detail in Section 3.3.4.

2.4.5 Steel

For calculating the environmental impact of manufacturing, steel estimates are critical. These are required for a selection of uses, including: part material, and construction materials for the factory, and as one of the materials contained within production machines. There are a few studies that have estimated energy for the steel production process.

In his Ph.D. dissertation, Buranakarn [132] completed an assessment of a selection of construction materials, including steel. He included an assessment of two furnace systems— an electric arc furnace (EAF) and a basic oxygen furnace (BOF). The first can use only scrap steel as an input, while the second can support only high quality scrap steel as a minor fraction of the input. The resulting values are given in Table 2.10.

Bargigli and Ulgiati [126] also completed an analysis for the structural steel used in construction. In their work, the authors completed three scenarios: a complete BOF analysis for virgin steel, a complete EAF analysis for 100% recycled steel, and a mixed scenario including both BOF and EAF steel-making, reflecting the average German scrap steel recycling rate in the 1990s. For the mixed scenario, this assumption led to 17% EAF and 83% BOF proportions steels, with the EAF using 100% recycled steels. It should be noted that this study explicitly includes refining and finishing steps to produce useful materials for construction, something not explicitly noted in Buranakarn's dissertation [132]. Bargigli and Ulgiati's results are summarized in Table 2.10.

Zhang et al. [133] completed an analysis of the sustainability of the Chinese steel industry from 1998 through 2004. The authors completed the analysis for a steel product that includes some recycling and, as such, a combination of steel-making technologies. The recycling mix and the use of the output products, though, is not documented in the study. The resulting UEVs are included in Table 2.10.

Pan et al. [134] followed a similar methodology as Zhang et al. [133], but instead of looking at the entire Chinese steel economy, Pan et al. [134] reviewed a specific steel facility in Sichuan Province, China. The production here included both BOF and EAF steel-making, with recycled materials included as part of the inputs, though the specific percentages of scrap steel melted through the EAF processes were not included. Additionally, not noted are the specifics regarding the output steel products. The resulting UEV is included in Table 2.10.

Ma et al. [135] completed an assessment based on data from the Yuhua Steel Co. Ltd. in Wuan City, China. The output of this facility is cold rolled (CR) steel coil, using only a BOF process. The resulting UEV is included in Table 2.10.

Table 2.10. Summary of UEVs from Literature for Steel

Type	Source	Location	Output	UEV (sej/g)	
				With L & S*	No L & S*
Structural steel (all virgin)	[126]	Europe	Structural steel	5.47E+09	4.69E+09
Structural steel (with recycle)	[126]	Europe	Structural steel	4.81E+09	4.02E+09
EAF process (virgin)	[132]	US	Structural steel	5.28E+09	5.21E+09
EAF process (100% post-consumer scrap)	[132]	US	Structural steel	5.61E+09	5.56E+09
EAF process (30% post-consumer & 70% in-house scrap)	[132]	US	Structural steel	5.39E+09	5.33E+09
BOF process (virgin)	[132]	US	Structural steel	6.80E+09	6.75E+09
BOF process (25% in-house scrap)	[132]	US	Structural steel	6.80E+09	6.75E+09
1998 China	[133]	China	Unknown	9.94E+09	N/A
1999 China	[133]	China	Unknown	8.68E+09	N/A
2000 China	[133]	China	Unknown	6.44E+09	N/A
2001 China	[133]	China	Unknown	6.44E+09	N/A
2002 China	[133]	China	Unknown	5.03E+09	N/A
2003 China	[133]	China	Unknown	5.08E+09	N/A
2004 China	[133]	China	Unknown	5.39E+09	N/A
2016 China	[134]	China	Unknown	3.52E+09	N/A
CR coil	[135]	China	Cold rolled steel coil	N/A	3.93E+09

*L & S = labor and services

Reviewing the steel UEVs shown in Table 2.10, the outputs most closely match the raw material for steel parts is the CR coil. It should be noted that though cold rolled coil has additional processing steps [135] versus structural steel, which is generally hot rolled only [126]. Since CR coil has more processing steps the expected value would be higher, not approximately 2% less than that of recycled structural steel. It should be noted, though, that since labor and services are not included in these two values, the added emergy that would be found in the CR coil may lie completely within the labor and services. The other

key item to note is the difference in UEVs based on the technology used to create the steel, plus the amount of scrap included in the process. In Chapter 3 the choice of a representative UEV for use in this dissertation study will be discussed. The variation of the UEV for steel will be investigated further in Chapter 4.

2.4.6 Emergy Software

Dedicated software for emergy is limited to two packages. The first was developed at Luxembourg Institute of Science and Technology (LIST) [136], known as SCALEM[®]. The software is focused on translating LCAs to emergy values. This allows existing environmental assessments of products conducted as LCAs to be put in emergy terms. It is under active development at LIST. The second is an open-source software known as EmSim [137], which allows users to build emergy systems graphically by creating ESL diagrams and calculate transformities from the diagrams. The last update for the software on SourceForge [138] was in 2013.

Otherwise, some purpose-built models for completing emergy assessments have been built in BASIC [60, 114], Excel [103, 114], MATLAB (focused on construction) [139], and other programming languages [114]. No emergy software tools were discovered that focused on part manufacturing directly.

2.4.7 Mapping Literature to Manufacturing Accounting Categories

Table 2.11 summarizes the applicable areas in manufacturing accounting for the emergy literature. It should be noted that mapping does not necessarily require a direct reference to the accounting element in question, but may be applicable for its methodology. In Chapter 3, the detailed relationship between the literature and the proposed model will be established.

Table 2.11. Applicable Literature for Addressing Manufacturing Accounting Elements in Emergy Analyses.

Manufacturing Accounting	Applicable Emergy Literature
Material of part(s)	[79, 98, 99, 102, 126, 132–135]
Direct labor	[103–106, 128, 130]
Manuf. equipment	[98, 100, 101]
Factory	[79, 93–98, 122, 123]
Process power	[97, 98, 131]
Process supplies	[99]
Tooling (dies)	[102]
Building utilities	[93, 95, 98]
Support labor	[96, 98, 105]
Machine setup	[99, 102]
Waste disposal/remediation*	[99, 102, 123]
Waste impact*	[99]

* Not included in current cost-accounting model.

2.5 Software Evaluation

This dissertation study includes an evaluation by a group of engineering students of an extension to the aPriori software to aid in eco-design evaluations of manufactured parts. Surveys are commonly used for evaluating engineering methodologies related to sustainability. Telenko and Wood [27] asked participants to evaluate the sustainability and innovativeness of a selection of products via a survey and compared that to their reported expertise in the area of sustainability. Midžić et al. [140] had participants rank different design alternatives of the same product for environmental friendliness. In a second step, Midžić et al. [140] asked the participants to identify if a selection of different ecological design guidelines were represented by the designs. In both of these cases, the participants were asked to make these rankings without the use of any tool, but only with their accumulated knowledge.

There are a selection of examples for evaluating software sustainability tools for usability in the literature, including Sinclair et al. [141], Borrion et al. [142], and González-Pérez et al. [143]. Borrion et al. [142] developed a sustainability calculator for a region of Portugal. During a workshop they trained non-expert community members on its use, then

allowed them to explore various inputs and settings. Sinclair et al. [141] tested the usability of the developed sustainability analysis tool against a selection of others, including nonsoftware-based tools for evaluating a set of decisions in a community in the UK. The participants were given background and training on the tools during a series of workshops. Pérez et al. [144] tested a toolset for accessing sustainability data with a set of specialized participants, including librarians, researchers, and students and focused on the usability of the software for these groups. Telenko and Wood [27] recruited participants attending an engineering sustainability conference.

The design of the software and the evaluation experiment for this dissertation study is detailed in Chapter 5.

CHAPTER 3

Emergy Model

3.1 Introduction

Emergy, with its single value output and comprehensive coverage of the inputs of industrial systems, provides the opportunity for strong decision support for design engineers. ABC methodologies gather together all meaningful activities within a production facility to manufacture a product. In reviewing the literature, as discussed in Section 2.4.7, methods are available to support the calculation of emergy values for all common ABC inputs to manufacturing, as well as the known environmental impact areas currently not captured in the ABC taxonomy examined in Section 2.1.1. In this chapter, emergy models for each of the taxonomy areas identified are developed to support the decisions of design engineers and reviewed with examples.

To conduct an emergy assessment of part manufacturing, the following series of steps are recommended. These steps for decision support are adapted from those previously proposed by Bligh et al. [145] and Almieda et al. [98] and are summarized in Figure 3.1:

1. Complete DFM Cost Analysis
 - (a) Collect product designs and manufacturing processes for each design alternative.
 - (b) Define cost and cycle-time equations for each manufacturing process.
 - (c) Estimate cost and cycle-times for each process of each part in the analysis.
2. Complete Emergy Analysis
 - (a) Draw ESL diagrams for each process.

- (b) Create analogous available energy, material, and information equations from corresponding cost equations where available.
 - (c) Convert the material, energy and information inputs and outputs of the production to emergy. Multiply by the appropriate UEVs: transformities (sej/J), specific emergies (e.g., sej/g, sej/m²), or emergy to money ratio (sej/\$).
3. Compute the total emergy budget for each process on a per unit basis, including any negative effects on the environment.
 4. Compare design alternatives. Select the alternative that produces products with the lowest per unit energy input while meeting other design criteria.

Figure 3.1. The steps in completing an emergy analysis for designs.

In Sections 3.2 and 3.3 Steps 2a and 2b will be addressed for the generic case. The full workflow from Steps 1, 2 and 3 will be reviewed using an example shown in Section 3.4. Step 4 will be the focus of the workshop evaluation detailed in Chapter 5.

3.2 Energy Systems Diagram

Shown in Figure 3.2 is the ESL diagram representing the analysis of a general manufacturing system for a part within a process or a set of parts in an assembly process. The scope of the emergy analysis is noted by the large solid box, with the factory represented by the large dashed box. Entering into the factory on the right is the *Raw Material*. The detail on this model is included in Section 3.3.1. The raw material is brought into the manufacturing

Figure 3.2. ESL showing a general manufacturing system. Large box represents scope of the analysis. Dashed box represents factory. Details of: in Section 3.3.1, Raw Material in Section 3.3.2, Machine in Section 3.3.3, Machine in Facility in Section 3.3.3, Facility in Section 3.3.7, Electric (electricity) in in Section 3.3.4, Supplies in Section 3.3.5, Machine Setup in Section 3.3.6, and Waste Impact and Remediation in Section 3.3.8.

process. The process runs for a given time (t_c), and has a total earned number of hours in a year (t_e).

Supporting the process is *Labor*, with the time required for labor to complete the process based on a multiple of the cycle time. The detailed emergy model for labor is presented in Section 3.3.2. The process also draws from the *Machine in Facility*, which includes its construction, installation, and maintenance. The model for machine construction, represented outside the factory in the box labeled *Machine* is described in detail in Section 3.3.3, and is supported by the same labor model used for the main process. The installation and maintenance, represented by machine in facility which occur after the machine has been brought into the factory, are also discussed in detail in Section 3.3.3.

The machine exists within a *Facility*, supported by labor, the factory building, and utilities. The detail of the factory model is discussed in Section 3.3.7. The facility has a number of hours available for the full capacity, which are used with the cycle time to attribute a fraction of the facility emergy to the manufactured product. Utilities to support the facility are purchased from the wider economy based on incoming revenue from product sales.

When the process runs, it uses electricity (*Electric*), *Supplies*, and labor. The model for the power required to support the process is discussed in Section 3.3.4. The supplies are drawn based on the cycle time of the machine, and supplies are purchased, like utilities, using revenue from the wider economy. The details of the supply model are included in Section 3.3.5. Before the machine runs, it must be set up; hence, the switch connection between *Machine Setup* and *Process*. The detailed model for machine setup is included in Section 3.3.6. The setup activity requires inputs from labor, the machine, electricity, and—depending on the process at hand—supplies.

Exiting from the diagram are any remaining manufacturing steps, where the in-process part would enter as the raw material for the next process, recycling, and remediation. Due to the choices of processes to examine for this study, *Waste Impact and Remediation* are

not considered part of the emergy for analysis, but possible models are discussed briefly in Section 3.3.8. *Recycling* is another possible path out for waste, but is not considered as part of the model and is left as a future topic.

Inputs to manufacturing are listed, approximately, in order of increasing emergy per hour. For example, for most processes Labor has the highest emergy per hour and Supplies the lowest. The activities of manufacturing are arranged both in hierarchical order, from high-to-low, and decreasing emergy. For example, Setup is required for the Process, but the Machine in Facility is required for the Setup. As such, Process is to the left of Setup, and Setup is to the left of Machine in Facility. Additionally, the placement also implies emergy-per-hour, with the process overall having the highest and the Facility having the lowest.⁷

Not included within this model is tooling, such as molds or dies to support manufacturing. These are not considered part of the current emergy calculation due to the processes chosen for this analysis. A basic approach, though, for completing this calculation is provided in Section 3.3.9

3.3 Emergy Equations

Reproduced in Equation 32 is the total cost equation for manufacturing a part from the review of DFM cost analysis in Section 2.1.1. It represents the raw material required for manufacture (C_m), labor (C_l), direct overhead costs related to the machine (C_{OH}), indirect overhead costs related to the facility (C_{IOH}), and setup costs (C_{set}) summed over each process involved in manufacturing.

$$C_{total} = C_m + \sum_i (C_{l,i} + C_{OH,i} + C_{IOH,i} + C_{set,i}) \quad (32)$$

⁷This depends greatly on the assumptions made about both the facility and the machine, as the hourly values for the facility and the machine are close in their emergy-per-hour contributions.

Taking this framework and variable definition of the cost equations from Section 2.1.1 and the ESL diagram in Figure 3.2, the corresponding equation for the total emergy of a given product running through i processes is:

$$Em_{manf} = Em_{raw} + \sum_i (Em_{l,i} + Em_{OH,i} + Em_{facility,i} + Em_{set,i} + Em_{w,i} + Em_{im,i}) \quad (33)$$

where it can be noted that two additional elements are added to the total emergy, the emergy from waste (Em_w) and the emergy from the impact of waste or other effluent on the environment (Em_{im}). Additionally, a small change has been made for clarity: $Em_{facility}$ replaces the indirect overhead term C_{IOH} . These are further defined as follows:

$$Em_{OH} = Em_{equip} + Em_{power} + Em_{sup} \quad (34)$$

$$Em_{facility} = Em_{build} + Em_{util} + Em_{l,fact} \quad (35)$$

where the emergy of the operation of the machine is split into that related to the machine in the facility (Em_{equip}), the power used by the machine (Em_{power}), and the supplies (Em_{sup}). The emergy for the facility is also split into three components: the emergy of the factory building (Em_{build}), utilities (Em_{util}) and supporting labor ($Em_{l,fact}$).

Table 3.1 summarizes the equations for each of the emergy estimates given in Equations 33, 34, and 35. These equations—except for those describing waste disposal, remediation, and impact—are based on equations used for estimating costs as described in Section 2.1.1. The following Sections detail the models for each of the emergy equations shown in Table 3.1, as well as background regarding data sources and methods for completing the calculations. Included in Table 3.1 but not included in the previous equations, is a method for estimating the cost of multi-use tools and dies. A full analysis of tools is not relevant to the current study, but a basic approach to tooling is included in Section 3.3.9.

Table 3.1. Equations for Cost from Section 2.1.1 and Proposed Emery Equations

Mfg Element and Symbol	Cost	Emery	Ref
Raw Material (Em_{raw})	$m_{rough}C_{kg}$	$T_{mat}m_{rough} + T_{\$}(C_m - P_{mat}m_{rough})$	[79, 98, 99, 102]
Process Labor (Em_l)	$t_l n_p h_p$	$T_l t_l n_p$	[103–106]
Machine in Factory (Em_{equip})	$\frac{c_{mach}(1+f_{inst})}{t_{life}} + \frac{c_{mach}f_{maint} + c_{int}}{t_{earn}} t_c$	$\frac{E_{mach} + c_{mach}f_{inst}T_{\$}}{t_{life}} + \frac{c_{mach}f_{maint}T_{\$}}{t_{earn}} t_c$	[98, 100, 101]
Process Power (Em_{power})	$h_{eng}P_{mach}t_c$	$T_{elec}P_{mach}t_c$	[98, 99]
Process Supplies (Em_{sup})	$\frac{c_{sup}}{t_{earn}} t_c$	$\sum_{i=1}^n (T_{mat,i} + (C_{sup} - C_{mat})T_{\$})(R_{sup,i})(t)$	[99]
Machine Setup (Em_{set})	$\frac{(C_{OH} + C_l)t_{set}}{n_b}$	$\frac{(\frac{E_{mach} + E_{labor}}{t_c})t_{set}}{n_b}$	[99]
Factory (Em_{build})	$\frac{(A_{mach} + A_{gap} + A_{space})(R_A)(1 + f_{fire} + f_{loss} + f_{lab})}{t_{earn}} t_c$	$\frac{(A_{mach} + A_{gap} + A_{space})(\frac{T_A}{t_{life}})}{t_{earn}} t_c$	[79, 94–97]
Facility Utilities (Em_{util})	$\frac{c_{rent}(f_w + f_{gas} + f_{elec})}{t_{earn}} t_c$	$\frac{c_{rent}(f_w + f_{gas} + f_{elec})T_{\$}}{t_{earn}} t_c$	[95]
Facility Labor ($Em_{l,act}$)	$\frac{W_{cap}(h_{qsg} + h_{pur}S_{pur} + h_{eng}S_{eng} + h_{l,ec}S_{lc} + h_{l,ms}S_{fm})}{t_{earn}} t_c$	$\frac{W_{cap}(T_{qsg} + T_{pur}S_{pur} + T_{eng}S_{eng} + T_{lc}S_{lc} + T_{l,ms}S_{fm})}{t_{earn}} t_c$	[105]
Waste Disp./Remed. (Em_w)	-	$T_{\$}C_{rem} + T_{\$}C_{dis}$ $E_l + E_o + E_f + E_{set} + T_{\$}C_{dis}$	[99, 102]
Waste Impact (Em_{im})	-	$C_j + E_{Gibbs}$	[99]
Tooling (Dies)*	$m_{base}C_{kg,b} + m_oC_{kg,o} + h_{OH}(t_{c,tool}) + h_{l,tool}(t_{l,assy} + t_{l,mach} + t_{l,try})$	$\sum_i Em_{manf,i} + Em_{mach}(BOM) + Em_{set}(t_{try})$	[146]

*aPriori includes an approach for tooling dies. Notes included in Appendix B.

Before an emergy analysis for a part or assembly is conducted, a basic DFM analysis should be completed. With that in mind, data related to a DFM analysis is assumed to be available. These data include process cycle times, part masses, worker types, and supporting values for machine and facility costs. In the following sections, terms available from a previously conducted DFM analysis are identified.

3.3.1 Material

A manufactured part is made from material that is an output of previous processing steps. For example, a steel sheet is made from iron ore, which is refined, shaped, rolled, and treated. When considering the emergy content within the material used to make a part, all these steps, plus the emergy the earth contributes to concentrate an ore that can be mined are included.

Figure 3.3. ESL for material.

Figure 3.3 demonstrates this model via an ESL diagram for material. The precursor material enters into a material processing step, where labor and services interact with the processing step to transform the material from one form to a production-ready material.

This would be equivalent to starting with mined bauxite and transforming it to aluminum sheet or starting with hot rolled band steel and transforming it to a cold-rolled sheet.

With this structure in mind and considering the cost equation for material based on the rough mass (Equation 2), the emergy within the material used for a part has a rough mass of m_{rough} (as determined through a DFM analysis) and can be found using the following equation, which includes the emergy contribution from the material precursor and added labor and services:

$$Em_{raw} = T_{mat}m_{rough} + T_{\$}(C_m - P_{mat}m_{rough}) \quad (36)$$

where T_{mat} is the UEV for the raw material in units of $\frac{sej}{g}$ representing a material at a certain stage of processing, $T_{\$}$ is the UEV for money, C_m is the cost of the material assessed as part of the DFM analysis as shown in Equation 2, and P_{mat} is the price of the raw material on the open market. The raw material price must reflect a similar stage of processing as the material UEV to avoid double counting of emergy content. Section 3.4.7 describes the methodology used in this study for estimating both material prices and UEVs.

The inclusion of labor and services based on the commodity cost of the material is used when the full emergy of a raw material is not known. If a specific emergy value available for the material in the final raw material form, that value would be used for T_{mat} and the second portion of the equation used to calculate the labor and services would be set to zero. In this case C_m would be equal to the P_{mat} multiplied by the rough mass (m_{rough}).

3.3.2 Labor

Most manufacturing activities include some element of labor involvement. Figure 3.4 proposes an ESL diagram for the emergy added by a worker when producing a product. For this study, the mode from Campbell et al. [104] regarding occupational education, described in Section 2.4, is expanded to calculate a more comprehensive bottom-up value for T_l for a factory worker as suggested by Bergquist et al. [128]. These additions include other

Figure 3.4. Proposed conceptual ESL model for labor.

required support for workers, including services, metabolic needs, on-the-job training, and previous experience.

The worker, as shown in Figure 3.4, is represented by two storages: one representing Know-how (knowledge) and the other representing the physical body (physical capabilities). The input of energy from formal education assumes the model introduced by Campbell and Lu [103]. The energy of formal education for a worker contributes to know-how when the education interacts with the physical body. Also, contributing to know-how are three elements: on-the-job experience, formal job training, and independent information gathering.

The physical well-being to support work is based on calories consumed and external energy contributions, such as home heating and cooling, and transportation. The calories are purchased using money earned in the economy by completing a job task. The job task requires a worker with the know-how to do the job learned from formal education, training,

experience, and external information, plus the physical well-being to be present and support the manufacturing task. Indeed, the interaction of the physical body with know-how allows the worker to complete a job successfully to create products. Over time, both knowledge and physical capability decrease, as is shown with storage sinks. Know-how degrades based on the quantity of know-how as described by Odum [76] (i.e. the more one knows, the more work needs to be done to maintain that knowledge). The physical body is assumed to degrade linearly.

The applicability of this model can be understood by reviewing a basic manufacturing work task of fastening two parts together on an assembly using a bolt in a pretapped hole to a specific loading. The following assumptions for the setup are considered: all tools and parts are within reach in appropriate bins and the two parts being assembled have previously been loaded into a fixture. With that in mind, the steps in the task taken by the worker would be as follows:

1. Get bolt from part bin.
2. Move bolt to hole in part.
3. Insert bolt into hole.
4. Spin bolt into tapped hole approximately three turns.
5. Get torque wrench.
6. Place wrench on bolt.
7. Manually turn torque wrench until appropriate force is reached.
8. Lay aside torque wrench.

With the ESL diagram shown in Figure 3.4 in mind, all steps are supported by physical acts enabled by the expenditure of calories by the body. Caloric load required for an activity will be estimated based on the time engaged in an activity (see Appendix I for how such

estimates can be completed). The average number of kilocalories expended by a worker per day is defined by Odum as 2500 kcal [60]. While this likely underestimates the caloric load required for any given action, it provides a lower bound for expended caloric energy as used by Boustead and Hancock [58]. A more accurate accounting of the work required to support these actions could be measured on the factory floor. With Step 7 (Manually turn torque wrench until appropriate force is reached) for example, the number of cranks of the torque wrench, plus the total number of degrees turned could be measured with data on the force required for the turns gathered from a sensor placed in the wrench. The total energy required could be measured. With some knowledge of the efficiency of the human body to turn calories into work, the number of calories required to complete the task could be measured. For this work, since exact physical movements for the workers are not known, an averaged approach is used.

These physical actions, though, are also supported by know-how. Knowledge for completing Steps 1, 2, 3, 4, and 5 are most likely created through on-the-job experience and training. For example, when being trained on this activity, a worker would be instructed where the bolts and wrench are located in the assembly cell, as well as, how to finger-start the bolt into the assembly before getting the wrench. While Steps 6 and 7 could be supported either through on-the-job training or the task may have been learned as part of formal or personal education.

Over time, skill sets may degrade. Degradation could come from lack of reinforcement of the know-how (perhaps the worker is assigned to another job in the factory), or because of injury or age the worker may be physically unable to complete the task. Throughout most of a worker's career, though, their skill-set remains effective to complete the job. Indeed, the median years of tenure for a production employee in 2018 is 4.4 years [147], so it can be expected that during their time in a job, a worker will be equally effective. It is reasonable to assume that the degradation in know-how and physical capability are balanced by the sum of experience, training and personal information gathering. With

this assumed compensation of degradation, the worker tightening this bolt can expect to perform consistently at this task for the majority of their time in this role.

The calculation of the contribution of the emergy from labor within a part can be based on the model presented in Equation 3 for labor cost in a DFM assessment. The emergy model consists of the time labor is engaged (t_l), and the number of workers required for the machine (n_p), which is provided by the DFM analysis. The hourly UEV, T_l , is for the type of labor supporting the process:

$$Em_l(t_l) = T_l t_l n_p \quad (37)$$

It should be noted that t_l is equal to t_c (machine cycle time) plus t_h (part handling-time) as given in Equation 3. Based on the above model, the yearly emergy for a worker in an occupation would be:

$$Em_{worker} = Em_{ed} + Em_{met} + Em_{serv} + Em_{train} + Em_{info} + Em_{exp} - Em_{age} \quad (38)$$

Consideration that any production worker will have a multiyear tenure at their job [147], it is feasible to assume they will maintain a similar skill set across that time. Thus it can be assumed that the losses of know-how and reduced physicality would be compensated by additional training and experience, then the emergy from the tasks completed by a worker would be:

$$Em_{worker,adj} = Em_{ed} + Em_{met} + Em_{serv} \quad (39)$$

To apply this to an hourly rate, it would be:

$$T_l = \frac{Em_{worker,adj}}{h_y} \quad (40)$$

where h_y is the number of hours in a year. This gives an estimate for an hourly emergy rate that can be applied to any job, meeting the suggestion from Kamp et al. [105] of using the more fundamental unit of time to estimate the emergy from labor. Additionally, this approach provides a more comprehensive method for evaluating the impact of a variety of industrial decisions involving labor. Zhang [57] discussed such examples in her dissertation, including evaluation of labor-intensive industries, decisions regarding the ratio of labor to automation, location-based decisions, and trade-offs in the pricing of labor in comparison to energy used elsewhere in manufacturing. A short discussion of how emergy might be used to conduct such trade-offs is included in Appendix E.

The values for each of the emergy factors are constructed using a selection of methods. The values Em_{ed} were updated to more recent years using the same methodologies used for Americans given in Campbell et al. [104] and Campbell and Lu [103], as described in Section 2.4. Em_{met} is estimated based on calories an American consumes in a year [128, 130] and Em_{serv} is estimated based on the primary energy consumption of an average American.

The yearly results for the emergy from formal education as published by Campbell and Lu [103] is included in Table 3.2. Campbell et al. [104] assumed that a worker would draw on their full know-how, either directly or indirectly, through a year on the job. For this portion of this dissertation study, the assumption will be maintained, because it aligns with a worker maintaining their ability to complete work throughout their career. The impact of alternative assumptions regarding the use of a worker's knowledge base throughout their career is investigated in Section 4.4.

Campbell et al. [104] divided education over the number of hours worked in a year, assuming the education is primarily used within a worker's job. In this dissertation study, the education UEV per worker per year is divided over the total number of hours in a year. This assumption was made as activities are completed outside of work that contribute to an individual being a productive worker. Many of these activities (math for maintaining

Table 3.2. UEVs for individuals with various levels of educational completion.

Yearly from Campbell et al. [104] in 1.20×10^{15} Global Baseline														Linear Forecast						
E.d. Level	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	R ²	2012	2013	2014	2015	2016	2017	2018
Primary school	5.946E+17	6.035E+17	6.181E+17	6.269E+17	6.389E+17	6.486E+17	6.612E+17	6.668E+17	6.792E+17	6.745E+17	6.806E+17	6.862E+17	0.959	7.041E+17	7.126E+17	7.212E+17	7.298E+17	7.384E+17	7.470E+17	7.556E+17
HS Grad	8.169E+17	8.273E+17	8.385E+17	8.418E+17	8.593E+17	8.740E+17	8.966E+17	9.133E+17	9.309E+17	9.365E+17	9.441E+17	9.431E+17	0.962	9.705E+17	9.837E+17	9.968E+17	1.010E+18	1.023E+18	1.036E+18	1.049E+18
Some college	9.486E+17	9.647E+17	9.788E+17	9.866E+17	9.980E+17	1.005E+18	1.028E+18	1.047E+18	1.073E+18	1.091E+18	1.097E+18	1.095E+18	0.983	1.121E+18	1.136E+18	1.151E+18	1.165E+18	1.180E+18	1.194E+18	1.209E+18
Bachelors	1.096E+18	1.111E+18	1.124E+18	1.138E+18	1.150E+18	1.167E+18	1.179E+18	1.204E+18	1.224E+18	1.239E+18	1.249E+18	1.263E+18	0.990	1.281E+18	1.296E+18	1.312E+18	1.328E+18	1.343E+18	1.359E+18	1.375E+18
Masters	1.221E+18	1.244E+18	1.256E+18	1.270E+18	1.288E+18	1.307E+18	1.323E+18	1.343E+18	1.356E+18	1.370E+18	1.383E+18	1.405E+18	0.992	1.420E+18	1.436E+18	1.453E+18	1.469E+18	1.486E+18	1.502E+18	1.518E+18
Prof. degree	1.284E+18	1.301E+18	1.324E+18	1.336E+18	1.354E+18	1.373E+18	1.395E+18	1.411E+18	1.432E+18	1.433E+18	1.452E+18	1.467E+18	0.994	1.489E+18	1.506E+18	1.523E+18	1.540E+18	1.557E+18	1.573E+18	1.590E+18
Ph.D.	1.353E+18	1.364E+18	1.381E+18	1.404E+18	1.419E+18	1.439E+18	1.461E+18	1.483E+18	1.501E+18	1.509E+18	1.514E+18	1.536E+18	0.995	1.560E+18	1.577E+18	1.595E+18	1.612E+18	1.629E+18	1.647E+18	1.664E+18
MD	1.491E+18	1.513E+18	1.527E+18	1.541E+18	1.557E+18	1.572E+18	1.593E+18	1.621E+18	1.633E+18	1.651E+18	1.671E+18	1.649E+18	0.972	1.692E+18	1.708E+18	1.724E+18	1.741E+18	1.757E+18	1.774E+18	1.790E+18
Primary school	6.783E+13	6.884E+13	7.051E+13	7.152E+13	7.289E+13	7.400E+13	7.543E+13	7.607E+13	7.748E+13	7.694E+13	7.765E+13	7.828E+13		8.032E+13	8.130E+13	8.228E+13	8.326E+13	8.423E+13	8.521E+13	8.619E+13
HS Grad	9.319E+13	9.438E+13	9.565E+13	9.603E+13	9.802E+13	9.970E+13	1.023E+14	1.042E+14	1.062E+14	1.068E+14	1.077E+14	1.076E+14		1.107E+14	1.122E+14	1.137E+14	1.152E+14	1.167E+14	1.182E+14	1.197E+14
Some college	1.082E+14	1.101E+14	1.117E+14	1.125E+14	1.139E+14	1.147E+14	1.173E+14	1.194E+14	1.224E+14	1.244E+14	1.252E+14	1.249E+14		1.279E+14	1.296E+14	1.312E+14	1.329E+14	1.346E+14	1.363E+14	1.379E+14
Bachelors	1.251E+14	1.267E+14	1.282E+14	1.299E+14	1.312E+14	1.331E+14	1.344E+14	1.374E+14	1.397E+14	1.414E+14	1.425E+14	1.441E+14		1.461E+14	1.479E+14	1.497E+14	1.515E+14	1.533E+14	1.550E+14	1.568E+14
Masters	1.393E+14	1.419E+14	1.432E+14	1.449E+14	1.469E+14	1.491E+14	1.510E+14	1.532E+14	1.547E+14	1.563E+14	1.578E+14	1.602E+14		1.620E+14	1.639E+14	1.657E+14	1.676E+14	1.695E+14	1.713E+14	1.732E+14
Per Individual, per hour (sef/hr)	1.465E+14	1.484E+14	1.510E+14	1.524E+14	1.544E+14	1.566E+14	1.592E+14	1.610E+14	1.634E+14	1.635E+14	1.656E+14	1.673E+14		1.699E+14	1.718E+14	1.737E+14	1.757E+14	1.776E+14	1.795E+14	1.814E+14
Prof. degree	1.543E+14	1.550E+14	1.575E+14	1.601E+14	1.619E+14	1.641E+14	1.666E+14	1.692E+14	1.712E+14	1.722E+14	1.728E+14	1.752E+14		1.779E+14	1.799E+14	1.819E+14	1.839E+14	1.859E+14	1.878E+14	1.898E+14
Ph.D.	1.701E+14	1.720E+14	1.742E+14	1.758E+14	1.776E+14	1.793E+14	1.817E+14	1.849E+14	1.863E+14	1.883E+14	1.906E+14	1.881E+14		1.930E+14	1.948E+14	1.967E+14	1.986E+14	2.005E+14	2.023E+14	2.042E+14
MD																				

Table 3.3. Mapping of OOH [129] Educational Categories

OOH [129]	Campbell and Lu [103]
Less than high school diploma	Primary school
High school diploma or equivalent	High school graduate
Some college, no degree	Some college, no degree
Postsecondary nondegree / certificate award	Some college, no degree
Associates	Some college, no degree
Bachelors	Bachelors
Masters	Masters
Doctoral or professional degree	PhD

a budget, reading for medical notices, etc.) if not taught directly in school, are learned indirectly during the process of formal education. A more refined estimate could be reached by assuming these life-skills are acquired in a particular level of schooling (budgeting in high school, for example). For the basic calculation, the resulting hourly UEVs for each education level are provided in Table 3.2.

Calculations by Campbell and Lu [103] of hourly UEVs were completed for data through 2011. To estimate labor UEVs for more recent years, it was found the data from the year 2000 through 2011 has a very strong linear fit with an R^2 above 0.90 for each educational level. A linear projection was used to determine the yearly labor UEV for years through 2018. The projected values were then split over the number of hours in a year to find hourly UEVs for each education level.

To calculate Em_{ed} for any given job in a factory, the method used by Campbell et al. [104] was followed, with data gathered from the BLS *Occupational Outlook Handbook* (BLS OOH) for 2018 [129]. The OOH includes the percentage of workers of various education levels that can be found in a given job code. The OOH data do not map directly to the educational categories used for the hourly emergy calculation. Table 3.3 maps the OOH categories to those used by Campbell and Lu [103] for this dissertation study.

The resulting hourly UEV for any given worker type can be estimated using the following equation:

$$\frac{Em_{ed}}{h_y} = s_n T_{ed,n} + s_{hs} T_{ed,h} + (s_{sc} + s_{cert} + s_{as}) T_{ed,sc} + s_b T_{ed,b} + s_m T_{ed,m} + s_p T_{ed,p} \quad (41)$$

where s_n , s_{hs} , s_{sc} , s_{cert} , s_{as} , s_b , s_m , and s_p are the percentages of workers in a given occupation with specific educational attainment. $T_{ed,n}$, $T_{ed,h}$, $T_{ed,sc}$, $T_{ed,b}$, $T_{ed,m}$, and $T_{ed,p}$ are the hourly UEVs calculated in Table 3.2.

For Em_{serv} a bottom-up calculation method is used. This calculation is in contrast to the top-down method described by Zang and Dornfeld [57] and Zhang [59]. A bottom-up method is preferred as the double-counting issues described by Zhang [59] remain for much of the support energy required for an American worker when a top-down method is used. The attribution of commercial consumption and industrial sector transportation to individuals, as was used by Zang and Dornfeld [57] and Zhang [59], is a method particularly susceptible to double-counting, as noted by Kamp et al. [105]. To reduce concerns regarding double-counting, this dissertation study proposes the use of a new lower bound for consumed embodied energy (in the form of energy) for worker support services (Em_{serv}) based only on direct consumption to support residential heating, cooling, and electricity (Em_{res}), plus fuel used for cars and light trucks (Em_{cars}). This calculation takes the form:

$$Em_{serv} = Em_{cars} + Em_{res} \quad (42)$$

To calculate Em_{cars} , an average number of gallons per person consumed per year was determined based on data available from the US Energy Information Administration (EIA) [148]. The data separate cars and light trucks into two groups—one with a small wheel base (less than 121 inches), and a second with a large wheel base (greater than 121 inches). The US EIA reported the average number of gallons of fuel used per vehicle class. For this application, these two values were averaged assuming equal populations. Per Sivak [149], US household averaged 1.95 cars in 2017, and US census data from 2010 [150] reported

households averaged 2.58 people. These values result in a per-person per-year consumption of 428.17 gallons of fuel. It is assumed that all fuel consumed by cars and light trucks in the US is gasoline. The UEV for gasoline from Bastianoni et al. [151] was used to calculate the results in Table 3.4.

Table 3.4. Calculation of Emergy of Labor Support Services

Category		Consumption				Emergy (per	
		Yearly	Units	Household	Person	UEV*	Person $\frac{sej}{yr}$)
Vehicles	Short Wheel Base	474	$\frac{gal}{car}$				
	Long wheel base	659	$\frac{gal}{car}$				
	Average	566.5	$\frac{gal}{car}$	1104.68	428.17	3.78E+09	$\frac{sej}{g}$ 1.19E+16
Home	Natural gas	3.96E+12	$\frac{cf}{yr}$	33527.92	12995.32	5.18E+04	$\frac{sej}{J}$ 2.49E+10
	Fuel oil	3.38E+09	$\frac{gal}{yr}$	28.60	11.09	3.45E+09	$\frac{sej}{g}$ 1.22E+14
	Electricity	1.27E+12	$\frac{kWh}{yr}$	10719.12	4154.70	5.83E+14	$\frac{sej}{MWh}$ 2.42E+15
	Propane	3.95E+09	$\frac{gal}{yr}$	33.43	12.96	4.03E+09	$\frac{sej}{g}$ 9.75E+13
						Total ($\frac{sej}{yr}$)	1.46E+16
						Hourly ($\frac{sej}{hr}$)	1.66E+12

*All UEVs include labor and services.

For home consumption of electricity and fuel, Em_{res} , a separate data set from the EIA [152] was used, which aggregates values from 2015 for natural gas, fuel oil, propane, and electricity. While all households are not using all fuels an average value per household was determined, based on the number of households cited in the data from the EIA. This was further divided by the number of people per household, as with the vehicle calculation. The UEVs for fuel oil and natural gas are from Bastianoni et al. (2009) [151], and Bastianoni et al. (2005) [153], respectively. A UEV for propane was estimated from the value for liquefied gasses from Bastianoni et al. (2009) [151]. The UEV for electricity is from this dissertation study and is calculated as described in Section 3.3.4. With appropriate unit conversion, the total per-person per-year emergy load for labor support services, Em_{serv} , was found to be 1.4587E+16 sej/year, which when divided by the number of hours per year, gives an hourly emergy rate for services consumed by labor as 1.6640E+12 sej/hr. It should be noted that all UEVs for this calculation include labor and services, with all resulting emergy rates and values thereby including labor and services.

Two methodological choices should be described in more detail: (1) The use of the entire household versus using only workers for amortizing service elements, and (2) The use of the entire year versus only working hours for determining an hourly emergy value. For (1), the heating and electricity use, as well as the driving completed by members of the household, is assumed to support each member equally.⁸

This assumption differs from that of Zhang and Dornfeld [57], who allocate energy use over the worker population only, arguing that such an approach accounts for the full life cycle of the worker. This assumption, though, implies a value judgment that only paid work is adding value and productivity to society, where significant unpaid work occurs by the activities of stay-at-home adults, volunteer activities, unpaid internships, and education. Data from 2018 notes that 77.34 million adults volunteered in documented organizations, totaling almost 6.9 million hours [154]. Additionally, every adult over 15 in the US spent on average 1.78 hours per day on unpaid household tasks [155], which totals 650 hours per year, or 36% of the average number of hours worked per year [156]. While these estimates are based on statistical data, this gives insight into how allocation of energy over the working population only may over-estimate any given workers energy use compared to their output.

For (2), services support all aspects of life, such as heating and cooling the house while sleeping, lighting the house during morning and evening, and driving to support activities outside the daily commute. As such, these services support every hour of the day, not only the hours spent working, and are thereby split across all hours in the year.

The estimate for metabolic consumption is summarized in Table 3.5. Since a comprehensive analysis of the food industry is not currently available in emergy literature, the emergy value for input calories was estimated by the average price of calories in the US.

⁸While any individual case may favor one approach over another—in some homes driving supports only those commuting to work where for others driving mostly supports the activities of school-age children; whereas electricity use in some homes may mostly support media consumption, where in others it might support cooling or heating—a reasonable assumption is that everyone benefits equally in the household from each consumption element in supporting emergy usage and conversion.

This method provides a reasonable estimate of the emergy content of an American's daily intake, as retail prices of foods are dominated by the supply chain with less than 15% attributable to direct agricultural costs and presumably less to materials versus services [157].

Em_{met} can be calculated as:

$$Em_{met} = \frac{F_{day} C_{cal}}{h_d} T_{\$} \quad (43)$$

where F_{day} is the number of calories consumed in a day, C_{cal} is the cost per calorie, h_d is the number of hours in a day, and $T_{\$}$ is the emergy-to-money ratio. The cost of a calorie for a high- and low-health diet is from McDermott and Stephens [158] and was averaged for a single value. From there the emergy-to-money ratio for 2011 from Campbell et al. [127] was used to convert the cost to an emergy value. This results in a UEV for metabolic input of 1.02E+12 sej/hr.

Table 3.5. Hourly Cost of Metabolic Calories

Item	Value	Units	Source
Calories per day	2500	kcal/day	[60]
Cost per calorie	\$ 0.004836	USD	[158]
Per hour cost	0.50375	USD/hr	
Emergy per dollar	2.02E+12	sej/USD	[127]
Emergy Per Hour	1.02E+12	sej/hr	

The complete model for T_l supports a number of labor calculations as part of the emergy calculations for manufacturing. These include direct labor calculation for the operator of the process, the indirect labor calculation for the facility support staff, the emergy of machine setup, and the labor calculation used in estimating Em_{equip} . This value can be applied to provide an emergy value for labor in any situation where a time during which labor is engaged is known or can be estimated.

Figure 3.5. ESL diagram representing the manufacture of a machine used within a manufacturing process.

3.3.3 Machine in Factory

The manufacturing equipment contributes emergy to a product (Em_{equip}) from three parts of its life-cycle: the manufacturing of the machine itself, its one-time installation, and its continued maintenance over its life. Once a machine is manufactured and sold, it is installed at a factory and used to produce parts. Over time, the machine requires maintenance and these actions lead to the addition of emergy to the machine. Figure 3.5 shows this energy flow. The purchased machine enters the system and is installed via the use of labor purchased with the money created downstream through the use of the machine. Over time, the machine requires maintenance. This, like the installation, is conducted via purchased labor.

Reviewing Equation 44, the emergy of installation and maintenance are calculated based on the cost of the machine using fixed factors (f_{inst} and f_{maint} , respectively) and the money-to-emergy UEV (T_s). For a more precise calculation, an estimate could be made regarding the amount of time required for installation and maintenance for a more precise value. This could be completed either with direct time measurement of installation and

maintenance activities on similar machines or by completing a similar assessment to that proposed later in this section for estimating the time to assemble a machine during its manufacture. For the current study, though, the approximation based on economic factors are maintained from the DFM equation (see Equation 4 and Table 3.1).

These elements are summed then multiplied by the fraction of the time the machine is engaged (t) and the earned hours (t_{earn}) for the machine. This amortization splits the emergy used to build the machine over the time used to create the part. The earned hours represent the amount of time available on the machine for a year—the amount of time the machine is able to run to make products, and earn profit.

This relationship is represented by the following equation:

$$Em_{equip}(t) = \frac{\frac{E_{mach} + c_{mach} f_{inst} T_{\$}}{t_{life}} + c_{mach} f_{maint} T_{\$}}{t_{earn}} t \quad (44)$$

where E_{mach} is the emergy built into the machine itself via its manufacture. The emergy to money ratio ($T_{\$}$) is used for the installation and maintenance terms, since the current data do not provide a more detailed breakdown.

The most common method in the literature for calculating E_{mach} is to estimate the amount of a primary material in the machine and identify a corresponding UEV for the material. Almeida et al. [97] and Saladini et al. [122] used the mass of the machines and the UEV of steel to estimate the emergy in the equipment. This method, though, does not include labor and services added to the machine through its manufacture, only the material emergy for the major material in the composition of the equipment. The approach of Puca et al. [101] for computers includes consideration of the materials plus of the labor and services based on the price of the computer as part of the analysis.

In this dissertation study, a revised method of emergy accounting is proposed based on use of the bill of materials (BOM) for the manufacturing machine, material prices, similar to Puca et al. [101], but also adding in the estimation of the assembly time of the machine. Figure 3.6 demonstrates this model in an ESL diagram. There are three main

Figure 3.6. An ESL diagram representing the manufacture of a machine used within a manufacturing process.

steps in the creation of the machine: the processing of materials from a precursor form into a form usable for manufacturing (for example processing bauxite ore to aluminum sheets), manufacturing parts from raw material, and assembling the parts once they are manufactured. The input in the diagram is the material precursor. The amount of emergy added in the processing of materials step will vary depending on the state of the precursor. For example, a bauxite precursor would require more emergy to transform into aluminum sheets, versus aluminum ingots. The model used for this dissertation study is intended to handle all precursor cases.

During the transformation of a material from precursor to usable material for manufacturing, labor and services are required. The money for these steps come from the up-stream sale of the final product on the market. Once the material is prepared for manufacturing, it is turned into parts with the addition of further labor and services. When all the parts in the BOM are manufactured, the machine is assembled. With knowledge of the BOM, the assembly time (shown in the diagram as t_a) can be estimated and an appropriate amount of labor can be applied to the activities. It should be noted that this model assumes that for any

given part no major material from another source is added throughout the manufacturing process.

Figure 3.7. A proposed process for estimating an energy value for a manufactured machine.

The process for completing this calculation is given in Figure 3.7. With the machine BOM available, the next step is to identify the mass, primary materials, and retail price for each of the parts. With that information, an emergy value for the parts (Em_{parts}) can be determined based on the following equation:

$$Em_{parts} = \sum_i \left(\left(\sum_j m_{part,i,j} T_{mat,i,j} \right) + \left(P_{part,i} - \left(\sum_j m_{part,i,j} P_{mat,i,j} \right) \right) T_{\$} \right) \quad (45)$$

where $m_{part,i,j}$ is the mass of material j found in part i , $T_{mat,i,j}$ is the UEV for material j in part i , $P_{part,i}$ is the purchase price of part i , $P_{mat,i,j}$ is the price per mass of material j for part i , and $T_{\$}$ is the energy-to-money ratio. This approach follows the method suggested by Odum [60] as described in Section 2.4. A detailed review of this procedure for welding equipment is given in Section 3.4.7.

Next, an assembly time t_{assy} is estimated based on a Maynard Operation Sequence Technique (MOST) [159] (Appendix I gives a short introduction to this technique and a detailed MOST analysis for welding equipment is described in Section 3.4.7). An appro-

priate worker type is selected from the labor pool and their UEV in $\frac{sej}{hr}$ is applied to this time. Following the structure of Equation 37, this gives a calculation for the emergy in assembly Em_{assy} :

$$Em_{assy} = Tln_p t_{assy} \quad (46)$$

with the following giving the total emergy in the machine:

$$Em_{mach} = Em_{parts} + Em_{assy} \quad (47)$$

The resulting value for Em_{equip} is used in the model any time a machine is involved. This is most notably within the operation of the process, but is also relevant within the setup activity, because the machine is also occupied during that time.

3.3.4 Process Power

The amortization of the emergy of machine manufacture, installation, and maintenance only accounts for upstream emergy contributions. When the machine is operating to create a part or as part of setup activities, it consumes power to operate. This emergy is based directly on the time the machine is engaged in testing during setup or manufacturing.

Figure 3.8 shows the ESL diagram representing the power in the form of electricity used in a manufacturing process. The prerequisite of an installed machine is indicated by the use of a logical switch. The machine properties and the time the process is running influence the amount of electricity used. This ESL diagram does not have a specific output other than heat because it represents the power drawn during operation. If a machine is run without a part in place, all of this energy is nonproductive and, therefore, lost as heat and noise, which may occur during batch setup. The equation, based on the energy portion of Equation 4, and as displayed in Table 3.1, representing the emergy due to the power used for operation of the machine is:

Figure 3.8. An ESL Diagram representing the electricity used to run a process.

$$Em_{power}(t) = T_{elec}p_{mach}t \quad (48)$$

where p_{mach} is the power rating of the machine, t is the time the machine is running, and T_{elec} is the UEV for electricity in $\frac{\text{sej}}{\text{kWh}}$.

T_{elec} is estimated in units of $\frac{\text{sej}}{\text{MWh}}$ based on the method described by Häyhä et al. [131]. For this dissertation study, the estimate for T_{elec} is completed for the United States as a whole. It should be noted that this estimate could be adjusted for any locality where electricity generation mix is known. To complete this calculation for the United States, the electricity generation mix for 2017 was used as collected by the U.S. Department of Energy (DOE) [152]. These data are summarized in Table 3.6. The category of Other includes all power generation methods with less than 5% contribution, for example, petroleum liquids, petroleum coke, gases other than natural gas, solar thermal and photovoltaic, wood and wood-derived fuels, other biomasses, geothermal, hydroelectric pumped storage, and all other generation methods.

UEVs for each generation method are sourced from Häyhä et al. [131] and Campbell et al. [160], and multiplied by the net generation in joules, to estimate the total emjoules

(sej) for each generation method. For the Other category of power generation, an average of all other contributing methods was used, since this category includes both renewable and non-renewable power generation methods. For 2017, the estimated electricity UEV for the United States is $5.83\text{E}+14$ sej/MWh. This value serves for T_{elec} in the machine electricity, factory building, and labor supporting services calculations.

Table 3.6. Net Electricity Generation in 2017 for the United States with Estimated Emery Equivalent with UEVs from Häyhä et al. [131] Unless Otherwise Noted

Generation Method	Net Gen. (MWh) [†]	Net Gen. (J)	UEV (sej/J)	Emjoules (sej)
Coal	1.21E+09	4.34E+18	2.18E+05	9.46E+23
Natural gas	1.30E+09	4.67E+18	2.17E+05	1.01E+24
Nuclear	8.05E+08	2.90E+18	4.81E+04*	1.39E+23
Conventional hydro	3.00E+08	1.08E+18	8.51E+04	9.20E+22
Wind	2.54E+08	9.15E+17	8.35E+04	7.65E+22
Other	1.79E+08	6.44E+17	1.30E+05	1.64E+23
Total	4.03E+09			2.35E+24
			Elec UEV:	5.83E+14 sej/MWh

*Sourced from Campbell et al. [160]

† Sourced from Department of Energy [152]

3.3.5 Process Supplies

When a machine is operating it consumes supplies at a given rate. Depending on the supply in question, there will be an emery consumption rate based on the properties of the machine and the specific supply. The total amount of supplies is based on the time the machine is operating. It should be noted that operation of a machine could be enabling either setup of the machine or product production.

Figures 3.9 and 3.10 represent two models used in this dissertation study for estimating the emery in the supplies used by a manufacturing process. Figure 3.9 uses a similar model to that given for raw materials in Section 3.3.1 where the supply precursor enters the system and moves to a processing step where labor and services are added bringing the precursor to the state required for use in the processing step. The amount of labor and services is based on the price of the product on the open market compared with the commodity price

of the precursor. The amount of a supply consumed by a process is based on the time the machine is running, shown as the state variable t . The process itself supports downstream profit-making activity, which provides money for purchasing the supply.

Figure 3.9. ESL Diagram representing supplies used by a process where energy value for the exact supply is not available.

With this method, the the amount of emergy in the supplies required for a process can be estimated with the following equation:

$$Em_{sup}(t) = \sum_i (T_{mat,i} + (C_{sup,i} - C_{mat,i})T_{\$})(R_{sup,i})(t) \quad (49)$$

where $T_{mat,i}$ is UEV for the i th supply precursor, C_{sup} is the cost on the open market per mass for the supply in the form required for the process, C_{mat} is the cost of the precursor material on the open market per mass, $T_{\$}$ is the money to emergy UEV, $R_{sup,i}$ is the rate the supply is used by the machine in units of mass per time, and t is the time the machine runs. This approach is best applied when supplies do not have a previously calculated UEV, and data to determine an appropriate value would be beyond the scope of this work. An

example of such a supply is flux cored weld wire, where emergy data for steel is available, but data on wire drawing and the addition of flux to the wire is not. In this case, the additional processing of the material to the form of a wire is represented by the difference in cost between the two forms.

Figure 3.10. ESL diagram representing supplies used by a process where emergy value for supply is available.

Alternatively, Figure 3.10 represents the case where material supporting the supply in question is in a form that can be directly used within the process. Here, the quantity of the supply used is based on the time the process runs, but a separate material processing step is not required. This modifies Equation 50 slightly, removing the economic portion:

$$Em_{sup}(t) = \sum_{i=1}^n (T_{mat,i} R_{sup,i}) t \quad (50)$$

The cost equation for supplies—in Table 3.1 and Equation 4—assumes the cost of supplies is assessed over a year. While this is a reasonable assumption based on the data available on supplies and the usual impact on cost, the emergy equation has been altered to use the run-time of the machine. This has the advantage of being directly tied to the use of a supply by a processing step by a machine, as well as continuing the application of a consistent bottom-up emergy methodology.

3.3.6 Machine Setup

Figure 3.11 shows the ESL diagram representing the the setup of the machine. The installed machine is required before it enters the setup activity via a logical switch. Additionally, the energy required to build the machine is amortized over the time the machine is engaged in the setup activity (see Equation 44). Time (t_s) serves as a state variable on the setup activity. The state variable also has a relationship with the labor, electricity, and supplies required to support the setup. The details on how each of these state variables are calculated can be found in Equations 37, 48, and 49, respectively.

Figure 3.11. ESL Diagram representing setup required on a machine.

With Figure 3.11 in mind, the emergy for machine setup on a per-part basis is:

$$Em_{set} = \frac{Em_{equip}(t_s) + Em_{power}(t_s) + Em_{sup}(t_s) + Em_l(t_s)}{n_b} \quad (51)$$

where Em_{equip} , Em_{power} , Em_{sup} , and Em_l are each functions of t_s , the setup time, and n_b is the number of parts in a batch. Equation 51 and the cost equation, Equation 10, that it is based on both assume the machine runs and uses supplies during the setup activity. For

some machines with short setup times or that require calibration activities, running and use of supplies during the majority of setup may be a reasonable assumption. For others with long setup times where the machine is partially disassembled, such as a stamping press, this would not be reasonable. The inclusion of supplies for setup is discussed further in Section 3.4.10.

3.3.7 Facility

Figure 3.12 shows the ESL diagram for the energy added to a part via facility operation on a yearly basis. The installed machine enters with the materials and land to support the factory. As described by Li et al. [93], a building has three contributing energy components: the land it sits on, the building itself, and the waste produced during construction. The building estimate follows the model used by Saladini et al. [122], including the primary materials of steel and concrete. Additionally, labor and services for building construction are included to cover the remaining materials and construction activities. From the construction, some waste is created, which is sent to the recycling stream or landfill.

The yearly inputs of gas and water are functions of the rent for the factory for this model. In an application to a real factory, data on utilities could be gathered and direct energy values used. For this dissertation study the application is a generic factory, and the best-practice factors for the utility costs come from the DFM analysis. There are five labor functions applied at the facility level—quality assurance, purchasing, engineering, tool crib, and facility maintenance—and are included as part of the facility energy as a function of the state variable, W_c , which is the total hourly capacity for a year. The money for transforming the cost of gas, water, and electricity into energy comes from downstream profit-making activities occurring within the facility. The area of the factory taken up by the installed machine serves to amortize the energy involved in construction. The remaining area of the factory is dedicated to other machines. Finally, this sum is multiplied by the

Figure 3.12. ESL Diagram representing factory.

ratio of the processing time (t) to the earned hours for the machine (t_{earn}), giving an emergy value for the time on the machine.

With Figure 3.11 in mind and considering Equation 5 for cost, the emergy accountable to the factory that is delivered on a per-part basis is a sum of three main terms representing the yearly impact of the factory building (Em_{build}), the utilities for the factory (Em_{util}), and the supporting factory-level labor ($Em_{l, fact}$), is multiplied by the ratio of the cycle time for the individual activity over the total earned hours for the machine⁹:

$$Em_{facility} = (Em_{build} + Em_{util} + Em_{l, fact}) \quad (52)$$

The emergy for the building is accounted to the machine, similar to Equation 6 for the cost of rent, as:

$$E_{build} = \frac{(A_{mach} + A_{gap} + A_{space}) \left(\frac{T_A}{t_{exp}} \right) t_c}{t_{earn}} \quad (53)$$

where A_{mach} , A_{gap} , and A_{space} are the same area factors for the machine as seen in the cost calculation (see Equation 5), and t_{exp} is the expected useful life of the building. The area of the machine, the gap around it, and other attributable factory space come from the DFM analysis. T_A is a UEV for the building in the form of sej per area and is calculated as a combination of methods from Li et al. [93], Saladini et al. [122], Cavalett and Ortega [124], and Pulsilli et al. [94] from the factory footprint, A :

$$T_A = \frac{Em_{mat}}{A} + Em_{L\&S} + T_{ground} + Em_{waste, const} \quad (54)$$

The mass of materials used to construct the factory are estimated in the same manner as used by Saladini et al. [122], including only steel and concrete:

⁹It should be noted that insurance, which is included in the analogous cost equation (Equation 5) has been removed from this analysis and remains a future topic.

$$Em_{mat}(A) = m_{concrete}(A)T_{concrete} + m_{steel}(A)T_{steel} \quad (55)$$

where $m_{concrete}$ and m_{steel} are estimated as a function of the factory footprint, A , as shown in Equations 28 and 29 respectively. Both UEVs for concrete ($T_{concrete}$) and (T_{steel}) can be found in the literature.

The emergy in the building construction waste ($Em_{waste,const}$) can be estimated based on the mass of waste per area of construction (ρ_{waste}), then multiplied by a UEV for the emergy per mass of waste for its transportation plus its landfill impact (as estimated for Potenza, Italy, by Franzese et al. [123]), as follows:

$$Em_{waste,const} = \rho_{waste}T_{landfill} \quad (56)$$

The labor and services estimate for the building construction can be calculated based on the cost per area for factory construction without the cost of land ($\rho_{construct}$) and subtracting the cost of elements with emergy estimates and multiplying the remainder by the emergy-per-money ratio. As noted, this would be the cost densities of concrete materials, steel materials, and waste removal and disposal (ρ_{disp}), as follows:

$$Em_{L\&S} = \left(\rho_{construct} - \frac{m_{concrete}(A) + m_{steel}(A)}{A} - \rho_{disp} \right) T_{\$} \quad (57)$$

The cost of the rent (c_{rent}) is used, as noted above in the ESL diagram description, as a method for estimating utility costs, as provided in Equation 7 for cost. This leads to the following equation:

$$Em_{util} = \frac{(c_{rent}(f_w + f_{gas} + f_{elec})T_{\$})t_c}{t_{earn}} \quad (58)$$

where the factors for water, gas, and electricity (f_w , f_{gas} , and f_{elec} , respectively) are sourced from the DFM analysis, and this sum is multiplied by the money-to-emergy ratio ($T_{\$}$).

Finally, the emergy for the five types of supporting labor in the facility is calculated as follows:

$$Em_{l,fact} = \frac{(W_{cap}(T_q s_q + T_{pur} s_{pur} + T_{eng} s_{eng} + T_{tc} s_{tc} + T_{fm} s_{fm})) t_c}{t_{earn}} \quad (59)$$

where W_{cap} is the total capacity at the facility in a year and T_q , T_{pur} , T_{eng} , T_{tc} , and T_{fm} are the UEVs for the quality, purchasing, engineering, tool crib, and facility maintenance workers, respectively. These values are calculated in the same manner as described for the more general UEV for labor, as described in Section 3.3.2. These are multiplied by s_q , s_{pur} , s_{eng} , s_{tc} , and s_{fm} , which are the support fractions, as described in Section 2.1.1 and Equation 9, sourced from the DFM analysis.

3.3.8 Waste Disposal, Impact and Remediation

Based on the target processes for this dissertation study, a full accounting of the disposal, impact and remediation of waste is not being considered. This Section, though, provides an outline of an approach using previously described models as shown in the ESL diagram in Figure 3.13.

Waste from manufacturing enters the scope of analysis, along with money from product sales and renewable resources from the environment at large. The waste from manufacturing passes into the remediation process, which is modeled as a manufacturing process as shown in Figure 3.2, and Equation 33. Out of the remediation process, material flows directly into the environment, with the emergy due to that interaction based on the ability for the environment to absorb the particular effluent and the impact on other environmental systems, such as human life. Any effluent that cannot be absorbed into the environment around the factory will require paid disposal.

Based on this model, the total emergy in the disposal, impact, and remediation of wastes i is equal to:

Figure 3.13. ESL Diagram representing waste disposal, impact and remediation.

$$Em_{waste} = \sum_i (Em_{d,i} + Em_{im,i}) \quad (60)$$

Waste disposal ($Em_{w,d}$) can be handled in one of two approaches. The first approach is based on that used by Almeida et al. [99], where remediation is conducted inside the plant:

$$Em_d = Em_{manf} + T_{\$}c_{dis} \quad (61)$$

and where the remediation activity is treated as an additional machine as used in Equation 33. The incoming effluent as the raw material and the term $T_{\$}c_{dis}$ accounts for the additional cost of disposing any remediated waste. The alternative approach is suggested by Liu et al. [102]:

$$Em_d = T_{\$}c_{rem} + T_{\$}c_{dis} \quad (62)$$

where the machine-based remediation is replaced by a cost-based remediation approach, with c_{rem} representing the cost of remediation.

The approach for the impact of any emissions to the environment is suggested by Almeida et al. [99] to be:

$$Em_{im} = C_j + E_{Gibbs} \quad (63)$$

where C_j is the impact of emissions on human health, as defined in Equation 23, and E_{Gibbs} is the impact of emissions on the environment as defined in Equation 24, both of which are discussed in Section 2.2.3.

3.3.9 Tooling

Figure 3.14. An ESL Diagram representing tooling manufacture.

Based on the manufacturing processes being used in the proof-of-concept model, developing a full approach to tooling is not relevant for the current assessment. The discussion here is intended to provide the outline of a generic approach that would be used in work beyond the current example and will demonstrate the modularity of the previously described

energy models.¹⁰ To construct an emergy model based on this description, the ESL diagram shown in Figure 3.14 includes a combination of three models.

The first model component in Figure 3.14, is the manufacture of parts required for the assembly of tooling (A). This usually consists of a tooling base of steel and individual components that are manufactured from a selection of raw materials. The model most suited to represent this step is the full manufacturing model shown in Figure 3.2 and Equation 33, which includes the input of raw materials and the output of parts with further processing steps.

The second model component, represented by B in Figure 3.14, is the assembly of the produced parts into a tool. This is best represented by the model presented for calculating the emergy in machine construction, as shown in the Figure 3.6 and Equation 44. This model includes many materials from combination of parts, purchased parts, and includes the final assembly into a finish product.

The final model component, represented by C in Figure 3.14, is the testing (or tryout) of the tool to ensure it functions as expected. This functionality is most analogous to the setup model, as presented in Figure 3.11 and Equation 51. This model supports the machine the tool is tested in and the labor required to support the testing activity.

The resulting model can be summarized as follows:

$$Em_{tool} = \sum_i Em_{manf,i} + Em_{mach}(BOM) + Em_{set}(t_{tryout}) \quad (64)$$

where the emergy of manufacturing (Em_{manf}) for each part i in the tooling BOM is summed and added to the assembly of the tool with purchased parts (Em_{mach}), as a function of the BOM, and the tryout of the tool is calculated using the setup model (Em_{set}) as a function of the tryout time (t_{tryout}). The combination of these models also gives insight into the recursive nature of manufacturing: to make a product that will make a part, a full manufacturing model is required.

¹⁰A brief description of an activity-based costing model for tooling is included in Appendix B.

3.4 Example

To demonstrate an analysis using the emergy equations summarized in Table 3.1, a simple assembly was selected. The assessment starts by describing the assembly, followed by reviewing its DFM assessment, then conducting the emergy analysis. This covers Steps 1, 2 and 3 presented in Section 3.1.

3.4.1 The Assembly

The assembly used in this example is a small laser cut, bent, and welded assembly. The starting assembly was found on GrabCAD [161], then modified to allow for welding (the original assembly was riveted) and to follow DFM guidelines for the creation of bends in a press-brake (also known as a bend brake or bending machine). A specific function for the assembly was not identified when downloaded, but based on the design it is most likely an HVAC component. The assembly following these adjustments is shown in Figure 3.15.

Figure 3.15. The example assembly shown with parts numbered.

The assembly consists of six parts, as listed in the BOM shown in Table 3.7. The finished mass (excluding scrap from holes and nesting) included in the table is for an assembly

made from steel. The numbers shown in the first column are used in Figure 3.15 to identify the parts. Note that there are two identical lugs, one on each side of the assembly. The overall envelope of the assembly is 193 mm x 187 mm x 124 mm (7.60 in x 7.36 in x 4.88 in).

Table 3.7. BOM for Example Assembly

Number	Part Name	Level	Qty	Finished Mass (kg)
	Bracket Assembly	0	1	1.75
1	Side Flange RH	1	1	0.31
2	Lug	1	2	0.27
3	Stiffener	1	1	0.28
4	Side Flange LH	1	1	0.31
5	Base Flange	1	1	0.54

3.4.2 DFM Assessment

A DFM assessment of the assembly was completed using the aPriori physics-based costing software to estimate cycle times, material usage, and identify machine settings. To prepare the assembly for assessment, Virtual Welds were added to the model in the aPriori software. The definition of each weld is shown in Table 3.8 and its placement on the assembly in Figure 3.16. In addition to adding welds, the following adjustments were made to the default behavior of the software:

- An average US regional model (aPriori USA VPE, Baseline Version 2019R1 _ SP00 _ F00 _ (2019-03)) was used as the base calculation
- The annual volume of the assembly was set to 10,000 per year and part volumes adjusted to support that value
- Cold rolled 1020 steel was used for all parts
- The routing of laser-bend was selected for all parts
- The selection the machines was overridden

- Laser: Cincinnati CL850
 - Bend: Amada SPH-60C
 - Weld: Miller DeltaWeld 652
- The two bends on the lug are assumed to be completed in a single hit of the brake using a channel tool
 - The purchase price of the Miller DeltaWeld 652 welder was overridden to represent the configuration used in this dissertation study
 - The pick and place activity (loading of parts into fixture) was altered to be completed by the same worker and in the same cell as the welding activity
 - The cost of anti-splatter spray and welding gas were removed based on the selection of using a welder with in-wire flux

Figure 3.16. Welds added for DFM analysis. Welds are shown in orange

With those adjustments complete, the parts and assembly costs were collected. The detailed reports for each part are included in Appendix F. A summary of the relevant

Table 3.8. Welds Added in aPriori Software

Weld Number	Type	Interval	Length (mm)	Width (mm)	Depth (mm)
Weld:1	Fillet	Continuous	45	3	3
Weld:2	Fillet	Continuous	45	3	3
Weld:3	Fillet	Continuous	117	3	3
Weld:4	Fillet	Continuous	36	3	3
Weld:5	Fillet	Continuous	45	3	3
Weld:6	Fillet	Continuous	36	3	3
Weld:7	Fillet	Continuous	45	3	3
Weld:8	Fillet	Continuous	117	3	3
Weld:9	Fillet	Continuous	117	3	3
Weld:10	Fillet	Continuous	117	3	3
Weld:11	Fillet	Continuous	9	3	3
Weld:12	Fillet	Continuous	9	3	3

part outputs are included in Table 3.9. As can be noted, each part includes both laser and bend steps with labor (t_l) and cycle time (t_c) recorded for each. These, the rough mass (m_{rough}) and cost of material (c_{mat}) were calculated by the aPriori software. The mass of the two supplies for the laser—the assist gas ($m_{lasergas,1}$) and laser gas ($m_{lasergas,2}$)—are not included in the software-based estimate and were calculated separately using the method described in in Appendix H.

The data for the welding result is summarized in Table 3.10. In the aPriori software, the handling for welding is split out separately from the welding step, with the labor and cycle time being equal for each since a worker is engaged fully through each activity. These values and the mass of weld wire are reported by the software.

In addition to the direct manufacturing analysis, additional values were extracted from the software to support the emergy assessment and are summarized in Tables 3.11 and 3.12. Table 3.11 lists the variables based on machine qualities. The area of the machine (A_{mach}) is used with a machine-specific factor to calculate the gap around the machine (A_{gap}), and the additional space in the factory attributed to the machine (A_{space}). The coverage factor for the plant maintenance worker (s_{fm}) is calculated based on an assumed area and the sum

Table 3.9. Summary of DFM Analysis Results from aPriori for Parts

Part	Variable	Material	Laser	Bend
Base	t_l (sec)		20.33	14.95
	t_c (sec)		12.51	11.5
	m_{rough} (kg)	0.61		
	c_{mat}	2.13		
	n_b		833	833
	$m_{supp,1}$ (kg)		1.03E-03	
	$m_{supp,2}$ (kg)		1.36E-08	
Side Flange (LH)	t_l (sec)		16.55	34.45
	t_c (sec)		10.18	26.5
	m_{rough} (kg)	0.41		
	c_{mat}	1.44		
	n_b		833	833
	$m_{supp,1}$ (kg)		8.35E-04	
	$m_{supp,2}$ (kg)		9.17E-09	
Side Flange (RH)	t_l (sec)		16.8	34.45
	t_c (sec)		10.34	26.5
	m_{rough} (kg)	0.43		
	c_{mat}	1.52		
	n_b		833	833
	$m_{supp,1}$ (kg)		8.48E-04	
	$m_{supp,2}$ (kg)		9.61E-09	
Stiffener	t_l (sec)		12.35	24.7
	t_c (sec)		7.6	19
	m_{rough} (kg)	0.3		
	c_{mat}	1.04		
	n_b		833	833
	$m_{supp,1}$ (kg)		6.23E-04	
	$m_{supp,2}$ (kg)		6.71E-09	
Lug	t_l (sec)		20.35	14.95
	t_c (sec)		12.52	11.5
	m_{rough} (kg)	0.187		
	c_{mat}	0.65		
	n_b		1666	1666
	$m_{supp,1}$ (kg)		1.03E-03	
	$m_{supp,2}$ (kg)		4.18E-09	

Table 3.10. Summary of DFM Analysis Results from aPriori for Welding

Variable	Handling	Welding
t_l (sec)	129	169.36
t_c (sec)	129	169.36
m_{supp} (kg)		0.026
n_b	833	833
c_{wire} (USD/kg)		1.85

of the machine area, the gap, and additional attributed space. The remainder of the values are standard values based on data from the aPriori software.

Table 3.11. Summary of Machine-Based Qualities

Variable	Laser	Bend	Weld	Units
c_{mach}	\$ 600,000.00	\$ 88,843.60	\$ 8,571.61	USD
t_{life}	10	10	10	years
p_{mach}	7.14	7.99	10	kW
A_{mach}	57.54	2.12	0.59	m ²
A_{gap}	57.54	4.23	14.20	m ²
A_{space}	34.53	1.91	4.44	m ²
t_s (hr)	0.083	0.75	1	hr
n_p	1	1	1	people
s_{fm}	0.0343	0.0019	0.0044	

Table 3.12 lists the values from the plant assessment. The total capacity W_{cap} is calculated based on the working hours per shift, shifts per day, and working days per year and varies based on regional assumptions. The earned hours (t_{earn}) are calculated based on an assumed 80% machine up-time. The remainder of the values are standard values based on data from the aPriori software.

3.4.3 Energy Systems Language Diagram

Shown in Figure 3.17 is the ESL diagram representing the manufacturing steps in creating the example assembly and its supporting parts. The fundamental building block of this ESL diagram is the generic model ESL diagram given in Figure 3.2. Each of the five parts in the assembly is represented with the Lug shown twice. For the Base part a complete

Table 3.12. Summary of Plant Based Qualities

Variable	Value	Units
f_{inst}	0.20	
f_{maint}	0.05	
t_{earn}	3238.40	hrs
W_{cap}	4048.00	hrs
f_{water}	0.01	
f_{gas}	0.10	
f_{elec}	0.01	
s_q	0.05	
s_{pur}	0.05	
s_{eng}	0.07	
s_{tc}	0.02	
f_{space}	0.30	
c_{rent}	112.73	USD/m ²

ESL diagram is shown, including both the laser and bend step. For the remaining parts, the individual process steps were not represented for space considerations, and they are each represented by a generic process box, with a gray-filled arrow corresponding to the expected inputs. The additional parts, if they were included in this diagram, would be portrayed in a similar manner as the Base, since they are made using the same manufacturing processes.

The system inputs are arranged based on emergy-per-hour values based on the analysis reviewed in Section 3.4.11, decreasing from left-to-right, with the laser having the largest emergy rate and weld wire having the lowest. All the parts represented in the diagram occur in parallel, at the same hierarchical level, but are arranged by emergy per unit. The base, having the highest emergy value, is placed toward the lower-left and the lug with lowest is placed toward the upper-right of the diagram. The Laser is a higher transformity process, and as such, it is placed at the lower-left of the bending machine.

Welding occurs at a higher level in the hierarchy of the system, since all the parts must be completed for welding to occur. For that reason, it is placed toward the right-hand side of the diagram. It is also a higher emergy provider than the laser or bend process. For that reason, it is placed lower in the diagram than the laser process.

Figure 3.17. The ESL for the example assembly.

The facility supports all the processes, and is considered to be at a different hierarchical level than the processes, so it is placed farthest to the right in the diagram. It also has at a lower level of emergy-per-hour than the other activities in the factory, so is placed near the top.

3.4.4 Raw Material

To determine the emergy in the material for the parts, Equation 36 is used directly with the rough mass (m_{rough}) and the cost of the material for each part (C_m) coming from the DFM analysis, as shown in Table 3.9. The UEV used for the material (T_{mat}) comes from Bargigli and Ulgiati [126] and represents structural steel from non-recycled (virgin) material without labor and services. In selecting an UEV for steel, an all-virgin material using the BOF process not including labor and services was preferred. An all-virgin material was selected to avoid any discrepancy in comparing different material mixes, and BOF is the more common process to use with all-virgin material [126, 132]. Additionally, this set of qualifiers has two data points providing some guidance for the possible range of values.

Reviewing Table 2.10, these criteria eliminate Zhang et al. [133] and Ma et al. [135] from consideration, leaving Buranakarn [132] and Bargigli and Ulgiati [126]. In comparing these two values, Bargigli and Ulgiati (4.69×10^9 sej/g) were selected since that of Buranakarn (6.75×10^9 sej/g) represents the upper end of the range for all steel values without labor and services. The impacts on the total emergy value in a part or assembly due to the choice of a value for the steel is investigated further in Chapter 4.

To complete the labor and services portion of the calculation, a commodity material price for hot rolled band from 2019 is used [162]. While this is not a perfect match for the level of processing represented by the UEV for structural steel reported by Bargigli and Ulgiati's [126], hot rolled band has a similar level of processing to the most basic structural steel shapes. Additionally, the hot rolled band has a similar level of processing as the inputs material for cold rolling [163]. The 2011 value of the emergy-to-money ratio ($T_{\$}$) for the

United States, is taken from Campbell et al. [127] to estimate the emergy in labor and services beyond the state of processing in the steel UEV selected to reach the price noted in the DFM analysis for 1020 Cold Rolled Steel. The impact on total emergy from choosing an alternative value for the steel UEV is reviewed in Section 4.4.

3.4.5 Labor

In Equation 37, the value for the time attributed to labor (t_l) and the number of people working at a machine (n_p) are gathered from the DFM analysis. The labor UEV (T_l) is different for the workers at each machine. Table 3.13 summarizes the UEV inputs for the occupations of the workers used in the study.

Table 3.13. Emergy Results for Direct and Indirect Labor Occupations based on OOH [129] data

Occupation	Total UEV (sej/hr)	Ed UEV (sej/hr)	Labor Type	OOH Code	No HS Grad	HS	Some college	Certif	Assoc	BS
Brake Operator	1.51E+14	1.49E+14	Direct	51-4031	9%	67%		18%		
Engineering	1.80E+14	1.77E+14	Indirect	17-2112				14%	13%	62%
Facility Maintenance	1.33E+14	1.30E+14	Indirect	49-9071	15%	37%		30%		
Laser Operator	1.51E+14	1.49E+14	Direct	51-4031	9%	67%		18%		
Machine Installation	1.46E+14	1.43E+14	Direct	49-9041		25%		48%		8%
Machine Maintenance	1.66E+14	1.63E+14	Direct	49-9043		39%	25%	31%		
Purchasing	2.06E+14	2.03E+14	Indirect	13-1023			5%	10%		85%
Quality	1.26E+14	1.24E+14	Indirect	51-9061	14%	52%		14%		
Tool Crib	1.33E+14	1.30E+14	Indirect	49-9071	15%	37%		30%		
Welder	1.64E+14	1.61E+14	Direct	51-4121		40%	13%	41%		
Assembly	8.64E+13	8.37E+13	Direct	51-2023		53%				

The UEV for formal education requires the inputs of the percentage of workers in each of nine educational categories, as noted in Equation 41. Data with these splits can be found for a wide selection of jobs in the Occupational Outlook Handbook (OOH) by the US BLS [129]. Table 3.13 shows the 2016 OOH data for 11 different occupations included in this model. Of the nine educational categories, six are included here: primary school, high school (HS), some college (no degree), certificate, Associates degree, and Bachelor's degree (BS). The remaining educational categories were not relevant for this selection of jobs. In cases where the OOH data did not add up to 100%, the ratios of the reported data were averaged to reach 100%.

Also included in Table 3.13 are the OOH designated codes for each job, as well as if the job is involved in direct labor (making the parts) or indirect labor (supporting the facility). To the resulting hourly education UEV for each occupation, the metabolic (T_{met}) and services UEVs (T_{serv}) were added from Tables 3.5 and 3.4, respectively. This provides a single UEV for each of the labor types to be used in the place of T_l for any given role.

3.4.6 Laser and Brake Machine

To support the emergy calculation for the laser and brake machines, the majority of the values in Equation 44—the cost of the machine (c_{mach}), the maintenance and installations factors (f_{maint}, f_{inst}), the earned hours on the machine (t_{earned}), the machine life (t_{life}), and the time attributed to the machine (t)—are gathered from the DFM analysis. The remaining values are the emergy in the machine and the emergy-to-money ratio. As noted in Section 3.4.4, the 2011 value of the emergy-to-money ratio ($T_{\$}$) for the United States, is taken from Campbell et al. [127] and is used throughout this dissertation study.

Due to the complexity of laser and bend brake machines, the extended piece-by-piece analysis described in Section 3.3.3 was not used for calculating Em_{mach} for these processes. Instead, an adaptation of the approach employed by Almeida et al. in studies from 2013 [97] and 2018 [99] is used. In these cases, the mass and price of the machine are used in Equation 36 to calculate an emergy value using the UEV for the primary material and the emergy-to-dollar ratio to calculate labor and services. It is assumed the entire machine is made of steel.

The calculations for each machine are summarized in Tables 3.14 and 3.15. In each table the emergy due to the machine, its one-time installation, and its yearly maintenance are included. The final total gives the hourly UEV. This method should be considered to give a general order-of-magnitude estimate, as it considers only the primary material by mass (steel) and not any other materials that may be less common within the product, but have a higher UEV (e.g., copper and ceramics).

Table 3.14. Emergy for Cincinnati CL850 Laser Machine

Item	Value	Unit	UEV	Unit	Source	Total Emergy	Emergy Per Year	Emergy Per Hour
Laser Machine Material	16397.35	kg	4.69E+09	sej/g		7.69E+16	7.69E+15	2.38E+12
Laser Machine LS	\$589,571.28	USD	2.02E+12	sej/USD		1.19E+18	1.19E+17	3.68E+13
Laser Installation	\$120,000.00	USD	2.02E+12	sej/USD		2.43E+17	2.43E+16	7.49E+12
Laser Maintenance	\$ 30,000.00	USD/year	2.02E+12	sej/USD			6.06E+16	1.87E+13
Total								6.54E+13

Table 3.15. Emergy for Amada SPH-60C Bending Machine

Item	Value	Unit	UEV	Unit	Source	Total Emergy	Emergy Per Year	Emergy Per Hour
Brake Machine Material	5500	kg	4.69E+09	sej/g		2.58E+16	2.58E+15	7.97E+11
Brake L & S	\$ 85,345.60	USD	2.02E+12	sej/USD	[127]	1.73E+17	1.73E+16	5.33E+12
Brake Installation	\$ 17,768.72		2.02E+12	sej/USD	[127]	3.59E+16	3.59E+15	1.11E+12
Brake Maintenance	\$ 4,442.18		2.02E+12	sej/USD	[127]		8.98E+15	2.77E+12
Total								1.00E+13

3.4.7 Welding Machine

The hourly contribution to the assembly's emergy value from the welding machine is found using Equation 44. The majority of the values—the cost of the machine (c_{mach}), the maintenance and installations factors ($f_{maint}f_{inst}$), the earned hours on the machine (t_{earned}), the machine life (t_{life}), and the time attributed to the machine (t)—are gathered from the DFM analysis. The remaining values are the emergy in the machine and the emergy-to-money ratio. As noted in Section 3.4.4, the 2011 value of the emergy-to-money ratio ($T_{\$}$) for the United States, is taken from Campbell et al. [127] is used throughout this dissertation study.

The general methodology for estimating the emergy within a manufacturing machine proposed in this study involves estimating the emergy held within each part, and estimating the emergy added in the assembly of these parts into a productive machine. The description of the former is completed in this section. For the latter, see Appendix I.

BOMs for the three main pieces of equipment supporting a MIG welding station were found in the owner manuals for the welder (Miller DeltaWeld 652) [164], the wire feeder (Miller S-74S) [165], and the gun (Miller Ironmate FC-1150) [166]. It should be noted that a flux-core gun was selected. This avoids the need for welding gas and is a reasonable choice for a small-scale manufacturing environment.

The BOMs in the owner manuals for the welder, feeder, and gun included the part number, a short description of the part, and the quantity required of each part. Each BOM has been reproduced in Appendices D.1, D.2, and D.3. Some line items are split into subassemblies within the BOM. In the original format, these are indented, whereas, in the Appendices child parts of an assembly are noted with an increased value in the Level column. For example, Part number 203778 on the Welder (Section D.1) is a parent assembly called “Connector/Capacitor, w/leads” and has a Level of 1. It has children “RCPT w/SCKTS (service kit)” and “CAPACITOR, cer disc .05 uf 500 VDC strip,” which are both at Level 2.

The BOMs provided by Miller in the owner manuals [164–166] did not include information regarding the mass of the parts, the price, or the material (generally) the part is made from. Since this information is required to estimate the emergy embodied in each part, a web-based search was undertaken. These searches were completed using Google [167]. BR Welding Supply Inc. [168] and Amazon.com [169] were found to include both a retail price and shipping weight for each of the parts available on their site. Such data were available for the majority of parts from either one of those two sources. The full URLs for all of the parts are included in the Source column in Appendices D.1, D.2, and D.3.

In some cases, parts had been eliminated or replaced by other part numbers or, otherwise, could not be found. In the majority of these cases, similar parts were identified via the superseding part numbers, and these masses and costs were used. In cases where no superseding part could be found, a similar part within the assembly was used as a data source. Details on alternative methods of estimation are included in the Notes column. In the case of part number 164717, a bus bar, its weight was interpolated based on its price and the prices of two other bus bars with known weights: part numbers 162817, and 182660.

For material types, it was generally not possible to know the exact material used for each part. Each of the BOMs, though, was reviewed and the most likely material group selected for every part based on the function, type of attachment, mass, and, where possible,

review of a picture found using Internet searches. Materials used for all circuit boards were addressed using a separate procedure, described later. Up to two materials were assigned to each part, with a percentage of each material by weight being estimated using a similar heuristic as described above for the material type. Plastic materials were not identified directly, but were grouped into an overarching group. The two materials and the attributed percentages are given in the columns % Mat 1, Mat 1, % Mat 2, and Mat 2 in Appendices D.1, D.2, and D.3.

For each part, the emergy held by the part was determined based on the material UEV and the mass. For parts including multiple materials, the following equation was used to estimate the total emergy held in the materials in the part ($Em_{mat,part}$):

$$Em_{mat,part} = m_{part}(T_{mat1}f_{mat1} + T_{mat2}f_{mat2}) \quad (65)$$

where m_{part} is the mass of the part; T_{mat1} and T_{mat2} are the UEVs for material 1 and 2, respectively; and f_{mat1} and f_{mat2} are the fractions of material 1 and material 2 in the part by mass, respectively. For some materials, UEVs were not readily available and were developed based on a selection of techniques. Details for these cases are described in Appendix G.

This assessment, though, covers merely the emergy in the raw material. The emergy added to the material through labor and services is not yet included. This can be estimated based on the cost of the item not allocated to materials ($C_{L\&S}$), which can be estimated with the following equation:

$$C_{L\&S} = \frac{C_{part}}{f_{markup}} - m_{part}(P_{mat1}f_{mat1} + P_{mat2}f_{mat2}) \quad (66)$$

where C_{part} is the cost of the part, f_{markup} is the estimated retail markup on the part when bought individually, and P_{mat1} and P_{mat2} are the prices of individual materials per mass based on commodity pricing values—details on sources for these data are included below in

the discussion of finding the emergy for circuit boards. The value for f_{markup} was calculated as follows:

$$f_{markup} = \frac{\sum_i P_{part,i}}{P_{retail} - (t_{assy}h_{assy})} \quad (67)$$

where $P_{part,i}$ is the price of the i th part in the machine element, P_{retail} is the retail price of the full machine element, t_{assy} is the assembly time for the machine element as calculated via the MOST method (see Appendix I), and h_{assy} is the median hourly rate for an assembler in the United States, as can be identified through the US BLS OOH [129].

The resulting cost ($C_{L\&S}$) for labor and services is multiplied by the emergy-to-dollar ratio, providing an estimated emergy value for the labor and services added to the part. $C_{L\&S}$ is summed with Em_{mat} , as calculated in Equation 65, to give a final result of the total emergy in the given part. To estimate the emergy among all machines, the individual emergy for each part is summed and the resulting emergies for all machine elements are also summed:

$$Em_{mach} = \sum_i Em_{part,i} + \sum_j Em_{part,j} + \sum_k Em_{part,k} \quad (68)$$

where, in the case of the welder, $Em_{part,i}$ represents the emergy of i th part of the welder, $Em_{part,j}$ represents the emergy of the j th part of the feeder, and $Em_{part,k}$ represents the emergy of the k th part of the gun. It should be noted that the model of the welder has three terms. This sum would expand or contract based on the number of pieces of equipment involved in the machine or manufacturing station.

Both the main welding unit and the feeder, as shown in the BOMs in Appendix D, include a selection of circuit boards. While the emergy for a computer has been estimated by Puca et al. [101], as described in Section 2.4, an estimate for circuit boards has not been conducted. The full estimation procedure is shown in Figure 3.18.

Figure 3.18. Process used for estimating energy in circuit boards.

To support an estimate of the total energy for the main welding unit and the feeder an estimate was conducted based on the materials within boards as identified by Cucchiella et al. [170]. Table 3.16 shows the split by percentage of the mass for the materials in two types of boards from Cucchiella et al. [170]. Category 1 boards are those found in large home appliances, such as air conditioners and washing machines, and Category 3 boards are those found in computers and communications equipment, which include liquid crystal displays (LCDs).

For each material, an UEV was identified. For most elemental materials, the identified UEVs are based on ore values from Cohen et al. [172]. For steel, the value for virgin steel was used from Bargigli and Ulgiati [126]. Copper as found in Raugei et al. [125] in reference to wiring found in photovoltaic panels. The value for chlorine (Cl) was sourced from Campbell and Ohrt [160], which was calculated based on chemical reactions related to caustic soda. The general value for plastics was sourced from Buranakarn [132], who estimated a value based on the inputs into plastics manufacturing from 1992 data. Cuc-

Table 3.16. Circuit Board Materials Content from Cucciella et al. [170] with UEVs and Calculated sej/g for Two Board Types

Material	% of Mass		UEV (sej/g)	Ref	Emergy per gram of board (sej/g)	
	Cat 1	Cat 3			Cat 1	Cat 3
Steel	15.450%	14.100%	4.69E+09	[126]	7.25E+08	6.61E+08
Copper	13.000%	20.000%	2.30E+11	[125, 171]	2.99E+10	4.60E+10
Silver	0.010%	0.170%	3.42E+11	[172]	3.42E+07	5.81E+08
Gold	0.003%	0.040%	3.83E+11	[172]	1.15E+07	1.53E+08
Palladium	0.003%	0.010%	9.34E+10	[172]	2.80E+06	9.34E+06
Aluminium	7.650%	3.380%	4.11E+09	[172]	3.14E+08	1.39E+08
Beryllium	0.000%	0.002%	8.35E+11	[172]	0.00E+00	1.67E+07
Bismuth	0.000%	0.020%	2.43E+14	[172]	0.00E+00	4.86E+10
Chromium	0.020%	0.540%	1.15E+11	[172]	2.31E+07	6.23E+08
Tin	1.490%	0.690%	1.28E+12	[172]	1.90E+10	8.80E+09
Zinc	1.940%	1.350%	5.47E+10	[172]	1.06E+09	7.38E+08
Antimony	0.080%	0.130%	3.19E+12	[172]	2.55E+09	4.15E+09
Arsenic	0.000%	0.001%	3.46E+12	[172]	0.00E+00	1.73E+07
Bromine	0.160%	0.820%	2.63E+12	[172]	4.20E+09	2.15E+10
Cadmium	0.000%	0.000%	2.58E+13	[172]	0.00E+00	2.58E+05
Chlorine	0.200%	0.010%	8.49E+09	[160]	1.70E+07	8.49E+05
Lead	1.250%	0.790%	3.65E+11	[172]	4.56E+09	2.88E+09
Nickel	0.070%	1.130%	1.52E+11	[172]	1.06E+08	1.72E+09
Plastics	41.500%	30.200%	4.00E+09	[132]	1.66E+09	1.21E+09
Epoxy	8.500%	0.920%	1.27E+10	This Study	1.08E+09	1.17E+08
Ceramics	7.000%	15.020%	1.09E+11	This Study	7.64E+09	1.64E+10
Glass	0.000%	2.000%	1.07E+09	[173]	0.00E+00	2.14E+07
Others	2.200%	8.380%	5.23E+10	This Study	1.15E+09	4.38E+09
Liquid Crystals	0.000%	0.160%	1.53E+10	This Study	0.00E+00	2.46E+07
Emergy Per Mass of Circuit Board (sej/g)					7.41E+10	1.59E+11

chiella et al. [170] did not provide any detail regarding the makeup of the materials in the Others category. For this application, an UEV was estimated from the seven materials with the highest percentages: iron, copper, aluminum, plastics, epoxy, ceramics and glass.

For a few materials—epoxy, ceramics, and liquid crystals—it was not possible to identify UEVs within the current literature. Estimates for each of these were found under the guidance of Daniel Campbell [174], and are detailed in Appendix G. The UEVs are reported in Table 3.16.

Table 3.17. Average Prices and Estimated Materials based on Alibaba Factory Sources

Product	Price Units	Price 1	Source	Price 2	Source	Price 3	Source	Avg Price
Ceramics	USD/kg	\$46.00	[175]	\$25.50	[176]	\$10.50	[177]	\$27.33
Liquid Crystal	USD/g	\$44.50	[178]	\$44.50	[179]	\$25.50	[180]	\$38.17
Epoxy	USD/kg	\$7.00	[181]	\$5.90	[181]	\$9.25	[182]	\$7.38
Polyurethane	USD/kg	\$6.85	[183]	\$5.00	[184]	\$11	[185]	\$7.62
Ferric Chloride	USD/metric ton	\$625.00	[186]	\$300.00	[187]	\$567.00	[188]	\$497.33
Glass Raw Material	USD/ton	\$190.00	[189]	\$105.00	[190]	\$290.00	[191]	\$195.00

In a conversation with Mariano Alvira [192], a subject matter expert regarding industrial circuit design, it was conveyed that industrial boards are covered with a polyurethane (PU) conformal coating. While Paoli et al. [193] include in their study an UEV for PU, it is sourced from Buranakarn’s [132] value for polyvinyl chloride (PVC) with no adjustments. Based on a short review of the processes for making PVC [194] and PU [195], it was determined that PVC was not a reasonable alternative. Instead, the calculation completed with the assistance of Campbell [174] for the UEV of epoxy, as presented in Appendix G.3 was substituted due to the chemical similarity of PU to epoxy.

The volume of PU coating required was estimated based on the individual circuit board size (estimated from diagrams and online searches), and an average coating thickness of 8 μm . Table 3.18 summarizes these calculations for the two circuit boards in the main welding unit and the three boards in the feeder.

Table 3.19 shows the full list of board materials, source cost and units, and cost per kg, which are used in calculating labor and services for each of the boards. Raw material prices were sourced from the *The CRB Commodity Yearbook 2018* [196] and from the United

Table 3.18. Estimated PU Conformal Coating per Circuit Board with Estimated Board Dimensions

Location	Part #	Board Name	L (m)	W (m)	H (m)	Resin Vol (m ³)	Resin Mass (kg)
Welder	208772	CIRCUIT CARD, control (60Hz)	0.23	0.15	0.05	8.67E-06	7.80E-03
Welder	214827	CIRCUIT CARD, digital meter	0.15	0.08	0.05	3.72E-06	3.34E-03
Feeder	237042	Circuit Card Assembly, Meter	0.23	0.15	0.05	8.67E-06	7.80E-03
Feeder	238469	Circuit Card Assy, Motor Control	0.23	0.23	0.05	1.21E-05	1.09E-02
Feeder	237048	Circuit Card, Digital Tach	0.11	0.06	0.01	1.39E-06	1.25E-03

States Geological Survey 2014 *Historical Statistics for Mineral and Material Commodities in the United States* [197] for as many materials as possible. For the category plastics, monthly resin price data from 2017 for four common commodity plastics (e.g., PP, HDPE, PC, and ABS¹¹) was gathered from Plastics Insight [198], as shown in Table 3.20.

For materials that are not commonly indexed elsewhere, three sources were found from Alibaba.com [199]. The suppliers usually provided a range of prices depending on volume purchased. This range was averaged, then each of the supplier averages were again average to reach the final price reported in Table 3.17. The last two entries in Table 3.17 give an average cost-per-mass for ferric chloride (the source of chlorine in circuit boards) and the raw material for glass (silica powder).

The data in Table 3.19 are used, as shown in Table 3.21, to calculate a cost-per-gram for Category 1 and Category 3 board types, resulting in a cost of \$0.0088 and \$0.0894 USD per gram of circuit board, respectively. With these data available, an emergy calculation for labor and services based on the price of the boards can be made following the recommendation from Odum [60] to exclude the cost of raw materials using the following equation:

$$C_{L\&S} = \frac{C_{board}}{f_{markup}} - m_{board}P_{board} - m_{PU}P_{PU} \quad (69)$$

where C_{board} and m_{board} are the cost and the mass of the board as included with the BOM in Appendix D; P_{board} is the price per gram of the board per category type, as shown in Table

¹¹PP = polypropylene; HDPE = high-density polyethylene; PC = polycarbonate; ABS = acrylonitrile butadiene styrene

Table 3.19. Calculation of Cost per kg of Board Material Based on Data from Various Sources

Materials	Values	Units	In USD/kg	Sources
Steel	\$636.00	USD/tonne	\$0.64	[162]
Copper	\$2.86	USD/lb	\$6.30	[196]
Silver	\$17.07	USD/t oz	\$548.66	[196]
Gold	\$1,257.53	USD/t oz	\$40,430.47	[196]
Palladium	\$874.22	USD/t oz	\$28,106.78	[196]
Aluminum	\$1,967.70	USD/tonne	\$1.97	[196]
Beryllium	\$485,000	USD/ton	\$534.62	[197]
Bismuth	\$4.94	USD/lb	\$10.89	[196]
Chromium	\$2,250	USD/ton	\$2.48	[197]
Tin	\$9.37	USD/lb	\$20.66	[196]
Zinc	\$1.40	USD/lb	\$3.08	[196]
Antimony	\$7,200	USD/ton	\$7.94	[197]
Arsenic	\$0.88	USD/lb	\$1.94	[196]
Bromine	\$1,390	USD/ton	\$1.53	[197]
Cadmium	\$79.45	USD/lb	\$175.16	[196]
Chlorine	\$497.33	USD/tonne	\$0.50	This study
Lead	\$1.15	USD/lb	\$2.53	[196]
Nickel	\$5.22	USD/lb	\$11.50	[196]
Plastics	\$5,546.50	USD/ton	\$6.11	This study
Epoxy	\$7.38	USD/kg	\$7.38	This study
Ceramics	\$27.33	USD/kg	\$27.33	This study
Glass	\$195.00	USD/ton	\$0.21	This study
Others	\$7.08	USD/kg	\$7.08	This study

Table 3.20. Monthly Data for 2017 Available from Plastics Insight [198] for Four Common Commodity Resins

Material	Monthly Data												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
PP	\$3,410	\$3,800	\$3,740	\$3,630	\$3,740	\$3,730	\$3,720	\$3,800	\$3,740	\$1,730	N/A	N/A	\$3,504
HDPE	\$7,730	\$7,780	\$7,850	\$8,030	\$8,020	\$7,780	\$7,900	\$7,860	\$8,030	\$8,440	N/A	N/A	\$7,942
PC	\$6,455	\$6,450	\$6,075	\$5,886	\$5,644	\$5,930	\$5,970	\$6,005	\$5,848	\$5,861	\$6,220	\$5,980	\$6,027
ABS	\$4,460	\$4,695	\$4,770	\$4,920	\$4,900	\$4,675	\$4,580	\$4,605	\$4,685	\$4,840	N/A	N/A	\$4,713

All costs in USD/ton. Data from 2017 for all months available.

Table 3.21. Material Costs Calculated per gram of Board

Item	% of Mass		Material Cost (USD/g of board)	
	Cat 1	Cat 3	Cat 1	Cat 3
Iron	15.450%	14.100%	\$0.0001	\$ 0.0001
Copper	13.000%	20.000%	\$0.0008	\$ 0.0013
Silver	0.010%	0.170%	\$0.0001	\$ 0.0009
Gold	0.003%	0.040%	\$0.0012	\$ 0.0162
Palladium	0.003%	0.010%	\$0.0008	\$ 0.0028
Aluminum	7.650%	3.380%	\$0.0002	\$ 0.0001
Beryllium	0.000%	0.002%	\$ -	\$ 0.0000
Bismuth	0.000%	0.020%	\$ -	\$ 0.0000
Chromium	0.020%	0.540%	\$0.0000	\$ 0.0000
Tin	1.490%	0.690%	\$0.0003	\$ 0.0001
Zinc	1.940%	1.350%	\$0.0001	\$ 0.0000
Antimony	0.080%	0.130%	\$0.0000	\$ 0.0000
Arsenic	0.000%	0.001%	\$ -	\$ 0.0000
Bromine	0.160%	0.820%	\$0.0000	\$ 0.0000
Cadmium	0.000%	0.000%	\$ -	\$ 0.0000
Chlorine	0.200%	0.010%	\$0.0000	\$ 0.0000
Lead	1.250%	0.790%	\$0.0000	\$ 0.0000
Nickel	0.070%	1.130%	\$0.0000	\$ 0.0001
Plastics	41.500%	30.200%	\$0.0025	\$ 0.0018
Epoxy	8.500%	0.920%	\$0.0006	\$ 0.0001
Ceramics	7.000%	15.020%	\$0.0019	\$ 0.0041
Glass	0.000%	2.000%	\$ -	\$ 0.0000
Others	2.200%	8.380%	\$ 0.0002	\$ 0.0006
Liquid Crystals	0.000%	0.160%	\$ -	\$ 0.0611
Total Material Price (USD/g of board):			\$ 0.0088	\$ 0.0894

3.21; m_{PU} is the mass of PU conformal coating on the board as calculated in Table 3.18; P_{PU} is the price per mass of PU as estimated in Table 3.17; and f_{markup} is the approximate retail markup for the price of the board as a replacement part versus as a part of purchasing the welder, as described in Equation 67.

With material estimates calculated, the emergy in each of the five boards can be calculated. These are shown in Table 3.22, where emergy for each of the five boards are split into three calculations: the board material, the PU conformal coating, and the labor and services. These are summed to include the total with and without labor and services. It should be noted that the “CIRCUIT CARD, digital meter” from the main welding unit, and “Circuit Card Assembly, Meter W/Program” from the feeder are considered Category 3 boards due to their digital displays, and the remaining are considered Category 1 boards. Since these boards are in different categories, different Board Material UEVs are used.

The MOST method described in Section 3.3.3 and Appendix I was applied to the assembly of a Miller DeltaWeld 652 MIG welder, a Miller S-74D Wire Feeder, and a Miller FC-1150 Welding Gun based on the part lists and diagrams provided in the owner manuals [164–166]. In conducting the analysis, the following assumptions were made:

1. All parts are manually handled by a single worker.
2. Assembly occurs at a table at a correct ergonomic height for the worker and this assembly.
3. All parts and tools are within reach.
4. The worker is standing and/or sitting on a stool during the assembly procedure.
5. No testing was conducted during the assembly process.

It should be noted that since the actual assembly of the welder was not observed and a set of work instructions for completing the assembly of the welder were not available, the

Table 3.22. Emergy Totals for the Circuit Boards in the Welding Equipment

Item	Value	Unit	UEV	Unit	Source	Total Emergy (sej)
CIRCUIT CARD, control (60Hz)						
Board Material	0.83	lbs	7.41E+10	sej/gram	This Study	2.79E+13
Coformal Coating	7.80E-03	kg	1.54E+13	sej/kg	This Study	1.20E+11
Labor and Services	\$ 284.29	USD	2.02E+12	sej/USD	[127]	5.75E+14
Total with L&S						6.03E+14
Total without L&S						2.80E+13
CIRCUIT CARD, digital meter						
Board Material	0.38	lbs	1.59E+11	sej/gram	This Study	2.74E+13
Coformal Coating	3.34E-03	kg	1.54E+13	sej/kg	This Study	5.15E+10
Labor and Services	\$ 286.12	USD	2.02E+12	sej/USD	[127]	5.78E+14
Total with L&S						6.06E+14
Total without L&S						2.74E+13
Circuit Card Assembly, Meter W/Program						
Board Material	0.12	lbs	1.59E+11	sej/gram	This Study	8.64E+12
Coformal Coating	7.80E-03	kg	1.54E+13	sej/kg	This Study	1.20E+11
Labor and Services	\$ 202.43	USD	2.02E+12	sej/USD	[127]	4.09E+14
Total with L&S						4.18E+14
Total without L&S						8.76E+12
Circuit Card Assy, Motor Control W/Program						
Board Material	1.1	lbs	7.41E+10	sej/gram	This Study	3.69E+13
Coformal Coating	1.09E-02	kg	1.54E+13	sej/kg	This Study	1.67E+11
Labor and Services	\$ 327.23	USD	2.02E+12	sej/USD	[127]	6.62E+14
Total with L&S						6.99E+14
Total without L&S						3.71E+13
Circuit Card, Digital Tach						
Board Material	0.09	lbs	7.41E+10	sej/gram	This Study	3.02E+12
Coformal Coating	1.09E-02	kg	1.54E+13	sej/kg	This Study	1.67E+11
Labor and Services	\$ 71.87	USD	2.02E+12	sej/USD	[127]	1.45E+14
Total with L&S						1.48E+14
Total without L&S						3.19E+12

assembly time calculated here is an estimate. The summary of these times are included in Table 3.23 with an estimate of 0.690 hours of assembly for the three elements.

Table 3.23. Summary of Assembly Times for Welding Station Support Machines

Component	Assembly Time (hrs)
Welder	0.4205
Feeder	0.2186
Gun	0.0498
Total	0.6889

The total emergy for the welder is given in Table 3.24. Overall, about half of the emergy cost of the sum-total of all machine elements is due to labor and services and half due to the material making up the product.

With the value for the emergy in the welding equipment (E_{mach}) estimated, a total hourly rate can be calculated, including the one-time installation and yearly maintenance. This calculation is summarized in Table 3.25. From here, an hourly UEV for the weld machine can be determined for use in assessments.

3.4.8 Facility

For calculating the emergy of the factory building to attribute to the cycle time of the example assembly values are required for Em_{build} , Em_{util} , and $Em_{l, fact}$, as shown in Equation 52. The calculation of Em_{build} requires a UEV value for the building based on the materials, waste, land, and labor and services for constructing the building. The calculations supporting these values are shown in Tables 3.26 and 3.28.

Table 3.26 shows the calculations for each of the categories within Em_{build} . The materials are split into two calculations, one for the concrete and one for the steel in the building. A 4130.79 square meter factory was assumed, based on data for the average US factory size as available from the U.S. EIA Manufacturing Survey [200]. The calculation for the building concrete and iron follows the methods used by Saladini et al. [122] and Cavalett et al. [124], given in Equations 28 and 29. For the factory supporting this example, the wall

Table 3.24. Emergy Totals for Machine Elements Required in a MIG Welding Station

Item	Value	Unit	UEV	Unit	Source	Total Emergy (sej)
Welder						
Part Materials					This Study	1.56E+16
Part Labor & Services					This Study	1.13E+16
Assembly Labor - Transportation	0.4205	hrs	1.36E+12	sej/hr	This Study	5.73E+11
Assembly Labor - Service Energy	0.4205	hrs	3.01E+11	sej/hr	This Study	1.27E+11
Assembly Labor - Education	0.4205	hrs	1.20E+14	sej/hr	This Study	5.03E+13
Assembly Labor - Metabolic	0.4205	hrs	1.02E+12	sej/hr	This Study	4.28E+11
Total with L&S						2.70E+16
Total without L&S						1.56E+16
Feeder						
Part Materials					This Study	2.14E+15
Part Labor & Services					This Study	4.17E+15
Assembly Labor - Transportation	0.2186	hrs	1.36E+12	sej/hr	This Study	2.98E+11
Assembly Labor - Service Energy	0.2186	hrs	3.01E+11	sej/hr	This Study	6.59E+10
Assembly Labor - Education	0.2186	hrs	1.20E+14	sej/hr	This Study	2.62E+13
Assembly Labor - Metabolic	0.2186	hrs	1.02E+12	sej/hr	This Study	2.23E+11
Total with L&S						6.33E+15
Total without L&S						2.14E+15
Gun						
Part Materials					This Study	2.20E+14
Part Labor & Services					This Study	1.13E+15
Assembly Labor - Transportation	0.0498	hrs	1.36E+12	sej/hr	This Study	6.79E+10
Assembly Labor - Service Energy	0.0498	hrs	3.01E+11	sej/hr	This Study	1.50E+10
Assembly Labor - Education	0.0498	hrs	1.20E+14	sej/hr	This Study	5.96E+12
Assembly Labor - Metabolic	0.0498	hrs	1.02E+12	sej/hr	This Study	5.07E+10
Total with L&S						1.35E+15
Total without L&S						2.20E+14
Sum of all Welding Equipment						
Total with L&S						3.47E+16
Total without L&S						1.80E+16

Table 3.25. Total Emergy in Welding Machine Equipment

Item	Value	Unit	UEV	Unit	Source	Total Emergy (sej)	Emergy Per Year (sej/yr)	Emergy Per Hour (sej/hr)
Weld Machine					This Study	3.47E+16	3.47E+15	1.07E+12
Weld Installation	\$ 1,714.32	USD	2.02E+12	sej/USD	[127]	3.47E+15	3.47E+14	1.07E+11
Weld Maintenance	\$ 428.58	USD/year	2.02E+12	sej/USD	[127]		8.66E+14	2.68E+11
Total								1.45E+12

height was estimated based on guidance from a factory construction firm [201]. For the remaining variables related to the mass of materials, values from Cavalett et al. [124] were used.

The supporting calculations for the land are completed following the method presented by Li et al. [93], as given in Equation 27. Additionally, following Li et al. [93], the waste impact is based on the solid waste transferred to a landfill. The authors, though, complete their study in China where they were able to assume the full quantity of solid waste was shipped to a landfill. For the United States (though it varies by state), some portion of waste is recycled. Aggregate data on construction debris recycling for the United States was not available, but data was found for the United Kingdom [202], covering a selection of construction materials. This was combined with data from the US EPA [203] on the quantity of construction debris in the United States from 2014. These data are combined in Table 3.27 and used to estimate a fraction of material mass expected to go to the landfill for new building construction in the United States. The remaining mass was assumed to be recycled, the impact of which was not included in this study, as the impact is assumed to be small compared with landfill impact. The percentage of material landfilled was multiplied by the average mass of construction waste per area as provided by Osmani et al. [204]. These authors provided a range of 30 to 40 kg/m² from which the average of 35 kg/m² was used.

The otherwise unaccounted for labor and services required for the building construction were calculated based on the construction costs per area and subtracting the costs of iron, concrete, and tipping (dumping of waste in the landfill) fees. The construction costs per area were calculated based on data from a construction management data firm [205]. These data included high and low construction costs per area for 21 metropolitan areas across the United States and for three types of factory buildings: Warehouse-Regional Distribution, Warehouse-Light Industrial, and Manufacturing-Tech Laboratory. To produce a single number, the high and lows for each metropolitan area and each factory building type

were averaged. The resulting averages were averaged across the metropolitan areas, resulting in a cost-per-area value for each of the three manufacturing types. While none of the three options directly resemble a light-manufacturing shop, Warehouse-Light Industrial was considered the best match and used for the calculation.

The cost of steel per square foot of factory areas was calculated by dividing the total mass of steel and dividing that by the area of the factory, then multiplying it by the commodity price for hot-rolled band [162]. The cost per area of concrete was calculated similarly with the cost of ready-made concrete taken from an industry survey from 2017 [206]. The cost of dumping waste to landfill was from an analysis of landfill tipping fees in the US by The Environmental Research Education Foundation (EREF) [207].

Table 3.28 summarizes the UEVs per area for each of the five impact areas detailed in Table 3.26. Both the full UEV for the factory building per area and the amortized UEV per year split over the useful life of the building are included. The useful life of the building was assumed to be 50 years based on guidelines from the U.S. Federal Reserve [209]. The resulting UEV of 1.09×10^{14} sej/m² per year serves as the value for T_A as used in Equation 53. A note should be made regarding the calculation of the emergy load of the waste. The UEV used in this calculation is from Franzese et al. [123], where the authors include the construction of the landfill amortized over its life, collection, hauling, and disposal of the waste, as well as labor and services. The tipping fee from the The EREF [207] does not include the collection and hauling of the waste. This results in a mismatch of data. It was calculated based on data from Franzese et al. [123] on the fraction of emergy that accounted for waste collection and hauling (0.0455). To avoid double-counting, the collection was removed from the emergy calculation and was assumed to be accounted for as part of the general labor and services impact for the building.

It should also be noted that in the labor and service calculation for the building, three costs were removed to avoid double-counting: the cost of the steel, the cost of the concrete and the tipping fees. The steel and concrete costs are removed as recommended by Odum

Table 3.26. Calculations to Support Building Emergy

Category	Item	Value	Units	Sources
Factory Building Concrete	Factory Footprint	4130.79	m ²	[200]
	Factory Perimeter	257.08	m	
	Wall Height	4.50	m	[201]
	Walls Area	1156.88	m ²	
	Total Constructed Area	5287.67	m ²	
	Mean cement thickness	0.20	m	[124]
	Total Cement Volume	231.38	m ³	
	Density of cement	2400.00	kg/m ³	[124]
	Mass of Cement	555303.53	kg	
	Concrete UEV	1.37E+12	sej/kg	[208]
Factory Building Steel	Steel Reinforcement in concrete	35.00	kg/m ³	[124]
	Mass of steel in floor and wall	8098.18	kg	
	Steel sheet in roof. 1.25 mm thick	10.00	kg/m ²	[124]
	Mass of roof	41307.93	kg	
	Total Mass of Steel	49406.10	kg	
	Steel UEV	4.69E+12	sej/kg	[126]
Factory Building Labor and Services	Construction Costs Per Square Meter Factory	\$ 2,541.90	USD/m ²	[205]
	Cost of Steel	\$ 7.61	USD/m ²	[162]
	Cost of Concrete	\$ 7.91	USD/m ²	[206]
	Cost of Tipping	\$ 1.15	USD/m ²	
	Labor and Services Costs	\$ 2,525.23	USD/m ²	
	Emergy to Money Ratio	2.02E+12	sej/USD	[127]
Land Calculation	Depth of Soil	0.03	m	[93]
	Energy per Area	1.00E+09	J/m ²	[93]
	Land UEV	9.42E+04	sej/J	[94]
Waste (includes L&S)	Average US Tipping Fees	55.11	USD/Ton	[207]
	Waste Per Square Meter Construction	35.00	kg / m ²	[204]
	Waste to Landfill	18.94	kg / m ²	
	Fraction Collection in Emergy Calculation	0.0445		[123]
	Landfill UEV	8.73E+08	sej/g	[123]

Table 3.27. Construction Waste to Landfill Calculation Estimate

Item	Building Waste % [203]	Const Waste from (tons)			Avg. Recovery [202]	Building Waste Landfilled
		All [203]	Building	Building Mass Split		
Timber	96%	2922	2818	23.35%	57.00%	13.31%
Plasterboard	100%	3317	3317	27.49%	30.00%	8.25%
Ceramics / Masonry	100%	211	211	1.75%	75.00%	1.31%
Concrete	23%	21664	4893	40.55%	75.00%	30.41%
Miscellaneous	100%	828	828	6.86%	12.00%	0.82%
Building Waste Mass to Landfill:						54.10%

[60]. Tipping fees were removed as the waste impact UEV provided by Franzese et al. [123] includes labor and services that could not be easily removed from their calculation. By removing the tipping feeds from value used for calculating for labor and services, double-counting is again avoided.

Table 3.28. UEV per Area for Factory Building

Item	Full UEV (sej/m²)	UEV per Year* (sej/m²)
Factory Building Concrete	1.84E+12	3.67E+12
Factory Building Iron	5.61E+13	1.12E+12
Factory Building Labor and Services	5.11E+15	1.02E+14
Land	9.46E+13	1.89E+12
Waste in Landfill	1.58E+13	3.16E+11
Total	5.46E+15	1.09E+14

*Factory life assumed at 50 years per U.S. Federal Reserve [209]

3.4.9 Setup

For the setup on each of the machines, the power, machine, operator(s), and supplies UEVs per hour are summed. These are shown in Tables 3.29, 3.31, and 3.30. The resulting values can be applied to the setup times from the DFM analysis for each machine. The result was divided by the number of parts in a batch. As a result, the lug, which has a higher batch size, will have a lower total emergy for setup.

It should be noted in Table 3.30 that weld wire has not been included in the emergy value of setup. This follows the weld model used by the aPriori software, which does not consider weld wire a consumable supply used during setup.

3.4.10 Process Supplies

Two types of supplies are considered within this assembly: gases supporting the operation of the laser and the wire used for welding. The owner manual for the Cincinnati CL800 laser cutter [210] includes data regarding pressures and flow rates for gases required to support the laser cutting processes. Table 3.32 summarizes these data for the two main gases

Table 3.29. Hourly setup UEV for Brake

Item	Value	Units	Source
Power UEV	4.66E+12	sej/hr	This Study
Machine UEV	1.00E+13	sej/hr	This Study
Operator UEV	1.23E+14	sej/hr	This Study
Total	1.37E+14	sej/hr	

Table 3.30. Hourly setup UEV for Welder

Item	Value	Units	Source
Power UEV	5.83E+12	sej/hr	This Study
Machine UEV	1.45E+12	sej/hr	This Study
Operator UEV	1.33E+14	sej/hr	This Study
Total	1.40E+14	sej/hr	

Table 3.31. Hourly setup UEV for Laser

Item	Value	Units	Source
Power UEV	4.16E+12	sej/hr	This Study
Machine UEV	6.54E+13	sej/hr	This Study
Operator UEV	1.23E+14	sej/hr	This Study
Laser Gas	6.94E+09	sej/hr	This Study
Laser Assist Gas	3.61E+08	sej/hr	This Study
Total	1.92E+14	sej/hr	

supporting this manufacturing process: laser gas, and assist gas. The emergy approach for the gasses is the approach with no precursor material, as shown in Figure 3.10.

The laser gas is a mix of helium, nitrogen, and carbon dioxide with helium being the primary gas. This mix is always run at 28 psi with a 0.36 ft³/hr flow rate. The CL800 supports a selection of assist gasses. Based on common practice for mild steel [211, 212], oxygen was chosen as the assist gas for this study. The assist gas can be run at a wide range of pressures, but for this study—again, based on common practice [211, 212]—50 psi was used with a 0.08 inch nozzle. The CL800 owner manual notes that these selections result in a flow rate of 333 ft³/hr. These volumetric flow rates were converted to mass flow rates (assuming standard temperature) in Table 3.32. UEVs for each of the gasses were then identified from which per-hour consumption UEVs could be determined.

Table 3.32. UEV Calculation for Gases Required for Laser Operation

Type	Gas	Percent	kg/hr	UEV	Units	Source	UEV (sej/hr)
Laser @ 28 psi			8.05E-05	8.62E+10	sej/g	This Study	6.94E+09
	He	0.6	1.34E-05	3.97E+11	sej/g	[127]	
	N ₂	0.35	5.48E-05	2.95E+10	sej/g	[127]	
	CO ₂	0.05	1.23E-05	3.05E+07	sej/g	[213]	
Assist @ 50 psi							
	O ₂	1	0.30	1.22E+06	sej/g	[127]	3.61E+08

It should be noted that the pre-industrial UEV for N₂ from Campbell et al. [213] was used here. This was chosen after a discussion with Campbell [174] who recommended its use. His suggestion was based on the fact that much of the N₂ currently existing in the atmosphere was produced prior to the industrial age, which created a large supply. With that in mind, any N₂ extracted for use in a gas as applied here uses the pre-industrial UEV.

For weld wire, the emergy approach used is as shown in Figure 3.9, where a steel precursor material is assumed, but that additional processing is required. The price of the weld wire was found in the DFM analysis and the material UEV is as used for steel and described in Section 3.4.4.

3.4.11 Total Emergy for Example Assembly

Table 3.33 shows the emergy results for the example assembly, organized by contribution area. The total emergy in the example assembly is 4.94E+13 sej. When displaying the results of an emergy analysis, it is typical to split the contributions into those with and without labor and services. While contributions have been split for the majority of categories it was not possible complete such a calculation with the facility (Plant Overhead) value, as described in Section 3.4.8.

Table 3.33. Total Emergy for Example Assembly Categorized by Contribution Area and Part Name

Item	Part	Qty	Value	Unit	UEV	Unit	Ref	Emergy (sej)
Material								
	Base	1	0.61	kg	4.69E+09	sej/g	[126]	2.86E+12
	Side Flange (LH)	1	0.41	kg	4.69E+09	sej/g	[126]	1.92E+12
	Side Flange (RH)	1	0.43	kg	4.69E+09	sej/g	[126]	2.02E+12
	Stiffener	1	0.30	kg	4.69E+09	sej/g	[126]	1.41E+12
	Lug	2	0.19	kg	4.69E+09	sej/g	[126]	1.75E+12
Material - Labor and Services								
	Base	1	1.74	USD	2.02E+12	sej/USD	[127]	3.52E+12
	Side Flange (LH)	1	1.18	USD	2.02E+12	sej/USD	[127]	2.38E+12
	Side Flange (RH)	1	1.25	USD	2.02E+12	sej/USD	[127]	2.52E+12
	Stiffener	1	0.85	USD	2.02E+12	sej/USD	[127]	1.72E+12
	Lug	2	0.53	USD	2.02E+12	sej/USD	[127]	2.15E+12
Labor - Laser								
	Base	1	20.33	sec	1.23E+14	sej/hr	This Study	6.93E+11
	Side Flange (LH)	1	16.55	sec	1.23E+14	sej/hr	This Study	5.64E+11
	Side Flange (RH)	1	16.80	sec	1.23E+14	sej/hr	This Study	5.72E+11
	Stiffener	1	12.35	sec	1.23E+14	sej/hr	This Study	4.21E+11
	Lug	2	20.35	sec	1.23E+14	sej/hr	This Study	1.39E+12

Item	Part	Qty	Value	Unit	UEV	Unit	Source	Emergy (sej)
Labor - Bend								
	Base	1	14.95	sec	1.23E+14	sej/hr	This Study	5.09E+11
	Side Flange (LH)	1	34.45	sec	1.23E+14	sej/hr	This Study	1.17E+12
	Side Flange (RH)	1	34.45	sec	1.23E+14	sej/hr	This Study	1.17E+12
	Stiffener	1	24.70	sec	1.23E+14	sej/hr	This Study	8.42E+11
	Lug	2	14.95	sec	1.23E+14	sej/hr	This Study	1.02E+12
Labor - Weld								
	Assembly	1	298.36	sec	1.33E+14	sej/hr	This Study	1.10E+13
Mfg Equipment - Laser								
	Base	1	12.51	sec	6.54E+13	sej/hr	This Study	2.27E+11
	Side Flange (LH)	1	10.18	sec	6.54E+13	sej/hr	This Study	1.85E+11
	Side Flange (RH)	1	10.34	sec	6.54E+13	sej/hr	This Study	1.88E+11
	Stiffener	1	7.60	sec	6.54E+13	sej/hr	This Study	1.38E+11
	Lug	2	12.52	sec	6.54E+13	sej/hr	This Study	4.55E+11
Mfg Equipment - Bend								
	Base	1	11.50	sec	1.00E+13	sej/hr	This Study	3.20E+10
	Side Flange (LH)	1	26.50	sec	1.00E+13	sej/hr	This Study	7.37E+10
	Side Flange (RH)	1	26.50	sec	1.00E+13	sej/hr	This Study	7.37E+10
	Stiffener	1	19.00	sec	1.00E+13	sej/hr	This Study	5.28E+10
	Lug	2	11.50	sec	1.00E+13	sej/hr	This Study	6.39E+10
Mfg Equipment - Weld								
	Assembly	1	169.36	sec	1.45E+12	sej/hr	This Study	6.80E+10
Mfg Machine Operating Power - Laser								
	Base	1	12.51	sec	4.16E+12	sej/hr	This Study	1.45E+10
	Side Flange (LH)	1	10.18	sec	4.16E+12	sej/hr	This Study	1.18E+10
	Side Flange (RH)	1	10.34	sec	4.16E+12	sej/hr	This Study	1.20E+10
	Stiffener	1	7.60	sec	4.16E+12	sej/hr	This Study	8.79E+09
	Lug	2	12.52	sec	4.16E+12	sej/hr	This Study	2.90E+10
Mfg Machine Operating Power - Bend								
	Base	1	11.50	sec	4.66E+12	sej/hr	This Study	1.49E+10

Item	Part	Qty	Value	Unit	UEV	Unit	Source	Emergy (sej)
	Side Flange (LH)	1	26.50	sec	4.66E+12	sej/hr	This Study	3.43E+10
	Side Flange (RH)	1	26.50	sec	4.66E+12	sej/hr	This Study	3.43E+10
	Stiffener	1	19.00	sec	4.66E+12	sej/hr	This Study	2.46E+10
	Lug	2	11.50	sec	4.66E+12	sej/hr	This Study	2.98E+10
Mfg Machine Operating Power - Weld								
	Assembly	1	169.36	sec	5.83E+12	sej/hr	This Study	2.74E+11
Processing Supplies - Laser Gas								
	Base	1	12.51	sec	6.94E+09	sej/hr	This Study	2.41E+07
	Side Flange (LH)	1	10.18	sec	6.94E+09	sej/hr	This Study	1.96E+07
	Side Flange (RH)	1	10.34	sec	6.94E+09	sej/hr	This Study	1.99E+07
	Stiffener	1	7.60	sec	6.94E+09	sej/hr	This Study	1.46E+07
	Lug	2	12.52	sec	6.94E+09	sej/hr	This Study	4.83E+07
Processing Supplies - Laser Assist Gas								
	Base	1	12.51	sec	3.61E+08	sej/hr	This Study	1.25E+06
	Side Flange (LH)	1	10.18	sec	3.61E+08	sej/hr	This Study	1.02E+06
	Side Flange (RH)	1	10.34	sec	3.61E+08	sej/hr	This Study	1.04E+06
	Stiffener	1	7.60	sec	3.61E+08	sej/hr	This Study	7.62E+05
	Lug	2	12.52	sec	3.61E+08	sej/hr	This Study	2.51E+06
Processing Supplies - Weld								
	Wire L & S	1	0.03	USD	2.02E+12	sej/USD	[127]	6.36E+10
	Wire	1	0.03	kg	4.69E+09	sej/g	[126]	1.22E+08
Setup - Laser								
	Base	1	0.08	hrs/batch	1.92E+14	sej/hr	This Study	1.92E+10
	Side Flange (LH)	1	0.08	hrs/batch	1.92E+14	sej/hr	This Study	1.92E+10
	Side Flange (RH)	1	0.08	hrs/batch	1.92E+14	sej/hr	This Study	1.92E+10
	Stiffener	1	0.08	hrs/batch	1.92E+14	sej/hr	This Study	1.92E+10
	Lug	2	0.08	hrs/batch	1.92E+14	sej/hr	This Study	1.92E+10
Setup - Brake								
	Base	1	0.75	hrs/batch	1.37E+14	sej/hr	This Study	1.24E+11
	Side Flange (LH)	1	0.75	hrs/batch	1.37E+14	sej/hr	This Study	1.24E+11

Item	Part	Qty	Value	Unit	UEV	Unit	Source	Emergy (sej)
	Side Flange (RH)	1	0.75	hrs/batch	1.37E+14	sej/hr	This Study	1.24E+11
	Stiffener	1	0.75	hrs/batch	1.37E+14	sej/hr	This Study	1.24E+11
	Lug	2	0.75	hrs/batch	1.37E+14	sej/hr	This Study	1.24E+11
	Setup - Weld							
	Assembly	1	1.00	hrs/batch	1.40E+14	sej/hr	This Study	1.68E+11
	Plant Overhead - Laser							
	Base	1	12.51	sec	4.54E+13	sej/hr	This Study	1.58E+11
	Side Flange (LH)	1	10.18	sec	4.54E+13	sej/hr	This Study	1.28E+11
	Side Flange (RH)	1	10.34	sec	4.54E+13	sej/hr	This Study	1.30E+11
	Stiffener	1	7.60	sec	4.54E+13	sej/hr	This Study	9.58E+10
	Lug	2	12.52	sec	4.54E+13	sej/hr	This Study	3.16E+11
	Plant Overhead - Brake							
	Base	1	11.50	sec	3.44E+13	sej/hr	This Study	1.10E+11
	Side Flange (LH)	1	26.50	sec	3.44E+13	sej/hr	This Study	2.54E+11
	Side Flange (RH)	1	26.50	sec	3.44E+13	sej/hr	This Study	2.54E+11
	Stiffener	1	19.00	sec	3.44E+13	sej/hr	This Study	1.82E+11
	Lug	2	11.50	sec	3.44E+13	sej/hr	This Study	2.20E+11
	Plant Overhead - Weld							
	Assembly	1	298.36	sec	3.53E+13	sej/hr	This Study	2.92E+12
Total								4.94E+13

Figures 3.19a and 3.19b summarize the top-level contributions using two different schemas. Figure 3.19a splits the total emergy up by part and assembly process. As can be seen, the assembly process contributes the most emergy compared with the individual parts. The base, the second largest contributor, represents slightly more than half of the emergy from welding. Figure 3.19b summarizes the emergy contributions for the full assembly by manufacturing element. From this comparison of data, the labor and material

dominate the emergy contribution with the plant overhead coming in a distant third at about one-fifth that of the material contribution.

(a) Energy for parts and welding in example assembly.

(b) Energy in example assembly by manufacturing elements.

Figure 3.19. Emery in example assembly.

Figure 3.20 gives emery composition for each of the five parts plus the assembly activity. Figure 3.20a shows the breakdown of the welding step, where labor is the major contributor with a small addition from facility overhead. Reviewing the remaining graphs

for the components, the largest contributor for each is material, followed by labor. For the lug, the material contribution is much lower than for other parts, and the base much higher.

(a) The composition of energy for welding. (b) The composition of energy for stiffener part.

(c) The composition of energy for side flange RH part. (d) The composition of energy for side flange LH part.

(e) The composition of energy for lug part. (f) The composition of energy for base flange LH part.

Figure 3.20. The emergy in the example assembly by manufacturing elements for each part and welding.

CHAPTER 4

Model Implementation

4.1 Software Design

To support the calculation of the total emergy for individual parts created through the laser and weld machines and for MIG welded assemblies directly from a CAD file, an emergy model was built in parallel with a cost model in the aPriori software. This emergy model could then be accessed through a custom display tool, known as aPriori macros. Figure 4.1 diagrams this structure for part calculations. Shapes in gray have been customized as part of the implementation of the emergy model.

Figure 4.1. The structure of customizations to aPriori software to support emergy calculation for parts [14].

The aPriori software supports three areas for customization: the data layer, the cost model, and the macro layer. The data layer consists of customizable data tables that define

machines, materials, and other values required to complete calculations. The cost model defines the calculations for cost, taking the values in the data layer and from a geometry engine, which decomposes the input CAD file into the geometric elements that drive cost in manufacturing (for example, mass, flattened size, and hole dimensions). These inputs are used to produce the outputs of the cost model layer, including: manufacturing cost, and, in the case of this dissertation study, emergy. The macro layer is used by aPriori to create custom displays of data calculated by the cost model. The cost model layer can be executed headless (without opening the user interface), which gives the opportunity to override values in the model, and review specific outputs using an automation tool set.

To support the emergy calculation, variables were added to the data layer to support calculations in the cost model. Data were added to each of the part processing machine definitions—laser and bend—and a selection of variables were added to the general variables in the data layer. These variables are leveraged in the cost model. Two existing cost model files were altered—the process taxonomy files for both the laser and bend—to include calculations for emergy, and access to relevant inputs and outputs to support headless execution. In addition, two function library files were created to support the emergy calculations in the taxonomy files. The remainder of the cost model was left as is. Details on the code added to the taxonomy files and the emergy function libraries are presented in Appendix J. It should be noted that these files are written in CSL, a language for the aPriori cost models.

Two files are required to support the custom display built in the macro layer for showing emergy results. The XML (eXtensible markup language) file defines the display output, including the layout of the outputs and other user interface controls. The XML file is supported by a CSL file, which calls values from the cost model. Both these files are entirely custom, built only in support of this dissertation study. The macro code files are presented in Appendix J.3.

Figure 4.2 shows a similar layout for the calculation of cost and emergy at the assembly level. The assembly level calculation consists of the same basic structure, with a data layer, a cost model, and a macro layer. What is added, though, is a reference to the previously calculated parts that make up the assembly BOM. These data are accessible to the cost model at the assembly level. It should be noted that calculations must be completed prior to the assembly-level calculations to ensure that data are correctly summed. Additionally the geometry engine pulls the structure of the assembly BOM, as well as the definition for each weld added in the aPriori software.

Figure 4.2. The structure of customizations to aPriori software to support emergy calculation for welded assemblies [14].

To support the emergy calculation at the assembly level, the data layer has three updated elements: the definition of the pick-and-place (load and unload) activity, the manual MIG welding machine definition, and the addition of general variables to support the emergy calculation. Due to the architecture of the aPriori software, the same variables defined at the part level must be redefined at the assembly level. The cost model, similar to the part level, has two modified files—the process taxonomy files for both pick-and-place, and manual MIG welding—plus the addition of two function library files to support the emergy

calculations in the taxonomy files. Again, these files contain similar content, but due to architectural reasons, they must be recreated within the assembly cost model. Access to relevant inputs and outputs to support headless execution of the aPriori software was also added to these files. The remainder of the cost model was left as is. Details on the CSL code added to the taxonomy files and the emergy function libraries are presented in Appendix J.

Within the macro layer, a separate XML file is defined for supporting the assembly user interface. These references to the CSL files are leveraged by both the assembly and the part XML macro files. As noted with the part macro, both these files are entirely custom, built only in support of this dissertation study. The code for these files are presented in Appendix J.3.

4.2 Method

4.2.1 Changes to the aPriori Software Model

Changes were made to the standard USA region VPE in the aPriori software to better align with the emergy assessment, in addition to adding code specific to emergy. This Section gives a short summary of these adjustments so they can be reproduced by trained aPriori cost model builders. These are not intended to serve as step-by-step instructions for executing cost modeling changes.

An initial set of changes were completed to streamline the content of the model. To better align the baseline aPriori model with the emergy model, the following were included:

- Copying the baseline USA VPE, removing all processes except sheet metal, assembly, and user guided costing
- Editing routings
 - Removing all assembly routings, but pick-and-place, followed by manual MIG welding

- Removing all sheet metal routings except CTL/Laser/Bend, then editing to remove CTL and all bending processes other than brake
- Removing cost of welding gas and antisplatter spray from the cost model
- Adjusting pick-and-place machine data (size, worker type) to align with that of the weld station
- Removing all machines for manual MIG welding, laser cut, and bend brake except those noted in Section 3.4.2

Following this base set of changes, code to support the emergy calculation was added with the addition of structural elements. The code additions, detailed in Appendix J, consisted of calculations added to process taxonomy files for laser cut, bend brake, manual MIG welding, and pick- and-place processes. Supporting library files were also created.

Based on the structure of the VPE, two additional activities were completed that are not shown in the code in Appendix J. The changes were (i) including emergy sums through routing nodes, (ii) creating exposed variables, and (iii) building process setup options. The combination of these changes enabled access of summed emergy values throughout the nodes of the cost model tree, including access to the part-level emergy results at the assembly level, and access to emergy inputs and outputs for automation of the model, and the use of the macro layer.

4.2.2 Macros

The code changes noted in Section 4.2.1 supported the use of the macro layer in the aPriori software to provide the emergy information in a custom user interface window. Two macros were constructed, one to support part-level evaluations and one to support assembly-level evaluations. The code written for the macros and the supporting calculation code are provided in Appendix J.3.

Figures 4.3 and 4.4 show the outputs of the assembly and part-level macros, respectively. Both macros show similar information, with a summary on the left side of the window and the detailed break down of energy data on the right. The summary includes the total energy for the analysis—either for the part or assembly—and a breakdown of the energy into different categories with percentage contribution for each of those groups. Each category is split further, with the detailed contributions within each.

Figure 4.3. The display with aPriori Macros showing part energy [14].

The part categories, as shown in Figure 4.3, are the material, the laser, and the bend. The material category covers the energy in the raw material. The laser and bend categories show the contributions for processing with each of the machines for the part displayed by aPriori software. For material, the contributions are split into those from the material directly and those from labor and services. With contributions from both the laser and the bend processing, the total is split into that from the operator, the machine (the equipment, its installation, and its maintenance), the power required to run the machine, the setup, and

Figure 4.4. The display with aPriori Macros showing assembly emergy [14].

the indirect overhead from the facility (support staff, utilities, and factory building). The laser additionally includes the supplies for gases.

The emergy accounting sum at the assembly-level includes the emergy of each part plus that from the assembly activities. The summary includes three categories: the material, the welding, and the components. The material category is the sum of all the material emergy values for the parts making up the assembly. Much like the part layout, emergy is included for the material directly and the labor and services associated with the material. The welding category includes both the pick-and-place and welding activities. The weld category is further split into the same categories as both the bend and laser with a single supplies grouping covering the weld wire. Finally, the emergy from the processing (laser and bend activities) for the parts are summed for the component category. The sum of all the components are combined into the same manner as for welding, with the supplies category representing a sum of the laser and assist gas from each component.

With these macros installed in combination with the changes outlined in Section 4.2.1, an user of the aPriori software can find the total emergy for any part that is laser cut and bent or for any assembly of laser cut and bent parts that are welded. This allows comparison of emergy at both the part and assembly level to support decision-making during the design process.

4.3 Example Output

Figure 4.5 shows the macro output from the aPriori software for all the components that make up the example assembly explored in Section 3.4.11. As can be seen in comparing the values, the output given in the aPriori software for total emergy— $4.936\text{E}13$ sej—is equal to that displayed in Table 3.33— $4.94\text{E}13$ sej. A similar comparison for each part, as shown in Figure 4.6, can be made, showing identical results. These results verify accurate implementation of the emergy equations based on the DFM results of the analyses produced by the aPriori software.

Figure 4.5. The display in aPriori Macros showing the total emergy in the example assembly.

(a) The display in aPriori Macros showing the total energy in the example part Base Flange. (b) The display in aPriori Macros showing the total energy in the example part Side Flange LH.

(c) The display in aPriori Macros showing the total energy in the example part Side Flange RH. (d) The display in aPriori Macros showing the total energy in the example part Stiffener.

Figure 4.6. The emergy display in aPriori software showing the outputs for the example parts.

(e) The display in aPriori Macros showing the total energy in the example part Lug.

Continued Figure~4.6. The emergy display in aPriori software showing the outputs for the example parts.

4.4 Sensitivity Analysis of Emergy Inputs

When building the aPriori model, the entire model for emergy outlined in Chapter 3 was initially encoded into a spreadsheet to provide an easy method for validating results. The spreadsheet was created to work for a the DFM analysis of a single design and was used to generate the results in Section 3.4 for the example design. The design of the spreadsheet allowed for easy automation by modeFRONTIER™ from ESTECO [214] for investigating the sensitivity of various inputs into the emergy model for manufacturing.

Figure 4.7 shows the workflow in modeFRONTIER for completing the sensitivity analysis. The definition of input values for the analysis are listed above the main workflow. A design of experiments was used, with a uniform Latin hypercube (ULH) distribution of points. In the center of the the workflow is the spreadsheet interaction. A selection of inputs are shown above the Excel node. Figure 4.7 has a representative set of inputs. The

Figure 4.7. The modeFRONTIER [214] workflow for completing sensitivity analysis of spreadsheet-based emergy model.

full set of inputs and their ranges are given in Table 4.1. Below the spreadsheet node is the single output of total emergy.

The input variables selected for sensitivity investigations were the key inputs and the largest contributors as shown in Figure 3.19b: material, labor, and plant overhead (facility-related emergy). In reviewing the breakdown for the materials of any given part in the example assembly, as given in Figure 4.6b, it can be noted that material cost is the sum of material and the related labor and services.

To address material aspect, the UEV for steel was included in the analysis (variable name: Steel_Virgin_UEV_no_L_S), with the range defined based on the values for steel discussed in Sections 2.4.5 and 3.4.4. The selected upper bound corresponded to the highest value in Table 2.10 for BOF steel from Buranakarn [132]. The lower bound corresponded to a value provided for CR Coil from Ma et al. [135], which was the lowest value provided in Table 2.10 for any process type. It should be noted that this variable also contributes to the UEV for the manufacturing equipment and the steel in the construction of the factory.

Table 4.1. Variables Used in Sensitivity Analysis for the Spreadsheet Based Emergy Model

Variable Name	Definition	Units	Bounds	
			Lower	Upper
Number_of_Years_for_Education	Number of years emergy of education is split across	yr	1	30
UEV_Concrete_noLS	UEV for concrete	sej/g	1.23E9	1.51E9
Dollar_UEV_no_LS	Emergy-to-dollar ratio	sej/USD	1.39E12	2.65E12
Metabolic_Calories_Per_Day	Metabolic calories per day required for a human	kcal	2400	2900
UEV_Land_Erosion_no_L_S	UEV for land erosion under construction	sej/J	84780	103620
UEV_Hourly_Labor_Services	UEV for services (power, heat, vehicles) supporting labor	sej/hr	1.50E12	1.83E12
Steel_Virgin_UEV_no_L_S	UEV for virgin BOF steel	sej/g	3.93E9	6.75E9

The labor and services for raw material was driven by the emergy-to-dollar ratio, which was included in the analysis (variable name: Dollar_UEV_no_LS). The lower bound for this variable was defined based on the value for the emergy-to-dollar ratio for the year 2000 from Campbell et al. [127]. For the upper bound, the value from 2000 was subtracted from the 2011 value from the same source, with that difference added to the 2011 value. It should be noted that this variable contributes to other areas, such as factory construction, the emergy value for machines and supplies.

The emergy calculation for labor had three contributing elements, as noted in Section 3.3.2: metabolic, education, and supporting services. Variations in each was examined in the analysis. For the metabolic value, the number of kilocalories required per day (variable name: Metabolic_Calories_Per_Day) was varied between 2400 kcal and 2900 kcal. The upper bound was 100 kcals higher than the value used by Zhang and Dornfeld [57] and the lower bound was 100 kcals lower than that used by Odum [60]. A major assumption of the emergy of education attributed to a worker was the number of years the education was

distributed across (variable name: Number_of_Years_for_Education), as noted in Section 3.3.2. For the main part of this dissertation study, it was assumed to be 1 year, which was used for the lower bound of this analysis, and the upper bound was set to 30 years based on the highest value gathered for a career length from the US BLS [215].

The final contributing factor evaluated for labor was the UEV for services supporting labor, such as electricity and heat (variable name: UEV_Hourly_Labor_Services), which was calculated in Section 3.3.2. For this, the upper and lower bounds were set to $\pm 10\%$ of the initial value. It should be noted that changing these factors also impacted the indirect labor in the facility emergy value, as detailed in Section 3.3.7, and the value for emergy in the welder, since that includes an estimated assembly time, which was detailed in Section 3.4.7.

The emergy calculation for the factory includes two other components not covered by previously defined variables for analysis: the UEV for impact of the land (variable name: UEV_Land_Erosion_no_L_S) and the UEV of concrete (variable name: UEV_Concrete_noLS). For each of these, the default values, described in Section 3.4.8, were varied by $\pm 10\%$ to establish lower and upper bounds, respectively. These two inputs have no impact elsewhere in the emergy model.

Within the context of this model, input variables listed for sensitivity analysis are independent of each other. Not included here are the impacts of changing values of these inputs for supporting models—for example, the education model produced by Campbell et al. [103], includes an emergy-to-money ratio to produce the emergy outputs for the various education levels. Adjustment of these models is not included as part of this analysis. Finally, all variables were defined as continuous variables.

A total of 1010 iterations were completed and a sensitivity analysis using an SSANOVA was conducted in modeFRONTIER, resulting with an R^2 of 0.98, and an average colinearity for the input variables of 1.003. Throughout these iterations, the output emergy varied from 1.94E13 sej (iteration 735) to 5.04E13 sej (iteration 8). Appendix K.1 lists the full set of

responses ordered by iteration number. The resulting contributions to variance are shown in Figure 4.8. The variable with the largest effect on variance is the energy-to-dollar ratio, followed closely behind by the number of years over which the energy of education was split. At half the effect is the UEV for steel with no labor and services included. The remaining inputs have comparatively no impact.

Figure 4.8. The contribution to variance results in the emergy model as shown in modeFRONTIER software.

Figure 4.9 shows the correlation matrix from modeFRONTIER using the Pearson coefficient (a measure of a linearity between two variables) with a scatter plot of each input and the output emergy. As expected from the contributions to variance, the Pearson coefficients with the largest absolute value (therefore, the most correlated), when evaluated against the total emergy of the example assembly are related to the energy-to-dollar ratio, the UEV for steel, and the number of years over which the emergy of education is divided. The first two variables have a direct relationship with the total emergy, whereas the number of years over which the emergy of education is divided has an inverse (negative) correlation. These

results are reasonable based on the model. Both the steel and emergy-to-dollar ratio are used in a direct manner, as shown in Equations 36, 45, and 57. The number of years over which the emergy of education is divided, though, would serve as a divisor of the values in Table 3.2; hence, the negative correlation.

Figure 4.9. The correlation matrix of energy model as shown in modeFRONTIER software.

The scatter plots in the most-right column of the correlation matrix in Figure 4.9 show the resulting total emergy graphed against the input variables. In reviewing these results, the behavior of the number of years the emergy of education is divided over demonstrates a much higher effect for lower values, with the effect becoming difficult to see at higher values. Looking more closely at these data, as shown in Figure 4.10, this impact disappears completely around 7 years.

The effect can also be seen in the scatter plots of the emergy-to-dollar ratio and the steel UEV in the most-right column of the correlation matrix in Figure 4.9. In both of these scatter plots there is a main band of emergy responses, with a clear floor. On the

Figure 4.10. A scatter plot showing total emergy of example assembly versus number of years over which the emergy of education is divided.

far-right, though, there is a scattered result of points. During investigation, it was found that the most of these points are from cases where the number of years the emergy of education is divided over is less than 2 years. Figure 4.11 shows this case more clearly: the circled points indicate where the emergy of education is split over less than 2 years. Similar behavior can be seen with all remaining scatter plots in the right-hand column.

Figure 4.11. Scatter plot showing total emergy of example assembly versus energy-to-dollar ratio, with points where the number of years over which the emergy of education is divided is less than 2 years circled.

4.5 Sensitivity Analysis of Geometry

Sensitivity analysis based on geometric changes to a CAD model was conducted on by leveraging a headless execution mode in the aPriori software. The automation of the evaluation was conducted using modeFRONTIER. Figure 4.12 shows this workflow. The definition of the design of experiments is the input to the workflow, and used a (ULH) distribution of points. Connected to the scheduler is the SolidWorks node, which interacts with the CAD model being altered. Above and connected to the SolidWorks node are the inputs to the geometry and below it are two outputs from the geometry: the physical volume and the mass.

Figure 4.12. The software workflow in modeFRONTIER for completing sensitivity analysis of energy based on geometry.

The remaining nodes in the workflow show the interaction with the aPriori software. The node named EasyDriver3 executes the command-line script to run the aPriori software in headless mode. The inputs from above this node represent the supporting files required to execute the aPriori software. The aPriori software outputs a spreadsheet file that provides the outputs required by analysis. This case includes the cost to manufacture the part from based on the aPriori cost model, the material utilization for the part, and its emergy.

For this assessment, a single, parametrically modeled part provided by ESTECO was used, as shown in Figure 4.13. Four dimensions were chosen as parameters to vary: the

thickness of the raw material, the diameter of the hole, the width of the strip. and overall height of the part. These are marked in Figure 4.13. Table 4.2 gives the lower and upper bounds used for each of the variables in this assessment.

Figure 4.13. The parametrically modeled part used for sensitivity analysis of geometry.

Table 4.2. The variables used in completing sensitivity analysis for geometry impact to energy.

Variable Name	Definition	Units	Bounds	
			Lower	Upper
Width	Width of U-shape	mm	30.0	60.0
Thickness	Thickness of raw material	mm	1.0	8.0
HoleDiam	Diameter of internal hole	mm	2.0	8.0
Height	Overall height of strip	mm	30.0	70.0

After test runs, additional changes were made in the aPriori cost model. First, it was found that due to CAD modeling errors, two bends on the part would fail to generate a cycle time at higher thicknesses. The failure is due to a standard manufacturing rule to avoid cracks in materials. The rule checking this in the aPriori software was overridden to avoid failure. Additionally related to the bend are rules related to the flap size of the bend. If the open side of a bend is too short relative to its thickness, it can require special

handling. For this part, it was assumed that all bend flaps could be made with standard tooling. As such, this rule was disabled.

Finally, the hole on the part cannot be made by the laser if the diameter of the hole is less than one-half the thickness of the material based on recommended kerf size (width of cut and laser-effected zone) for the material thickness. In these cases, the aPriori software was producing the hole with a drilling operation on a 3-axis mill. Since the 3-axis mill was not included as part of the energy modeling, the option to have the hole made in that manner was removed. The rule evaluating this, though, was not removed. The effect of leaving this rule in place is discussed later in this Section.

A ULH algorithm was used to choose 1000 points for a design of experiments. The set of completed runs and results were ordered by the iteration number in Appendix K.2. The main effects sensitivity results for the contributions of variance using an SSANOVA in modeFRONTIER are shown in Figure 4.14. As can be seen, the thickness had the largest effect, the height and width had smaller effects, and the hole diameter had almost no effect. The R^2 for this result is 0.98, with a mean colinearity for the inputs of 1.0003.

Figure 4.14. The contribution to variance results from the sensitivity analysis in modeFRONTIER software for the main effects of geometry.

A sensitivity analysis of the interaction effects was also completed. These results are shown in Figure 4.15. Here, the thickness still dominated with height being the second contributor, but two interactions are included before the width—the interaction between

the height and thickness, and the interaction between the hole diameter and thickness. The R^2 for this result is 0.99, with a mean colinearity for the inputs of 1.008.

Figure 4.15. The contribution to variance results from the sensitivity analysis in mode-FRONTIER software for the interaction effects of geometry.

The largest value for energy was on iteration number 206 with an energy value of 9.88E12 sej. The geometry for this part is shown in Figure 4.16b. The smallest value for energy was on iteration number 854 with an energy value of 2.96E12 sej. This is shown in Figure 4.16a. The values for each of the inputs for these examples are shown in Table 4.3. As can be noted, the largest energy value is associated with a large part and the smallest is associated with a small part.

Table 4.3. Input Geometry Values for Iterations with Smallest (854) and Largest (206) energy values.

Iteration Number	206	854
Height	69.43	30.19
Hole Diam (mm)	6.02	4.56
Thickness (mm)	7.95	1.23
Width (mm)	58.15	33.66
Energy (sej)	9.88E+12	2.96E+12
Part Cost (USD)	3.15	0.74

To examine these results further, Figure 4.17 shows the correlation matrix from mode-FRONTIER for this set of data using the Pearson coefficient with a scatter plot. Each input is plotted against each other and the output energy, cost, and material utilization. First

(a) The geometry of the test part for iteration number 854. (b) The geometry of the test part for iteration number 206.

Figure 4.16. Geometry for iterations with the smallest (854) and largest (206) energy values from the sensitivity analysis.

of note is the Pearson coefficient between cost and energy as a value 1, showing a direct correlation between the two values. The energy model used within this dissertation study is built as an analogy to the the cost model implemented in the aPriori software.

Reviewing the major contributors identified in the sensitivity analysis, thickness has a high direct relationship with energy. This relationship is demonstrated with the scatter plot of thickness versus energy shown in Figure 4.18a. This plot shows a greater variation of energy results at larger thicknesses as other variables adjust, which is due to the impact of the material overall on the energy, as explored in Section 4.4. At larger thicknesses changes to the other variables (width, height) result in a larger absolute variation of the rough mass than with smaller thicknesses, as shown in Figure 4.18b.

As shown in the correlation matrix in Figure 4.17, the utilization of the sheet has a strong inverse relationship with energy. This is expected since as the utilization increases there is less sheet scrap attributed to a part and potentially more parts per sheet resulting in a different expression of rough mass. Figure 4.19a shows the iterations plotted by rough

Figure 4.17. The correlation matrix output from modeFRONTIER based on the sensitivity analysis of geometry.

mass versus energy. Viewing these data in this way demonstrates the offset of a group of data to a higher energy level, starting at 0.03 kg, than would be expected following the trend of points with rough masses less than 0.03 kg.

Following an investigation of the implemented energy model, two reasons were identified for the offset data. The first has to do with how the cycle time for the laser is calculated in the aPriori software. The speed at which the laser cuts and pierces the sheet is based on the thickness of the material being cut with steps occurring at specific thicknesses. For the laser used here, the Cincinnati CL800, there are two such break points—one at 4.57 mm and a second at 6.35 mm. Figure 4.19b replots the rough mass data versus energy showing the data grouped by these breakpoints with triangles and Xs showing the thickest parts—those above 6.35 mm.

With this solution in mind, the next concern is why there is a split in the data above 6.35 mm. Those marked by X clearly have higher energy than those marked with a triangle.

(a) A scatter plot showing total part energy versus thickness.

(b) A scatter plot showing rough mass versus thickness.

Figure 4.18. Two scatter plots of thickness.

A selection of the iterations marked with a triangle were reviewed and it was discovered that these are parts where the diameter of the hole was less than half the thickness of the material. In this case, the hole fails and is not included in the energy calculation, and results in a lower total energy value than expected for a thick part.

In completing this investigation, an additional factor was identified as contributing to an unexpected energy values. This factor was related the contributor ranked second in Figure 4.14: the height. While the correlation for the height is much smaller than that of

(a) A plot of showing total part energy versus rough mass.

(b) A plot of showing total part energy versus rough mass with various sheet thickness detailed.

Figure 4.19. Two plots of rough mass graphed versus energy.

the thickness for the full set of iterations, height has a much larger impact when parts are thicker. From the full set of 1000 points, those with a thickness greater than 6.35mm were selected, for a total of 238 points. A sensitivity analysis was run on this set of iterations resulting in the contributions to variance shown in Figure 4.20. The R^2 for this analysis was 0.98, and colinearities for the input variables of 1.007.

Figure 4.20. The contribution to variance from the sensitivity analysis in the modeFRONTIER software for main effects of geometry for iterations with thickness greater than 6.35 mm.

The difference in this result can be clearly seen in the correlation matrix for this reduced set of iterations, shown in Figure 4.21. The explanation for this behavior change relates to the number of parts per sheet. When parts are thin, the extra mass of the sheet and cycle time to complete the additional cuts on the skeleton (see Appendix A) add limited emergy per part, so the number of parts per sheet is less critical. For thicker parts, both the extra mass and cycle time for the skeleton cuts increase, so there is a larger decrease in emergy for every additional part per sheet.

The effect of these behaviors can also be seen in the cost versus emergy plot for the full set of iterations, shown in Figure 4.22. The same behaviors as seen in the rough mass

Figure 4.21. The correlation matrix of geometry inputs from modeFRONTIER software for iterations thicker than 6.35 mm thick.

versus energy can be seen in the cost versus energy plot. An offset for the iterations where the hole failed, resulted in thick parts with small values for the height (and thus a high number of parts per sheet), which fell well below the expected line, and caused a jump in the expected energy result for designs with a thickness above 6.35mm and the hole included.

(a) A plot of energy versus cost showing splits by thicknesses and whether the hole was included for the thickest parts.

(b) A zoomed-in version of energy versus cost showing the differences for including or not including the laser cut hole.

Figure 4.22. Two plots of cost versus energy.

CHAPTER 5

Workshop

5.1 Purpose of the Workshop

To test the effectiveness of the emergy tool described in Chapter 4 to improve the sustainability of products designed by engineers, an experimental workshop was designed. Experimental workshops are commonly used to test sustainability decision-making techniques and evaluate software, as described in Section 2.5. Following the workflow shown in Figure 5.2, participants completed two sets of surveys to evaluate the sustainability of alternative designs: one before the introduction of emergy and the prototyped software tool and one after.

This structure follows a common procedure for evaluation of a tool. Both Midžić et al. [140] and Telenko and Wood [27] had study participants initially rank designs for sustainability based on their current level of knowledge. Like Midžić et al. [140], this dissertation study asked participants to compare different alternatives of the product or design. This dissertation study, though, did not look at an entire product, as done in both of these previous studies. Instead, it focused on the example assembly introduced in Chapter 3. Additionally, it specifically evaluated the sustainability of the series manufacturing processes used, instead of the life-cycle sustainability of the entire product.

Like Sinclair et al. [141], Borrion et al. [142], and González-Pérez et al. [143], this study tested the usability of a software tool and included training within the experiment on how to use the tool. Whereas Sinclair et al. [141] and Borrion et al. [142] tested with nonspecialized community members, this study used an approach like that of González-Pérez et al. [143] and Telenko and Wood [27] targeting a group of participants who have specialized knowledge or educational background.

5.2 Design Alternatives

As noted in the previous section, a selection of design alternatives for the example assembly introduced in Chapter 3 were created to support the workshop. Starting with the original design, 10 additional design alternatives were developed, using principles from DFM and DFA [9, 11]. The 10 design alternatives, the principles used to develop them, and the outputs from the energy macro in the aPriori software for each assembly, and the parts they consist of are given in Appendix L. A summary of the energy results for the alternatives are shown in Figure 5.1.

Figure 5.1. A summary of energy results for design alternatives A through J.

From these 10 alternatives, six were selected (A, B, D, F, G, and J) for use within the workshop as representing the breadth of possible results while balancing a manageable number of alternatives for the workshop. Some were selected due to unintuitive results based on standard DFM and eco-design recommendations. For example, a common rule for reducing material usage, which is a principle of both DFM and eco-design, was to reduce part count. Alternative B, which had fewer parts, had higher energy than the original design.

For each of these seven alternatives (six new designs and the original), information regarding the manufacturing results were gathered from the aPriori software analysis. This included the rough mass, material utilization, routing, and cycle-time for each part, as well

as the cycle-time and finish mass of the assembly. This information was organized into a single slide for each alternative, as shown in Appendix N. The use of these slides will be described in the next section.

5.3 Participants and Setup

Engineering students at the University of Rhode Island (URI) were recruited for the study. Study participants were required to be over the age of 18 and enrolled in or have completed an engineering degree. Preference was given to those in industrial and mechanical engineering, though all engineering disciplines were accepted. The survey used to determine eligibility is included in Appendix M. The experiment was conducted in an engineering computer lab at the URI, Kingston campus. Prior to the workshop, the aPriori software was installed on the computers. Into the aPriori software database, the seven relevant design alternatives were loaded along with the VPE that included energy calculations. Additionally, the customized energy macros were installed within the aPriori setup to support energy evaluation of the designs.

The ranking portion of the surveys was evaluated to see if the participants correctly ranked the most and the least environmentally friendly designs. This is the quantitative focus of the survey. The chances of this occurring randomly (p) would be:

$$p = \frac{1}{n_{alts}} \frac{1}{n_{alts} - 1} \quad (70)$$

where n_{alts} is the number of designs the participants evaluated. Seven designs are proposed, giving a probability of guessing the correct position for these two designs randomly at 2.4%. Since ranking individual designs for sustainability was not a common task within a population of engineers, it is unlikely that performance on this task was better than random. With the software, the expectation was that the participants were able to correctly rank all designs. With this in mind, the standard sample-size equation is used:

$$s = \frac{Z_{1-\alpha/2}^2 p(1-p)}{d^2} \quad (71)$$

where a *p-value* (α) of 0.05 is assumed resulting in a $Z_{1-\alpha/2}^2$ a value of 1.96 and a value for the margin of error (d) of 0.05, representing a 5% confidence level. Both of these are deemed acceptable since prescreening occurred when choosing participants. This resulted in a target sample size of 36 participants, which is validated by looking at similar studies drawing from similar populations. Smaller sample sizes were used by Midžić et al. [140] and Telenko and Wood [27].

5.4 Workshop

Figure 5.2. The workflow for participants in the experimental workshop conducted for this study.

The workflow for the workshop is shown in Figure 5.2. The eligible participants attended the experiment during an arranged workshop time. Upon check in, participants received consent forms. Once they completed the consent form, they received a number and the first survey. The experimental lead, after a short introduction, gave a 10-minute presentation covering the schedule of the experiment, how to understand the data provided

on the design alternatives, and basic instructions for completing the survey. This presentation was also provided to the participants as a file on the computer. This presentation is provided in Appendix N.

The initial survey included questions on participants' backgrounds related to both engineering and environmental analysis. The participants were then asked to rank the design alternatives against each other for manufacturing sustainability based on the provided information for each. The full survey used is included in Appendix O.

Once the first task was completed, the participants were given the second survey and two presentations. The first was an approximately 25 minute introduction to the concept of emergy, as provided in Appendix N.2. This presentation included an introduction to why energy, generally, is a powerful sustainability metric, and why emergy, specifically, is the strongest of the common energy measures. Following this, some detail was given on how emergy evaluation works, including two examples from the literature by Odum [60] and Almeida et al. [99]. The examples shown were the emergy of a forest provided by Odum [60], as shown in Figure 2.11; and the emergy in coated fasteners from Almeida et al. [99].

Building on this structure, the analogy of emergy-to-cost was introduced, with a review of detailed equations. This led into a discussion of the model built into the aPriori software and how to read the results from the system for assemblies and parts. The presentation finished with a clear instruction on comparing the emergy in two alternatives and how the lower emergy is the more sustainable option.

Following the introduction to emergy and addressing questions asked by participants during the presentation, the participants were instructed to open the software and requested to follow along with a short training on how to open the assemblies and evaluate their emergy. This also included basic instructions for completing the second survey. The slides used to provide the software training are provided in Appendix N.3.

The second survey asked the participants to use the tool developed in aPriori Macros to evaluate the manufacturing sustainability of the same designs reviewed in the first survey. In these cases, though, the participants were able to access the emergy results, as shown in Appendix L, for the design alternatives. Following this activity, the survey had a set of questions regarding the ease of use of the software, the ease or difficulty of understanding the metric of emergy, and if the metric of emergy provided enough information for them to compare designs. Finally, the survey had a question for each participant to suggest three further improvements to the most sustainable design. The full second survey is provided in Appendix P. Once the participants completed the second survey, they were each given a \$30 gift card to compensate them for their time and effort.

5.5 Results

The completed surveys and a summary of results are included in Appendix Q. In this Section, the demographics of participants, the survey results related to ranking the design alternatives, the feedback in the areas of ease of use, ease of understanding, meaningfulness of the metric, and a summary of the alternative designs are included.

5.5.1 Summary of Participants

A total of 19 people—all active students—participated in the workshop. Figure 5.3 reports the background and experience of the participants. As seen in Figure 5.3a, slightly more than half (10) of the participants were seniors or in the fifth year or beyond. Two of the remaining participants were graduate students, with 7 being other undergraduates. Just over half the group (10) were industrial engineering students, as shown in Figure 5.3b, with the second largest group (6) being mechanical engineering students. The remainder (3) were from other engineering disciplines.

Figure 5.3c shows the highest level of experience related to sustainability of the participants. Slightly more than half (10) had no background in sustainability, where just less than

one-third (6) have taken a class on sustainability, and (3) have evaluated the sustainability of a manufactured part or product. The participants had much more experience designing parts, as shown in Figure 5.3d with more than three-quarters having experience varying from having previously designed parts in a class (10), being actively designing parts in a class (2), or having previously designed parts in a job or for research purposes (3). The remainder (4) had no experience designing parts or products.

5.5.2 Design Alternative Rankings

Tables 5.1 and 5.2 show the frequency that the participants ranked each design in the initial and final surveys. When comparing the frequency data between tables, it can be seen that the initial case had little consensus for most of the design alternatives. The one exception is for design F, which more than half the participants ranked as the design with the worst sustainability. This design, as shown in Appendices L and N, is a single-part design with no welding, but has the lowest sheet utilization of all the design alternatives. While a low sheet utilization can imply poor sustainability, in this case, design F has the lowest energy value and, thereby, is considered the most sustainable.

As can be noted by the averages and standard deviations of the rankings, the the visual improvement of the frequency comparisons are supported by statistics, with the standard deviations of the position of the ranking decreasing greatly between the two surveys. When the participants used the software tool, there was much more consensus in the rankings.

To evaluate how well the participants performed on the task of ranking the designs, the average distance d_{avg} between the correct placement of the alternative and the location chosen by the participant were calculated as:

$$d_{avg} = \sum_i \frac{|p_{act,i} - p_{par,i}|}{n_{alts}} \quad (72)$$

where p_{act} is the actual ranking of sustainability for the design alternative based on ordering the alternatives from highest to lowest energy value, p_{par} is the ranking position for

(a) The participants shown by year in school. (b) The participants shown by engineering major.

(c) The experience of participants related to environmental sustainability for manufactured parts.

(d) The experience of participants related to designing parts.

Figure 5.3. The demographics of participants in the experimental workshop.

Table 5.1. Frequency on Initial Survey for Sustainability Ranking of Each Design Alternative

		Design Alternatives						
		high ←———Emergy————→ low						
		D	G	B	S	A	J	F
Sustainability Ranking*	1	1	4	1	1	1	0	11
	2	7	7	1	1	0	7	2
	3	6	2	2	1	1	0	2
	4	3	0	9	5	0	1	0
	5	1	3	3	4	7	1	2
	6	0	1	3	3	6	3	1
	7	1	2	0	4	3	6	1
Avg Rank		3.00	3.11	4.11	4.84	5.33	4.61	2.32
Std Dev		1.37	2.05	1.29	1.71	1.46	2.28	1.97

* 1 = Least sustainable, 7 = Most sustainable.

the same design alternative provided by the participant, and n_{alts} is the number of design alternatives the participants were asked to rank. Figure 5.4 summarizes the performance of the participants in both ranking activities.

Figure 5.4 shows the initial survey results with an average distance between the provided versus the correct placement of 2.09 positions and a standard deviation of 0.8 positions. In the final ranking the participants used the output from the aPriori software to review the emergy for the alternatives. A lower emergy value represented a higher sustainability product. With that in mind, performance on this task should have been better as the participants had the total emergy value for each alternative and could have put them in numerical order. The average distance for the second ranking activity was 0.2 positions, with a standard deviation of 0.53 positions. There were two participants—12 and 15—who performed poorly. These two participants had average distances of 2.14 and 1.00 were shown as outliers in Figure 5.4. While other participants appeared to make mistakes with the

Table 5.2. Frequency on Final Survey for Sustainability Ranking of Each Design Alternative

		Design Alternatives						
		high <————Energy————> low						
		D	G	B	S	A	J	F
Sustainability Ranking*	1	18	2	0	1	0	0	0
	2	1	16	0	0	1	0	0
	3	0	0	17	0	0	1	0
	4	0	1	1	15	2	0	0
	5	0	0	1	2	16	0	0
	6	0	0	0	0	0	17	2
	7	0	0	0	0	0	1	17
Avg Rank		1.05	2.00	3.16	3.94	4.74	5.89	6.89
Std Dev		0.23	0.58	0.50	0.80	0.73	0.74	0.32

*1 = Least sustainable, 7 = Most sustainable.

Figure 5.4. The performance of participants based on average distances from correct ranking from the two survey results.

placement of one pair of designs (see participants 3, 5, and 19), participants 12 and 15 may have misunderstood the task and not used the values from the software for directly ranking the designs. When these two outliers are removed, the revised average is 0.05 positions with a standard deviation of 0.11.

A two-sample paired t -test on the initial survey average distances against the final survey average distances was performed. The null hypothesis for the test was that the difference between the means was not greater than zero. The test was conducted both on the full set of samples and with participants 12 and 15 removed. The value for alpha was assumed to be 0.05. Table 5.3 shows the output for the t -test on the full set of data. Since the calculated value for t based on the data sets was greater than the one-tail critical value ($t_{0.05}$), the null hypothesis is rejected, concluding the difference between the means is greater than zero. For completeness, the same analysis was completed removing participants number 12 and 15. These results are shown in Table 5.4 and show the same rejection of the null hypothesis, concluding the difference between the means was greater than zero. Between these two results, it can be concluded that the use of the emergy software tool to rank sustainability has an effect on participants ability to rank design alternatives by sustainability.

Table 5.3. t -Test Results for All d_{avg} Data

	d_{avg} Survey 1	d_{avg} Survey 2
Mean	2.08	0.21
Variance	0.65	0.28
Observations	19.00	19.00
Hypothesized Mean Difference	0.00	
df	18.00	
t Stat	10.15	
P(T<=t) one-tail	3.53E-09	
t Critical one-tail	1.73	

5.5.3 Feedback on Ease of Use

Question 2 on the final survey asked the participants to rank how easy the software tool was to learn for evaluating manufacturing sustainability compared to other engineering

Table 5.4. t -Test Results for d_{avg} with Participants 12 and 15 Removed.

	d_{avg} Survey 1	d_{avg} Survey 2
Mean	2.00	0.05
Variance	0.66	0.01
Observations	17.00	17.00
Hypothesized Mean Difference	0.00	
df	16.00	
t Stat	10.25	
P(T $\leq t$) one-tail	9.68E-09	
t Critical one-tail	1.75	

software tools they have used. This tool was new to all participants in the study, and the general aPriori software has not been taught at URI in the last two-and-a-half years. As such, the only training any participants could be expected to have is during this study. Appendix N.3 includes the slides used for the software training.

A histogram of the ranking responses is shown in Figure 5.5. A response of 1 indicated *Much easier than other engineering tools* and 10 is *Much harder*. The median and average of responses were both 3 with a standard deviation of 1.76, as shown in the box and whisker plot in Figure 5.6.

Figure 5.5. Responses show the ease-of-use rankings of the software tool used during the study.

Figure 5.6. Answers to questions 2, 3, and 4 from the final survey.

Participants were asked for their comments on the software ease-of-use. Comments were not required. Those whose rank on this question was 4 and higher, a total of five participants, included comments such as:

- “To use it for our survey application, it was easy but from the complexity of the options, it looks like it could be a maze of tabs”
- “It seems like it could be easy to get used to and logical after spending a few hours with it”
- “Easy instructions to understand what parts needed to be evaluated in the software”

From those who ranked the software as 3 or less comments included:

- “The software was very simple to use”
- “It gives a lot of information without me having to look for it too hard. The information is easy to understand.”
- “Took a moment to locate tabs, but it was simple to repeat the process for each assembly. Curious if other tools in the software are as simple to use.”

Based on the statistical results and the comments highlighted above, the software implementation completed for this dissertation study was considered, at worst, no more difficult than other engineering software. For the specific use during the survey, it can be considered a straight forward information workflow.

5.5.4 Feedback on Ease of Emergy to Understand

Emergy was expected to be a new thermodynamic topic for all participants since it is not currently discussed in any classes at the URI. With that in mind, the only exposure participants in the study would have to emergy and how it is modeled is a 20 to 30 minute presentation (included in Appendix N.2) during the study. Question 3 asked participants to rank how easy the metric of emergy was to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies.

Figure 5.7 shows a histogram of the results of the ranking by participants, where a rank of 1 is *Emergy is very easy to understand* and 10 is *Emergy is very hard to understand*. The average of the rankings was 3.4 with a median of 3 and a standard deviation of 2.01. These results are also shown in the box and whisker plot in Figure 5.6, where an outlier response of 8 is noted.

Figure 5.7. A histogram showing the responses on the ease of understanding emergy.

Participants were asked for any comments they had regarding how easy emergy was to understand. Comments related to higher rankings tended to include comments about emergy being a new concept, such as “Not so easy to understand. Never heard the concept of emergy before” from a participant giving a ranking of 8. Additionally, participants were interested in knowing more about the methods and background of calculating transformities. For example, the following comments came from participants who provided a rank of 4 and 3, respectively:

- “The general concept of the metric of emergy was easy to understand, but it was difficult to follow where the specific values came from and how they were calculated”
- “I would like to learn more about how they generated a transformity constant to assign to each material since there are a lot of factors that go into it”

The feedback included two comments regarding how in the initial ranking the participants had not considered anything beyond the cycle-time and material usage provided with the summaries of the alternatives and that emergy provided an easy to grasp concept for calculating sustainability.

Considering this feedback, the topic of emergy was a new concept for participants. As such, there was interest in gaining further understanding about how it is calculated and how it can be used. From the statistical and qualitative feedback, despite this being a new topic, the short introduction given to the participants was enough background for the participants to gain a basic understanding and to support the evaluation they were asked to complete.

5.5.5 Feedback on Perception of Emergy to Evaluate Sustainability

Since emergy, as noted in Section 5.5.4, was a new metric for the study participants, Question 4 of Survey 2 asked if they felt that the metric of emergy provided them the perception to meaningfully compare the design alternatives. In other words, did they feel there was enough information provided to understand why a design was more or less environmentally friendly.

Figure 5.7 shows a histogram of the results of the ranking by participants, where 1 represents the feeling the metric did not provide enough information to meaningfully compare design and 10 represents the feeling the metric provided sufficient information. The average of the rankings was 8.25, with a median of 8 and a standard deviation of 1.76. These results are also shown in the box and whisker plot in Figure 5.6.

Figure 5.8. Responses on the ability to meaningfully compare the sustainability of design alternatives.

While not technically an outlier, a single rank of 3 stands out from the rest of the ranks in Figure 5.8. The comment provided with the rank—“Based on the software outputs, it was clear which products used less / more emergy”—does not provide a clear explanation for this choice of ranking. It may be that the participant accidentally ranked the question low in reverse, since the previous two questions had the positive answer with a low rank instead of a high rank.

The remaining participants’ comments noted that using the single metric made it easier to understand which alternative used more or less emergy. There were comments regarding missing aspects of the metric based on the presentation provided in the experiment, in particular, the comments of two participants can be highlighted:

- “Emergy is a great metric to meaningfully compare designs; however, it is not obvious as to how environmentally friendly a product is. We do not have an idea of the direct implication the specific manufacture product has on the environment”
- “Only issue is that they are only comparable to each other, but not to a global benchmark”

In the first case, the topic of direct impact on the environment was not included in the model as described in Section 3.3.8, but it can be estimated and included in the emergy model. The second comment, from a participant who had taken a class on sustainability, refers to the idea from LCA analysis that two analyses can only be compared to each other in a relative sense, not to an absolute value for sustainability. While not a focus of this research, the geobiosphere emergy baseline, briefly described in Section 2.2.3, provides the global yearly inflow budget from which a benchmark could be derived.

A concern raised in the previous question regarding the background of the calculations was again raised on this question by a number of participants:

- “Yes, however, I wasn’t positive if certain categories of emergy (such as laser vs. material) are technically worse or better or if they have all been equivalent essentially”
- “The presentation was sufficient, but was curious to have values for emergy that were originally obtained”
- “Yes, however if I wanted to make a more in-depth analysis, I would need to know how those calculations were obtained”
- “There was sufficient information to compare the general designs, but it was hard to trace how the information came together to create the quantitative value of emergy for a specific design”

Since emergy is a new concept for participants with a very limited time for introduction, such responses are expected. Despite these concerns, though, from the statistical and

general qualitative feedback, participants felt they were able to use emergy to meaningfully compare designs.

5.5.6 Design Changes to Improve Total Emergy

In the last section of the final survey, the participants were asked to give three additional changes to the design they noted as most sustainable and would be likely to further increase the sustainability of this alternative. Based on the emergy values for the alternatives provided, the correct answer for most sustainable was design alternative F. This alternative was a single-part solution for the product. The emergy output from the aPriori software is shown in Figure 5.9. The sheet utilization for the design was very low (57%), and this design was ranked as unsustainable in the first ranking exercise with an average ranking of 2.31 (low is less sustainable) and a standard deviation of 1.97 positions.

The changes provided by participants were reviewed, then affinitized into 15 topics, which were further grouped into 6 categories, as shown in Table 5.5. Since every participant provided up-to three possible improvements, there were a total of 57 changes provided. Figure 5.10 shows the percentage of responses in each category. Almost two-thirds of the suggested changes related to the material. Processing changes, such as decreasing cycle-time and changing the process, was the next largest category. This reflects the split of emergy in design alternative F, as shown in Figure 5.9, where over 76% of the emergy comes from material.

Figure 5.11 shows the suggested changes in the material category. Between *Use more of the sheet* and *reduce the material on the part*, there were 20 suggestions for changes. These suggestions reflected the low sheet utilization for this design alternative. The suggestions for changing the material and reducing the labor and services address the UEV for the material directly by either changing the material to one with a lower UEV or reducing the labor and services required for the current material. The UEV per mass would be directly impacted, and there would be an expectation of a decrease in the material emergy.

Figure 5.9. The emergy values from the aPriori Macro for design alternative F.

Table 5.5. Count of Design Change Responses Grouped by Topic and Category

Category	Topic	Count
Energy	Renewable energy	3
Machines	Change equipment	3
	Reduce install time	1
	Setup time	1
Material	Change material	7
	Use more of sheet	11
	Reduce material on part	9
	Reduce material labor and services	4
	Use scrap	4
	Use recycled material	2
Operator	Remove operator	2
	Reduce operator impact	1
Part count	Reduce parts in assembly	1
Processing	Change Process	3
	Decrease Cycle Time	5

Figure 5.10. A pie chart showing percent of design changes in each category.

The last two material-related suggestions of using the scrap downstream in the process or using recycled material as an input provided an opportunity for reducing the emergy value. Indeed, as reviewed in Section 2.4.5, recycled material does provide an opportunity for reduced steel UEVs.

Figure 5.11. Percent of design changes suggested by participants in the material category.

The operator category in Table 5.5, which accounts for approximately 16% of the total emergy, was split into two groups of suggestions. The first is to remove the operator by increasing automation of the manufacturing process. This is an interesting solution, as the more automated machine may require more emergy to build, install, and maintain, but as briefly explored in Appendix E, the emergy efficiency of automation is a question for further research. The other solution for operators to reduce their UEV overall was explored in part through the sensitivity analysis in Section 4.4. From this analysis, the education portion has a greater impact versus the emergy from the metabolic or support services contribution.

A final design suggestion is the use of renewable energy to power the machines and plant. The total power contribution is less than 1% of the overall emergy total for alternative F. As shown in Section 3.3.4, renewable energy does have a lower emergy value. Electricity

itself, though is a low overall contributor to the energy of the product, and focusing on other areas will provide faster gains in improving sustainability.

CHAPTER 6

Discussion

6.1 Introduction

This dissertation study focused on comprehensively addressing how to support real-time, geometry-based sustainability decision-making for design engineers. To address this question, the investigation expanded on the existing literature in a variety of areas in both the fields of eco-design and emergy. The expansions specifically included

- Modifications to an existing procedure for using emergy accounting to support eco-design
- A refinement to the approach for determining the emergy in manufacturing equipment
- A proposed framework for the environmental impact of labor
- Support of emergy within the structure of commercial engineering software
- The introduction to the use of emergy as a metric for engineering students.

This Section addresses these areas by briefly referencing the current literature and addressing how this dissertation study expanded on each topic.

6.2 Emergy Accounting for Eco-Design

The support of eco-design assessments using emergy was first proposed by Almiédia et al. [99], using the procedure outlined in Section 2.2.3. In a previous study [145] by the author of this dissertation study, a revised set of steps for completing an eco-design assessment based on DFM data was proposed. This was further refined and initially tested against an example assembly, as demonstrated in Section 3.1.

The work completed in this dissertation study serves to provide more specificity and alternative methods of analysis compared to the procedure outlined by Almeida et al. [99]. Table 6.1 compares these two procedures. Starting with Steps 1 and 2, Almeida et al. suggested defining the system boundaries and the context for the system. For this dissertation study, both the system boundaries and the context are assumed to be the manufacturing plant. Within this context, a DFM cost analysis was performed, which provides cycle times, costs, and other inputs for the emergy analysis. Section 3.4.2 reviews a DFM analysis completed in the aPriori software for an example assembly with an identified set of manufacturing processes.

Steps 3 and 4 from Almieda et al. [99] focused on creating the ESL for the manufacturing process. Within this dissertation study the construction of the ESL diagram for the example assembly occurred in tandem with the development of the emergy equations. The generic ESL for any manufacturing process and its corresponding equations were developed in Sections 3.2 and 3.3 with the majority of the equations based on manufacturing cost-accounting equations presented in Section 2.1.1. These tasks were completed on the example assembly, as demonstrated in Sections 3.4.3 through 3.4.11. Additionally, the generic equations were coded into the aPriori software to support emergy evaluation for any given part using the same manufacturing processes, as described in Section 4.1.

Almieda et al. [99] listed Step 5 as calculating the emergy indicators based on the previous steps. In this dissertation study, this step is described for the example assembly in Section 3.4.11. Also, since the generic equations have been coded into software, any updates to the design can be easily evaluated once a new CAD design has been completed. A limitation of this dissertation study is the lack of impacts manufacturing wastes and effluent on the environment.

The final step listed by Almieda et al. [99] focused on the use of output from the analysis to drive decision-making. The authors focus on management-level activities and the output focuses on a year of production. Alternatively, in this dissertation study, the target is to give

Table 6.1. Comparison of Eco-design Processes with Emergy [99].

Step	Description from Almieda et al. [99]	Corresponding Steps Proposed in this Dissertation (Refined from Bligh et al. [145])
1.	Define the system to to set boundaries for analysis.	Complete DFM cost analysis a. Collect product designs and the manufacturing processes required for each design.
2.	Understand the context of the system and complete a mass balance.	b. Define cost and cycle time equations for each manufacturing process. c. Estimate cost and cycle times for each process of each part in the analysis.
3.	Create an ESL diagram.	Complete emergy analysis a. Draw an ESL diagram for each process.
4.	Modify the energy flow diagram with collected data.	b. Create analogous available energy, material, and information equations from the corresponding cost equations, where available. c. Convert the material, energy, and information inputs and outputs of the production from the DFM analysis to emergy using the appropriate UEVs.
5.	Calculate emergy indicators.	Compute the total emergy budget for each process on a per unit basis, including any negative effects on the environment.
6.	Review for driving management activities and other decision-making.	Compare design alternatives. Select the alternative that produces products with the lowest per unit emergy input while meeting other design criteria.

design engineers the ability to evaluate the environmental impact of their design changes as they work on a per-unit basis, enabling real-time comparisons during early development. This pushes the knowledge of the potential impact of a product earlier into the product development process (PDP) when there are more opportunities to alter the design.

With these comparisons in mind, the contributions from this dissertation study to the process of producing emergy assessments in support of eco-design are:

- Use of outputs from commonly performed engineering analyses (DFM cost analysis) as inputs to emergy calculations
- Creation of a standardized method for building bottom-up emergy equations based on cost analogy
- Creation of generalized, unit-manufacturing, process-based equations for calculating emergy based on DFM assessment
- Providing a per-unit emergy value for manufacturing, analogous to cost, to drive engineer-level decision-making
- Coding of generic emergy equations into commercially available software to enable evaluations on a per-alternative basis in real time during the PDP.

6.3 Emergy in Manufacturing Equipment

The most common method for calculating the emergy in manufacturing equipment, as noted in Section 3.3.3, was to use the mass of the product and the UEV for the dominant material. While there had been some work related to computers by Puca et al. [101] to breakdown the materials in more detail, a similar approach had not been applied to the equipment used in a manufacturing-based emergy assessment.

In this dissertation study, a bottom-up emergy assessment was proposed for the manufacturing equipment, as outlined in Section 3.3.3. The emergy assessment included assessing the material for each part in the equipment plus the assembly time of the final product.

This procedure was demonstrated on the welding machine used to add welds to the example assembly in Section 3.4.7. To support this assessment, a full BOM of the machine was assessed, including identification of materials, masses, and prices for each part. Additionally, the MOST methodology was used to estimate the cycle-time for assembling the welding machine. With the assembly cycle-time estimated and using the labor model developed in Section 3.3.2, the emergy added to the welder through its assembly was estimated. Finally, an assessment was completed on the circuit boards within the welder based on material mass data.

While the assessment of computers by Puca et al. [101] suggests the usefulness of doing a more comprehensive breakdown of the materials in a product, the authors did not include an estimate of the assembly time for the parts making up the product or an estimate of the labor and services added for the manufacture of each part within the computer. The addition of a more rigorous analysis proposed in this dissertation pushes closer toward capturing all energy inputs embedded within a manufacturing process as described in Chapter 1 and demonstrates the potential for recursive analysis of emergy within a manufacturing system.

6.4 Labor Definition

The topic of labor has been addressed from both energy [57, 112] and emergy [104–106, 128, 130] perspectives. Those reporting in the emergy literature argue for a bottom-up perspective in determining the emergy of labor with some focusing on the contribution of education [104, 128, 130], and others focusing on emergy from the energy used by participants in a society [105, 106]. Finding emergy based on energy used sets a similar boundary to the research done on the energy of labor [57, 112]. The emergy researchers [105], though, criticize the energy work [57, 112] as being susceptible to double-counting due its top-down approach because it includes energy beyond that directly consumed by workers. Finally, while the metabolic consumption of energy through calories in food had been considered as a lower bound for the energy of labor [57, 58, 60, 112] and has been incorporated into some

models of labor [104], it had not been extended to include the energy required to produce the input calories.

In this dissertation study, a revised emergy model for hourly labor was proposed, which includes the emergy model for education of workers proposed by Campbell et al. [103, 104], a proposed bottom-up approach for the energy directly consumed by workers, and a proposed method for estimating the emergy in food calories based on average cost-per-calorie. The bottom-up approach for energy directly consumed by workers, in particular, is a proposal that addresses concerns over double-counting related to the proposed [57, 112] aggregate methods of determining energy consumption by workers.

An assumption made within the education model for an occupation by Campbell et al. [104] was that since knowledge to engage in an occupation was reused, the emergy of education could be considered to renew year-on-year. This assumption was used in the main model within this dissertation study, as described in Section 3.3.2, but the sensitivity of this assumption on the total emergy for the example assembly was examined in Section 4.4. From this investigation it can be concluded that this assumption deserves more scrutiny, as values of less than 4 years for the renewal of knowledge have a clear impact on the resulting emergy, and values of less than 2 years may be responsible for possible outliers.

This dissertation study also directly addresses topics raised by Kamp et al. [105]. First, the authors proposed the use of UEVs for indirect labor to accurately capture the full labor chain. This topic is addressed in part in this dissertation study through the use of indirect labor within various levels of the model, including in supporting the facility (e.g., quality, purchasing, and tool crib workers) and the assembly labor in building the welding machine. In each case, an appropriate UEV was used for the local work being completed.

The second topic noted by Kamp et al. [105] was the preference to the use of time instead of money to assess labor. In this dissertation study, time is used as the determination of the amount of labor required in all cases of direct labor (e.g., operators for laser, bending,

and welding machines) and for a selection of indirect labor cases (e.g., facility support and assembly labor for the welding machine). Intrinsic in this application is the use of industrial engineering techniques for estimating labor time based on standard manufacturing-time equations from the aPriori software and the use of a work measurement system (MOST). These applications are new to this area of research.

6.5 Emergy in Software

As noted in Section 2.4.6, there are few dedicated software products for producing emergy estimates. No tools are focused on providing environmental assessments during the design process to engineers with limited sustainability knowledge. In this dissertation study, an extension to a commercially available physics-based costing software (aPriori) was built. By using a common DFM tool, this model can be easily extended to include other manufacturing processes and environmental impact categories by those with access to and knowledge of the software.

Since the aPriori software completes assessments based on CAD models, the implementation of an emergy model within it also provided the opportunity to understand the impacts of geometric changes on emergy in a product. This was investigated through a sensitivity analysis in Section 4.5 determining that the impact on variance of different dimensions can change based primarily on the thickness of the part in question. This investigation is novel in the emergy space and provides a methodology and initial results for further research.

6.6 Emergy for Engineers

Based on the literature reviewed in Sections 2.2.3, 2.4.1, and 2.4.2, there has been limited use of emergy to support design engineering decision-making and no assessment of the ease of understanding the concept of emergy by engineers as a group. While emergy is thought to be difficult for many outside the direct field to understand [78], participants

in the experimental workshop felt that with no more than 30 minutes of instruction they were able to grasp the basic concepts of emergy and productively use it for evaluating the provided set of design alternatives.

Beyond the qualitative assessment given by the participants in the ranking questions, the application of their newly gained knowledge to suggest further design improvements demonstrated an understanding of how to use emergy to improve sustainability by making design-level decisions. Of the 57 suggested changes to the design, almost two-thirds focused on the material, which accounted for more than 76% of the emergy of the part. The number of suggestions in the material category, as well as the grouping of the suggestions themselves, demonstrated that participants were able to productively and confidently use emergy to make sustainability decisions. This is in contrast to the initial task, where participants appeared to overvalue the role of sheet utilization, ranking the most sustainable design alternative based on emergy (design alternative F) as the least sustainable. In reality, reducing part count and removing welds had a larger impact on reducing the emergy on the design initially. This was a consideration that was not identified by the majority of participants based on their initial rankings of the design alternatives.

The impressions of emergy by those outside the field and the perceived level of difficulty in understanding how to apply emergy has been raised by a number of researchers [78, 118], but the topic has not been formally assessed in a published form from a review of the available literature. As such, this dissertation study establishes an initial benchmark regarding how quickly the newly introduced concept of emergy can be productively used for evaluation of design decisions by engineers, including the demonstration of using emergy data to make suggestions for further improvement of designs.

6.7 Conclusion

This dissertation study comprehensively investigated the potential use of emergy as a metric to support design engineers in creating more sustainably manufactured products.

The work included:

- A revision of the eco-design process previously proposed for emergy
- A definition of a taxonomy for the emergy of manufacturing analogous to cost-accounting
- Definitions of equations to support this taxonomy
- Creation of a reusable emergy model tied to the geometry and DFM assessment of product within a commercially available software package
- Expansion of existing approaches for emergy of manufacturing equipment and labor
- Assessment of sensitivities of UEVs and geometry within the proposed emergy model
- An experimental workshop to evaluate the effectiveness of this work in answering the original question of design decision support

By reviewing the end-to-end considerations of the use of emergy within engineering decision-making, this dissertation study strongly supports the feasibility and applicability of a single energy shadow metric for use by design engineers.

CHAPTER 7

Conclusion and Future Work

7.1 Introduction

This dissertation study comprehensively investigated the potential use of emergy as a metric to support design engineers in creating more sustainably manufactured products. It is one of few studies applying emergy as a metric in eco-design processes. A number of proposals for new and revised methodologies for emergy accounting were included and demonstrated with an example, setting initial benchmarks for further research. In this Section, a review of the projected areas for future research and potential impacts on the fields of manufacturing and emergy are described.

7.2 Future Work

7.2.1 Model Expansion

This dissertation study demonstrated an emergy-based model for assessing the manufacturing processes of laser cutting, bending, and MIG welding. While these are common manufacturing processes, they are used primarily on small-to-medium annual product volumes. There are a wide array of other metal-based processes, such as various casting (e.g., die, sand, and investment), machining (e.g., 3-axis, 5-axis, and mill-turn), and stamping (e.g., progressive die, tandem die, and basic press) processes that better support larger volume products and different geometries. In addition, plastics processes—including injection molding, vacuum forming, and blow molding—are commonly used throughout industry. Finally, additive manufacturing is becoming a more commonly considered alternative manufacturing process. All of these would be candidates for future emergy research.

The addition of emergy models for other processes gives the opportunity to investigate the sustainability trade-offs between different product embodiments. Within this disserta-

tion study, alternatives were limited to a single variation with no welding and six variations with welding. The addition of more energy process models would expand the comparison space and allow for energy evaluations of automation versus manual labor, as briefly discussed in Appendix E. More models would enable more comprehensive testing regarding the intuition of engineers regarding sustainability.

The energy model of products within this dissertation study focused on the direct manufacturing of the parts within a product's assembly, thus the short term sustainability of a product. It did not include negative effects on the environment, remediation of output, recycling of scrap, or the use of recycled material as input. Some initial thoughts were provided on addressing these areas, but further investigation of these approaches and integration of them into the broader model long term sustainability model would be required for a complete energy accounting for manufacturing.

Since this model focused on the manufacturing phase of the product, additional downstream phases of use, disposal, product recycling, and product remanufacture would also be areas for expansion. These phases are commonly investigated within energy analyses of buildings and nondurable products and within the LCAs completed for products. As such, an expansion of the product model to beyond manufacturing is clearly the next step for completely modeling the environmental impact of a product.

In developing the models within this dissertation study, a number of simplifying assumptions were made. These included:

- Equating the loss of energy by a worker due to age to the gain of energy from experience, on-the-job training, and personal information acquisition
- Using the dominant material approach for modeling the energy within the laser and bending machines versus employing the full BOM approach modeled for the MIG welder
- Not including the energy of reusable tooling on the bending machine

- Constant power drain by all machines in determining power usage in both operation and setup
- Involvement of an equal number of workers with identical skill levels in both setup and operation of the machines
- Including only home energy and vehicle use as the support service energy attributable to a worker
- No considerations regarding the emergy impact of insurance and other financial instruments
- Labor and services estimate used for construction based on cost of construction instead of labor-hours estimate
- Choice of nozzle size and gas-type on the laser

Further investigation of these assumptions and their impacts would help to increase the precision of the energy shadow captured within the emergy model for manufacturing.

A final area for expansion of the emergy model created within this dissertation study is to address other regions. The model assumed production for all steps occurred within the United States. It is common, though, for different steps within the manufacturing supply chain to occur in different countries, or completely outside the United States. Such investigations could include modeling labor, electricity, material prices, and the emergy of labor and services for a selection of regions. The development of regional models would improve the developed emergy model to reflect the current realities of global manufacturing.

7.2.2 Expand Testing Population

The experiment within this dissertation study tested the effective use of an emergy-based manufacturing model embedded in a manufacturing costing software tool for evaluating the short-term sustainability of product manufacturing by engineering students. The

population studied has a number of limitations. First, the students have limited-to-no experience in making design decisions within an industrial setting. Because of that lack of experience, the ability to fit the prototyped software tool within a standard development process was not considered. This is one area for further investigation by expanding the pool of population participants to include practicing engineers.

Second, while the level of knowledge of engineering students regarding sustainability may be approximately equal to that of a practicing design engineer in most industries, there are also engineers who focus on sustainability evaluations. These professionals may have a different view on the use of the software tool and on energy as a metric. From expanding the pool of participants to include those with expert-level sustainability experience, there would be the opportunity to gain further understanding regarding the strengths and weaknesses of the energy model.

Finally, while this dissertation study targeted 36 participants for the experimental workshop, it was only possible to find 19 within the available time. While many of the conclusions drawn from the survey results were clear enough based on the current population size, including more participants may bring to light additional trends within the rankings and suggestions of design improvements.

7.2.3 Further Model Characterization

Within this dissertation study, basic sensitivity analyses were completed related to UEV values and part geometry. Both of these areas offer opportunities for future research. The energy model for labor has a number of opportunities for further characterization, including the impact of the number of hours worked in a year and a broader consideration of the labor model inputs. This was investigated in part by including an investigation of the number of years over which the education supporting labor renews, but recommendations on the most reasonable duration should be developed based on a comprehensive knowl-

edge degradation model. Such future work would help to establish better guidelines for a standard model

Additional work related to labor would be to provide a refinement of the upper and lower bounds for labor energy presented by Zhang [112] and Zhang and Dornfeld [57] through translation of their model and the labor model presented in this dissertation study into common units. The data used by Zhang [112] and Zhang and Dornfeld [57] are an aggregate nonindustrial value that cannot be easily translated into emergy and the education emergy model used within this study cannot be easily translated into energy. Future work would be to develop a method for comparison that would provide further narrowing of the minimum and maximum energy/emergy bounds for a worker.

The investigation of the sensitivity of emergy to part geometry in this dissertation study was limited to a single simple part. Within the current manufacturing processes modeled, investigation of more complex parts and assemblies could be completed. This investigation would help to better understand the behaviors exhibited in the geometry sensitivity analysis. Additionally the design alternatives used for the experimental study provide opportunity for further understanding regarding the design of assemblies with lower emergy than a single part design, which generally go against eco-design heuristics. Finally, if more manufacturing processes are added to the emergy model, then more complex sensitivity investigations can be completed.

7.2.4 Further Integration Within Engineering Decision-Making Workflows

Within this dissertation study, the emergy manufacturing model was integrated into a single manufacturing costing software tool. While the aPriori software is a common tool within industry, there are many other software tools that are well suited to providing the information required for the emergy model. Investigation of these tools and their advantages and limitations would help develop broader possibilities for the use an emergy models within industry.

A common method now being used by design engineers within their development processes is optimization of their design over many variables and use of a selection of tools with a process integration and design optimization tool (PIDO). These investigations have included the aPriori software from a cost perspective [216]. In this dissertation study, a PIDO tool was used to conduct the sensitivity analyses, but it could alternatively be used to perform an optimization considering not only energy and cost from the aPriori software models, but also performance by linking in other software-based engineering tools such as finite element analysis and computational fluid dynamics.

7.3 Potential Impact on Field and Conclusion

There are wide selections of possible research directions from this dissertation study as was highlighted in Section 7.2. Though the potential for impact is diverse, it can be summarized in two primary areas.

First, in the area of engineering design decision-making, the prototype software extension demonstrates the usefulness of a consistent, single, sustainability metric in driving productive decisions helpful to the environment regarding designs. Since this prototype was built as an extension to commercially available manufacturing costing software, information critical for evaluating the sustainability of products is readily available. A potential impact on the field of this dissertation study is to encourage further development of environmental models embedded into software tools engineers use on a daily basis and to provide single-metric guidance for driving sustainability decisions.

Second, in the area of energy research, this study has proposed and demonstrated an end-to-end procedure for using energy within eco-design. In support of this, a selection of new energy models and modifications of existing energy models have been proposed. This work has the potential to greatly expand the focus within energy research in evaluating the short term sustainability for individual products, which can serve as a building block in building long term sustainability models for product manufacture.

Using this research there is the possibility of clarifying the impact human products have on the environment through a single metric. By enabling those involved in product development to use such a metric, more decisions toward less environmentally impactful designs can be made. By making more sustainable decisions visible within the development process, design engineers can drive their own discipline to work within the sustainable limits of our planet.

APPENDICES

Appendix A Feature Based Costing Example

The example part is shown in Figure A.1. The part is a support bracket from a welded assembly. The part is highlighted in yellow in Figure A.2. The part is made from 4mm thick 1020 sheet steel. It is assumed that this is a lower volume assembly of 5500 per year. The machine is setup to make this part 12 times a year, for a batch size of 458.

The yearly number of parts is an important input for driving manufacturing decisions, as smaller annual volumes tend to be made using processes such as laser, plasma, waterjet cutting or turret press, which do not require the creation of custom tooling for the part to be made. This is in contrast to processes, such as stamping, which require a custom tool for creating a part.

Figure A.1. The example part for physics-based costing example; a support from a bracket assembly.

The machine being used for the calculation is a 3000 Watt laser machine, with the following details:

Figure A.2. The example Part in its assembly.

- Rapid Traverse: 90,000 mm/min
- Shuttle Time (Auto Load/Unload): 18 sec
- Pierce for 4mm Steel: 1.72 sec
- Small Feature Feed Rate: 2286 mm/min
- Large Feature Feed Rate: 3048 mm/min

Cycle Time for the Laser

Figure A.3. The workflow of steps in the laser process.

The steps in the laser cut process are represented in the flow shown in Figure A.3. The process starts by loading a sheet into the machine. These can be done either by a human

or by a machine and will depend greatly on the factory where the work is happening. Prior to loading the sheet, the operator will have completed a nesting operation either within the machine's software or in a purpose-built software tool designed to fit as many parts as possible on the sheet. A nesting diagram for the example part (completed in the aPriori Professional software) is shown in Figure A.4. This nesting diagram will be used by the laser to determine its motion.

As the laser cutter begins its program, it will move to the first feature of the first part. This movement is completed at a “rapid traverse” rate, which is much faster than the speed at which the machine cuts. This speed varies based on the properties of the machine being used. When the laser reaches the point where the first cut will start, it initiates a “pierce”. This action makes a cut through the full depth of the sheet to start the cut. The length of time for the pierce varies depending on the thickness of the material and the material type. Once the pierce is complete, the cut starts. Most laser machines have two cut rates: a high-speed cut rate for large features (generally those with a radius greater than 5mm) and a slower cut rate for small features (those with a radius less than 5mm). Both of these cut rates vary based on the type and thickness of the material.

Figure A.4. The nesting diagram for the example part

When the first feature cut is complete, the laser will either move to the next feature on the part or to the next part on the sheet, if the part is complete. When all the parts have

been cut, there will be a remaining “skeleton” of the sheet, which is any border required around the edge of the sheet for clamping or between parts to avoid heat damage to the part nearby (this can vary based on the machine, material type and the thickness of the material). Generally the skeleton will be large and difficult to handle. To ease handling, a selection of cuts will be made in the skeleton. If the movement of sheets is automated, the sectioned skeleton is shuttled to an unloading area and a fresh sheet is shuttled to the cutting area as part of the same operation. The parts and skeleton are removed from the machine while the next sheet is being cut. Since these two operations are happening simultaneously, the unloading is considered “inside time” and is not included as part of the cycle time.

With that cycle in mind, the cycle time calculation used by the aPriori software for the laser cut process is:

$$t_{ct} = \frac{t_{shut} + t_{skel}}{n_p} + t_{rap} + \sum_{i=1}^n t_{feat,i} \quad (73)$$

where t_{shut} is the time to load the sheet into the machine. Within aPriori, an automated machine is assumed. t_{skel} is the cycle time for cutting the skeleton, which is cut at the large feature speed, includes a pierce for each of the cuts being made and rapid traverse time between cuts. Since these two values are calculated at the sheet level, they are divided by the number of parts per sheet, n_p , to determine a cycle time to apply to each part. t_{rap} is a calculation of the movement time between features on the part at the rapid traverse rate. Last is the sum of the features on the part. For any given feature, the calculation for the cycle time is:

$$t_{feat,i} = t_p + \frac{l_{cut,s,i}}{r_{cut,s}} + \frac{l_{cut,l,i}}{r_{cut,l}} \quad (74)$$

where t_p is the pierce time, which is consistent through all features. $l_{cut,s,i}$ is the length of cut at the small radius speed for feature i . $l_{cut,l,i}$ is the length of cut at the large feature speed for feature i . The sum of the two cut lengths is equal to the perimeter of the feature,

and is extracted from the CAD geometry. $r_{cut,s}$ is the small feature cut rate and $r_{cut,l}$ is the large feature cut rate. As noted above, this will either be the large or small feature cut rate.

It should be noted that the equation and method given here are commonly used in industry and similar methods can be found in spreadsheets built by manufacturing and cost engineers.

Laser Cycle Time Calculation

To estimate the example part using laser cutting in a physics-based costing software, the values for the perimeters for the two features are required and are shown in Figure A.1. Feature 1 is the external perimeter of the part, with only straight sections. Feature 2 is the internal perimeter of the part, with three straight sections and three curved sections that are below the 5mm threshold for using the small feature speed. With these values and the inputs of the machine given above, the total time for Feature 1 is:

$$t_{feat,1} = 1.72 + 60 \frac{0}{2286} + 60 \frac{367}{3048} = 8.9s \quad (75)$$

and for Feature 2:

$$t_{feat,2} = 1.72 + 60 \frac{37.7}{2286} + 60 \frac{83.4}{3480} = 4.1s \quad (76)$$

The shuttle time to load a new sheet and remove the last is equal to 18 seconds, the time to cut up the skeleton is 33.8 seconds and the rapid traverse time per part is 0.18 sec. The total cycle time is then:

$$t_{ct} = \frac{18 + 33.8}{458} + 0.18 + (4.2 + 8.9) = 13.4s \quad (77)$$

Such a resulting cycle time is used to determine the cost of labor, direct overhead (cost of running the machine), and indirect overhead (cost of the factory attributed to the part) associated with the part.

Appendix B Costing Tooling

Tooling can be similarly estimated using an ABC-style system applied to a CAD model. Indeed, aPriori uses the information it extracts from the geometry to estimate material, labor, and any manufacturing operations required for a full tooling cost (C_{tool}). Much like the rest of aPriori's model, the approach uses an ABC framework. The cost calculation varies slightly based on the type of tooling, but generally it will be:

$$C_{tool} = m_{base}c_{kg,b} + m_{other}c_{kg,o} + h_{l,tool}(t_{l,assy} + t_{l,mach} + t_{l,try}) + h_{OH,mach}(t_c, tool) \quad (78)$$

where m_{base} is the mass of the tool base and $c_{kg,b}$ is the cost per mass for the tool base material; m_{other} is the mass of other materials used in the mold and $c_{kg,o}$ is the cost per mass of those materials; $h_{l,tool}$ is the hourly labor rate for the toolshop and $t_{l,assy}$ is the labor time for assembling the mold, $t_{l,mach}$ is the labor time for any manufacturing operations performed on the tool (machining, electro-discharge machining), and $t_{l,try}$ is the tryout time (time to test the die on a line and ensure it makes the desired part); and finally $h_{OH,mach}$ is the hourly rate for the machines in the toolshop, and $t_{c,mach}$ is the cycle time on those machines. To emphasize, this is a conceptual model of aPriori's approach to tooling cost. The true model will vary based on the requirements of tooling manufacture for a specific process.

Appendix C Theoretical Energy for Three Manufacturing Processes

The goal of a manufacturing process is to alter a starting unit (raw material, part, assembly, etc.) in a desired manner. This may be to add material (weld, assembly, additive manufacturing, over molding, fiberglass layup, paint etc.), remove material (milling, turning, flame cutting, etc.), change the shape (forging, molding, bending), or alter the material properties (heat treat, chemical treat, anodize). To complete any of these activities, energy is required as an input. This basic structure is shown in Figure C.1. It is assumed that the box representing the manufacturing process includes any supporting supplies (paint, glue, weld wire, coolant, etc.) required to complete the process. The scope of this discussion focuses only on the added energy required to create the desired modification to the unit.

Figure C.1. The manufacturing process altering a unit in a desired manner.

Implied by the diagram are two different measures of energy. The first is the theoretical energy required to make the change, for instance, the amount of heat required to melt a kilogram of zinc for casting. The second is the amount of energy required as an input to the incoming unit to produce the desired effect, overcome any losses, and power any support equipment. Pfouga et al. [42] demonstrate this with an equation, where the total energy needed for manufacturing a part is equal to:

$$E_{total} = E_{th} + E_{additional} + E_{periphery} \quad (79)$$

where E_{th} is the minimum amount of energy to theoretically produce the effect of the process (for example, a bend in sheet steel), $E_{additional}$ is the amount of energy to support other machine functions (ex: computer control) or losses in the process, and $E_{periphery}$ is the energy required to power peripherals (ex: ventilation equipment) [44] [42]. For the scope of this discussion, $E_{periphery}$ will be ignored, as it is highly dependent on a specific manufacturing line. $E_{additional}$ will be discussed briefly in the context of losses and supporting functionality within a process. In the following sections, three theoretical calculations for imparting energy in manufacturing processes (E_{th}) for mid-volume sheet metal applications will be discussed: bending, laser and welding.

Following the introduction of these three processes, general principles regarding driving factors for estimating the theoretically required energy (E_{th}) are discussed. The paper concludes with a discussion of how multi-physics situations can be approached as well as the potential usefulness of E_{th} within an manufacturing environment.

C.1 Bending

Figure C.2. The layout of air bending.

Air bending is a common mid-volume manufacturing shaping process for sheet metal. The minimal force required with the layout shown in Figure C.2 for bending can commonly be found to be [217,218]:

$$F_b = \frac{C_1 T_S w t^2}{D} \quad (80)$$

where C_1 varies based on the relationship between the bending die and the thickness of the material and in manufacturing practice varies between 1.2 and 1.45 [218]. T_S is the ultimate tensile strength, w is the length of the bend (into the paper), t is the thickness of the sheet and D is the width of the opening in the bending die. To calculate the energy, the required distance d_{bend} for bending is required, which with θ as the bend angle is:

$$d_{bend} = \frac{D}{2 \tan \frac{\theta}{2}} \quad (81)$$

resulting in a minimum bend energy (E_b) of:

$$E_b = \frac{C_1 T_S w t^2}{2 \tan \frac{\theta}{2}} \quad (82)$$

The losses contained in $E_{additional}$ for air bending include friction between the die and workpiece, and heat generated due to the deformation of the part. Beyond the part itself, air brakes are computer controlled and many have hydraulic systems to support the bending activity, both of which require input energy [219]. These are best understood by reviewing a full break cycle, which consists of six phases [219]:

1. idle / waiting for next activity;
2. top die moving from “upper dead point” to mute point;
3. active bending;
4. clamp hold time;
5. decompression;
6. top die returning to upper dead point;

of which, only phase (3) is represented by Equation 82. Duflou et al. compared E_b to time studies and energy data gathered during air bending operations, finding total energy for the process is 40 to 156 times the theoretical estimate [217]

C.2 Laser

Laser cutting is also a common mid-volume manufacturing process, used for primary cutting of sheet metal to shape. Duflou et al. [217] provide the following equation based on heat transfer to a material for bringing the area under the laser (kerf) to its melting temperature and phase transition:

$$E_l = m_{kerf}c_p(T_m - T_0) + m_{kerf}h_f \quad (83)$$

which assumes there are no conduction losses and no material ablation. Here, m_{kerf} is calculated from the diameter of the laser beam and the thickness of the material. T_m and T_0 are the melting temperature of the material and the ambient temperature, respectively. c_p and h_f are, respectively, the specific heat capacity and the enthalpy of fusion for the material being cut.

The losses contained in $E_{additional}$ for laser cutting include losses through conduction, material ablation, and material reflection. Conduction losses, in particular, can be very high. High conductivity materials, such as aluminum, have recommended cut speeds at about 30 to 50% of those recommended for the same thickness of mild steel, demonstrating the practical effect of conductivity during the operation [220]. Beyond the effect from the material itself, Kellens et al. [53] document the various stages of a energy draw for a laser cutting machine as shown in Figure 2.5. The authors identify the following phases:

1. cooling device on idle
2. exhaust system turned on
3. laser cutting

4. cooling device turned on

of which only phase (3) is accounted for in E_l . As with air bending, Duflou et al. compare this result to time studies and data gathering results, finding the total energy for the process in operation is 57 to 121 times the theoretical estimate [217].

C.3 Welding

Parts created through laser and bend processes are very often welded into an assembly. The most common types of welding for these cases are fusion welding processes, where material is melted to join together multiple parts or assemblies. Shrivastava et al. provides minimum energy equations for two welding processes: arc welding, and oxy-acetylene [221]. For both of these welding processes, the total energy is:

$$E_w = E_J + E_M \quad (84)$$

where E_J is the joining energy, and E_M is the energy required to melt the filler rod. E_M is the same for both processes:

$$E_M = U l A \quad (85)$$

where U is the specific energy of the material being welded, l is the length of the weld, and A is the cross-sectional area of the same.

For arc welding, electricity is used to directly melt the material. The energy is calculated based on the applied voltage (V), current (I), and the known base (P_B) and idle (P_I) powers of the welding machine:

$$E_{J,arc} = V I t - (P_B + P_I) t \quad (86)$$

which is run for a known time t and gives us the energy required for joining $E_{J,arc}$.

Oxy-acetylene welding, on the other hand, is based on a set of chemical reactions:

releasing 1260 kJ of energy per mole of gas input. With one mole of gas having a mass of 26 grams, the energy consumed in joining for oxy-acetylene, $E_{J,oxy}$ in Joules is:

$$E_{J,oxy} = 1000 \frac{1260m}{26} \quad (88)$$

where m is the mass of the gas consumed in grams.

Considering the losses included in $E_{additional}$ for welding, the largest related directly to the process is heat loss. Zhang and Zhao [51] note that this consists of two terms:

$$E_{heat} = Q_{env} + Q_{bm} \quad (89)$$

where Q_{env} is the heat loss to the environment due to convection and radiation, and Q_{bm} is the loss to the base metal due to conduction, both of which can be estimated from the size of the welding pool. Beyond these heat transfers, Zhang and Zhao note losses to the inverter within the welding machines for electrically powered welding [51]. In the case of Oxy-acetylene, some portion of the reaction will not complete, and another portion of the mass of the reactants will react undesirably with impurities [222]. In the case of arc welding, the efficiency of the power generated from the voltage and current will be dependent on the resistance within the material being welded.

Beyond the effect from the welding activity, Shrivastava et al. [221] document the various stages of a energy draw for a welding process. The authors identify the following phases:

1. base power when turned on;
2. idle time when welding is active, but welding is not occurring;

3. joining time;
4. idle time between welds;
5. base power before shut down;

of which only phase (3) is accounted for in Equation 84. With this in mind, the overall process has significant loss of energy to the welding system when welding is not occurring.

C.4 Discussion

The principle factors governing the energy used by different manufacturing processes are based on the physics of the process. For most manufacturing processes, the physics is based on mechanical (bending), heat transfer (laser, weld melting), electrical (arc welding), or chemical (oxy-acetylene welding) principles. Table C.1 gives a summary of the main drivers for each type of physics.

Table C.1. Summary of Principle Drivers for Determining Energy for Various Manufacturing Process Physics

Physics	Geometry	Amb. Temp	Material	Active Temp	Reaction
Mechanical	✓		✓		
Heat Transfer	✓	✓	✓	✓	
Fluid	✓		✓		
Electrical			✓		
Chemical		✓			✓

Geometry, as shown in the weld, bend, and laser examples, is an important driver of the energy required. For bending, this is found in the shape and size of the bend. For the laser, it is in the mass of the kerf, and in welding melting in the length of the weld. The ambient temperature is most relevant in heat transfer situations, like that of the laser, and is implied with any chemical reaction. The selection of a material type drives a number of properties found in the equations above—the ultimate tensile strength for bending, the heat capacity and enthalpy of fusion for the laser, the specific energy for the material for weld melting, and the required voltage and current in arc welding. The desired or active temperature is

critical for heat transfer processes such as for a laser, and is implied by the specific energy in weld melting. Knowing the intended reaction is critical to determining the energy of any chemically based manufacturing process, such as oxy-acetylene welding.

Included in Table C.1 for completeness is fluid processes, though none of the processes described above use such physics explicitly. Injection molding is an example of a process that includes fluid dynamics as part of its energy calculation, as the molten plastic moves through the mold requires significant upstream pressure. Injection molding is also an example of a manufacturing process that exists across the physics models, as it also requires heat transfer calculations to determine the energy required to heat the plastic to a molten state. Many other processes exist across the borders of these physics divisions, such as hot stamping, reaction injection molding, and electro-discharge machining.

From a more practical standpoint, the bottom-up modeling from engineering principles demonstrated in previous sections provides a minimal value estimate for the energy input required to modify an input unit in a desired manner in only one physics-based dimension. In general, the energy for E_{th} necessitates more complex calculations. Comprehensively understanding the energetic requirements and losses is better suited to more computation methods of estimation versus the fundamental calculations above. This is easily done with modern multi-discipline engineering simulation tools. These tools can be automated to apply to any given geometry a design engineer creates in a CAD system. Such an automated approach could provide a baseline energy requirement estimate for the geometry. By using industrial-internet-of-things sensors on machines to measure input electricity during production, the performed efficiency of a production process could be determined. This data could be further analyzed and mined to better route parts of given geometries to the machines best suited to them in terms of energy efficiency.

Appendix D Welding Machinery BOMs with UEV Values

D.1 Welder BOM

Part Number	Level	Part Description	Count	% Mat1	Mat 1	% Mat2	Mat 2	Mass	Unit Price	Source	Notes	Mat 1 Energy	Mat 2 Energy	L&S UEV	UEV Units	Part UEV
179432	1	PANEL, side	2	100%	Steel, Virgin			13.00 lbs	\$90.48	www.brweldingsupplies.com		2.69E+14	0.00E+00	1.68E+14	sej/part	4.37E+14
179431	1	COVER, top	1	100%	Steel, Virgin			15.45 lbs	162.94	http://www.brweldingsupplies.com/miller-179431-cover-top/		1.60E+14	0.00E+00	1.53E+14	sej/part	3.13E+14
164903	1	BAFFLE, air	2	100%	Steel, Virgin			0.44 lbs	18.98	http://www.brweldingsupplies.com/miller-164903-baffle-air/	Used part number 164699, as listed part number cannot be found	9.10E+12	0.00E+00	3.63E+13	sej/part	4.54E+13
162816	1	CHANNEL, upright	4	100%	Steel, Virgin			3.22 lbs	20.23	http://www.brweldingsupplies.com/miller-162816-channel-upright/		1.33E+14	0.00E+00	7.47E+13	sej/part	2.08E+14
162820	1	BAR, mtg lift eye	2	100%	Steel, Virgin			4.38 lbs	31.4	http://www.brweldingsupplies.com/miller-162820-bar-mtg-lift-eye/		9.06E+13	0.00E+00	5.83E+13	sej/part	1.49E+14
162830	1	LIFT EYE	1	100%	Steel, Virgin			0.50 lbs	12.76	http://www.brweldingsupplies.com/miller-162830-lift-eye/		5.17E+12	0.00E+00	1.21E+13	sej/part	1.73E+13
177279	1	GASKET, lift eye	1	100%	Plastics			0.06 lbs	2.71	http://www.brweldingsupplies.com/miller-177279-gasket-lift-eye/		5.30E+11	0.00E+00	2.27E+12	sej/part	2.80E+12
604536	1	SCREW, 312-18 x 1.75 hexhd-pln gr 5	2	100%	Steel, Virgin			0.06 lbs	3.28	http://www.brweldingsupplies.com/miller-604536-screw-312-18x1-75-hex-hd-pln-gr-5-std/		1.24E+12	0.00E+00	6.28E+12	sej/part	7.52E+12
180066	1	STABILIZER	1	5%	Copper	95% Steel, Virgin		86.00 lbs	946.48	http://www.brweldingsupplies.com/miller-180066-stabilizer/	7cm x 34cm x 34cm (https://www.itemshub.com/index.php?route=product/product&product_id=34669) Price from: https://www.shopwelderparts.com/product/164717/	2.18E+15	8.45E+14	7.90E+14	sej/part	3.82E+15
164717	1	BUS BAR, stabilizer	1	100%	Copper			0.44 lbs	36.52			2.24E+14	0.00E+00	3.25E+13	sej/part	2.57E+14
168829	1	TRANSUDER, current 1000A	1	90%	Steel, Virgin	10% Copper		0.44 lbs	262	http://www.brweldingsupplies.com/miller-168829-transducer-current-1000a-module-max-1000-loop/		4.10E+12	2.23E+13	2.50E+14	sej/part	2.77E+14
115094	1	CONNECTOR & SOCKETS	1	80%	Plastics	20% Steel, Virgin		0.06 lbs	12	http://www.brweldingsupplies.com/miller-115094-housing-plus-3kts-service-kit/		4.24E+11	1.24E+11	1.13E+13	sej/part	1.18E+13
208405	1	CONTACTOR, def prp 30A 2P 24VDC Coil	1	80%	Steel, Virgin	20% Copper		0.46 lbs	41.42	http://www.brweldingsupplies.com/miller-254596-contact-def-30a-1p-24vdc-coil/	Superceded by 254596, per https://www.shopwelderparts.com/product/208405/	3.81E+12	4.66E+13	3.71E+13	sej/part	8.76E+13
173605	1	BRACKET, mtg contactor	1	100%	Steel, Virgin			5.81 lbs	8.6	http://www.brweldingsupplies.com/miller-173605-bracket-mtg-lem/		6.01E+13	0.00E+00	6.88E+12	sej/part	6.70E+13
163906	1	CAPACITOR, 50 and 60Hz	3	90%	Ceramics	10% Steel, Virgin		0.04 lbs	14.1	http://www.brweldingsupplies.com/miller-163906-capacitor/		1.32E+13	1.24E+11	3.79E+13	sej/part	5.12E+13
159042	1	TRANSFORMER, control 50VA 24V 230/460/575 (60Hz)	1	10%	Copper	90% Steel, Virgin		2.69 lbs	155	http://www.brweldingsupplies.com/miller-159042-xfmr-control-50va-24v-230-460-575-prt-60hz/		1.36E+14	2.50E+13	1.45E+14	sej/part	3.06E+14
159043	1	TRANSFORMER, control 50A 24V (50Hz)		N/A		N/A		2.75 lbs	102.99	http://www.brweldingsupplies.com/miller-159043-xfmr-control-50va-24v-20-380-400-415-440prt-50hz/		N/A	N/A	N/A		
159244	1	PRIMARY BOX, (includes)	1	100%	Steel, Virgin			2.00 lbs	130.87	http://www.brweldingsupplies.com/miller-159244-primary-box-lavout/		2.07E+13	0.00E+00	1.25E+14	sej/part	1.46E+14
601835	2	NUT, 10-32 brs	24	100%	Steel, Virgin			0.06 lbs	0.52	http://www.brweldingsupplies.com/miller-601835-nut-010-32-38hex-13h-brs/		1.49E+13	0.00E+00	1.17E+13	sej/part	2.65E+13
38887	2	STUD, prt bd brs 10-32 x 1.375	24	100%	Steel, Virgin			0.01 lbs	1.26	http://www.brweldingsupplies.com/miller-038887-stud-primary-board-brs-10-32x-1-375/		2.48E+12	0.00E+00	2.90E+13	sej/part	3.15E+13
10913	1	WASHER, flat 218 ID brs	24	100%	Steel, Virgin			0.06 lbs	1.54	http://www.brweldingsupplies.com/miller-010913-washer-flat-218id-460x0-031t-brs/		1.49E+13	0.00E+00	3.52E+13	sej/part	5.01E+13
601835	1	NUT, 10-32 brs	24	100%	Steel, Virgin			0.06 lbs	0.52	http://www.brweldingsupplies.com/miller-601835-nut-010-32-38hex-13h-brs/		1.49E+13	0.00E+00	1.17E+13	sej/part	2.65E+13
38618	1	LUNK, jumper term bd prt	8	100%	Copper			0.30 lbs	10	http://www.brweldingsupplies.com/miller-038618-lunk-jumper-term-bd-prt/		1.22E+15	0.00E+00	6.30E+13	sej/part	1.28E+15

159034	1 HOLDER, fuse mintr	1	100% plastics		0.07 lbs	19.52	https://www.brweldingsupplies.com/miller-159034-holder-fuse-mintr-10-3mm-x-33-3-to-38-1mm-panel-int/	6.18E+11	0.00E+00	1.84E+13 se/part	1.90E+13
Fig 8-5	1 PANEL, rear w/components		N/A	N/A					N/A	N/A	
156065	1 FUSE, crtg, 5A 600V time delay	1	10% Zinc	90% Glass	0.06 lbs	20.17	https://www.brweldingsupplies.com/miller-156065-fuse-crtg-5amp-600v-time-delay/	7.23E+11	1.27E+11	1.93E+13 se/part	2.02E+13
160794	1 CONTACTOR, def prt 75A 3P 24V	1	80% Steel, Virgin	20% Copper	3.41 lbs	404.99	https://www.amxson.com/Miller258661-Contactor-24VAC-Boxing/dp/800062AX65	2.82E+13	3.46E+14	3.69E+14 se/part	7.43E+14
140750	1 SWITCH, reed	1	90% Plastics	10% Steel, Virgin	0.29 lbs	88.01	http://www.brweldingsupplies.com/miller-140750-switch-reed/	2.30E+12	3.00E+11	8.31E+13 se/part	8.57E+13
217136	1 LABEL, warning electric shock	2	N/A	N/A		7.47			N/A	N/A	
176254	1 LABEL, general precautionary wordless, int (CE models only)	2	N/A	N/A		5.48			N/A	N/A	
163359	1 BASE	1	100% Steel, Virgin		34.00 lbs	223.88	https://www.brweldingsupplies.com/miller-163359-base/	3.52E+14	0.00E+00	2.07E+14 se/part	5.59E+14
221924	1 CAPACITOR ASSEMBLY, (includes)	1	N/A	N/A	4.48 lbs	290.57	https://www.brweldingsupplies.com/miller-221924-capacitor-assy-dos-and-neg/	N/A	N/A	N/A	
163535	2 CAPACITOR, elctt 16000uf 60VDC	6	90% Aluminum	10% Plastics	0.50 lbs	45	https://www.brweldingsupplies.com/miller-163535-capacitor-elctt-16000-uf-60-vdc-can-1-75-dia/	2.45E+13	2.65E+12	2.51E+14 se/part	2.78E+14
140002	2 RESISTOR, WW fxd 10W 500 ohm	1	40% Ceramics	60% Steel, Virgin	0.03 lbs	15.3	https://www.brweldingsupplies.com/miller-140002-resistor-ww-fxd-10-w-500-ohm-w-terms/	1.46E+12	1.86E+11	1.44E+13 se/part	1.60E+13
162817	2 BUS BAR, capacitor	2	100% Copper		0.28 lbs	23.07	https://www.brweldingsupplies.com/miller-162817-bus-bar-capacitor/	2.84E+14	0.00E+00	4.11E+13 se/part	3.25E+14
182660	2 BUS BAR, mtg capacitor	4	100% Copper		0.06 lbs	3.13	https://www.brweldingsupplies.com/miller-182660-bus-bar-mtg-capacitor/	1.22E+14	0.00E+00	1.06E+13 se/part	1.32E+14
218389	1 TRANSFORMER, pwr main 230/460/575	1	15% Copper	85% Steel, Virgin	75.00 lbs	4305.59	see notes	5.70E+15	6.59E+14	4.00E+15 se/part	1.04E+16
218388	1 TRANSFORMER, pwr main 380/400/440		N/A		75.00 lbs		see notes		N/A	N/A	
175405	1 THERMOSTAT, NC (included w/T1)	2	40% Steel, Virgin	60% Plastics	0.06 lbs	13.93	https://www.brweldingsupplies.com/miller-175405-thermostat-nc-open-135c-close-90c-w-insul-head/	4.96E+11	6.36E+11	2.48E+13 se/part	2.59E+13

168891	1 THERMOSTAT, NC (included w/TL)	2	40% Steel, Virgin	60% Plastics	0.06 lbs	19.67	https://www.brweldingsupplies.com/miller-168891-thermostat-nc-open-80-c-close-50-c-stab-act-w-term/			4.96E+11	6.36E+11	3.58E+13 se/part	3.70E+13
218413	1 HOUSING, plug pin/skt (service kit)	1	90% Plastics	10% Steel, Virgin	0.06 lbs	19.6		Mass and price estimated from: http://www.brweldingsupplies.com/miller-135556-housing-plug-skt-service-kit/		4.77E+11	6.20E+10	1.85E+13 se/part	1.91E+13
218408	1 HOUSING, plug pin/skt (service kit)	1	90% Plastics	10% Steel, Virgin	0.06 lbs	19.6		Mass and price estimated from: http://www.brweldingsupplies.com/miller-135556-housing-plug-skt-service-kit/		4.77E+11	6.20E+10	1.85E+13 se/part	1.91E+13
161294	1 BRACKET, mtg rectifier	2	100% Steel, Virgin		0.36 lbs	23.12	https://www.brweldingsupplies.com/miller-161294-bracket-mtg-rectifier/			7.45E+12	0.00E+00	4.43E+13 se/part	5.17E+13
Fig 8-2	0 PANEL front w/components		N/A	N/A						N/A	N/A	N/A	
192671	0 RECTIFIER, SCR main (Fig 8-4)		N/A	N/A	26.30 lbs	1741.27	https://www.brweldingsupplies.com/miller-192672-rectifier-scr-main/	Superceded by 274213 per: https://www.millerserviceparts.com/Product/ProductDetails?productId=6636		N/A	N/A	N/A	
								Price from: https://www.millerserviceparts.com/Product/ProductDetails?productId=17808 Weight from part 192672: http://www.brweldingsupplies.com/miller-192672-rectifier-scr-main/					
159863	1 ELECTRONICS BOX	1	100% Plastics		3.00 lbs	79.19	https://www.brweldingsupplies.com/miller-159863-electronics-box/			2.65E+13	0.00E+00	5.93E+13 se/part	8.58E+13
168847	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.40 lbs	19.83	https://www.brweldingsupplies.com/miller-168847-housing-plug-pins-skt-service-kit/			3.18E+12	4.14E+11	1.70E+13 se/part	2.06E+13
168845	1 CONNECTOR & PINS	1	90% Plastics	10% Steel, Virgin	0.10 lbs	20.05	https://www.brweldingsupplies.com/miller-168845-housing-rct-pins-skt-service-kit/			7.95E+11	1.03E+11	1.88E+13 se/part	1.97E+13
152249	1 CONNECTOR & PINS	1	90% Plastics	10% Steel, Virgin	0.03 lbs	54.39	https://www.brweldingsupplies.com/miller-152249-housing-plug-pins-skt-service-kit/			2.38E+11	3.10E+10	5.21E+13 se/part	5.24E+13
168846	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.01 lbs	38.43	https://www.brweldingsupplies.com/miller-168846-housing-rct-pins-skt-service-kit/			7.95E+10	1.03E+10	3.69E+13 se/part	3.70E+13
208772	1 CIRCUIT CARD, control (60Hz)	1	separate calc	separate calc	0.83 lbs	605.77	https://www.brweldingsupplies.com/miller-208772-circuit-card-assy-control/			2.66E+13		5.75E+14	6.02E+14
208773	1 CIRCUIT CARD, control (50Hz)		N/A	N/A	0.75 lbs	736.87	https://www.brweldingsupplies.com/miller-231170-circuit-card-assy-control/	Superceded by 231170 per https://www.millerserviceparts.com/Product/ProductDetails?productId=12000		N/A	N/A	N/A	
158720	1 CONNECTOR & SOCKETS, (see Fig 7-3 & 4)		N/A	N/A	0.06 lbs	29.48	https://www.brweldingsupplies.com/miller-158720-housing-plug-skt-service-kit/			N/A	N/A	N/A	
169240	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.03 lbs	33.78	https://www.brweldingsupplies.com/miller-169240-housing-plug-pins-skt-service-kit/			2.38E+11	3.10E+10	3.23E+13 se/part	3.26E+13
148439	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.06 lbs	32.21	https://www.brweldingsupplies.com/miller-148439-housing-plug-pins-skt-service-kit/			4.77E+11	6.20E+10	3.06E+13 se/part	3.12E+13
152249	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.03 lbs	54.39	https://www.brweldingsupplies.com/miller-152249-housing-plug-pins-skt-service-kit/			2.38E+11	3.10E+10	5.21E+13 se/part	5.24E+13
52964	1 RELAY, encl 24VDC DPDT	1	70% Steel, Virgin	30% Copper	0.70 lbs	33.9	https://www.brweldingsupplies.com/miller-052964-relay-encl-24vdc-dpdt-10a-120vac-8pin-flange-mtg/			5.07E+12	1.06E+14	2.66E+13 se/part	1.38E+14
6393	1 RELAY, encl 24VAC DPDT	1	70% Steel, Virgin	30% Copper	0.19 lbs	38	https://www.brweldingsupplies.com/miller-006393-relay-encl-24vac-dpdt-10a-120vac-8pin-flange-mtg/			1.38E+12	2.89E+13	3.49E+13 se/part	6.52E+13
93995	1 CIRCUIT BREAKER, main reset 1P 15A 250VAC	2	80% Steel, Virgin	20% Copper	0.13 lbs	12.42	https://www.brweldingsupplies.com/miller-093995-supplementary-pro-main-reset-1p-15a-250vac-frict/			2.15E+12	2.64E+13	2.24E+13 se/part	5.09E+13

604176	1 RECEPTACLE str dx grd 2P3W 15A 125V	1	70% Steel, Virgin	30% Plastics	0.25 lbs	18	https://www.bvwdingsupplies.com/miller-604176-rept-str-dx-grd-2p3w-15a-125v-15v/			1.81E+12	6.62E+11	1.52E+13 se/part	1.77E+13
203778	1 CONNECTOR/CAPACIT OR, w/leads (includes)	1	N/A	N/A	0.24 lbs	103.28	https://www.bvwdingsupplies.com/miller-203778-receptacle-capacitor-w-leads/			N/A	N/A		
143976	2 RPT w/SCKTS (service kit)	1	90% Plastics	10% Steel, Virgin	0.80 lbs	53	https://www.bvwdingsupplies.com/miller-143976-rpt-w-sckts-service-kit/			6.36E+12	8.27E+11	4.68E+13 se/part	5.40E+13
97749	2 CAPACITOR, cer disc .05 uf 500 VDC strip	4	40% Ceramics	60% Steel, Virgin	0.06 lbs	6.65	https://www.bvwdingsupplies.com/miller-97749-capacitor-cer-disc-05-uf-500-vdc-strip/			1.17E+13	1.49E+12	2.30E+13 se/part	3.62E+13
204143	1 PANEL, front	1	100% Steel, Virgin		7.55 lbs	119.21	https://www.bvweider.com/panel-front-204143/	Price from: https://www.millerserviceparts.com/Product/ProductDetails?productId=8275		7.81E+13	0.00E+00	1.13E+14 se/part	1.91E+14
181245	1 TERMINAL, pwr output red	2	70% Steel, Virgin	30% Plastics	0.35 lbs	32	https://www.bvwdingsupplies.com/miller-terminal-pwr-output-red-181245-74888-210865/			5.07E+12	1.85E+12	5.57E+13 se/part	6.26E+13
128750	1 CAPACITOR, cer disc .1uf 500VDC	3	40% Ceramics	60% Steel, Virgin	0.06 lbs	16.5	https://www.bvwdingsupplies.com/miller-128750-capacitor-cer-disc-1-uf-500-vdc-w-terminals/			8.77E+12	1.12E+12	4.56E+13 se/part	5.55E+13
161303	1 SPRING, cprsn .600 OD x .072 wire x 1.500 lg	3	100% Steel, Virgin		0.03 lbs	8.16	https://www.bvwdingsupplies.com/miller-161303-spring-cprsn-600-od-x-072-wire-x-1-500-oid/			9.31E+11	0.00E+00	2.35E+13 se/part	2.44E+13
181246	1 TERMINAL, pwr output black	1	70% Steel, Virgin	30% Plastics	0.55 lbs	32	https://www.bvwdingsupplies.com/miller-210866-74884-7-181-246-terminal-pwr-output-black/			3.98E+12	1.46E+12	2.62E+13 se/part	3.16E+13
174936	1 PLATE, control lower	1	100% Steel, Virgin		0.19 lbs	12.08	https://www.bvwdingsupplies.com/miller-174938-plate-control-lower/	Used part number 174938; unclear which material so estimated steel		1.96E+12	0.00E+00	1.16E+13 se/part	1.35E+13
217865	1 LABEL, warning electric shock and reduced air	1	N/A	N/A		10.12		Price from: https://www.millerserviceparts.com/Product/ProductDetails?productId=10068	N/A	N/A	N/A		
179563	1 LABEL, electric shock/reduce air flow (CE models only)	1	N/A	N/A		8.72		Price from: https://www.millerserviceparts.com/Product/ProductDetails?productId=5552	N/A	N/A	N/A		
172587	1 COVER, stud output	1	100% Plastics		0.88 lbs	24.93	https://www.bvwdingsupplies.com/miller-172587-cover-output-stud-general/			7.77E+12	0.00E+00	1.90E+13 se/part	2.68E+13
160935	1 CLIP, spring	3	100% Steel, Virgin		0.02 lbs	4.07	https://www.bvwdingsupplies.com/miller-160935-clip-spring/			6.20E+11	0.00E+00	1.17E+13 se/part	1.23E+13
601835	1 NUT, 10-32 brs	2	100% Steel, Virgin		0.06 lbs	0.52	https://www.bvwdingsupplies.com/miller-601835-nut-010-32-38hex-13h-brs/			1.24E+12	0.00E+00	9.71E+11 se/part	2.21E+12
10913	1 WASHER, flat, 218 ID x .460 OD x .031thk brs	1	100% Steel, Virgin		0.06 lbs	1.54	https://www.bvwdingsupplies.com/miller-010913-washer-flat-218id-x-460od-x-031thk-brs/			6.20E+11	0.00E+00	1.47E+12 se/part	2.09E+12
38887	1 STUD, prt bd brs 10-32 x 1.375	1	100% Steel, Virgin		0.01 lbs	1.26	https://www.bvwdingsupplies.com/miller-038887-stud-prtmarv-board-brs-10-32-x-1-375/			1.03E+11	0.00E+00	1.21E+12 se/part	1.31E+12
11609	1 SWITCH, tgl SPDT 15A 125VAC	2	70% Steel, Virgin	30% Plastics	0.13 lbs	17.82	https://www.bvwdingsupplies.com/miller-011609-switch-tgl-spdt-15a-125vac-on-10ne-on-spdt-term-cht/			1.88E+12	6.89E+11	3.21E+13 se/part	3.47E+13
198087	1 POTENTIOMETER, CP std slot 1/T 2W 1K ohm	1	80% Steel, Virgin	20% Plastics	0.70 lbs	45	https://www.bvwdingsupplies.com/miller-pot-cp-std-slot-1t-2-w-1k-linear-w-frictabs-198087/			5.79E+12	1.24E+12	3.93E+13 se/part	4.63E+13

214827	1 CIRCUIT CARD, digital meter	1	separate calc	separate calc	0.38 lbs	635	https://www.bvwdingsupplies.com/miller-300169-hi-field-digital-meters/	Superseded by 300169 per: https://www.millerserviceparts.com/Product/ProductDetails?productid=9709	4.72E+13	5.79E+14 se/part	6.26E+14	
153501	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.13 lbs	18.27	https://www.bvwdingsupplies.com/miller-13501-housing-blue-pls-sks-service-kit/		1.03E+12	1.34E+11	1.69E+13 se/part	1.81E+13
148439	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.06 lbs	32.21	https://www.bvwdingsupplies.com/miller-148439-housing-blue-pls-sks-service-kit/		4.77E+11	6.20E+10	3.06E+13 se/part	3.12E+13
192174	1 STAND-OFF	4	100% Steel, Virgin		0.01 lbs	2.12	https://www.bvwdingsupplies.com/miller-192174-stand-off-no-6-silflue-x-750-lk-310-hex-nvl-fem/		4.14E+11	0.00E+00	8.14E+12 se/part	8.55E+12
	1 NAMEPLATE (order by model and serial number)	1	N/A		N/A				N/A	N/A		
159039	1 SWITCH, rocker SPDT 15A 125VAC	1	90% Steel, Virgin	10% Plastics	1.00 lbs	61.99	https://www.bvwdingsupplies.com/miller-265931-kit-switch-replacement-for-159039/		9.31E+12	8.83E+11	5.66E+13 se/part	6.68E+13
185626	1 CONNECTOR, body 56 series	1	90% Plastics	10% Steel, Virgin	0.01 lbs	4	https://www.bvwdingsupplies.com/miller-185626-conn-body-56-series-5-pcs-female-term/		7.95E+10	1.03E+10	3.79E+12 se/part	3.88E+12
159522	1 LED, yellow	1	50% Steel, Virgin	50% Plastics	0.02 lbs	12.89	https://www.bvwdingsupplies.com/miller-159522-led-yellow-2-1v-20-ma-45-0-mcd-panel-mtk-250-hole/		1.03E+11	8.83E+10	1.20E+13 se/part	1.22E+13
159036	1 LENS, LED clear	1	100% Plastics		0.01 lbs	3.32		Price from: https://www.millerserviceparts.com/Product/ProductDetails?productid=4666 ; mass an estimate	8.83E+10	0.00E+00	3.13E+12 se/part	3.22E+12
97924	1 KNOB, pointer	1	100% Plastics		0.90 lbs	19.99	https://www.bvwdingsupplies.com/miller-knob-pointer-1-670-dia-x-250-lt-w-set-screws-plstc-171007/	Superceded by 171007 per: https://www.millerserviceparts.com/Product/ProductDetails?productid=2486	7.95E+12	0.00E+00	1.42E+13 se/part	2.21E+13
197868	1 SNUBBER, assy	1	40% Ceramics	60% Steel, Virgin	0.02 lbs	19.92	https://www.bvwdingsupplies.com/miller-197868-snubber-assy/	Appears to be a capacitor	9.75E+11	1.24E+11	1.89E+13 se/part	2.00E+13
10381	1 CONNECTOR, rectifier	2	50% Steel, Virgin	50% Plastics	0.06 lbs	4.22	https://www.bvwdingsupplies.com/miller-010381-connector-rectifier/		6.20E+11	5.30E+11	6.46E+12 se/part	7.61E+12
5107	1 BOLT, crg stl 250-20 x .750 GR5 pld	6	100% Steel, Virgin		0.06 lbs	4.35	https://www.bvwdingsupplies.com/miller-005107-bolt-crg-stl-250-20-x-750-gr5-pld/		3.72E+12	0.00E+00	2.50E+13 se/part	2.87E+13
162815	1 PANEL, front upper	1	100% Steel, Virgin		2.02 lbs	82.99	https://www.amazon.com/Miller-162815-Panel-Front-Upper/dp/B004HEBZAF/ref=sr_1_fmnull_17ke-words=millar+162815&id=1538014606&s=rat-ewav&sr=8-1-fknull		2.09E+13	0.00E+00	7.93E+13 se/part	1.00E+14
48420	1 CAPACITOR, cer disc .01uf 100VDC	6	40% Ceramics	60% Steel, Virgin	0.06 lbs	6.67	https://www.bvwdingsupplies.com/miller-048420-capacitor-cer-disc-01-uf-100v-vdc-w-term/		1.75E+13	2.23E+12	3.46E+13 se/part	5.44E+13
191989	1 BAR, mtg rectifier	2	100% Copper		0.75 lbs	19.5	https://www.bvwdingsupplies.com/miller-191989-bar-mtg-rectifier/		7.61E+14	0.00E+00	2.88E+13 se/part	7.89E+14
188691	1 CLAMP, thyristor rectifier 5.375	3	100% Steel, Virgin		0.44 lbs	25.64	https://www.bvwdingsupplies.com/miller-188691-clamp-thyristor-rectifier/		1.37E+13	0.00E+00	7.36E+13 se/part	8.73E+13
188839	1 HEAT SINK, rectifier snowflake .800	12	100% Aluminum		1.41 lbs	27.6	https://www.bvwdingsupplies.com/miller-188839-heat-sink-rectifier-snowflake-800-cast-al/		1.53E+14	0.00E+00	3.18E+14 se/part	4.72E+14
161668	1 THYRISTOR, SCR 300A 300V hockey puck	6	50% Silicon	50% Steel, Virgin	0.19 lbs	121.69	https://www.bvwdingsupplies.com/miller-161668-thyristor-scr-300-a-300v-hockey-puck-none/		1.72E+12	5.89E+12	7.01E+14 se/part	7.09E+14
166667	1 CLAMP, spring thyristor rectifier 5.500	3	100% Steel, Virgin		0.22 lbs	75.9	https://www.bvwdingsupplies.com/miller-166667-clamp-spring-thyristor-rectifier/		6.83E+12	0.00E+00	2.19E+14 se/part	2.26E+14
158720	1 CONNECTOR & SOCKETS	1	90% Plastics	10% Steel, Virgin	0.06 lbs	29.48	https://www.bvwdingsupplies.com/miller-158720-housing-blue-sks-service-kit/		4.77E+11	6.20E+10	2.80E+13 se/part	2.86E+13

192673	1 THERMOSTAT, rectifier	1	40% Steel, Virgin	60% Plastics	0.04 lbs	18.99	https://www.bvwdingsupplies.com/miller-192673-thermostat-inc-open-186f-close-166f/	1.65E+11	2.12E+11	1.76E+13 se/part	1.80E+13
192674	1 THERMOSTAT, rectifier	1	40% Steel, Virgin	60% Plastics	0.04 lbs	19.99	https://www.bvwdingsupplies.com/miller-192674-thermostat-inc-open-175f-close-105f-rectifier-assy/	1.65E+11	2.12E+11	1.86E+13 se/part	1.89E+13
173283	1 CHAMBER, plenum 14 in	1	100% Steel, Virgin		1.23 lbs	55.64	https://www.bvwdingsupplies.com/miller-173283-chamber-plenum-14-in/	1.27E+13	0.00E+00	5.32E+13 se/part	6.59E+13
180165	1 BLADE, fan 14 in 3wg 28deg .375 bore CCW	1	100% Steel, Virgin		1.06 lbs	42.21	https://www.bvwdingsupplies.com/miller-180165-blade-fan-14-000-3wg-28deg-375-bore-ccw-gal/	1.10E+13	0.00E+00	4.03E+13 se/part	5.13E+13
162807	1 PANEL, rear	1	100% Steel, Virgin		8.56 lbs	165.99	https://www.amazon.com/Miller-Electric-162807-Panel-Rear/dp/B004HEA1G/ref=sr_1_fkmrnu_1?keywords=miller+162807&qid=1558014663&s=gateways&sr=8-1-fkmrnu_1	8.85E+13	0.00E+00	1.57E+14 se/part	2.46E+14
168343	1 HINGE, door primary	2	100% Plastics		0.02 lbs	3.28	https://www.bvwdingsupplies.com/miller-168343-hinge-coit-polypropylene-copolymer-2-004-w-143h/	3.53E+11	0.00E+00	6.08E+12 se/part	6.43E+12
162818	1 DOOR, access primary	1	100% Steel, Virgin		1.50 lbs	89.99	https://www.amazon.com/Miller-162818-Door-Access-Primary/dp/B004HE65OW/ref=sr_1_fkmrnu_1?keywords=miller+162818&qid=15580147108&sr=ateways&sr=8-1-fkmrnu_1	1.55E+13	0.00E+00	8.61E+13 se/part	1.02E+14
217733	1 LABEL, warning electric shock & input power (EN/FR)	1	N/A	N/A		7.88	Price from: https://www.millerserviceparts.com/Product/ProductDetails?productId=10049	N/A	N/A	N/A	
179290	1 LABEL, warning electric shock input connection (CE models only)	1	N/A	N/A		3.57	Price from: https://www.millerserviceparts.com/Product/ProductDetails?productId=5539	N/A	N/A	N/A	
602177	1 SCREW, set 250-20 x .250kniprt sch stl	2	100% Steel, Virgin		0.06 lbs	3.52	https://www.bvwdingsupplies.com/miller-602177-screw-set-250-20x-25-knripst-sch-st-phi/	1.24E+12	0.00E+00	6.74E+12 se/part	7.98E+12
124274	1 BRACKET, mtg fan motor	1	100% Steel, Virgin		2.88 lbs	51.18	https://www.bvwdingsupplies.com/miller-124274-bracket-mtg-fan-motor/	2.98E+13	0.00E+00	4.85E+13 se/part	7.83E+13
114808	1 RESISTOR, WW fxd 375W 5 ohm	2	40% Ceramics	60% Steel, Virgin	0.94 lbs	54.88	https://www.bvwdingsupplies.com/miller-114808-resistor-ww-fxd-375-w-5-ohm-w-hardwal/	9.16E+13	1.17E+13	8.53E+13 se/part	1.89E+14
208402	1 MOTOR, 1/12HP 230V .83A	1	80% Steel, Virgin	20% Copper	6.95 lbs	220	https://www.bvwdingsupplies.com/miller-kit-fan-motor-replacement-238626/	5.75E+13	7.05E+14	1.71E+14 se/part	9.33E+14
10467	1 CONNECTOR, clamp cable 1.250	1	70% Plastics	30% Steel, Virgin	0.13 lbs	20.05	https://www.bvwdingsupplies.com/miller-10467-conn-clamp-cable-1-250/	8.03E+11	4.03E+11	1.87E+13 se/part	1.99E+13
								1.55E+16		1.16E+16	
					355.04	\$12,588.68					
						\$ 5,985.00	Retail				
							https://www.millerserviceparts.com/Equipment/Welders/mig-amaw/delta-weld-652-mig-welder-m04820				
						2.103371763	markup				

D.2 Feeder BOM

Part Number	Level	Part Description	Count	% Mat1	Material	% Mat2	Material 2	Mass	Unit	Price	Source	Notes	Mat 1 Energy	Mat 2 Energy	L&S UEV	UEV Units	Part UEV
159647	1	Insulator, Motor Clamp	1	100%	Plastics			0.06 lbs	\$	11.96	http://www.brweldingsupplies.com/miller-159647-insulator-motor-clamp/		5.30E+11	0.00E+00	9.84E+12 se/part		1.04E+13
159646	1	Clamp, Motor Base	1	100%	Steel, Virgin			0.86 lbs	\$	63.90	http://www.brweldingsupplies.com/miller-159646-clamp-motor-base/		8.89E+12	0.00E+00	5.42E+13 se/part		6.31E+13
159360	1	Insulator, Screw Machine	4	100%	Steel, Virgin			0.01 lbs	\$	0.71	http://www.brweldingsupplies.com/miller-159360-insulator-screw-machine/		4.14E+11	0.00E+00	2.41E+12 se/part		2.82E+12
Figure 9-3	1	Drive Assembly, Wire	1		N/A		N/A						N/A	N/A	N/A	se/part	0.00E+00
141753	1	Hub & Spindle Assembly, Consisting Of	1		N/A		N/A	1.56 lbs	\$	1.56	http://www.brweldingsupplies.com/miller-141753-hub-spindle-assy/		N/A	N/A	N/A	se/part	0.00E+00
58427	2	Ring, Retaining Spool	1	100%	Steel, Virgin			0.13 lbs	\$	28.50	http://www.brweldingsupplies.com/miller-058427-ring-retaining-spool/		1.34E+12	0.00E+00	2.42E+13 se/part		2.56E+13
180571	2	Shaft, Support Spool	1	100%	Steel, Virgin			0.94 lbs	\$	51.88	http://www.brweldingsupplies.com/miller-180571-shaft-assy-support-spool/		9.72E+12	0.00E+00	4.39E+13 se/part		5.36E+13
10233	2	Spring, Cprsn .970 Od X .120 Wire X 1.250 Id	1	100%	Steel, Virgin			0.2 lbs	\$	3.26	http://www.brweldingsupplies.com/miller-010233-spring-cprsn-970-od-x-120-wire-x-1-250-id/		2.07E+12	0.00E+00	2.73E+12 se/part		4.79E+12
57971	2	Washer, Flat Stl Keyed 1.500 Dia X .125 Hk	2	100%	Steel, Virgin			0.03 lbs	\$	4.40	http://www.brweldingsupplies.com/miller-057971-washer-flat-6321x1-500odx1-125-hk/	mass and price are source number divided by 2, since they are sold in pkgs of 2	6.20E+11	0.00E+00	7.47E+12 se/part		8.09E+12
10191	2	Washer, Fbr .656 Id X 1.500 Od X .125 Hk	2	100%	Steel, Virgin			0.03 lbs	\$	5.33	http://www.brweldingsupplies.com/miller-010191-washer-flat-656idx1-500odx1-125-hk/	mass and price are source number divided by 2, since they are sold in pkgs of 2	6.20E+11	0.00E+00	9.05E+12 se/part		9.68E+12
58628	2	Washer, Brake Stl	2	100%	Steel, Virgin			0.055 lbs	\$	4.50	https://www.amazon.com/Miller-058628-Washer-Brake-Stl/dp/B01X02R0P/	Cached Amazon page: mass and price are source number divided by 2, since sold in pkgs of 2	1.14E+12	0.00E+00	7.62E+12 se/part		8.76E+12
58428	2	Hub, Spool	1	100%	Plastics			0.44 lbs	\$	31.99	http://www.brweldingsupplies.com/miller-058428-hub-spool/		3.88E+12	0.00E+00	2.47E+13 se/part		2.86E+13
248974	2	Tubing, Stl .875 Od x 12 Ga Wall x .562	1	100%	Plastics			0.07 lbs	\$	4.42	http://www.brweldingsupplies.com/miller-248974-tubing-stl-875-od-x-12ga-wall-x-562/		6.18E+11	0.00E+00	3.37E+12 se/part		3.99E+12
135205	2	Nut, Stl Sifflng Hex Reg .625-11 W/Nylon Insert	1	100%	Steel, Virgin			0.13 lbs	\$	2.49	http://www.brweldingsupplies.com/miller-135205-nut-625-11-941hex-77h-stl-old-elastic-ston-nut/		1.34E+12	0.00E+00	2.09E+12 se/part		3.43E+12
200556	1	Support, Spool	1	100%	Steel, Virgin			4.97 lbs	\$	95.05	http://www.brweldingsupplies.com/miller-200556-support-spool/		5.14E+13	0.00E+00	7.97E+13 se/part		1.31E+14
201781	1	Knob, W/Extension Clamp	1	50%	Steel, Virgin	50%	Plastics	0.25 lbs	\$	16.99	http://www.brweldingsupplies.com/miller-201781-knob-w-extension-clamp/		1.29E+12	1.10E+12	1.10E+13 se/part		1.34E+13
156243	1	Clamp, Motor Top	1	100%	Plastics			0.42 lbs	\$	26.36	http://www.brweldingsupplies.com/miller-156243-clamp-motor-top/		3.71E+12	0.00E+00	2.01E+13 se/part		2.38E+13
145639	1	Strip, Buna N Compressed Sheet .062 X 4.000 X 4.000	1	100%	Plastics			0.06 lbs	\$	9.16	http://www.brweldingsupplies.com/miller-145639-strip-buna-n-062-x-4-000-x-4-000-compressed-stk/		5.30E+11	0.00E+00	7.46E+12 se/part		7.99E+12
200552	1	Base	1	100%	Steel, Virgin			8.89 lbs	\$	95.58	http://www.brweldingsupplies.com/miller-200552-base/		9.19E+13	0.00E+00	7.92E+13 se/part		1.71E+14
134306	1	Foot, Rubber 1.250 Dia X 1.375 High	4	100%	Plastics			0.13 lbs	\$	3.27	http://www.brweldingsupplies.com/miller-134306-foot-rubber-1-250-dia-x-1-375-dibb-no-10-screw/		4.59E+12	0.00E+00	8.21E+12 se/part		1.28E+13
200557	1	Stiffener, Base	1	100%	Steel, Virgin			1.58 lbs	\$	32.37	http://www.brweldingsupplies.com/miller-200557-stiffener-base/		1.63E+13	0.00E+00	2.72E+13 se/part		4.35E+13
Figure 9-2	1	Control Box	1		N/A		N/A						N/A	N/A	N/A		0.00E+00
200555	1	Wrapper, Feeder	1	100%	Steel, Virgin			4.15 lbs	\$	146.99	https://www.amazon.com/Miller-Electric-200555-Wrapper-Feeder/dp/B004HFEF0N/		4.29E+13	0.00E+00	1.24E+14 se/part		1.67E+14
238487	1	Label, Warning General Precautionary (CE/Domestic)	1		N/A		N/A						N/A	N/A	N/A		0.00E+00

213134	1 Knob, Encoder 1.670 Dia X .250 Id Push On W/Spring	1	100% Plastics			0.03 lbs	\$ 15.00	https://www.brweldingsupplies.com/millic-213134-knob-encoder-1-670-dia-x-250-id-push-on-w-spring/	2.65E+11	0.00E+00	1.26E+13	se/part	1.99E+13
213134	1 Knob, Encoder 1.670 Dia X .250 Id Push On W/Spring	1	100% Plastics			0.03 lbs	\$ 15.00	https://www.brweldingsupplies.com/millic-213134-knob-encoder-1-670-dia-x-250-id-push-on-w-spring/	2.65E+11	0.00E+00	1.26E+13	se/part	1.99E+13
203214	1 Nameplate, Upper W/Meters	1	N/A	N/A					N/A	N/A	N/A	se/part	0.00E+00
203216	1 Nameplate, Lower	1	N/A	N/A					N/A	N/A	N/A	se/part	0.00E+00
202237	1 Panel, Front	1	100% Steel				\$79.99		Price from: https://weldfabulous.com/search.php?search_query=202237&section=product				
48282	1 Rpt W/Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 24.00	https://www.brweldingsupplies.com/millic-048282-receptacle-kt-w-skits/	4.77E+11	6.20E+10	2.01E+13	se/part	2.06E+13
131054	1 Housing Rpt-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 23.10	https://www.brweldingsupplies.com/millic-131054-housing-rpt-skts-service-kt/	4.77E+11	6.20E+10	1.93E+13	se/part	1.99E+13
201665	1 Housing Plug-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.01 lbs	\$ 6.67	https://www.brweldingsupplies.com/millic-201665-housing-plug-skts-service-kt/	7.95E+10	1.03E+10	5.62E+12	se/part	5.71E+12
115094	1 Housing Plug-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 12.00	https://www.brweldingsupplies.com/millic-115094-housing-plug-skts-service-kt/	4.77E+11	6.20E+10	9.90E+12	se/part	1.04E+13
202592	1 Housing Plug Pins-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.01 lbs	\$ 8.58	https://www.brweldingsupplies.com/millic-202592-housing-plug-skts-service-kt/	7.95E+10	1.03E+10	7.25E+12	se/part	7.34E+12
136810	1 Housing Plug Pins-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 6.09	https://www.brweldingsupplies.com/millic-136810-housing-plug-skts-service-kt/	4.77E+11	6.20E+10	4.87E+12	se/part	5.41E+12
130203	1 Housing Plug-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 10.85	https://www.brweldingsupplies.com/millic-130203-housing-plug-skts-service-kt/	4.77E+11	6.20E+10	8.92E+12	se/part	9.46E+12
224597	1 Potentiometer, Cermet Std Flat 3.75t 2 W 10K Linear	1	80% Steel, Virgin	20% Plastics		0.04 lbs	\$ 70.00	http://www.brweldingsupplies.com/millic-224597-pot-cermet-std-flat-3-75t-2-w-10k-ohm-linear/	3.31E+11	7.06E+10	5.93E+13	se/part	5.97E+13
115091	1 Housing Plug-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 10.20	https://www.brweldingsupplies.com/millic-115091-housing-plug-skts-service-kt/	4.77E+11	6.20E+10	8.37E+12	se/part	8.91E+12
131055	1 Housing Plug-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.01 lbs	\$ 9.72	https://www.brweldingsupplies.com/millic-131055-housing-rpt-skts-service-kt/	7.95E+10	1.03E+10	8.22E+12	se/part	8.31E+12
158719	1 Housing Plug-Skts, (Service Kit)	1	90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 12.55	https://www.brweldingsupplies.com/millic-158719-housing-plug-skts-service-kt/	4.77E+11	6.20E+10	1.04E+13	se/part	1.09E+13
211989	1 Fitting, W/Screen	1	90% Brass	10% Steel, Virgin		0.13 lbs	\$ 49.88	https://www.brweldingsupplies.com/millic-211989-fitting-w-screen/	4.35E+13	1.34E+11	4.24E+13	se/part	8.61E+13
10668	1 Screw, Cap Stl Sch 250-20 X 1.500	4	100% Steel, Virgin			0.4 lbs	\$ 5.12	https://www.brweldingsupplies.com/millic-010668-screw-250-20x1-50-std-hex-#8-pln/	1.65E+13	0.00E+00	1.70E+13	se/part	3.36E+13
172075	1 Carrier, Drive Roll W/Components	4	75% Steel, Virgin	25% Plastics		0.24 lbs	\$ 45.99	https://www.grainger.com/product/MILLER-R-ELECTRIC-Drive-Roll-Carrier-49VAV90	7.45E+12	2.12E+12	1.50E+14	se/part	1.59E+14
149962	1 Spacer, Carrier Drive Roll	4	100% Steel, Virgin			0.06 lbs	\$ 8.58	https://www.brweldingsupplies.com/millic-149962-spacer-carrier-drive-roll/	2.48E+12	0.00E+00	2.91E+13	se/part	3.16E+13
149486	1 Pin, Rotation Arm Rocker	2	100% Steel, Virgin			0.06 lbs	\$ 21.53	https://www.brweldingsupplies.com/millic-149486-pin-rotation-arm-rocker/	1.24E+12	0.00E+00	3.66E+13	se/part	3.78E+13
132750	1 Arm, Pressure	2	100% Plastics			0.09 lbs	\$ 50.00	https://www.brweldingsupplies.com/millic-132750-arm-pressure/	1.59E+12	0.00E+00	8.41E+13	se/part	8.57E+13
150520	1 Spacer, Flat Stl .257 Id X .619 Od X .105	2	100% Steel, Virgin			0.06 lbs	\$ 4.46	https://www.brweldingsupplies.com/millic-150520-spacer-rotation-pin/	1.24E+12	0.00E+00	7.56E+12	se/part	8.80E+12
133493	1 Ring, Retaining Ext .250 Shaft X .025Hk	2	100% Steel, Virgin			0.3 lbs	\$ 3.55	price and mass copied from 133308	6.20E+12	0.00E+00	5.90E+12	se/part	1.21E+13
133350	1 Pin, Hinge	1	100% Steel, Virgin			0.06 lbs	\$ 8.30	https://www.brweldingsupplies.com/millic-133350-pin-hinge/	6.20E+11	0.00E+00	7.05E+12	se/part	7.07E+12
201230	1 Motor, Gear 1/8Hp 24VDC Standard Speed	1	80% Steel, Virgin	20% Copper		11.48 lbs	\$ 814.00	http://www.brweldingsupplies.com/millic-201230-283100-motor-gear-1-8hp-24vdc-standard-speed/	9.50E+13	1.16E+15	6.26E+14	se/part	1.89E+15

201231	1 Motor, Gear 1/8Hp 24VDC High Speed (Optional On S-74D)	N/A	N/A	11.5 lbs	\$ 885.77	http://www.brweldingsupplies.com/miller-201231-motor-gear-1-8hp-24vdc-high-speed/	N/A	N/A	N/A	0.00E+00	
153491	2 Kit, Brush Replacement (Consisting Of)	N/A	N/A	0.8 lbs	\$ 63.00	http://www.brweldingsupplies.com/miller-153491-kit-brush-replacement-60-series/	N/A	N/A	N/A	0.00E+00	
153492	3 Cap, Brush	N/A	N/A	0.06 lbs	\$ 7.28	http://www.brweldingsupplies.com/miller-153492-cap-brush/	N/A	N/A	N/A	0.00E+00	
*153493	3 Brush, Carbon	N/A	N/A				N/A	N/A	N/A	0.00E+00	
184136	2 Kit, Brush Holder Replacement	N/A	N/A	1.44 lbs	\$ 302.04	http://www.brweldingsupplies.com/miller-184136-kit-cover-motor-gear-box/	N/A	N/A	N/A	0.00E+00	
155098	1 Kit, Cover Motor Gearbox (Consisting Of)	N/A	N/A	1.19 lbs	\$ 307.02	http://www.brweldingsupplies.com/miller-155098-cover-motor-gear-box-with-gasket-screws/	N/A	N/A	N/A	0.00E+00	
153550	2 Cover, Motor Gearbox (Consisting Of)	100% Plastics		1.19 lbs	\$ 307.02	http://www.brweldingsupplies.com/miller-153550-cover-motor-gear-box-with-gasket-screws/	1.05E+13	0.00E+00	2.55E+14	se/part	
155099	3 Gasket, Cover	100% Plastics		0.05 lbs	\$ 10.10	http://www.brweldingsupplies.com/miller-155099-gasket-cover-motor-gear-box/	4.41E+11	0.00E+00	8.31E+12	se/part	
155100	3 Screw, Cover	100% Steel, Virgin		0.06 lb	\$ 0.66		cost and mass from 108940	3.10E+12	0.00E+00	2.74E+12	se/part
154031	2 Spacer, Locating	100% Steel, Virgin		0.12 lbs	\$ 5.70		cost and mass from 167387	2.48E+12	0.00E+00	9.64E+12	se/part
133493	2 Ring, Ring Ext. 250 Shaft Grv X .025Thk	100% Steel, Virgin		0.06 lbs	\$ 3.50		Mass from 133308; Price from: https://weldfabulous.com/miller-133493-ring-ring-ext-250-shaft-x-025-thk-c-style-pkg-2/	6.20E+11	0.00E+00	2.96E+12	se/part
203631	1 Pressure Arm, S/L & Vert S/R 4 Roll (Consisting Of)	N/A		1.02 lbs	\$ 106.32	http://www.brweldingsupplies.com/miller-203631-pressure-arm-s-l-vert-s-r-4-roll/	N/A	N/A	N/A	0.00E+00	
203641	2 Washer, Flat Indicator Spring Tension	100% Steel, Virgin		0.04 lbs	\$ 5.38	http://www.brweldingsupplies.com/miller-203641-washer-flat-indicator-spring-tension/	8.27E+11	0.00E+00	9.13E+12	se/part	
182415	2 Pin, Conter Hair	100% Steel, Virgin		0.06 lbs	\$ 0.99	http://www.brweldingsupplies.com/miller-182415-pin-cotter-hair-054-x-750/	6.20E+11	0.00E+00	8.28E+11	se/part	
203640	2 Knob, W/Extension Short Pressure Arm	80% Plastics	20% Steel, Virgin	0.12 lbs	\$ 19.46	http://www.brweldingsupplies.com/miller-203640-knob-w-extension-short-pressure-arm/	8.47E+11	2.48E+11	1.60E+13	se/part	
182156	2 Spring, Cpsn	100% Steel, Virgin		0.06 lbs	\$ 2.29	http://www.brweldingsupplies.com/miller-182156-spring-cpsn-527-od-x-065-wire-x-937-length/	1.24E+12	0.00E+00	3.87E+12	se/part	
182155	2 Spring	100% Steel, Virgin		0.1 lbs	\$ 6.00	http://www.brweldingsupplies.com/miller-182155-spring-cpsn-756-od-x-098-wire-x-781-length/	2.07E+12	0.00E+00	1.02E+13	se/part	
132746	2 Bushing Spring	100% Steel, Virgin		0.1 lbs	\$ 12.00	http://www.brweldingsupplies.com/miller-132746-bushing-spring/	2.07E+12	0.00E+00	2.04E+13	se/part	
203633	2 Shaft, Spring	100% Steel, Virgin		0.05 lbs	\$ 18.92	http://www.brweldingsupplies.com/miller-203633-shaft-spring/	5.17E+11	0.00E+00	1.61E+13	se/part	
203632	2 Carrier, Shaft Dual Knob	100% Plastics		0.56 lbs	\$ 42.00	http://www.brweldingsupplies.com/miller-203632-carrier-shaft-dual-knob/	4.94E+12	0.00E+00	3.26E+13	se/part	
133739	2 Washer, Flat Buna .375 Id X .625 Od X .062Hk	100% Plastics		0.02 lbs	\$ 2.80	http://www.brweldingsupplies.com/miller-133739-washer-flat-375id60-625od-062-rubber-buna-n/	3.53E+11	0.00E+00	4.54E+12	se/part	
203637	2 Knob, W/Extension Long Pressure Arm	80% Plastics	20% Steel, Virgin	0.14 lbs	\$ 19.16	http://www.brweldingsupplies.com/miller-203637-knob-w-extension-long-pressure-arm/	9.89E+11	2.90E+11	1.56E+13	se/part	
237048	1 Circuit Card, Digital Tach (Consisting Of)	separate calc		0.09 lbs	\$ 171.97	http://www.brweldingsupplies.com/miller-237048-circuit-card-assy-digital-tach/	3.04E+12		1.46E+14	se/part	
131204	2 Connector & Sockets	90% Plastics	10% Steel, Virgin	0.06 lbs	\$ 6.61	http://www.brweldingsupplies.com/miller-131204-housing-plug-kits-service-kit/	4.77E+11	6.20E+10	5.31E+12	se/part	
604311	2 Grommet, Rbr .250 Id X .375mg Hole .062 Groove	100% Plastics		0.06 lbs	\$ 5.10	http://www.brweldingsupplies.com/miller-604311-grommet-rbr-250-id-x-375-milg-hole-062-groove/	5.30E+11	0.00E+00	4.00E+12	se/part	

132611	1 Optical Encoder Disc	1	100% Steel, Virgin			0.06 lbs	\$ 11.69	https://www.brweldingsupplies.com/miller-132611-optical-encoder-disc/		6.20E+11	0.00E+00	9.93E+12	se/part	1.06E+13
603115	1 Weather Stripping, Adh .125 X .375	1	100% Plastics			0.1984162 lbs	\$ 10.99	Mass: https://www.itemshub.com/index.php?option=com_product/product&product_id=27796	Price from: https://weldfabulous.com/miller-603115-weatherstripping-adh-125-x-375-roll/	1.75E+12	0.00E+00	8.24E+12	se/part	9.99E+12
167387	1 Spacer, Locating	2	100% Steel, Virgin			0.12 lbs	\$ 5.70	https://www.brweldingsupplies.com/miller-167387-spacer-locating/		2.48E+12	0.00E+00	9.64E+12	se/part	1.21E+13
168825	1 Drive, Pinion	2	100% Steel, Virgin			0.06 lbs	\$ 18.63	https://www.brweldingsupplies.com/miller-168825-drive-pinion-312-21-240-376-bore/		1.24E+12	0.00E+00	3.17E+13	se/part	3.99E+13
133308	1 Ring, Retaining Ext .375 Shaft X .025Hk	1	100% Steel, Virgin			0.06 lbs	\$ 0.71	https://www.brweldingsupplies.com/miller-133308-ring-rtng-ext-375-shaft-x-025-thk/		6.20E+11	0.00E+00	5.90E+11	se/part	1.21E+12
134834	1 Hose, Sae .187 Id X .410 Od (Order By Ft)	1	100% Plastics			0.134 lbs	\$ 6.99	Mass Estimated from: https://erubber.com/products/hydraulic-hoses/	Price from: https://weldfabulous.com/miller-134834-hose-sae-187-id-x-410-od-xoil/	1.18E+12	0.00E+00	5.20E+12	se/part	6.38E+12
244579	1 Adapter Assy, Gun/Feeder Lh Accu-Mate (Consisting Of)	1	N/A		N/A					N/A	N/A	N/A	se/part	0.00E+00
601966	2 Screw, Cap Stl Hexhd .375-16 X 1.250	1	100% Steel, Virgin			0.06 lbs	\$ 2.87	https://www.brweldingsupplies.com/miller-601966-screw-375-16x1-25-hex-hd-ph-gr-5-pld/		6.20E+11	0.00E+00	2.43E+12	se/part	3.09E+12
149959	2 Fitting, Bx Barbed M 3/16Tbg X .312-24	1	100% Brass			0.06 lbs	\$ 16.72	https://www.brweldingsupplies.com/miller-149959-fbg-hose-bx-barbed-m-3-16-tbg-x-312-24/		2.23E+13	0.00E+00	1.42E+13	se/part	3.65E+13
167788	2 Nut, 375-16 56Hex 34H St Pld Sem Cone Wshr 88d	1	100% Steel, Virgin			0.01 lbs	\$ 0.60	https://www.brweldingsupplies.com/miller-167788-nut-375-16-56hex-34h-stl-pld-sem-cone-wshr-88d/	cost and mass from 108940	1.03E+11	0.00E+00	5.08E+11	se/part	6.11E+11
185624	2 Screw, 010-32X .50 Hexwhd 40D Stl Pld Slfing Tribob	2	100% Steel, Virgin			0.06 lb	\$ 0.66			1.24E+12	0.00E+00	1.09E+12	se/part	2.34E+12
242259	2 Clamp, Power Pin	1	100% Steel, Virgin			0.03 lbs	\$ 26.62	https://www.brweldingsupplies.com/miller-242259-clamp-power-pin/		3.10E+11	0.00E+00	2.26E+13	se/part	2.30E+13
242261	2 Lock, Power Pin	1	100% Steel, Virgin			0.02 lbs	\$ 8.76	https://www.brweldingsupplies.com/miller-242261-lock-power-pin/		2.07E+11	0.00E+00	7.45E+12	se/part	7.65E+12
231232	2 Washer, Flat .344IdX0.688OdX.0651 Stl Pld Ansl.312	1	100% Steel, Virgin			0.06 lbs	\$ 3.12	https://www.brweldingsupplies.com/miller-231232-washer-flat-344id-x0-688od-x0-0651-stl-pld-ansi-312/		6.20E+11	0.00E+00	2.64E+12	se/part	3.26E+12
151437	2 Knob, Plstc T 1.125 Lg X .312-18 X 1.500	1	100% Plastics			0.06 lbs	\$ 5.64	https://www.brweldingsupplies.com/miller-151437-knob-t1-500-br-w-312-18-stud-1-175-ig-plstc/		5.30E+11	0.00E+00	4.46E+12	se/part	4.99E+12
179277	1 Cover, Drive Roll (Consisting Of)	1	100% Plastics							N/A	N/A	N/A		0.00E+00
269731	2 Label, Warning Hot Surfaces And Moving Parts	1	N/A		N/A					N/A	N/A	N/A		0.00E+00
108940	1 Screw, Cap Stl Hexhd .250-20 X .750	4	100% Steel, Virgin			0.06 lb	\$ 0.66	https://www.brweldingsupplies.com/miller-108940-screw-250-20x-75-hexwhd-61d-gr-5-pld/		2.48E+12	0.00E+00	2.19E+12	se/part	4.67E+12
						55.74 lbs	\$ 4,819.05							
		Totals				25.34 kg	\$ 2,028.00	Retail price	https://www.millerwelds.com/accessories/wire-feeders/70-series-wire-feeder-m00454	2.15E+15		4.19E+15		6.33E+15
		Actual				lbs	2.3762574	Parts Markup						

D.3 Gun BOM

Part Number	Level	Part Description	Count	% Mat1	Material	% Mat2	Material 2	Mass	Unit	Price	Source	Notes	Mat 1 Energy	Mat 2 Energy	L&S UEV	UEV Units	Part UEV
201250	1	GOOSENECK, 82 deg bend	1	100%	Steel, Virgin			0.6	\$	87.99		Price from https://weldfabulous.com/miller-201250-gooseneck-82-deg-fc-1150-gun-1/	6.20E+12	0.00E+00	1.13E+14	sej/part	1.19E+14
201251	1	GOOSENECK, aluminum jacketed, 82 deg bend	1	70%	Steel, Virgin	30%	Aluminum	0.65 lbs	\$	95.99	https://www.amazon.com/Miller-201251-Gooseneck-Jacketed-FC-1150/dp/B004HEAPR8/		4.71E+12	1.77E+12	1.23E+14	sej/part	1.29E+14
201247	1	GOOSENECK, 25 deg bend	1	100%	Steel, Virgin			0.66875 lbs	\$	76.99	https://www.amazon.com/Miller-201247-Gooseneck-Deg-FC-1150/dp/B004HEAR62/		6.92E+12	0.00E+00	9.86E+13	sej/part	1.05E+14
201248	1	GOOSENECK, 45 deg bend	1	100%	Steel, Virgin			0.5875 lbs	\$	85.99	https://www.amazon.com/Miller-201248-Gooseneck-Deg-FC-1150/dp/B004HECA4Y/		6.08E+12	0.00E+00	1.10E+14	sej/part	1.16E+14
201249	1	GOOSENECK, aluminum jacketed, 45 deg bend	1	70%	Steel, Virgin	30%	Aluminum	0.6 lbs	\$	95.99		Price from https://weldfabulous.com/miller-201249-gooseneck-aluminum-jacketed-45-deg-fc-1150-gun/	4.34E+12	1.63E+12	1.23E+14	sej/part	1.29E+14
201252	1	GOOSENECK, straight, 5 deg bend	1	100%	Steel, Virgin			0.6 lbs	\$	106.99		Price from https://weldfabulous.com/miller-201252-gooseneck-straight-w-5-deg-bend-fc-1150-gun/	6.20E+12	0.00E+00	1.37E+14	sej/part	1.43E+14
201260	1	LINER, gooseneck replacement short	1	100%	Steel, Virgin			0.08 lbs	\$	10.99	https://www.amazon.com/Miller-201260-Gooseneck-Replacement-FC-1150/dp/B004HEFM6W/ref=lp_r_1_1_1?keywords=miller+201260&qid=156247761&s=gate&sr=8-1		8.27E+11	0.00E+00	1.41E+13	sej/part	1.49E+13
194714	1	HANDLE KIT, assembly (consisting of)		N/A		N/A							N/A	N/A	N/A	sej/part	0.00E+00
81664	2	RING, ring ext. 625 shaft grv x .042 thk e style	1	100%	Steel, Virgin			0.01 lbs	\$	0.31	http://www.brweldingsupply.com/miller-081664-ring-rtng-ext-625-shaft-grv-x-035-thk-c-style/		1.03E+11	0.00E+00	3.95E+11	sej/part	4.99E+11
198821	2	SHIELD, spatter	1	100%	Aluminum			0.01 lbs	\$	3.39	http://www.brweldingsupply.com/miller-198821-shield-spatter-gun-fc-1260/		9.06E+10	0.00E+00	4.35E+12	sej/part	4.44E+12
198820	2	CLAMP	1	100%	Plastics			0.01 lbs	\$	6.55	http://www.brweldingsupply.com/miller-198820-clamp-gun-fc-1260/		8.83E+10	0.00E+00	8.34E+12	sej/part	8.43E+12
198819	2	HANDLE	1	100%	Plastics			0.14 lbs	\$	17.70	http://www.brweldingsupply.com/miller-198819-handle-gun-fc-1260/		1.24E+12	0.00E+00	2.19E+13	sej/part	2.31E+13

133774	2	SCREW, cap stl sch .250-20 x .625 pld	1	100% Steel, Virgin			0.01 lbs	\$ 1.98	http://www.bweldingsupply.com/miller-133774-screw-cap-stl-sch-250-20x-625-pld/			1.03E+11	0.00E+00	2.54E+12	se/part	2.64E+12
194713	1	SWITCH KIT, assembly 15 ft (consisting of)	1	N/A	N/A		1.06 lbs	\$ 207.08	http://www.bweldingsupply.com/miller-194713-kit-switch-assembly-15-ft-fc-1260-gun/			N/A	N/A	N/A	se/part	0.00E+00
195735	1	SWITCH KIT, assembly 10 ft (consisting of)	1	60% Plastics	40% Steel, Virgin		0.86 lbs	\$ 195.71	http://www.bweldingsupply.com/miller-195735-kit-switch-assembly-10-ft-fc-1260-gun/			4.56E+12	3.56E+12	2.48E+14	se/part	2.56E+14
198743	2	CLAMP, switch housing		100% Steel, Virgin								0.00E+00	0.00E+00	0.00E+00	se/part	0.00E+00
602202	2	WASHER, tooth .168idx0.340od x .023t stl pld		100% Steel, Virgin			0.1 lbs	\$ 0.63	http://www.bweldingsupply.com/miller-602202-washer-tooth-168idx0-340odx-023t-stl-pld-int-8-a/			0.00E+00	0.00E+00	0.00E+00	se/part	0.00E+00
70001	2	SCREW, 008-32x .25 hexwhd-pln stl pld		100% Steel, Virgin			0.01 lbs	\$ 3.18	http://www.bweldingsupply.com/miller-070001-screw-008-32x-25-hexwhd-stl-pld/			0.00E+00	0.00E+00	0.00E+00	se/part	0.00E+00
79878	2	HOUSING PLUG+PINS, (service kit)		90% Plastics	10% Steel, Virgin		0.06 lbs	\$ 25.90	http://www.bweldingsupply.com/miller-079878-housing-plug-plns-service-kit/			0.00E+00	0.00E+00	0.00E+00	se/part	0.00E+00
79531	2	CONN, circ cpc clamp str rlf size 11 .453od		100% Plastics			0.06 lbs	\$ 19.11	http://www.bweldingsupply.com/miller-079531-conn-circ-cpc-clamp-str-rlf-size-11-453od/			0.00E+00	0.00E+00	0.00E+00	se/part	0.00E+00
198894	1	SCREW, set # 8-32x .312	1	100% Steel, Virgin			0.01 lbs	\$ 1.98		Price and mass copied from 133774		1.03E+11	0.00E+00	2.54E+12	se/part	2.64E+12
201246	1	KIT, replacement standard liner 15 ft (including)	1	100% Steel, Virgin			2.14 lbs	\$ 27.37	http://www.bweldingsupply.com/miller-201246-kit-3-32-1-8-replacement-liner-15-ft-fc-1150gun/			2.21E+13	0.00E+00	3.46E+13	se/part	5.67E+13
166575	2	WRENCH, hex .078 across flat	1	N/A	N/A		0.01 lbs	\$ 0.01	http://www.bweldingsupply.com/miller-166575-wrench-hex-078-across-the-flat-short-series/			N/A	N/A	N/A	se/part	0.00E+00
201276	1	LABEL, FC-1150 gun 10ft	1	N/A	N/A							N/A	N/A	N/A	se/part	0.00E+00
201277	1	LABEL, FC-1150 gun 15ft	1	N/A	N/A							N/A	N/A	N/A	se/part	0.00E+00
195733	1	KIT, insulator sleeve w/spring	1	100% Steel, Virgin			0.46 lbs	\$ 0.46	http://www.bweldingsupply.com/miller-195733-kit-insulator-slv-w-spring-fc-1260-gun-10-15-ft/			4.76E+12	0.00E+00	4.80E+11	se/part	5.24E+12
201245	1	SHIELD KIT, heat (including)	1	100% Aluminum			0.28 lbs	\$ 32.78	http://www.bweldingsupply.com/miller-201245-kit-heat-shield-fc-1150-gun/			2.54E+12	0.00E+00	4.20E+13	se/part	4.46E+13

135646	2	SCREW, 008-32x1.50 rnd hd-phl stl pld	2	100% Steel, Virgin	0.06 lbs	\$ 2.55	http://www.brweldingsupplies.com/miller-135646-screw-008-32x1-50-rnd-hd-phl-stl-pld/	1.24E+12	0.00E+00	6.51E+12 sej/part	7.75E+12
198681	2	NUT, 008-32 .34 hex. 23h stl pld elastic stop nut	2	100% Steel, Virgin	0.01 lbs	\$ 1.65	http://www.brweldingsupplies.com/miller-198681-nut-008-32-34hex-23h-stl-pld-elastic-stop-nut/	2.07E+11	0.00E+00	4.23E+12 sej/part	4.43E+12
201255	1	INSERT, ceramic	1	100% Ceramic	0.01 lbs	\$ 3.12	http://www.brweldingsupplies.com/miller-201255-insert-ceramic-fc-1150-gun/	1.22E+12	0.00E+00	4.00E+12 sej/part	5.22E+12
201254	1	INSERT, steel	1	100% Steel, Virgin	0.01 lbs	\$ 1.71	http://www.brweldingsupplies.com/miller-201254-insert-steel-fc-1150-gun/	1.03E+11	0.00E+00	2.19E+12 sej/part	2.29E+12
201253	1	LINER, locking screw 3/8 in-16	1	100% Steel, Virgin	0.06 lbs	\$ 5.99	Price from https://weldfabulous.com/miller-201253-liner-locking-screw-3-8-16-fc-1150-gun/	6.20E+11	0.00E+00	7.67E+12 sej/part	8.29E+12
201256	1	TIP, contact 3/32 in	1	100% Copper	0.0285 lbs	\$ 2.88	https://www.amazon.com/Miller-201256-Tip-Contact-Fc-1150-gp/B01LYDX28E	1.45E+13	0.00E+00	3.53E+12 sej/part	1.80E+13
201257	1	TIP, contact 7/64 in	1	100% Copper	0.0295 lbs	\$ 2.88	https://www.amazon.com/Miller-201257-Tip-Contact-Fc-1150-gp/B01M0XWEGU/ref=sr_1_1?keywords=miller+201257&qid=1559850546&s=hi&sr=1-1	1.50E+13	0.00E+00	3.52E+12 sej/part	1.85E+13
201258	1	TIP, contact .120 in	100% Copper					N/A	N/A	N/A	0.00E+00
201259	1	TIP, contact 1/8 in	1	100% Copper	0.026 lbs	\$ 2.88	https://www.amazon.com/Miller-201259-Tip-Contact-Fc-1150-gp/B01LY01FP4	1.32E+13	0.00E+00	3.54E+12 sej/part	1.67E+13
201261	1	NOZZLE, insulated	1	N/A	0.15 lbs	\$ 10.30	http://www.brweldingsupplies.com/miller-201261-nozzle-insulated-fc-1150-gun/	N/A	N/A	N/A	0.00E+00
201262	1	NOZZLE, insulated 2-3/4 in stick out	1	100% Copper	0.2 lbs	\$ 12.08	http://www.brweldingsupplies.com/miller-201262-nozzle-insulated-2-3-4-stick-out-fc-1150-gun/	1.01E+14	0.00E+00	1.43E+13 sej/part	1.16E+14
					8.08025	\$ 880.70					
						558.61	Retail				
							https://www.millerwelds.com/accessories/guns-torches/flux-cored-guns/flux-cored-mig-gun-350-amp-m00310#/?product-option-title=ironmate-flux-cored-gun-350-amps-15-ft-195729	2.19E+14	1.13E+15		1.36E+15
						1 57659	Parts Marking				

Appendix E Evaluating Labor vs. Automation Using Emergy

A common question asked within manufacturing is if a process should be automated or if it should be completed using manual labor. This is often evaluated based on cost, with the result that high-wage countries (e.g., Germany and the United States) have more automation within their factories versus low-wage countries (e.g., China, India, and Romania). Zhang and Dornfeld [57] propose the use of an hourly energy metric for labor as alternative method for completing this evaluation. By comparing the energy required for labor to complete the task to the energy required for reduced labor supported by automation to complete the task, a selection can be made for the lower energy option. Within their model, though, Zhang and Dornfeld [57] look only at the energy consumed by a process, not at the energy shadow.

Emergy provides a framework for giving a more comprehensive assessment of this comparison, capturing much more of the energy shadow. By completing the calculations presented in Section 3.1, it is possible to compare the emergy for a manual task versus that for an automated task. While this has not been completed within this dissertation study, some insight into how this may balance out can be gained by reviewing the data for the design alternatives presented in Appendix L.

Table E.1 summarizes the emergy data for the original example presented in Section 3.4.11 and design alternative A, presented in Figure L.1 in Appendix L. The goal of design alternative A was to reduce the number of parts, a common strategy within DFM for reducing cost [9, 11]. The material emergy and the part processing emergy values are very close at 0.4% and 3.9% difference, respectively.

The major savings between these two designs is in the welding, particularly around the reduction in labor. For this dissertation study, the hourly rate for the weld worker is $1.32\text{E}+14$ sej/hr and the highest hourly rate for a machine (removing the operator) is that of the laser at $6.96\text{E}+13$ sej/hr. From this we can conclude that if there is no operator at the laser, an hour of manual welding is equal to the emergenic value of 1.9 hours at the

Table E.1. Summary of Emergy Data for the Example Assembly and Alternative Design A

	Original	Alternative A	% Difference
Material Total	2.22E+13	2.21E+13	0.4%
Component Processing Total	1.28E+13	1.23E+13	3.9%
Welding Total	1.45E+13	7.83E+12	46.0%
Operator	1.10E+13	5.94E+12	46.0%
All Other Sources	3.50E+12	1.89E+12	46.0%

laser. In other words, the design would maintain the same required emergy if the time on the welder was replaced by 1.9 times the amount of time at a fully automated laser.

To consider in a generic case if automation is likely to decrease the emergy of manufacturing, the following procedure is proposed:

1. Gather hourly emergy UEVs for each of the processes and labor involved,
2. Determine the ratio of the total emergy values per hour for each of the automated and manual alternatives,
3. Estimate the times for all machines and labor involved in the completing the manufacturing for the automated and manual alternatives using DFM software or other industrial engineering tools,
4. Determine the ratio of time for each of the manufacturing alternatives,
5. Compare the ratios from Step 2 to the ratios from Step 3,
6. Select the manufacturing alternative where the ratio of time is less than that of emergy.

Using this procedure, the most emergy effective alternative for assembly can be selected. This improves on the simple comparison made by Zhang and Dornfeld [57] in two ways. First, it provides a generic methodology for applying to any case. Second, it includes the entire energy shadow of a product since it uses emergy as a metric.

Appendix F DFM Cost Reports

Part Cost Report

Part Number	BASE FLANGE	Rough Mass (kg)	0.61	Date costed	Oct 4, 2019
Scenario	bulk-initial	Finish Mass (kg)	0.54	Costed by	apriori
Description	-	Material Utilization	88%	Currency	USD
Revision	-	Material Unit Cost (USD / kg)	3.50	Unit System	Metric
Process Group	Sheet Metal				
Virtual Production Environment	Emergy Analysis				
Material	Steel, Cold Worked, AISI 1020				
Batch Size	833				
Annual Volume	10,000				
Production Life	5				
Total Planned Volume	50,000				
Cost Target (USD)	-				
Amount Variance (USD)	-				
Percent Variance	0%				
Total Projected Cost Difference (USD)	-				
Fully Burdened Cost (USD)	2.89

Processes				
	1	2	3	
	Material Stock	Laser Cut	Bend Brake	
Manufacturing Times				
Labor Time (s)	35.28	20.33	14.95	
Cycle Time (s)	24.01	12.51	11.50	
Batch Setup Time (hr)	0.83	0.08	0.75	
Manufacturing Rates (USD / hr)				
Labor Rate	0.00	20.99	20.99	
Direct Overhead Rate	0.00	34.66	5.67	
Indirect Overhead rate	0.00	14.81	8.33	
Total Overhead Rate	0.00	49.47	14.00	
Cost Summary (USD)				
Material Cost	2.13	0.00	2.13	0.00
Labor Cost	0.21	0.00	0.12	0.09
Direct Overhead	0.14	0.00	0.12	0.02
Amortized Batch Setup	0.03	0.00	0.01	0.02
Logistics	0.00	0.00	0.00	0.00
Material Overhead Cost	0.05	0.00	0.05	0.00
Expendable Tooling	0.00	0.00	0.00	0.00
Additional Direct Costs	0.00	0.00	0.00	0.00
Extra Costs	0.00	0.00	0.00	0.00
Other Direct Costs	0.00	0.00	0.00	0.00
Total Variable Costs	2.55	0.00	2.42	0.13
Period Overhead Allocations	0.09	0.00	0.05	0.03
SGA Cost	0.25	0.00	0.24	0.01
Margin	0.00	0.00	0.00	0.00
Piece Part Cost	2.89	0.00	2.72	0.18
Hard Tooling (Amortized)	0.00	0.00	0.00	0.00
Fixture Cost (Amortized)	0.00	0.00	0.00	0.00
Programming Cost (Amortized)	0.00	0.00	0.00	0.00
Additional Amortized Cost	0.00	0.00	0.00	0.00
Total Amortized Investments	0.00	0.00	0.00	0.00
Fully Burdened Cost	2.89	0.00	2.72	0.18
Hard Tooling	0.00	0.00	0.00	0.00
Fixture Cost	0.00	0.00	0.00	0.00
Programming Cost	0.00	0.00	0.00	0.00
Total Capital Investment	0.00	0.00	0.00	0.00

Part Number	SIDE FLANGE LH	Rough Mass (kg)	0.41	Date costed	Oct 4, 2019
Scenario	bulk-initial	Finish Mass (kg)	0.31	Costed by	apriori
Description	-	Material Utilization	76%	Currency	USD
Revision	-	Material Unit Cost (USD / kg)	3.50	Unit System	Metric
Process Group	Sheet Metal				
Virtual Production Environment	Energy Analysis				
Material	Steel, Cold Worked, AISI 1020				
Batch Size	833				
Annual Volume	10,000				
Production Life	5				
Total Planned Volume	50,000				
Cost Target (USD)	-				
Amount Variance (USD)	-				
Percent Variance	0%				
Total Projected Cost Difference (USD)	-				
Fully Burdened Cost (USD)	2.25

Material: Steel, Cold Worked, AISI 1020
(2.04 mm x 1.02 x 3.00 mm x 5.000.00 mm)

		Processes		
		1	2	3
		Material Stock	Laser Cut	Bend Brake
Manufacturing Times				
Labor Time (s)	51.00	0.00	16.55	34.45
Cycle Time (s)	36.68	0.00	10.18	26.50
Batch Setup Time (hr)	0.83	0.00	0.08	0.75
Manufacturing Rates (USD / hr)				
Labor Rate		0.00	20.99	20.99
Direct Overhead Rate		0.00	34.66	5.67
Indirect Overhead rate		0.00	14.81	8.33
Total Overhead Rate		0.00	49.47	14.00
Cost Summary (USD)				
Material Cost	1.44	0.00	1.44	0.00
Labor Cost	0.30	0.00	0.10	0.20
Direct Overhead	0.14	0.00	0.10	0.04
Amortized Batch Setup	0.03	0.00	0.01	0.02
Logistics	0.00	0.00	0.00	0.00
Material Overhead Cost	0.03	0.00	0.03	0.00
Expendable Tooling	0.00	0.00	0.00	0.00
Additional Direct Costs	0.00	0.00	0.00	0.00
Extra Costs	0.00	0.00	0.00	0.00
Other Direct Costs	0.03	0.00	0.03	0.00
Total Variable Costs	1.94	0.00	1.67	0.27
Period Overhead Allocations	0.11	0.00	0.04	0.07
SGA Cost	0.19	0.00	0.17	0.03
Margin	0.00	0.00	0.00	0.00
Piece Part Cost	2.25	0.00	1.88	0.36
Hard Tooling (amortized)	0.00	0.00	0.00	0.00
Fixture Cost (Amortized)	0.00	0.00	0.00	0.00
Programming Cost (Amortized)	0.00	0.00	0.00	0.00
Additional Amortized Cost	0.00	0.00	0.00	0.00
Total Amortized Investments	0.00	0.00	0.00	0.00
Fully Burdened Cost	2.25	0.00	1.88	0.36
Hard Tooling	0.00	0.00	0.00	0.00
Fixture Cost	0.00	0.00	0.00	0.00
Programming Cost	0.00	0.00	0.00	0.00
Total Capital Investment	0.00	0.00	0.00	0.00

Part Number	SIDE FLANGE RH	Rough Mass (kg)	0.43	Date costed	Oct 4, 2019
Scenario	bulk-initial	Finish Mass (kg)	0.32	Costed by	apriori
Description	-	Material Utilization	75%	Currency	USD
Revision	-	Material Unit Cost (USD / kg)	3.50	Unit System	Metric
Process Group	Sheet Metal				
Virtual Production Environment	Energy Analysis				
Material	Steel, Cold Worked, AISI 1020				
Batch Size	833				
Annual Volume	10,000				
Production Life	5				
Total Planned Volume	50,000				
Cost Target (USD)	-				
Amount Variance (USD)	-				
Percent Variance	0%				
Total Projected Cost Difference (USD)	-				
Fully Burdened Cost (USD)	2.33

		Processes		
		1	2	3
		Material Stock	Laser Cut	Bend Brake
Manufacturing Times	Part Totals			
Labor Time (s)	51.25	0.00	16.80	34.45
Cycle Time (s)	36.84	0.00	10.34	26.50
Batch Setup Time (hr)	0.83	0.00	0.08	0.75
Manufacturing Rates (USD / hr)				
Labor Rate		0.00	20.99	20.99
Direct Overhead Rate		0.00	34.66	5.67
Indirect Overhead rate		0.00	14.81	8.33
Total Overhead Rate		0.00	49.47	14.00
Cost Summary (USD)				
Material Cost	1.52	0.00	1.52	0.00
Labor Cost	0.30	0.00	0.10	0.20
Direct Overhead	0.14	0.00	0.10	0.04
Amortized Batch Setup	0.03	0.00	0.01	0.02
Logistics	0.00	0.00	0.00	0.00
Material Overhead Cost	0.04	0.00	0.04	0.00
Expendable Tooling	0.00	0.00	0.00	0.00
Additional Direct Costs	0.00	0.00	0.00	0.00
Extra Costs	0.00	0.00	0.00	0.00
Other Direct Costs	0.04	0.00	0.04	0.00
Total Variable Costs	2.02	0.00	1.76	0.27
Period Overhead Allocations	0.11	0.00	0.04	0.07
SGA Cost	0.20	0.00	0.17	0.03
Margin	0.00	0.00	0.00	0.00
Piece Part Cost	2.33	0.00	1.97	0.36
Hard Tooling (amortized)	0.00	0.00	0.00	0.00
Fixture Cost (Amortized)	0.00	0.00	0.00	0.00
Programming Cost (Amortized)	0.00	0.00	0.00	0.00
Additional Amortized Cost	0.00	0.00	0.00	0.00
Total Amortized Investments	0.00	0.00	0.00	0.00
Fully Burdened Cost	2.33	0.00	1.97	0.36
Hard Tooling	0.00	0.00	0.00	0.00
Fixture Cost	0.00	0.00	0.00	0.00
Programming Cost	0.00	0.00	0.00	0.00
Total Capital Investment	0.00	0.00	0.00	0.00

Part Number	BASE FLANGE	Rough Mass (kg)	0.61	Date costed	Oct 4, 2019
Scenario	bulk-initial	Finish Mass (kg)	0.54	Costed by	apriori
Description	-	Material Utilization	88%	Currency	USD
Revision	-	Material Unit Cost (USD / kg)	3.50	Unit System	Metric
Process Group	Sheet Metal				
Virtual Production Environment	Energy Analysis				
Material	Steel, Cold Worked, AISI 1020				
Batch Size	833				
Annual Volume	10,000				
Production Life	5				
Total Planned Volume	50,000				
Cost Target (USD)	-				
Amount Variance (USD)	-				
Percent Variance	0%				
Total Projected Cost Difference (USD)	-				
Fully Burdened Cost (USD)	2.89

		Processes		
		1	2	3
		Material Stock	Laser Cut	Bend Brake
Manufacturing Times	Part Totals			
Labor Time (s)	35.28	0.00	20.33	14.95
Cycle Time (s)	24.01	0.00	12.51	11.50
Batch Setup Time (hr)	0.83	0.00	0.08	0.75
Manufacturing Rates (USD / hr)				
Labor Rate		0.00	20.99	20.99
Direct Overhead Rate		0.00	34.66	5.67
Indirect Overhead rate		0.00	14.81	8.33
Total Overhead Rate		0.00	49.47	14.00
Cost Summary (USD)				
Material Cost	2.13	0.00	2.13	0.00
Labor Cost	0.21	0.00	0.12	0.09
Direct Overhead	0.14	0.00	0.12	0.02
Amortized Batch Setup	0.03	0.00	0.01	0.02
Logistics	0.00	0.00	0.00	0.00
Material Overhead Cost	0.05	0.00	0.05	0.00
Expendable Tooling	0.00	0.00	0.00	0.00
Additional Direct Costs	0.00	0.00	0.00	0.00
Extra Costs	0.00	0.00	0.00	0.00
Other Direct Costs	0.05	0.00	0.05	0.00
Total Variable Costs	2.55	0.00	2.42	0.13
Period Overhead Allocations	0.09	0.00	0.05	0.03
SGA Cost	0.25	0.00	0.24	0.01
Margin	0.00	0.00	0.00	0.00
Piece Part Cost	2.89	0.00	2.72	0.18
Hard Tooling (amortized)	0.00	0.00	0.00	0.00
Fixture Cost (Amortized)	0.00	0.00	0.00	0.00
Programming Cost (Amortized)	0.00	0.00	0.00	0.00
Additional Amortized Cost	0.00	0.00	0.00	0.00
Total Amortized Investments	0.00	0.00	0.00	0.00
Fully Burdened Cost	2.89	0.00	2.72	0.18
Hard Tooling	0.00	0.00	0.00	0.00
Fixture Cost	0.00	0.00	0.00	0.00
Programming Cost	0.00	0.00	0.00	0.00
Total Capital Investment	0.00	0.00	0.00	0.00

Part Number	STIFFENER	Rough Mass (kg)	0.30	Date costed	Oct 4, 2019
Scenario	bulk-initial	Finish Mass (kg)	0.28	Costed by	apriori
Description	-	Material Utilization	95%	Currency	USD
Revision	-	Material Unit Cost (USD / kg)	3.50	Unit System	Metric
Process Group	Sheet Metal				
Virtual Production Environment	Energy Analysis				
Material	Steel, Cold Worked, AISI 1020				
Batch Size	833				
Annual Volume	10,000				
Production Life	5				
Total Planned Volume	50,000				
Cost Target (USD)	-				
Amount Variance (USD)	-				
Percent Variance	0%				
Total Projected Cost Difference (USD)	-				
Fully Burdened Cost (USD)	1.64

		Processes		
		1	2	3
		Material Stock	Laser Cut	Bend Brake
Manufacturing Times	Part Totals			
Labor Time (s)	37.05	0.00	12.35	24.70
Cycle Time (s)	26.60	0.00	7.60	19.00
Batch Setup Time (hr)	0.83	0.00	0.08	0.75
Manufacturing Rates (USD / hr)				
Labor Rate		0.00	20.99	20.99
Direct Overhead Rate		0.00	34.66	5.67
Indirect Overhead rate		0.00	14.81	8.33
Total Overhead Rate		0.00	49.47	14.00
Cost Summary (USD)				
Material Cost	1.04	0.00	1.04	0.00
Labor Cost	0.22	0.00	0.07	0.14
Direct Overhead	0.10	0.00	0.07	0.03
Amortized Batch Setup	0.03	0.00	0.01	0.02
Logistics	0.00	0.00	0.00	0.00
Material Overhead Cost	0.02	0.00	0.02	0.00
Expendable Tooling	0.00	0.00	0.00	0.00
Additional Direct Costs	0.00	0.00	0.00	0.00
Extra Costs	0.00	0.00	0.00	0.00
Other Direct Costs	0.02	0.00	0.02	0.00
Total Variable Costs	1.41	0.00	1.21	0.20
Period Overhead Allocations	0.08	0.00	0.03	0.05
SGA Cost	0.14	0.00	0.12	0.02
Margin	0.00	0.00	0.00	0.00
Piece Part Cost	1.64	0.00	1.37	0.27
Hard Tooling (amortized)	0.00	0.00	0.00	0.00
Fixture Cost (Amortized)	0.00	0.00	0.00	0.00
Programming Cost (Amortized)	0.00	0.00	0.00	0.00
Additional Amortized Cost	0.00	0.00	0.00	0.00
Total Amortized Investments	0.00	0.00	0.00	0.00
Fully Burdened Cost	1.64	0.00	1.37	0.27
Hard Tooling	0.00	0.00	0.00	0.00
Fixture Cost	0.00	0.00	0.00	0.00
Programming Cost	0.00	0.00	0.00	0.00
Total Capital Investment	0.00	0.00	0.00	0.00

Appendix G Supporting UEV Calculations

G.1 Liquid Crystal

Per communications with Daniel Campbell [174], which included basic research on the composition of liquid crystal [223], it was determined that E7 liquid crystals were commonly used in LCDs and had pricing data available from Alibaba.com [178, 179, 224]. The principle component of E7 liquid crystals is biphenyl [223], which is synthesized from benzene [225] in a 5:1 ratio.

Bastianoni et al. [151] included a calculation for “Other oils for petroleum feed stock,” which for this estimate would include benzene. It should be noted that the UEV used in this calculation was adjusted to remove labor and services. Details on that adjustment can be found in Appendix G.4 The calculation is summarized in Table G.1.

Table G.1. Estimated UEV for E7 Liquid Crystals

Component	UEV (sej/g)	Source
Benzene UEV	2.37E+09	[151]*
Estimate for E7 (5:1 ratio)	1.18E+10	This Study

*Converted to remove labor and services; see Appendix G.4

G.2 Ceramics

A common ceramic used in capacitors is barium titanate [226]. Via communications with Daniel Campbell [174], a method was determined to estimate the base UEV for barium titanate based on its stoichiometry, whose chemical formula [227] is:

Table G.2 summarizes the calculation, which is based on the molar masses of the elements. The UEV for elemental oxygen was estimated based on the value for O₂ calculated by Campbell et al. [213] by dividing it by two, to give the UEV shown.

Table G.2. Estimated UEV for Barium Titanate

Element	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
Barium	137.33	58.891%	1.68E+11	[127]
Titanium	47.87	20.527%	4.87E+10	[172]
Oxygen	16.00	20.582%	3.22E+06	This study
Totals for BaTiO₃	233.19		1.09E+11	This study

G.3 Epoxy

Hardened epoxy is a critical component of circuit boards. Dan Campbell in personal communications [174], provided the following approach and final value for epoxy. Epoxy is most commonly composed of two components: epichlorohydrin (ECH) and bisphenol-A (BPA) [228]. Similar to G.2, a stoichiometric approach is used.

Epichlorohydrin is formed following a series of reactions, starting with a allyl chloride, to which hypochlorous acid is added, forming two isomeric alcohols. The emergy for the allyl chloride can be calculated from the chemical equation: C_3H_5Cl . It should be noted that the transformities selected for carbon assume it is generated from propylene [228]. This calculation is completed in Table G.3. A similar approach is used for hypochlorous acid HOCl, as shown in Table G.4.

Table G.3. UEV Calculation for Allyl Chloride

Element	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
C	12.011	47.09%	3.40E+09	[151]
H	1.008	6.59%	1.47E+10	[229]
Cl	35.453	46.33%	1.70E+10	[160]
Totals for C₃H₅Cl	76.526		5.75E+09	

A one-to-one mixture of the allyl chloride and hypochlorous acid results in two isomeric alcohols ($C_3H_6Cl_2O$), whose emergy value is shown in Table G.5. The final step is the combination of the isomeric alcohols with caustic soda (NaOH), which yields epichlorohydrin, salt (NaCl) and water. The emergy calculation of this is shown in Table G.6. It should

Table G.4. UEV Calculation for Hypochlorous Acid

Element	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
H	1.008	1.92%	1.47E+10	[229]
O	15.999	30.50%	6.11E+05	This study
Cl	35.453	67.58%	1.7E+10	[160]
Totals for HOCl	52.46		1.18E+10	

be noted that epichlorohydrin carries the full value of emergy, though there is more than one resulting compound, due to how emergy algebra handles co-products of a system (see Section 2.2.3).

Table G.5. UEV Calculation for Isomeric Alcohols

Compound	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
Allyl Chloride	76.526	59.33%	1.04E+10	This Study
Hypochlorous Acid	52.46	40.67%	1.18E+10	This Study
Totals for Two Alcohols (C₃H₆Cl₂O)	128.986		1.10E+10	

Table G.6. UEV Calculation for Epichlorohydrin

Compound	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
Isomeric Alcohols	128.986	76.33%	1.10E+10	This Study
NaOH	40	23.67%	9.47E+09	[230]
Epichlorohydrin	92.52		1.06E+10	
NaCl	58.44			
H ₂ O	18.015			

Epichlorohydrin is combined with bisphenol A to create epoxy resin. Bisphenol A is made from two molecules of phenol (C₁₅H₁₆O₂), and one acetone ((CH₃)₂CO). The emergy for each phenol and acetone have been calculated by Maccanti [231] in unpublished work. The result of this calculation is shown in Table G.7. The final epoxy resin, whose calculation is shown in Table G.8, is made from a ratio of one mole of bisphenol A to two moles of epichlorohydrin.

Table G.7. UEV Calculation for Bisphenol A

Compound	Molar Mass (g)	Molecular Fraction	UEV (sej/g)	Source
Phenol	94.11	66.67%	1.42E+10	[231]
Acetone	58.08	33.33%	2.35E+10	[231]
Bisphenol A	246.3		1.73E+10	

Table G.8. UEV Calculation for Epoxy Resin

Compound	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
Bisphenol A	246.3	57.10%	1.73E+10	This Study
Epichlorohydrin	92.52	42.90%	1.06E+10	This Study
Resin	431.34		1.44E+10	

Epoxy requires a hardener to be combined with the resin to form the final hardened material. The hardener is commonly a isopropanol amine (C_3H_9NO). This is formed through a series of reactions, starting with combining propene, a product of refining, with sulfuric acid. The product is a set of sulfate esters. The UEV for propene is adjusted to remove labor and services (see Appendix G.4) from Bastianoni et al. [151]. This calculation is summarized in Table G.9.

Table G.9. UEV Calculation for Sulfate Esters Required to Create Hardener

Compound	Molar Mass (g)	Molecular Fraction	UEV (sej/g)	Source
Propene	42.081	30.02%	3.07E+09	[151]
Sulfuric Acid	98.079	69.98%	5.80E+08	[230]
Sulfate Esters	140.16		1.33E+09	

The resulting sulfate ester is hydrolyzed to regenerate sulfuric acid and release ethanol. This step is not considered to add any energy since water generally has a specific energy many orders of magnitude less than the other compounds involved [232]. Next, the ethanol is combined with the sulfuric acid resulting in isopropyl alcohol and sulfate. This calculation, as shown in Table G.10 is different than the previous, since results of the previous reactions are recombined together, no additional energy is added to the system, but due

to the mass ratio required there is a small increase in energy. As such, the output for the esters above is slightly increased, moving into the final step, where the isopropyl alcohol is combined with ammonia. This calculation is summarized in Table G.11.

Table G.10. UEV Calculation for Isopropopyl Alcohol

Compound	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
Ethanol	46.07	31.96%	1.33E+09	This Study [230]
Sulfuric Acid	98.079	68.04%	5.80E+08	
Isopropopyl alcohol	60.1		3.18E+09	
Sulfate	84.046			

Table G.11. UEV Calculation for Hardener

Compound	Molar Mass (g)	Fraction Mass	UEV (sej/g)	Source
Ammonia	32.042	61.53%	4.47E+09	[213]
Isopropopyl alcohol	60.1	38.47%	3.18E+09	This study
Hardener	156.226		3.98E+09	

The final step in forming hardened epoxy is to combine together the resin and hardener in a five-to-one molecular ratio [233]. This results in the final calculation shown in Table G.12, with a UEV for hardened epoxy of 1.27×10^{10} sej/g.

Table G.12. UEV Calculation for Hardened Resin

Compound	Molar Mass (g)	Molecular Fraction	UEV (sej/g)	Source
Resin	431.34	83.33%	1.44E+10	This Study
Hardener	113.157	16.67%	3.98E+09	This Study
Hardened Epoxy			1.27E+10	

G.4 Petroleum Products

Bastinioni et al. [151] conducted a series of calculations for a selection of petroleum products based on analyses of a selection of US and Italian refinery datasets. Following these analyses the authors determined a transformity for the output fuels on the whole,

per unit energy. To determine a specific (sej/mass) emergy value for each of a number of possible outputs, the authors sourced a set of calorific values from the IPCC [234] for each refinery output representing the amount of energy available in a fuel per mass.

By multiplying the total emergy used to produce outputs found from their analysis by the calorific values, Bastinioni et al. are able to provide UEVs for each common output from the facilities. The final UEVs summarized in the paper, though, include labor and services. While these values are appropriate for some of the calculations in this study, others are better served by values without labor and services. To that end, new UEVs without labor and services were calculated by calculating a new transformity for the two US-based datasets provided in the paper, as shown in Tables G.13 and G.14. The Italian dataset was not used as it did not break out the labor and services in the same manner as the two US examples, and, as such, it was difficult to identify pure labor and services values for removal. It should be noted that these values are in the 9.26×10^{24} baseline used by Bastinioni et al.

Table G.13. Emergy Data for San Francisco Refinery Adapted from Bastinioni et al. [151], with Total Emergy for Fuels without Labor and Services Calculated From Items 1 Through 5; Using 9.26×10^{24} Baseline

Category and item		Raw data	Units per year	Emergy/unit (sej/unit)	Emergy (sej/year)
Material Inputs					
1	Crude oil & additives	1.59E+18	J	54200	8.62E+22
2	Natural gas	4.26E+16	J	43500	1.85E+21
3	Electricity	7.51E+12	J	170400	1.28E+18
4	Coal	5.73E+13	J	39200	2.25E+18
5	Steam	1.68E+09	g	1.30E+09	2.18E+18
Service Inputs					
6	Service in crude oil	4.61E+09	USD	1.20E+12	5.53E+21
7	Goods and services	8.21E+08	USD	1.20E+12	9.85E+20
8	Labor	1.43E+13	J	4.80E+07	6.86E+20
9	Investment	3.00E+08	USD	1.20E+12	3.60E+20
Outputs					
11	Fuels (net output)	1.50E+18	J	6.37E+04	9.56E+22
	Without Labor and Services			5.87E+04	8.80E+22

Table G.15, completes this calculation, using an average of the two US based calculations to produce adjusted baselines without labor and services. The final column converts

Table G.14. Data for 2004 USA Refining Industry Adapted from Bastinioni et al. [151], with Total Emery for Fuels without Labor and Services Calculated from Items 1, 3, 4, 5 and 6; using 9.26×10^{24} Baseline

Category and item	Raw data	Units per year	Emery/unit (sej/unit)	Emery (sej/year)
Inputs				
1 Crude oil & additives	3.473E+19	J	54200	1.88E+24
2 Service in crude oil	1.54E+11	USD	1.07E+12	1.64E+23
3 Natural gas	7.42E+17	J	43500	3.23E+22
4 Electricity	1.31E+14	J	170400	2.23E+22
5 Coal	1.00E+15	J	39200	3.92E+19
6 Steam	2.93E+10	g	1.30E+09	3.80E+19
7 Goods and services				3.50E+22
Outputs				
9 Fuels (net output)	3.27E+19		6.53E+04	2.13E+24
Without Labor and Services			5.92E+04	1.93E+24

the final average from the 9.26×10^{24} to the 1.2×10^{25} planetary baseline. These values are used when appropriate within calculations in this study.

Table G.15. Petroleum UEVs from Bastinanoni et al. (2009) Adjusted to Remove Labor and Services

Refinery Products	Calorific Value ^a (kJ/g)	SF ^{b,d} (sej/g)	US 2004 ^{c,d} (sej/g)	Avg ^d (sej/g)	Avg ^e (sej/g)
Liquefied gases	47.3	2.78E+09	2.80E+09	2.79E+09	3.61E+09
Motor gasoline	44.3	2.60E+09	2.62E+09	2.61E+09	3.38E+09
Aviation gasoline	44.3	2.60E+09	2.62E+09	2.61E+09	3.38E+09
Kerosene-type jet fuel	44.1	2.59E+09	2.61E+09	2.60E+09	3.37E+09
Kerosene refinery	43.8	2.57E+09	2.59E+09	2.58E+09	3.34E+09
Total distillate (diesel)	43	2.52E+09	2.54E+09	2.53E+09	3.28E+09
Residual fuel oil	40.4	2.37E+09	2.39E+09	2.38E+09	3.09E+09
Other oils for petrol. feed	40.2	2.36E+09	2.38E+09	2.37E+09	3.07E+09
Lubes	40.2	2.36E+09	2.38E+09	2.37E+09	3.07E+09
Waxes	40.2	2.36E+09	2.38E+09	2.37E+09	3.07E+09
Petroleum coke	32.5	1.91E+09	1.92E+09	1.92E+09	2.48E+09
Asphalt	40.2	2.36E+09	2.38E+09	2.37E+09	3.07E+09
Still gas	49.5	2.91E+09	2.93E+09	2.92E+09	3.78E+09
Miscellaneous	40.2	2.36E+09	2.38E+09	2.37E+09	3.07E+09

(a) From IPCC [234]

(b) Based on data from five refineries in San Francisco area between 1996 and 1998 [151]

(c) Based on data from the US refining industry from 2004 [151]

(d) 9.26×10^{24} Baseline

(e) 1.2×10^{25} Baseline

Appendix H Estimating Laser Gas Consumption

The DFM assessment of the aPriori software does not include a calculation of the gas used by the laser machine. The laser used in this study is the Cincinnati CL-850. The user manual for the machine [210] includes the gases used to support the laser cutting process. Five gas systems are included in the manual: laser, assist gas, two nozzle cooling gases, and beam purge gas. For this study, the laser, and the assist gas are considered as the remaining are supported by low-pressure dry air.

The laser gas is a mix of three gases—CO₂, helium, and nitrogen—in fractions of 0.05, 0.6, and 0.35 respectively. The Cincinnati CL-850 supports three types of assist gases: O₂, N₂ and air. For the application in this study, O₂ is assumed as it is the most common gas for non-fiber lasers, and is appropriate for the a mild steel, which assumed for the parts used here [211,212].

Table H.1 estimates the mass of gas used per hour during the laser cutting operations. The pressures assumed for the tanked gases are based on tables in the user guide. For the laser gas, the operating pressure is typically 28 psi. The flow rate is estimated in the user guide to be 0.36 cubic feet per hour, at standard temperature. For the assist gas, the user manual notes that operating pressures can range between 15 and 400 psi, depending on the cutting conditions and desired performance. For this study, 50 psi was selected based on common practice [211]. The estimated flow rate for the assist gas is also based on the nozzle diameter, which was chosen to be 0.08 inches. The user guide gives an estimated flow rate of 333 cubic feet per hour at standard temperature.

With these values identified, an estimated mass flow per hour was calculated, as shown in Table H.1. UEV for each constituent gas was found in the literature. For the laser gas, a UEV per gram was calculated based on the fractions of each constituent gas, from which the amount of emergy per hour of laser usage was found. A similar approach was used for the assist gas, though in this case it is all O₂, so the calculation is simplified. The resulting

Table H.1. Mass of Gas and Emergy Used per Hour for Laser Cutting Operations

Type	Gas	Percent	kg/hr	UEV	Units	Source	UEV (sej/hr)
Laser @ 28 psi			8.05E-05	7.82E+10	sej/g	This Study	6.29E+09
	He	0.6	1.34E-05	3.97E+11	sej/g	[127]	
	N ₂	0.35	5.48E-05	1.77E+10	sej/g	[127]	
	CO ₂	0.05	1.23E-05	3.05E+07	sej/g	[213]	
Assist @ 50 psi							
	O ₂	1	0.30	8.35E+06	sej/g	[127]	2.46E+09

UEVs can now be used in the equations for estimating the emergy of supplies required to support the operation of the laser.

Appendix I MOST Analysis

The Maynard Operation Sequence Technique is a work measurement system used to estimate the time it takes to complete manual activities, such as assembly or other motion within manufacturing. The technique breaks manual movements into three basic categories: general move, controlled move, and tool use, and systematically determines a time for the each. Each of these movement types are broken into specific steps.

I.1 General Move

A general move is the “spatial displacement of one or more objects” [159] and is broken into three phases: get, put and return. The get phase is broken into:

- The action distance (A) for an activity, which might be reaching or walking a number of steps;
- Body motion (B) required, such as bending or moving from sitting to standing; and
- Gaining control (G) of an item, such as grasping a part or tool.

The put phase involve the movement with the item back to the workspace, including an action distance (A), body motion (B) and a placement step (P), where the item is put down or otherwise placed into an assembly. In the return phase, there is an action distance (A) to return to ready for the next step.

Based on the difficulty and amount of motion, a number is assigned to each of the movements, such as the following for “grasp weld helmet and put on head”:

$A_1 B_0 G_1 A_1 B_0 P_1 A_0$

The number corresponds to the time it takes to complete the activity in time measurement units (TMU), with 1 TMU equal to one-hundred-thousandth of an hour (0001 hours) or 36 thousandths of a second (0.036 seconds).

I.2 Controlled Move

A controlled move is similar to a general move, but instead of a placement, one of the following is used:

- Move controlled (M), such as a button press movement of a cart or other pushing, pulling or turning;
- Process time (X), such as a machine running; and
- Alignment (I), such as aligning two pieces of paper, or aligning a mark on a part to a mark on another part.

An example of a controlled move for “grasp handwheel and crank 8 revs to align tool to scale mark” is as follows:

A₁ B₀ G₁ M₁6 X₀ I₆ A₀

I.3 Tool Use

With a tool use, it is broken into five phases, starting with most of the steps of a general move, where the tool or object is picked up and put in place (A B G A B P), the tool action is completed, the tool is put aside (A B P), and the operator returns to the ready position (A). For the tool action, there are seven possible indexes:

- Fasten (F) or Loosen (L), where a item is fastened in place or loosened with finger, wrist, or arm actions, or with a power tool;
- Cut (C), where an item is
- Surface treat (S), where an item or surface is cleaned of debris;
- Measure (M), where an item is measured with a tool such as calipers or a micrometer;
- Record (R), where information is written down; and

- Think (T), where the worker inspects or reads.

An example of a tool use for “get air hose, spot clean cavity behind machine and set aside hose” is as follows:

A₁ B₀ G₃ A₁ B₀ P₃ S₆ A₁ B₀ P₁ A₀

I.4 MOST Analysis for MIG Welder Assembly

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	
1	Basic MOST Analysis																																
2	Date Analyst																																
3	Page of																																
4	Total Time In: 0.4205 Hours 25.23 Minutes 1513.8 Seconds 42050 TMU																																
5	Step Number	Ass'y or Sub	Part #s Added	Method Description	Sequence Model																												
6			163359		Addit'l Steps PF FR SIMO TO TMU																												
7	1	Main		Get base and put into work area with two hands	A	3	B	0	G	3	A	3	B	0	P	1	A	1															
8					A	B	G	M	X	I	A																						
9					A	B	G	A	B	P	*								A	B	P	A											
10	2	Main	162816	Get channel and put into base	A	1	B	0	G	1	A	1	B	0	P	3	A	0															
11					A	B	G	M	X	I	A																						
12					A	B	G	A	B	P	*																						
13	3	Main	Fasteners	Collect 4 fasteners and put into hole manually with two spins	A	B	G	M	X	I	A																						
14					A	B	G	A	B	P	A																						
15					A	1	B	0	G	3	A	1	B	0	P	6	F	3	A	0	B	0	P	0	A	0							
16	4	Main		Get power tool and tighten screws	A	B	G	A	B	P	A																						
17					A	B	G	M	X	I	A																						
18					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	1	B	0	P	1	A	0							
19	5	Main	Fixture	Get fixture for main power transformer and place into alignment holes	A	B	G	M	X	I	A																						
20					A	B	G	A	B	P	*																						
21					A	1	B	3	G	3	A	1	B	3	P	3	A	0															
22	6	Main		Get main power transformer with two hands and place on fixture with two hands.	A	B	G	M	X	I	A																						
23					A	B	G	A	B	P	*																						
24					A	B	G	A	B	P	A																						
25	7	Main	Fasteners	Collect 8 fasteners and put into hole manually with two spins	A	B	G	M	X	I	A																						
26					A	1	B	0	G	3	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0							
27					A	B	G	A	B	P	A																						
28	8	Main		Get power tool and tighten screws	A	B	G	M	X	I	A																						
29					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0							
30					A	0	B	0	G	3	A	1	B	0	P	1	A	0															
31	9	Main		Remove fixture and set aside	A	B	G	M	X	I	A																						
32					A	B	G	A	B	P	*																						
33					A	1	B	0	G	1	A	1	B	0	P	3	A	0															
34	10	Main	Fixture	Get fixture for stabilizer and place into alignment	A	B	G	M	X	I	A																						
35					A	B	G	A	B	P	*																						
36					A	1	B	0	G	3	A	1	B	0	P	3	A	0															
37	11	Main	180066	Get stabilizer with one hand and place onto fixture with two hand alignment	A	B	G	M	X	I	A																						
38					A	B	G	A	B	P	*																						
39					A	B	G	A	B	P	A																						
40	12	Main	Fasteners	Collect 8 fasteners and put into hole manually with two spins	A	B	G	M	X	I	A																						
41					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0							
42					A	B	G	A	B	P	A																						
43	13	Main		Get power tool and tighten screws	A	B	G	M	X	I	A																						
44					A	1	B	0	G	1	A	1	B	0	P	6	F	3	A	0	B	0	P	1	A	0							
45					A	0	B	0	G	3	A	1	B	0	P	1	A	0															
46	14	Main		Remove fixture and set aside	A	B	G	M	X	I	A																						
47					A	B	G	A	B	P	*																						
48					A	1	B	0	G	1	A	1	B	0	P	1	A	0															
49	15	Rectifier	Fixture	Get fixture for rectifier assembly and place in workspace	A	B	G	M	X	I	A																						
50					A	B	G	A	B	P	*																						

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG				
561	185	Main		Place fixture in workspace	A	1	B	0	G	3	A	1	B	0	P	3	A	0													2	0	160			
562						A	B	G	M	X	I	A																								
563						A	B	G	A	B	P	*																								
564						A	1	B	0	G	3	A	1	B	0	P	3	A	0																	
565	186	Main		Get side panel and place into fixture	A	B	G	M	X	I	A																			2	0	160				
566						A	B	G	A	B	P	*																								
567						A	B	G	A	B	P	A																								
568						A	B	G	M	X	I	A																								
569	187	Main		Collect 3 fasteners and place tightening two finger turns	A	1	B	0	G	3	A	1	B	P	3	F	3	A	0	B	0	P	0	A	0					13	1	0	250			
570						A	B	G	A	B	P	A																								
571						A	B	G	M	X	I	A																								
572						A	1	B	0	G	3	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0									
573	188	Main		Get power tool and use to screw fasteners in place	A	B	G	M	X	I	A																									
574						A	1	B	0	G	3	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0									
575						A	B	G	M	X	I	A																								
576						A	B	G	A	B	P	*																								
577	190	Main		Place fixture in workspace	A	1	B	0	G	3	A	1	B	0	P	3	A	0													1	0	80			
578						A	B	G	M	X	I	A																								
579						A	B	G	A	B	P	*																								
580						A	1	B	0	G	3	A	1	B	0	P	3	A	0																	
581	191	Main		Get front panel and set in fixture	A	B	G	M	X	I	A																				1	0	80			
582						A	B	G	A	B	P	*																								
583						A	B	G	A	B	P	A																								
584						A	1	B	0	G	3	A	1	B	P	3	F	3	A	0	B	0	P	0	A	0										
585	193	Main		Get power tool and use to screw fasteners in place	A	B	G	A	B	P	A																									
586						A	B	G	M	X	I	A																								
587						A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0									
588						A	1	B	0	G	3	A	1	B	0	P	1	A	0																	
589	194	Main		Remove fixture and set aside	A	B	G	M	X	I	A																				1	0	60			
590						A	B	G	A	B	P	*																								
591						A	1	B	0	G	3	A	1	B	0	P	3	A	0																	
592						A	B	G	M	X	I	A																								
593	195	Main		Place fixture in workspace	A	B	G	A	B	P	*																				1	0	80			
594						A	B	G	M	X	I	A																								
595						A	1	B	0	G	3	A	1	B	0	P	3	A	0																	
596						A	B	G	M	X	I	A																								
597	197	Main		Collect 5 fasteners and place tightening two finger turns	A	B	G	A	B	P	A																									
598						A	B	G	M	X	I	A																								
599						A	1	B	0	G	3	A	1	B	P	3	F	3	A	0	B	0	P	0	A	0										
600						A	B	G	A	B	P	A																								
601	198	Main		Get power tool and use to screw fasteners in place	A	B	G	M	X	I	A																									
602						A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0									
603						A	1	B	0	G	3	A	1	B	0	P	1	A	0																	
604						A	B	G	M	X	I	A																								
605	199	Main		Remove fixture and set aside	A	B	G	A	B	P	*																				1	0	60			
606						A	1	B	0	G	3	A	1	B	0	P	3	A	0																	
607						A	B	G	M	X	I	A																								
608						A	B	G	A	B	P	*																								
609	201	Main		Collect 6 fasteners and place tightening two finger turns	A	B	G	A	B	P	A																									
610						A	B	G	M	X	I	A																								
611						A	1	B	0	G	3	A	1	B	P	3	F	3	A	0	B	0	P	0	A	0										
612																																				

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	
612					A	B	G	A	B	P	A																						
613	202	Main		Get power tool and use to screw fasteners in place	A	B	G	M	X	I	A																						
614					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0							

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG		
1																																		
2																																		
3																																		
4	Decription	Assembly of Miller Feeder S-74D. Assumptions: All parts are manually handled. Assembly occurs at a table. All parts and tools are within reach. Worker standing. All fasteners started with fingers, then power tool used																																
5																																		
6	Step Number	Ass'y or Sub	Part #s Added	Method Description	Sequence Model																													
7		Hub & Spindle Ass'y	200556	Get spool support and place on table	A	1	B	0	G	1	A	1	B	0	P	1	A	0																
8	1				A	B	G	M	X	I	A																							
9					A	B	G	A	B	P	*																							
10		Hub & Spindle Ass'y	180571	Get support spool shaft and hold in hand	A	1	B	0	G	1	A	1	B	0	P	0	A	0																
11	2				A	B	G	M	X	I	A																							
12					A	B	G	A	B	P	*																							
13		Hub & Spindle Ass'y	10233	Get spring and thread on shaft	A	1	B	0	G	3	A	1	B	0	P	3	A	0																
14	3				A	B	G	M	X	I	A																							
15					A	B	G	A	B	P	*																							
16		Hub & Spindle Ass'y	57971	Collect three washers and thread each on shaft	A	1	B	0	G	3	A	1	B	0	P	3	A	0																
17	4				A	B	G	M	X	I	A																							
18					A	B	G	A	B	P	*																							
19		Hub & Spindle Ass'y	58428	Get hub spool and thread on shaft	A	1	B	0	G	1	A	1	B	0	P	3	A	0																
20	5				A	B	G	M	X	I	A																							
21					A	B	G	A	B	P	*																							
22		Hub & Spindle Ass'y	058427	Get spool retaining ring and position on hub spool	A	1	B	0	G	1	A	1	B	0	P	3	A	0																
23	6				A	B	G	M	X	I	A																							
24					A	B	G	A	B	P	*																							
25		Hub & Spindle Ass'y		Tighten 2 screws on retaining ring	A	B	G	M	X	I	A																							
26	7				A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0								
27					A	1	B	0	G	3	A	1	B	0	P	3	A	0																
28		Hub & Spindle Ass'y	57971	Collect three washers and thread each on shaft	A	B	G	M	X	I	A																							
29	8				A	B	G	A	B	P	*																							
30					A	1	B	0	G	1	A	1	B	0	P	3	A	0																
31		Hub & Spindle Ass'y	248974	Get tubing and thread on shaft	A	B	G	M	X	I	A																							
32					A	B	G	A	B	P	*																							
33		Hub & Spindle Ass'y		Thread shaft assembly on spool support	A	0	B	0	G	0	A	1	B	0	P	6	A	0																
34	10				A	B	G	M	X	I	A																							
35					A	B	G	A	B	P	*																							
36		Hub & Spindle Ass'y	135205	Get nut and attach with two finger turns to shaft	A	B	G	A	B	P	A																							
37	11				A	B	G	M	X	I	A																							
38					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0								
39		Hub & Spindle Ass'y		Tighten nut with hand ratchet, holding opposing end of shaft with a second ratchet	A	B	G	A	B	P	A																							
40	12				A	1	B	0	G	3	A	1	B	0	P	3	F	10	A	1	B	0	P	1	A	0								
41					A	B	G	M	X	I	A																							
42		Main Ass'y	200557	Get base and place on table	A	B	G	A	B	P	*																							
43	13				A	B	G	A	B	P	A																							
44					A	B	G	A	B	P	*																							
45		Main Ass'y	200557	Get base stiffener and put in position under base	A	1	B	0	G	1	A	1	B	0	P	6	A	0																
46	14				A	B	G	M	X	I	A																							
47					A	B	G	A	B	P	*																							

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG		
48	15	Main Assy		Get hub & spindle assembly and position on base	A	1	B	0	G	1	A	1	B	0	P	6	A	0													1	0	90	
49					A	B	G	M	X	I	A																							
50					A	B	G	A	B	P	*			A	B	P	A																	
51	16	Main Assy		Collect 4 screws and finger tighten two turns	A	B	G	M	X	I	A																				20	1	0	320
52					A	1	B	0	G	3	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0								
53					A	B	G	A	B	P	A																							
54	17	Main Assy		Power tighten 4 screws	A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0						1	0	310
55					A	B	G	M	X	I	A																							
56					A	1	B	0	G	1	A	0	B	0	P	1	A	0																
57	18	Main Assy		Turn main assembly on side	A	1	B	0	G	1	A	0	B	0	P	1	A	0													1	0	30	
58					A	B	G	M	X	I	A																							
59					A	B	G	A	B	P	*			A	B	P	A																	
60	19	Main Assy	134306	Get rubber foot with screw and nut and remove screw	A	B	G	A	B	P	A																							
61					A	B	G	M	X	I	A																							
62					A	1	B	0	G	1	A	0	B	0	P	0	L	3	A	0	B	0	P	0	A	0								
63					A	B	G	A	B	P	A																							
64	20	Main Assy		Place rubber foot against main assembly and finger tighten screw two turns	A	B	G	M	X	I	A																							
65					A	0	B	0	G	0	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0								
66					A	B	G	A	B	P	A																							
67					A	B	G	M	X	I	A																							
68	21	Main Assy		Power tighten screw	A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0						4	0	400
69					A	B	G	M	X	I	A																							
69	22	Pressure Arm	203637	Collect spring shaft and cotter pin and press cotter pin into shaft	A	1	B	0	G	3	A	1	B	0	P	6	A	0														1	0	110
70			182156		A	B	G	M	X	I	A																							
71					A	B	G	A	B	P	*			A	B	P	A																	
72	23	Pressure Arm	132746	Get bushing and thread onto shaft	A	1	B	0	G	1	A	1	B	0	P	3	A	0																
73					A	B	G	M	X	I	A																							
74					A	B	G	A	B	P	*			A	B	P	A																	
75	24	Pressure Arm	182155	Collect two springs and thread on shaft	A	1	B	0	G	3	A	1	B	0	P	1	A	0																
76			182156		A	B	G	M	X	I	A																							
77					A	B	G	A	B	P	*			A	B	P	A																	
78	25	Pressure Arm	203641	Collect two washers and one knob and thread two washers onto shaft, compressing spring and hold in place with one hand	A	1	B	0	G	3	A	1	B	0	P	6	A	0																
79			203640		A	B	G	A	B	P	*			A	B	P	A																	
80			133739		A	B	G	M	X	I	A																							
81	26	Pressure Arm		Place knob on end of shaft and hand tighten with 9 wrist turns	A	B	G	A	B	P	A																							
82					A	B	G	M	X	I	A																							
83					A	0	B	0	G	0	A	0	B	0	P	3	F	16	A	0	B	0	P	0	A	0								
84	27	Pressure Arm	203632	Get carrier and place on table	A	1	B	0	G	1	A	1	B	0	P	1	A	0																
85					A	B	G	M	X	I	A																							
86					A	B	G	A	B	P	*			A	B	P	A																	
87	28	Pressure Arm		Get shaft and thread through carrier	A	1	B	0	G	1	A	1	B	0	P	3	A	0																
88					A	B	G	M	X	I	A																							
89					A	B	G	A	B	P	*			A	B	P	A																	
90	28	Pressure Arm	203641	Get washer and thread on shaft	A	1	B	0	G	1	A	1	B	0	P	3	A	0																
91					A	B	G	M	X	I	A																							
92					A	B	G	A	B	P	*			A	B	P	A																	
93	29	Pressure Arm	182155	Collect two springs and thread on shaft and hold springs in place with one hand	A	1	B	0	G	3	A	1	B	0	P	3	A	0																
94			182156		A	B	G	M	X	I	A																							
95					A	B	G	A	B	P	*			A	B	P	A																	
96	30	Pressure Arm	132746	Get bushing and thread onto shaft and hold springs in place with one hand	A	1	B	0	G	1	A	1	B	0	P	3	A	0																
97					A	B	G	M	X	I	A																							
98					A	B	G	A	B	P	*			A	B	P	A																	

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG			
405	132	Main Assy		Place motor assembly in fixture	A	1	B	0	G	1	A	1	B	0	P	3	A	0																	
406					A	B	0	G	M	X	I	A																				1	0	60	
407					A	B	0	G	A	B	P	*		A	B	P	A																		
408					A	0	B	0	G	1	A	1	B	0	P	1	A	0																	
409	133	Main Assy		Get Buna sheet, place on motor and hold in place with one hand	A	B	0	G	M	X	I	A																				1	0	30	
410					A	B	0	G	A	B	P	*		A	B	P	A																		
411					A	0	B	0	G	1	A	1	B	0	P	6	A	0																	
412					A	B	0	G	M	X	I	A																							
413	134	Main Assy		Get top clamp, seat in base, push down and hold in place with one hand	A	B	0	G	A	B	P	*			A	B	P	A													1	0	80		
414					A	1	B	0	G	3	A	1	B	0	P	3	A	0																	
415					A	B	0	G	M	X	I	A																							
416					A	B	0	G	A	B	P	*		A	B	P	A																		
417	136	Main Assy		Screw clamp knob into base with 5 turns	A	B	0	G	A	B	P																								
418					A	B	0	G	M	X	I	A																							
419					A	0	B	0	G	0	A	1	B	0	P	3	F	10	A	0	B	0	P	0	A	0									
420					A	1	B	0	G	1	A	1	B	0	P	6	A	0																	
421	137	Main Assy		Get feeder wrapper and position on assembly	A	B	0	G	A	B	P	*			A	B	P	A														1	0	90	
422					A	B	0	G	A	B	P	*		A	B	P	A																		
423					A	B	0	G	A	B	P	A																							
424					A	B	0	G	M	X	I	A																							
425	138	Main Assy		Collect 8 screws and finger tighten two turns	A	1	B	0	G	3	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0						48	1	0	600
426					A	B	0	G	A	B	P	A																							
427					A	B	0	G	M	X	I	A																							
428					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0								48	1

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG					
1	Basic MOST Analysis																	Analyst										Date									
2	Description Assembly of Miller Gun FC-1150. Assumptions: All parts are manually handled. Assembly occurs at a table. All parts and tools are within reach. Worker standing. All fasteners started with fingers, then power tool used																	Page										of									
3																		Total Time in:										0.0498 2.988 179.28 4980									
4	Step Number	Ass'y or Sub	Part #s Added	Method Description	Sequence Model																	Addit'l Steps	PF	FR	SIMO TO TMU												
5	6	1	Main	198819	Get handle and hold in hand	A	1	B	0	G	1	A	1	B	0	P	0	A	0																		
7	7				A	B	G	M	X	I	A																										
8	8				A	B	G	A	B	P	*	A	B	P	A																						
9	9	2	Main	198829	Get clamp and put into handle, place handle on table	A	1	B	0	G	1	A	1	B	0	P	6	A	0																		
10	10				A	B	G	M	X	I	A																										
11	11				A	B	G	A	B	P	*	A	B	P	A																						
12	12				A	1	B	0	G	1	A	1	B	0	P	0	A	0																			
13	13	3	Main		Get hose and hold in hand	A	B	G	M	X	I	A																									
14	14				A	B	G	A	B	P	*	A	B	P	A																						
15	15				A	B	G	A	B	P	A																										
16	16	4	Main	201246	Get liner and insert in hose using arm action for 10 feet	A	B	G	M	X	I	A																									
17	17				A	1	B	0	G	1	A	1	B	0	P	3	F	54	A	0	B	0	P	0	A	0											
18	18				A	B	G	A	B	P	A																										
19	19	5	Main		Trim linear to fit with pliers	A	B	G	M	X	I	A																									
20	20				A	1	B	0	G	1	A	1	B	0	P	1	F	6	A	0	B	0	P	1	A	0											
21	21				A	B	G	A	B	P	A																										
22	22	6	Main	198894	Get screw and tighten two finger turns	A	B	G	M	X	I	A																									
23	23				A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0											
24	24				A	B	G	A	B	P	A																										
25	25	7	Main		Power tighten screw	A	B	G	M	X	I	A																									
26	26				A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0											
27	27				A	1	B	0	G	1	A	1	B	0	P	6	A	0																			
28	28	8	Main		Get line and put connector into handle	A	B	G	M	X	I	A																									
29	29				A	B	G	A	B	P	*	A	B	P	A																						
30	30				A	1	B	0	G	1	A	1	B	0	P	0	A	0																			
31	31	9	Main	081664	Get retaining ring and hold in hand	A	B	G	M	X	I	A																									
32	32				A	B	G	A	B	P	*	A	B	P	A																						
33	33				A	1	B	0	G	1	A	1	B	0	P	3	A	0																			
34	34	10	Main		Get tool and put retaining ring on tool	A	B	G	M	X	I	A																									
35	35				A	B	G	A	B	P	*	A	B	P	A																						
36	36				A	B	G	A	B	P	A																										
37	37	11	Main		Get Handle and using tool, put retaining ring on line connector	A	B	G	M	X	I	A																									
38	38				A	1	B	0	G	1	A	0	B	0	P	3	C	3	A	1	B	0	P	1	A	0											
39	39				A	1	B	0	G	1	A	1	B	0	P	3	A	0																			
40	40	12	Main	198821	Get Spatter shield and put in handle	A	B	G	M	X	I	A																									
41	41				A	B	G	A	B	P	*	A	B	P	A																						
42	42				A	B	G	A	B	P	A																										
43	43	13	Main	133774	Get screw and finger tighten two turns	A	B	G	M	X	I	A																									
44	44				A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0											
45	45				A	B	G	A	B	P	A																										
46	46	14	Main		Power tighten screw	A	B	G	M	X	I	A																									
47	47				A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0											
48	48				A	1	B	0	G	1	A	1	B	0	P	0	A	0																			
49	49	15	Main	201247	Get gooseneck and hold in hand	A	B	G	M	X	I	A																									
50	50				A	B	G	A	B	P	*	A	B	P	A																						

51	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG		
52	16	Main	201260	Get liner and insert in gooseneck	A	1	B	0	G	1	A	1	B	0	P	6	A	0																
53					A	B	G	M	X	I	A																							
54					A	B	G	A	B	P	*	A	B	P	A																			
55	17	Main		Put gooseneck assembly into connector in handle and hold in hand	A	0	B	0	G	0	A	1	B	0	P	6	A	0																
56					A	B	G	M	X	I	A																							
57					A	B	G	A	B	P	*	A	B	P	A																			
58	18	Main	195735	Get switch kit and open bag	A	B	G	M	X	I	A																							
59					A	1	B	0	G	1	A	1	B	0	P	0	L	6	A	0	B	0	P	0	A	0								
60	19	Main	198743	Get Clamp and switch from bag and put switch on table	A	0	B	0	G	1	A	1	B	0	P	1	A	0																
61					A	B	G	M	X	I	A																							
62					A	B	G	A	B	P	*	A	B	P	A																			
63					A	1	B	0	G	1	A	1	B	0	P	3	A	0																
64	20	Main		Pick up handle and place clamp in position on handle	A	B	G	M	X	I	A																							
65					A	B	G	A	B	P	*	A	B	P	A																			
66					A	1	B	0	G	1	A	1	B	0	P	3	A	0																
67	21	Main		Pick up switch and position on handle and hold assembly in left hand	A	B	G	M	X	I	A																							
68					A	B	G	A	B	P	*	A	B	P	A																			
69					A	1	B	0	G	1	A	1	B	0	P	1	A	0																
70	22	Main	602202	Get Washer and transfer to left hand	A	B	G	M	X	I	A																							
71					A	B	G	A	B	P	*	A	B	P	A																			
72					A	B	G	M	X	I	A																							
73	23	Main	070001	Get screw, thread washer and finger tighten 2 turns	A	B	G	M	X	I	A																							
74					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0								
75	24	Main		Power 4 tighten screws	A	B	G	A	B	P	A																							
76					A	B	G	M	X	I	A																							
77					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0								
78	25	Main	201245	Get shield kit and open bag	A	B	G	A	B	P	A																							
79					A	B	G	M	X	I	A																							
80					A	1	B	0	G	1	A	1	B	0	P	0	L	6	A	0	B	0	P	0	A	0								
81					A	1	B	0	G	1	A	1	B	0	P	3	A	0																
82	26	Main		Remove shield from bag and put on handle	A	B	G	M	X	I	A																							
83					A	B	G	A	B	P	*	A	B	P	A																			
84					A	1	B	0	G	1	A	1	B	0	P	3	A	0																
85	27	Main	135646	Get screw and thread through shield	A	B	G	M	X	I	A																							
86					A	B	G	A	B	P	*	A	B	P	A																			
87					A	B	G	A	B	P	A																							
88	28	Main	198681	Get nut and finger tighten two turns	A	B	G	M	X	I	A																							
89					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0								
90					A	B	G	A	B	P	A																							
91	29	Main		Power tighten 2 screws	A	B	G	M	X	I	A																							
92					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0								
93					A	1	B	0	G	3	A	1	B	0	P	3	A	0																
94	30	Main	201255	Collect inserts and liner and put in gooseneck	A	B	G	M	X	I	A																							
95					A	B	G	A	B	P	*	A	B	P	A																			
96					A	1	B	0	G	1	A	1	B	0	P	3	A	0																
97	31	Main	201256	Collect tip and put in gooseneck	A	B	G	M	X	I	A																							
98					A	B	G	A	B	P	A																							

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
39			201262		A	B	G	A	B	P	A																					
100	32	Main		Collect nozzle and finger tighten 8 turns	A	B	G	M	X	I	A																			1	0	140
101					A	1	B	0	G	1	A	1	B	0	P	3	F	8	A	0	B	0	P	0	A	0						
102			195733		A	1	B	0	G	1	A	1	B	0	P	3	A	0														
103	33	Main		Get Insulator sleeve and thread on hose	A	B	G	M	X	I	A																			1	0	60
104					A	B	G	A	B	P	*							A	B	P	A											
105			Fasteners		A	B	G	A	B	P	A																A	1				
106	34	Main		Get two screws and finger tighten two turns	A	B	G	M	X	I	A																		6	1	0	160
107					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	0	A	0						
108					A	B	G	A	B	P	A																A	1				
109	35	Main		Power tighten 2 screws	A	B	G	M	X	I	A																		6	1	0	170
110					A	1	B	0	G	1	A	1	B	0	P	3	F	3	A	0	B	0	P	1	A	0						

Appendix J Supporting Code Added to aPriori for Emergy Calculation

J.1 Sheet Metal

J.1.1 Library File for Calculations

```
// Material Calculations

emMaterial(emPerKg,roughMassKg)= emPerKg * roughMassKg

// Process Calculations

emMachineLabor(uevWorker ,laborTimeMachine)= (uevWorker / 3600) *
    laborTimeMachine

emMachine(equipMass ,materialUEV ,price ,commodityCost) = emMaterial(
    materialUEV ,equipMass) + _
emLaborServices(price ,commodityCost ,equipMass ,uevDollar)

emElectricity(powerReqkW) = powerReqkW * uevElectricity /1000

// Plant Calculations

emPlantAreaYearly(area) = uevFactory * area

emPlantUtilitiesYearly = utilitiesCost * uevDollar

emPlantOverheadYearly(workerUEV ,workerAllocation) = workerAllocation *
    workerUEV * workCenterCapacity

emPlantMaintenanceYearly(area ,workerAllocation ,workerUEV) = area *
    workerUEV * workCenterCapacity * workerAllocation

// General Calculations
```



```
emSupplies(uev,usage) = uev * usage
```

```
emLaborServices(finalCost,commodityCost,massValue,uevMoney)= (finalCost  
- commodityCost*massValue)*uevMoney
```

J.1.2 Library File for Values

```
emPerMass = material.emPerKg
```

```
uevDollar = plant.uevDollar
```

```
partMaterialCommodityCost = material.commodityPrice
```

```
uevOperator = machine.uevLaborMachine
```

```
machineMass = machine.mass
```

```
machineMaterialUEV = machine.uevMachineMaterial * 1000 //table entry in  
sej/g; convert to sej/kg
```

```
machineMaterialCommodityCost = machine.materialCommodityPrice
```

```
uevElectricity = plant.uevElectricity
```

```
uevLaserGas = machine.uevLaserGas
```

```
uevAssistGas = machine.uevAssistGas
```

```
uevFactory = plant.uevFactoryYearlyPerArea
```

```
totalMachineAttributedArea = workcenterFootprint * (1 +  
nonProductionFootprintFactor)
```

```

uevQualityWorker = plant.uevQualityWorkerHourly

uevPurchasingWorker = plant.uevPurchasingWorkerHourly

uevEngineeringWorker = plant.uevEngineeringWorkerHourly

uevToolCribWorker = plant.uevToolCribWorkerHourly

uevPlantMaintenanceWorker = plant.uevPlantMaintenanceWorkerHourly

```

J.1.3 Laser Cut

```

import libEmergyValues.csl
import libEmergyCalcs.csl

//Emergy Calculation Elements

totalProcessEmergy = setup.emLaborMachinePSO
emMaterialTotal = setup.emPartMaterialLSPSO + setup.emPartMaterialPSO
emPartMaterial = emMaterial(roughMass,emPerMass)
emPartMaterialLS = emLaborServices(materialCost,
    partMaterialCommodityCost,roughMass,uevDollar)

emLaborMachine = emMachineLabor(uevOperator,laborTime)

emDOH = setup.emEquipmentPSO + setup.emInstallationPSO + setup.
    emMaintenancePSO + setup.emPowerPSO
emEquipment = (emHourlyMachine)*(cycleTime/3600)
emInstallation = (emHourlyInstallation)*(cycleTime/3600)
emMaintenance = (emHourlyMaintenance)*(cycleTime/3600)
emPower = (emHourlyMachinePower)*(cycleTime/3600)

emHourlyMachine = emMachine(machineMass,machineMaterialUEV,machinePrice,
    machineMaterialCommodityCost)/machineLife/annualEarnedMachineHours

```

```

emHourlyInstallation = installationCost * uevDollar / machineLife /
    annualEarnedMachineHours
emHourlyMaintenance = maintenanceCost * uevDollar /
    annualEarnedMachineHours
emHourlyMachinePower = emElectricity (GetMachinePowerReq)

emBatchSetup = setup.emSetupPSO
emSetup =(emHourlyMachine + emHourlyInstallation + emHourlyMaintenance +
    emHourlyMachinePower+ uevOperator + uevAssistGas + uevLaserGas) *
    setupTimePerPart / 3600

emLogistics = TODO
emMaterialOH = TODO
emExpendableTooling = TODO
emAdditionalDirect = TODO

emExtra = setup.emLaserGasPSO + setup.emAssistGasPSO
emLaserGas = emSupplies(uevLaserGas ,cycleTime) / 3600
emAssistGas = emSupplies(uevAssistGas ,cycleTime) / 3600

emIOH = setup.emPlantAreaPSO + setup.emPlantUtilitiesPSO + setup.
    emPlantOverheadPSO
emPlantArea = (emPlantAreaYearly(totalMachineAttributedArea) /
    annualEarnedMachineHours) * (cycleTime / 3600)
emPlantUtilities =(emPlantUtilitiesYearly / annualEarnedMachineHours) *
    (cycleTime / 3600)
emPlantOverhead = ((emPlantOverheadYearly(uevQualityWorker ,
    qualitySupportAllocation) + _
emPlantOverheadYearly(uevPurchasingWorker , purchasingSupportAllocation) +
    -

```

```

emPlantOverheadYearly(uevEngineeringWorker , engineeringSupportAllocation)
+ _
emPlantOverheadYearly(uevToolCribWorker , toolCribSupportAllocation)+ _
emPlantMaintenanceYearly( totalMachineAttributedArea , supportAllocation ,
    uevPlantMaintenanceWorker) _
)/ annualEarnedMachineHours) * (cycleTime / 3600)

```

```

emSGA = TODO
emMargin = TODO

```

```

emHardTooling = TODO
emFixtures = TODO
emProgramming = TODO
emAdditionalInvestments = TODO

```

```

TODO=0

```

J.1.4 Bend Break

```

import libEmergyValues.csl
import libEmergyCalcs.csl

```

```

//Emergy Calculation Elements

```

```

totalProcessEmergy = setup.emLaborMachinePSO

```

```

emLaborMachine = emMachineLabor(uevOperator , laborTime)

```

```

emDOH = setup.emEquipmentPSO + setup.emInstallationPSO + setup.
    emMaintenancePSO + setup.emPowerPSO

```

```

emEquipment = (emHourlyMachine)*(cycleTime/3600)

```

```

emInstallation = (emHourlyInstallation)*(cycleTime/3600)

```

```

emMaintenance = (emHourlyMaintenance)*(cycleTime/3600)
emPower = (emHourlyMachinePower)*(cycleTime/3600)

emHourlyMachine = emMachine(machineMass , machineMaterialUEV , machinePrice ,
    machineMaterialCommodityCost)/ machineLife / annualEarnedMachineHours
emHourlyInstallation = installationCost * uevDollar / machineLife /
    annualEarnedMachineHours
emHourlyMaintenance = maintenanceCost * uevDollar /
    annualEarnedMachineHours
emHourlyMachinePower = emElectricity (GetMachinePowerReq)

emBatchSetup = setup.emSetupPSO
emSetup =(emHourlyMachine + emHourlyInstallation + emHourlyMaintenance +
    -
    emHourlyMachinePower+ uevOperator ) * setupTimePerPart / 3600

emLogistics = TODO
emMaterialOH = TODO
emExpendableTooling = TODO
emAdditionalDirect = TODO

emIOH = setup.emPlantAreaPSO + setup.emPlantUtilitiesPSO + setup.
    emPlantOverheadPSO
emPlantArea = (emPlantAreaYearly (totalMachineAttributedArea) /
    annualEarnedMachineHours) * (cycleTime / 3600)
emPlantUtilities =(emPlantUtilitiesYearly / annualEarnedMachineHours) *
    (cycleTime / 3600)
emPlantOverhead = ((emPlantOverheadYearly (uevQualityWorker ,
    qualitySupportAllocation) + _
    emPlantOverheadYearly (uevPurchasingWorker , purchasingSupportAllocation) +
    -

```

```

emPlantOverheadYearly(uevEngineeringWorker , engineeringSupportAllocation )
    + _
emPlantOverheadYearly(uevToolCribWorker , toolCribSupportAllocation)+ _
emPlantMaintenanceYearly( totalMachineAttributedArea , supportAllocation ,
    uevPlantMaintenanceWorker) _
)/ annualEarnedMachineHours ) * (cycleTime / 3600)

```

```

emSGA = TODO
emMargin = TODO

```

```

emHardTooling = TODO
emFixtures = TODO
emProgramming = TODO
emAdditionalInvestments = TODO

```

```

TODO = 0

```

J.2 Assembly

J.2.1 Library File for Calculations

```

totalWireCost = wireCost * weldWeight

```

```

// Process Calculations

```

```

emMachineLabor(uevWorker , laborTimeMachine)= (uevWorker / 3600) *
    laborTimeMachine

```

```

emMachine = machineLSEmergy + machineMaterialEmergy

```

```

emElectricity(powerReqkW) = powerReqkW * uevElectricity /1000

```

```

// Plant Calculations

```

```

emPlantAreaYearly(area) = uevFactory * area

emPlantUtilitiesYearly = utilitiesCost * uevDollar

emPlantOverheadYearly(workerUEV, workerAllocation) = workerAllocation *
    workerUEV * workCenterCapacity

emPlantMaintenanceYearly(area, workerAllocation, workerUEV) = area *
    workerUEV * workCenterCapacity * workerAllocation

// General Calculations

emSupplies(uev, usage) = uev * usage

emLaborServices(finalCost, commodityCost, massValue, uevMoney) = _
    (finalCost - commodityCost*massValue)*uevMoney

```

J.2.2 Library File for Values

```

uevDollar = plant.uevDollar

uevOperator = machine.uevLaborMachine

machineMaterialEmergy = machine.emergyEquipMat

machineLSEmergy = machine.emergyEquipLS

uevElectricity = plant.uevElectricity

uevFactory = plant.uevFactoryYearlyPerArea

totalMachineAttributedArea = workcenterFootprint * (1 +
    nonProductionFootprintFactor)

```

```

uevQualityWorker = plant.uevQualityWorkerHourly

uevPurchasingWorker = plant.uevPurchasingWorkerHourly

uevEngineeringWorker = plant.uevEngineeringWorkerHourly

uevToolCribWorker = plant.uevToolCribWorkerHourly

uevPlantMaintenanceWorker = plant.uevPlantMaintenanceWorkerHourly

uevWeldWire = machine.uevWeldWire

wireCommodityCost = machine.wireCommodityCost

```

J.2.3 Pick and Place

Two files at different hierarchical levels support the Pick and Place process. The delimitation between the two files is marked with a comment.

```

//*****ptax file*****
import libEmergyValues.csl
import libEmergyCalcs.csl

//Emergy

totalProcessEmergy = emLaborMachine

emLaborMachine = setup.emLaborMachinePSO

emLaborCalc = emMachineLabor(uevOperator,laborTime)

emIOH = setup.emPlantAreaPSO + setup.emPlantUtilitiesPSO + setup.
    emPlantOverheadPSO

```



```

emPlantArea = (emPlantAreaYearly(totalMachineAttributedArea) /
    annualEarnedMachineHours) * (cycleTime / 3600)
emPlantUtilities =(emPlantUtilitiesYearly / annualEarnedMachineHours) *
    (cycleTime / 3600)
emPlantOverhead = ((emPlantOverheadYearly(uevQualityWorker ,
    qualitySupportAllocation) + _
emPlantOverheadYearly(uevPurchasingWorker , purchasingSupportAllocation) +
    _
emPlantOverheadYearly(uevEngineeringWorker , engineeringSupportAllocation)
    + _
emPlantOverheadYearly(uevToolCribWorker , toolCribSupportAllocation)+ _
emPlantMaintenanceYearly(totalMachineAttributedArea , supportAllocation ,
    uevPlantMaintenanceWorker) _
)/ annualEarnedMachineHours) * (cycleTime / 3600)

```

```

//Component Emergy

```

```

emComponentMaterial = setup.componentEmergyMaterialSumPSO
emComponentMaterialLS = setup.componentEmergyMaterialLSSumPSO

```

```

emComponentEquipment = setup.componentEmergyEquipmentSumPSO
emComponentInstallation = setup.componentEmergyInstallationSumPSO
emComponentMaintenance = setup.componentEmergyMaintenanceSumPSO
emComponentMachineLabor = setup.componentEmergyLaborMachineSumPSO
emComponentMachinePower = setup.componentEmergyMachinePowerSumPSO
emComponentMachineSetup = setup.componentEmergyMachineSetupSumPSO
emComponentSupplies = setup.componentEmergySuppliesSumPSO

```

```

emComponentPlantArea = setup.componentEmergyPlantAreaSumPSO
emComponentPlantWorkers = setup.componentEmergyPlantWorkersSumPSO
emComponentPlantUtilities = setup.componentEmergyPlantUtilitiesSumPSO

```

```

componentEmergyMaterialSum = select sum(x.componentEmergyMaterial) from
    childOps x
componentEmergyMaterialLSSum = select sum(x.componentEmergyMaterialLS)
    from childOps x

componentEmergyEquipmentSum = select sum(x.componentEmergyEquipment)
    from childOps x
componentEmergyInstallationSum = select sum(x.
    componentEmergyInstallation) from childOps x
componentEmergyMaintenanceSum = select sum(x.componentEmergyMaintenance)
    from childOps x
componentEmergyLaborMachineSum = select sum(x.
    componentEmergyLaborMachine) from childOps x
componentEmergyMachinePowerSum = select sum(x.
    componentEmergyMachinePower) from childOps x
componentEmergyMachineSetupSum = select sum(x.
    componentEmergyMachineSetup) from childOps x
componentEmergySuppliesSum = select sum(x.componentEmergySupplies) from
    childOps x

componentEmergyPlantAreaSum = select sum(x.componentEmergyPlantArea)
    from childOps x
componentEmergyPlantWorkersSum = select sum(x.
    componentEmergyPlantWorkers) from childOps x
componentEmergyPlantUtilitiesSum = select sum(x.
    componentEmergyPlantUtilities) from childOps x

//*****Load otax file*****
//Component Emergy

componentEmergyMaterial = foreach (x : part.childScenarios) getSum(var)
    {
with {

```

```

val = x.currentCostSummary.nestedResults.results.emPartMaterial
name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEnergyMaterialLS = foreach (x : part.childScenarios) getSum(var
    ) {
with {
val = x.currentCostSummary.nestedResults.results.emPartMaterialLS
name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEnergyEquipment = foreach (x : part.childScenarios) getSum(var
    {
with {
val = x.currentCostSummary.nestedResults.results.emEquipment
name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEnergyInstallation = foreach (x : part.childScenarios) getSum(
    var) {
with {
val = x.currentCostSummary.nestedResults.results.emInstallation
name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEnergyMaintenance = foreach (x : part.childScenarios) getSum(
    var) {
with {
val = x.currentCostSummary.nestedResults.results.emMaintenance

```

```

name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEmergyLaborMachine = foreach (x : part.childScenarios) getSum(
    var) {
with {
val = x.currentCostSummary.nestedResults.results.emLaborMachine
name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEmergyMachinePower = foreach (x : part.childScenarios) getSum(
    var) {
with {
val = x.currentCostSummary.nestedResults.results.emPower
name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEmergyMachineSetup = foreach (x : part.childScenarios) getSum(
    var) {
with {
val = x.currentCostSummary.nestedResults.results.emSetup
name = x.gcd.partModelName}
var = {val if name == gcd.partNumber 0 otherwise}
}

componentEmergySupplies = foreach (x : part.childScenarios) getSum(var)
{
with {
val = x.currentCostSummary.nestedResults.results.emExtra
name = x.gcd.partModelName}

```

```

var = { val if name == gcd.partNumber 0 otherwise}
}

componentEmergyPlantArea = foreach (x : part.childScenarios) getSum(var)
{
  with {
    val = x.currentCostSummary.nestedResults.results.emPlantArea
    name = x.gcd.partModelName}
    var = { val if name == gcd.partNumber 0 otherwise}
  }

componentEmergyPlantWorkers = foreach (x : part.childScenarios) getSum(
  var) {
  with {
    val = x.currentCostSummary.nestedResults.results.emPlantOverhead
    name = x.gcd.partModelName}
    var = { val if name == gcd.partNumber 0 otherwise}
  }

componentEmergyPlantUtilities = foreach (x : part.childScenarios) getSum
  (var) {
  with {
    val = x.currentCostSummary.nestedResults.results.emPlantUtilities
    name = x.gcd.partModelName}
    var = { val if name == gcd.partNumber 0 otherwise}
  }
}

```

J.2.4 Welding

```

import libEmergyValues.csl
import libEmergyCalcs.csl

```

```

totalProcessEmergy = setup.emLaborMachinePSO

emLaborMachine = emMachineLabor(uevOperator ,laborTime)

emDOH = setup.emEquipmentPSO + setup.emInstallationPSO + setup.
    emMaintenancePSO + setup.emPowerPSO
emEquipment = (emHourlyMachine)*(cycleTime/3600)
emInstallation = (emHourlyInstallation)*(cycleTime/3600)
emMaintenance = (emHourlyMaintenance)*(cycleTime/3600)
emPower = (emHourlyMachinePower)*(cycleTime/3600)

emHourlyMachine = emMachine/machineLife/annualEarnedMachineHours
emHourlyInstallation = installationCost * uevDollar/machineLife/
    annualEarnedMachineHours
emHourlyMaintenance = maintenanceCost * uevDollar/
    annualEarnedMachineHours
emHourlyMachinePower = emElectricity(GetMachinePowerReq)

emBatchSetup = setup.emSetupPSO
emSetup =(emHourlyMachine + emHourlyInstallation + emHourlyMaintenance +
    -
    emHourlyMachinePower + uevOperator) * setupTimePerPart / 3600

emLogistics = TODO
emMaterialOH = TODO
emExpendableTooling = TODO
emAdditionalDirect = TODO

emExtra = setup.emSuppliesPSO

```

```

emWeldWire = emSupplies(uevWeldWire,weldWeight) + emLaborServices(
    totalWireCost , wireCommodityCost , weldWeight , uevDollar) //weld wire
    calc goes here

emIOH = setup.emPlantAreaPSO + setup.emPlantUtilitiesPSO + setup.
    emPlantOverheadPSO
emPlantArea = (emPlantAreaYearly(totalMachineAttributedArea) /
    annualEarnedMachineHours) * (cycleTime / 3600)
emPlantUtilities =(emPlantUtilitiesYearly / annualEarnedMachineHours) *
    (cycleTime / 3600)
emPlantOverhead = ((emPlantOverheadYearly(uevQualityWorker ,
    qualitySupportAllocation) + _
emPlantOverheadYearly(uevPurchasingWorker , purchasingSupportAllocation) +
    _
emPlantOverheadYearly(uevEngineeringWorker , engineeringSupportAllocation)
    + _
emPlantOverheadYearly(uevToolCribWorker , toolCribSupportAllocation)+ _
emPlantMaintenanceYearly(totalMachineAttributedArea , supportAllocation ,
    uevPlantMaintenanceWorker) _
)/ annualEarnedMachineHours) * (cycleTime / 3600)

emSGA = TODO
emMargin = TODO

emHardTooling = TODO
emFixtures = TODO
emProgramming = TODO
emAdditionalInvestments = TODO

TODO = 0

```

J.3 aPriori Macro Code for Emergy Display in User Interface

J.3.1 Sheet Metal

```
<ProjectType name="EmergyView" cslModule="EmergyView.csl">
```

```
<InputSpecs displayBorder="false "  
fixedWidth="false "  
fixedHeight="false "  
layoutDirection="horizontal">
```

```
<InputSpecs displayBorder="false ">  
<InputSpecGroup displayName="Emergy_Summary" displayBorder="true "  
minWidth="120 "  
maxWidth="200 "  
labelAlignment="right">
```

```
<InputSpec displayName="Total "  
cslVarName="totalInput "  
cslFormulaForDefaultValue="scientificNotationFormatting(total) "  
renderMode="outputOnly "  
type="String "  
numColumns="12 "  
displayDecimalPlaces="0 "  
fontType="FontType.bold "  
formatterName="string"/>
```

```
<InputSpec displayName="Material "  
cslVarName = "materialPercentInput "  
cslFormulaForDefaultValue="materialPartText "  
renderMode="outputOnly "  
type="String "  
numColumns="12 "
```



```

displayDecimalPlaces="2"
fontType="FontType . bold"
formatterName="percentFormatter"/>
<InputSpec displayName="Laser"
  cslVarName = "laserPercentInput"
  cslFormulaForDefaultValue = "laserText"
  renderMode="outputOnly"
  type="String"
  numColumns="12"
  displayDecimalPlaces="2"
  fontType="FontType . bold"
  formatterName="percentFormatter"/>
<InputSpec displayName="Bend"
  cslVarName = "bendPercentInput"
  cslFormulaForDefaultValue = "bendText"
  renderMode="outputOnly"
  type="String"
  numColumns="12"
  displayDecimalPlaces="2"
  fontType="FontType . bold"
  formatterName="percentFormatter"/>

</InputSpecGroup>

</InputSpecs>

<InputSpecs displayName="" layoutDirection="vertical" displayBorder="
  false">
  <InputSpecGroup displayBorder="true"
    displayName = "Material_Emergy"
    minWidth="50"

```

```

maxWidth=" 120 "
labelAlignment=" right ">

<InputSpec displayName=" Material "
cslVarName=" materialEmergyInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (
    emPartMaterialValue )"
renderMode=" outputOnly "
type=" String "
numColumns=" 12 "
displayDecimalPlaces=" 0 "
formatterName=" string " />
<InputSpec displayName=" Material_Labor_+_Services "
cslVarName=" materialEmergyLSInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (
    emPartMaterialLSValue )"
renderMode=" outputOnly "
type=" String "
numColumns=" 12 "
displayDecimalPlaces=" 0 "
formatterName=" string " />

</InputSpecGroup>

<InputSpecGroup displayBorder=" true "
displayName = " Laser_Emergy "
minWidth=" 50 "
maxWidth=" 120 "
labelAlignment=" right ">

<InputSpec displayName=" Operator "
cslVarName=" laserOperatorEmergyInput "

```

```

cslFormulaForDefaultValue="scientificNotationFormatting(
    emLaborMachineLaserValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment"
cslVarName="laserEquipmentEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emEquipmentLaserValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment_Installation"
cslVarName="laserEquipmentInstallationInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emInstallationLaserValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment_Maintenance"
cslVarName="laserEquipmentMaintenanceInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emMaintenanceLaserValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"

```

```

formatterName=" string "/>
<InputSpec displayName="Machine_Power"
cslVarName="laserMachinePowerInput "
cslFormulaForDefaultValue="scientificNotationFormatting(
    emPowerLaserValue )"
renderMode="outputOnly "
type="String "
numColumns="12 "
displayDecimalPlaces="0"
formatterName=" string "/>
<InputSpec displayName="Supplies:_Laser_Gas"
cslVarName="suppliesLaserGasInput "
cslFormulaForDefaultValue="scientificNotationFormatting(emLaserGasValue)
    "
renderMode="outputOnly "
type="String "
numColumns="12 "
displayDecimalPlaces="0"
formatterName=" string "/>
<InputSpec displayName="Supplies:_Assist_Gas"
cslVarName="suppliesAssistGasInput "
cslFormulaForDefaultValue="scientificNotationFormatting(emAssistGasValue
    )"
renderMode="outputOnly "
type="String "
numColumns="12 "
displayDecimalPlaces="0"
formatterName=" string "/>
<InputSpec displayName="Machine_Setup"
cslVarName="laserMachineSetupInput "
cslFormulaForDefaultValue="scientificNotationFormatting(
    emSetupLaserValue )"
renderMode="outputOnly "

```

```

type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Indirect_Overhead"
cslVarName="laserIohInput"
cslFormulaForDefaultValue="scientificNotationFormatting(iohTotalLaser)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
</InputSpecGroup>

```

```

<InputSpecGroup displayBorder="true"
displayName = "Bend_Emergy"
minWidth="50"
maxWidth="120"
labelAlignment="right">

```

```

<InputSpec displayName="Operator"
cslVarName="bendOperatorEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emLaborMachineBendValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment"
cslVarName="bendEquipmentEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emEquipmentBendValue)"

```

```

renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment_Installation"
cslVarName="bendEquipmentInstallationInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emInstallationBendValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment_Maintenance"
cslVarName="bendEquipmentMaintenanceInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emMaintenanceBendValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Machine_Power"
cslVarName="bendMachinePowerInput"
cslFormulaForDefaultValue="scientificNotationFormatting(emPowerBendValue
    )"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Machine_Setup"

```

```

cslVarName=" bendMachineSetupInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (emSetupBendValue
    )"
renderMode=" outputOnly "
type=" String "
numColumns=" 12 "
displayDecimalPlaces=" 0 "
formatterName=" string " />
<InputSpec  displayName=" Indirect_Overhead "
cslVarName=" bendIohInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (iohTotalBend )"
renderMode=" outputOnly "
type=" String "
numColumns=" 12 "
displayDecimalPlaces=" 0 "
formatterName=" string " />
</InputSpecGroup>

</InputSpecs>

</InputSpecs>
</ProjectType>

```

J.3.2 Assembly

```

<ProjectType  name="EmergyView"  cslModule="EmergyView.csl">

<InputSpecs  displayBorder=" false "
fixedWidth=" false "
fixedHeight=" false "
layoutDirection=" horizontal ">

<InputSpecs  layoutDirection=" vertical "  displayBorder=" false ">

```

```

<InputSpecGroup displayName="Emergy_Summary"
  displayBorder="true "
  minWidth="120 "
  maxWidth="200 "
  labelAlignment="right ">

<InputSpec displayName="Total_Emergy_( sej )"
  cslVarName="assebmlyLevelTotalsInput "
  cslFormulaForDefaultValue="scientificNotationFormatting(
    assemblyLevelTotal )"
  renderMode="outputOnly "
  type="String "
  numColumns="12 "
  displayDecimalPlaces="0"
  fontType="FontType . bold "
  formatterName="string "/>

<InputSpec displayName="Material "
  cslVarName = "materialAssyPercentInput "
  cslFormulaForDefaultValue="materialText "
  renderMode="outputOnly "
  type="String "
  numColumns="20 "
  displayDecimalPlaces="2 "
  fontType="FontType . bold "
  formatterName="stringFormatter "/>
<InputSpec displayName="Welding "
  cslVarName = "weldingPercentInput "
  cslFormulaForDefaultValue ="weldText "
  renderMode="outputOnly "
  type="String "
  numColumns="20 "

```



```

displayDecimalPlaces="2"
fontType="FontType . bold"
formatterName=" string "/>
<InputSpec displayName="Component"
cslVarName = "componentPercentInput"
cslFormulaForDefaultValue = "componentText"
renderMode="outputOnly"
type="String"
numColumns="20"
displayDecimalPlaces="2"
fontType="FontType . bold"
formatterName=" string "/>

</InputSpecGroup>
</InputSpecs>
<InputSpecs displayName="" layoutDirection="vertical" displayBorder="
false">
<InputSpecGroup displayBorder="true"
displayName = "Component_Material_Emergy"
minWidth="50"
maxWidth="1200"
labelAlignment="right">

<InputSpec displayName="Material"
cslVarName="totalMaterialEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
componentEmergyMaterialSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"

```

```

formatterName=" string "/>

<InputSpec displayName="Material_Labor+_Services"
cslVarName="totalMaterialLSEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergyMaterialLSSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName=" string "/>
</InputSpecGroup>
<InputSpecGroup displayBorder="true"
displayName = "Welding_Emergy"
minWidth="50"
maxWidth="1200"
labelAlignment="right">

<InputSpec displayName="Operator_"
cslVarName="weldOperatorEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(laborTotalWeld)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName=" string "/>
<InputSpec displayName="Equipment_"
cslVarName="weldEquipmentEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emEquipmentAssyValue)"
renderMode="outputOnly"
type="String"
numColumns="12"

```

```

displayDecimalPlaces="0"
formatterName=" string " />
<InputSpec displayName="Equipment_Installation "
cslVarName=" weldEquipmentInstallationInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (
    emInstallationAssyValue )"
renderMode=" outputOnly "
type=" String "
numColumns=" 12 "
displayDecimalPlaces="0"
formatterName=" string " />
<InputSpec displayName="Equipment_Maintenance "
cslVarName=" weldEquipmentMaintenanceInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (
    emMaintenanceAssyValue )"
renderMode=" outputOnly "
type=" String "
numColumns=" 12 "
displayDecimalPlaces="0"
formatterName=" string " />
<InputSpec displayName="Machine_Power "
cslVarName=" weldMachinePowerInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (emPowerAssyValue
    )"
renderMode=" outputOnly "
type=" String "
numColumns=" 12 "
displayDecimalPlaces="0"
formatterName=" string " />
<InputSpec displayName="Machine_Setup "
cslVarName=" weldMachineSetupInput "
cslFormulaForDefaultValue=" scientificNotationFormatting (emSetupAssyValue
    )"

```

```

renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Indirect_Overhead"
cslVarName="weldIohInput"
cslFormulaForDefaultValue="scientificNotationFormatting(iohTotalWeld)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Supplies"
cslVarName="weldSuplies"
cslFormulaForDefaultValue="scientificNotationFormatting(
    emSuppliesAssyValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
</InputSpecGroup>

<InputSpecGroup displayBorder="true"
displayName = "Component_Emergy"
minWidth="50"
maxWidth="1200"
labelAlignment="right">

<InputSpec displayName="Operator"
cslVarName="weldOperatorEmergyInput"

```

```

cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergyLaborMachineSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment"
cslVarName="componentEquipmentEmergyInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergyEquipmentSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment_Installation"
cslVarName="componentEquipmentInstallationInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergyInstallationSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
<InputSpec displayName="Equipment_Maintenance"
cslVarName="componentEquipmentMaintenanceInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergyMaintenanceSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"

```

```

formatterName=" string "/>
<InputSpec displayName="Machine_Power"
cslVarName="componentMachinePowerInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergyMachinePowerSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName=" string "/>
<InputSpec displayName="Machine_Setup"
cslVarName="componentMachineSetupInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergyMachineSetupSumValue)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName=" string "/>
<InputSpec displayName="Indirect_Overhead"
cslVarName="componentIohInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    iohTotalComponents)"
renderMode="outputOnly"
type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName=" string "/>
<InputSpec displayName="Supplies"
cslVarName="componentSuppliesInput"
cslFormulaForDefaultValue="scientificNotationFormatting(
    componentEmergySuppliesSumValue)"
renderMode="outputOnly"

```

```

type="String"
numColumns="12"
displayDecimalPlaces="0"
formatterName="string"/>
</InputSpecGroup>

```

```

</InputSpecs>

```

```

</InputSpecs>
</ProjectType>

```

J.3.3 Supporting Code

```

//***** Supporting Calculations
*****

getPsoValue(pg,pn,pso) = getCurrentPsoValue(skey,atn,vpe,ppg(pg,pn),pso)

skey = currentlyOpenScenario.scenarioKey
atn = 'Component'
vpe = currentlyOpenScenario.currentCostSummary.plantName
ppg(ppg,ppn) = asProcessInstanceKey(ppg,ppn,0)

scientificNotationFormatting(input) = msg(upfront(input),' E ',power(
    input))
upfront(num) = roundEps(num/10^power(num),0.001)
power(value) = rounddown(ln(value)/ln(10))

sheetMetal = 'Sheet Metal'
assembly = 'Assembly'
laserCut = 'Laser Cut'
bendBrake = 'Bend Brake'
welder = 'Manual MIG Welding'

```

```

pick = 'Pick and Place'

//***** Supporting Calculations for Assembly
Macro*****

//Welding Caculations

weldPlantAreaValue = safeGet(getPsoValue(assembly , welder , 'emPlantAreaPSO
    '),0)
weldPlantUtilitiesValue = safeGet(getPsoValue(assembly , welder , '
    emPlantUtilitiesPSO '),0)
weldPlantWorkerOverheadValue = safeGet(getPsoValue(assembly , welder , '
    emPlantOverheadPSO '),0)

ppPlantAreaValue = safeGet(getPsoValue(assembly , pick , 'emPlantAreaPSO ')
    ,0)
ppPlantUtilitiesValue = safeGet(getPsoValue(assembly , pick , '
    emPlantUtilitiesPSO '),0)
ppPlantWorkerOverheadValue = safeGet(getPsoValue(assembly , pick , '
    emPlantOverheadPSO '),0)

iohTotalWeld = weldPlantAreaValue + weldPlantUtilitiesValue +
    weldPlantWorkerOverheadValue + ppPlantAreaValue +
    ppPlantUtilitiesValue + ppPlantWorkerOverheadValue

ppLaborValue = safeGet(getPsoValue(assembly , pick , 'emLaborMachinePSO ') ,0)
weldLaborValue = safeGet(getPsoValue(assembly , welder , 'emLaborMachinePSO
    '),0)

laborTotalWeld = ppLaborValue + weldLaborValue

emEquipmentAssyValue = safeGet(getPsoValue(assembly , welder , '
    emEquipmentPSO '),0)

```



```

emInstallationAssyValue = safeGet(getPsoValue(assembly , welder , '
    emInstallationPSO ') ,0)
emMaintenanceAssyValue = safeGet(getPsoValue(assembly , welder , '
    emMaintenancePSO ') ,0)
emPowerAssyValue = safeGet(getPsoValue(assembly , welder , 'emPowerPSO ') ,0)
emSetupAssyValue = safeGet(getPsoValue(assembly , welder , 'emSetupPSO ') ,0)
emSuppliesAssyValue = safeGet(getPsoValue(assembly , welder , 'emSuppliesPSO
    ') ,0)

```

```

//Component Calculations

```

```

componentPlantAreaValue = safeGet(getPsoValue(assembly , pick , '
    componentEmergyPlantAreaSumPSO ') ,0)
componentPlantUtilitiesValue = safeGet(getPsoValue(assembly , pick , '
    componentEmergyPlantUtilitiesSumPSO ') ,0)
componentPlantWorkerOverheadValue = safeGet(getPsoValue(assembly , pick , '
    componentEmergyPlantWorkersSumPSO ') ,0)

```

```

iohTotalComponents = componentPlantAreaValue +
    componentPlantUtilitiesValue + componentPlantWorkerOverheadValue

```

```

componentEmergyMaterialSumValue = safeGet(getPsoValue(assembly , pick , '
    componentEmergyMaterialSumPSO ') ,0)
componentEmergyMaterialLSSumValue = safeGet(getPsoValue(assembly , pick , '
    componentEmergyMaterialLSSumPSO ') ,0)

```

```

componentEmergyLaborMachineSumValue = safeGet(getPsoValue(assembly , pick
    , ' componentEmergyLaborMachineSumPSO ') ,0)
componentEmergyEquipmentSumValue = safeGet(getPsoValue(assembly , pick , '
    componentEmergyEquipmentSumPSO ') ,0)
componentEmergyInstallationSumValue = safeGet(getPsoValue(assembly , pick
    , ' componentEmergyInstallationSumPSO ') ,0)

```

```

componentEmergyMaintenanceSumValue = safeGet ( getPsoValue ( assembly , pick , '
    componentEmergyMaintenanceSumPSO ' ) , 0 )
componentEmergyMachinePowerSumValue = safeGet ( getPsoValue ( assembly , pick
    , ' componentEmergyMachinePowerSumPSO ' ) , 0 )
componentEmergyMachineSetupSumValue = safeGet ( getPsoValue ( assembly , pick
    , ' componentEmergyMachineSetupSumPSO ' ) , 0 )
componentEmergySuppliesSumValue = safeGet ( getPsoValue ( assembly , pick , '
    componentEmergySuppliesSumPSO ' ) , 0 )

```

```

// Totals

```

```

assemblyLevelTotal = weldTotals + materialTotals +
    componentProcessingTotals

```

```

weldTotals = iohTotalWeld + laborTotalWeld + emEquipmentAssyValue +
    emInstallationAssyValue + emMaintenanceAssyValue + emPowerAssyValue
    + emSetupAssyValue + emSuppliesAssyValue

```

```

materialTotals = componentEmergyMaterialSumValue +
    componentEmergyMaterialLSSumValue

```

```

componentProcessingTotals = componentEmergyLaborMachineSumValue +
    componentEmergyEquipmentSumValue +
    componentEmergyInstallationSumValue +
    componentEmergyMaintenanceSumValue +
    componentEmergyMachinePowerSumValue +
    componentEmergyMachineSetupSumValue +
    componentEmergySuppliesSumValue + iohTotalComponents

```

```

// Percents

```

```

assyMaterialPercent = (materialTotals / assemblyLevelTotal) * 100
assyWeldingPercent = (weldTotals / assemblyLevelTotal) * 100
assyComponentProcessingPercent = (componentProcessingTotals /
    assemblyLevelTotal) * 100

//Concatenate Welding Emergy Summary

weldEmergyTotalOutput = scientificNotationFormatting(weldTotals)
materialEmergyTotalOutput = scientificNotationFormatting(materialTotals)
componentEmergyTotalOutput= scientificNotationFormatting(
    componentProcessingTotals)

materialText = msg(materialEmergyTotalOutput , '      ',roundEps(
    assyMaterialPercent ,0.01) ,'%')
weldText = msg(weldEmergyTotalOutput , '      ',roundEps(
    assyWeldingPercent ,0.01) ,'%')
componentText = msg(componentEmergyTotalOutput , '      ',roundEps(
    assyComponentProcessingPercent ,0.01) ,'%')

//***** Supporting calculations for part macro
*****

//PSOs

emPartMaterialValue = safeGet(getPsoValue(sheetMetal ,laserCut ,'
    emPartMaterialPSO ') ,0)
emPartMaterialLSValue = safeGet(getPsoValue(sheetMetal ,laserCut ,'
    emPartMaterialLSPSO ') ,0)

emLaborMachineLaserValue = safeGet(getPsoValue(sheetMetal ,laserCut ,'
    emLaborMachinePSO ') ,0)

```

```

emEquipmentLaserValue = safeGet(getPsoValue(sheetMetal , laserCut , '
    emEquipmentPSO ') ,0)
emInstallationLaserValue = safeGet(getPsoValue(sheetMetal , laserCut , '
    emInstallationPSO ') ,0)
emMaintenanceLaserValue = safeGet(getPsoValue(sheetMetal , laserCut , '
    emMaintenancePSO ') ,0)
emPowerLaserValue = safeGet(getPsoValue(sheetMetal , laserCut , 'emPowerPSO
    ') ,0)
emLaserGasValue = safeGet(getPsoValue(sheetMetal , laserCut , 'emLaserGasPSO
    ') ,0)
emAssistGasValue = safeGet(getPsoValue(sheetMetal , laserCut , '
    emAssistGasPSO ') ,0)
emSetupLaserValue = safeGet(getPsoValue(sheetMetal , laserCut , 'emSetupPSO
    ') ,0)

emLaborMachineBendValue = safeGet(getPsoValue(sheetMetal , bendBrake , '
    emLaborMachinePSO ') ,0)
emEquipmentBendValue = safeGet(getPsoValue(sheetMetal , bendBrake , '
    emEquipmentPSO ') ,0)
emInstallationBendValue = safeGet(getPsoValue(sheetMetal , bendBrake , '
    emInstallationPSO ') ,0)
emMaintenanceBendValue = safeGet(getPsoValue(sheetMetal , bendBrake , '
    emMaintenancePSO ') ,0)
emPowerBendValue = safeGet(getPsoValue(sheetMetal , bendBrake , 'emPowerPSO
    ') ,0)
emSetupBendValue = safeGet(getPsoValue(sheetMetal , bendBrake , 'emSetupPSO
    ') ,0)

//IOH

laserPlantAreaValue = safeGet(getPsoValue(sheetMetal , laserCut , '
    emPlantAreaPSO ') ,0)

```

```

laserPlantUtilitiesValue = safeGet(getPsoValue(sheetMetal , laserCut , '
    emPlantUtilitiesPSO ') ,0)
laserPlantWorkerOverheadValue = safeGet(getPsoValue(sheetMetal , laserCut
    , 'emPlantOverheadPSO ') ,0)

iohTotalLaser = laserPlantAreaValue + laserPlantUtilitiesValue +
    laserPlantWorkerOverheadValue

bendPlantAreaValue =safeGet(getPsoValue(sheetMetal , bendBrake , '
    emPlantAreaPSO ') ,0)
bendPlantUtilitiesValue = safeGet(getPsoValue(sheetMetal , bendBrake , '
    emPlantUtilitiesPSO ') ,0)
bendPlantWorkerOverheadValue = safeGet(getPsoValue(sheetMetal , bendBrake
    , 'emPlantOverheadPSO ') ,0)

iohTotalBend = bendPlantAreaValue + bendPlantUtilitiesValue +
    bendPlantWorkerOverheadValue

// Total

materialSumPart = emPartMaterialValue + emPartMaterialLSValue

laserSum = emLaborMachineLaserValue + emEquipmentLaserValue +
    emInstallationLaserValue + emMaintenanceLaserValue +
    emPowerLaserValue + emLaserGasValue + emAssistGasValue +
    emSetupLaserValue + iohTotalLaser

bendSum = emLaborMachineBendValue + emEquipmentBendValue +
    emInstallationBendValue + emMaintenanceBendValue + emPowerBendValue
    + emSetupBendValue + iohTotalBend

total = materialSumPart + laserSum + bendSum

```

```

// Percents

materialPercent = (materialSumPart / total)*100

laserPercent = (laserSum / total)*100

bendPercent = (bendSum / total)*100

materialPartEmergyTotalOutput = scientificNotationFormatting(
    materialSumPart)
laserEmergyTotalOutput = scientificNotationFormatting(laserSum)
bendEmergyTotalOutput= scientificNotationFormatting(bendSum)

materialPartText = msg(materialPartEmergyTotalOutput , '          ',roundEps(
    materialPercent ,0.01) ,'% ')
laserText = msg(laserEmergyTotalOutput , '          ',roundEps(laserPercent
    ,0.01) ,'% ')
bendText = msg(bendEmergyTotalOutput , '          ',roundEps(bendPercent ,0.01)
    ,'% ')

```

Appendix K Sensitivity Analysis Data

K.1 Data for Spreadsheet Sensitivity Analysis

<ID>	no_L5	Dollar_UEV_rises	Per_Day	Metabolic_Calo	Number_of_Year_s_for_Education	UEV_no_L_UEV_Concrete_nols	UEV_Hourly_L_Erosion_	totalEnergy
0	2.08E+12	2.87E+03	1.84E+01	5.57E+09	1.37E+09	1.57E+12	8.55E+04	2.75E+13
1	1.52E+12	2.79E+03	7.06E+00	5.19E+09	1.40E+09	1.75E+12	1.02E+05	2.28E+13
2	1.99E+12	2.82E+03	2.82E+01	6.03E+09	1.46E+09	1.63E+12	8.93E+04	2.83E+13
3	1.47E+12	2.65E+03	1.40E+01	4.89E+09	1.45E+09	1.56E+12	9.41E+04	2.18E+13
4	2.24E+12	2.44E+03	1.12E+01	6.53E+09	1.33E+09	1.51E+12	9.97E+04	3.08E+13
5	2.59E+12	2.73E+03	2.59E+01	4.01E+09	1.31E+09	1.60E+12	9.10E+04	2.78E+13
6	1.87E+12	2.63E+03	1.75E+01	4.72E+09	1.35E+09	1.79E+12	8.80E+04	2.42E+13
7	2.28E+12	2.48E+03	2.21E+01	4.42E+09	1.25E+09	1.71E+12	9.68E+04	2.65E+13
8	2.52E+12	2.58E+03	1.11E+00	5.68E+09	1.48E+09	1.68E+12	9.45E+04	5.05E+13
9	1.70E+12	2.52E+03	6.19E+00	6.40E+09	1.27E+09	1.83E+12	1.03E+05	2.72E+13
10	2.64E+12	2.81E+03	2.47E+01	6.12E+09	1.31E+09	1.52E+12	9.72E+04	3.27E+13
11	2.04E+12	2.77E+03	1.10E+01	4.10E+09	1.31E+09	1.71E+12	9.56E+04	2.42E+13
12	2.26E+12	2.70E+03	2.13E+01	6.48E+09	1.51E+09	1.82E+12	9.55E+04	3.08E+13
13	1.50E+12	2.46E+03	9.16E+00	3.98E+09	1.33E+09	1.78E+12	9.63E+04	2.03E+13
14	2.18E+12	2.85E+03	2.98E+01	4.19E+09	1.29E+09	1.74E+12	1.00E+05	2.53E+13
15	2.63E+12	2.45E+03	1.55E+01	6.32E+09	1.48E+09	1.71E+12	1.03E+05	3.30E+13
16	1.79E+12	2.49E+03	2.33E+01	4.65E+09	1.51E+09	1.50E+12	8.54E+04	2.35E+13
17	2.41E+12	2.48E+03	2.21E+01	5.31E+09	1.30E+09	1.51E+12	8.57E+04	2.92E+13
18	2.64E+12	2.56E+03	1.17E+01	5.71E+09	1.25E+09	1.59E+12	9.14E+04	3.18E+13
19	1.74E+12	2.66E+03	2.91E+01	6.58E+09	1.25E+09	1.57E+12	9.55E+04	2.73E+13
20	1.74E+12	2.44E+03	4.90E+00	5.83E+09	1.49E+09	1.78E+12	9.74E+04	2.66E+13
21	2.09E+12	2.66E+03	2.10E+01	4.25E+09	1.37E+09	1.67E+12	9.41E+04	2.48E+13
22	1.91E+12	2.73E+03	1.83E+01	5.09E+09	1.46E+09	1.63E+12	9.18E+04	2.53E+13
23	2.48E+12	2.73E+03	9.32E+00	4.13E+09	1.35E+09	1.82E+12	1.01E+05	2.75E+13
24	2.19E+12	2.57E+03	6.13E+00	5.38E+09	1.27E+09	1.68E+12	1.04E+05	2.85E+13
25	2.57E+12	2.78E+03	1.89E+01	4.80E+09	1.36E+09	1.52E+12	1.01E+05	2.94E+13
26	1.64E+12	2.43E+03	1.54E+01	6.11E+09	1.31E+09	1.71E+12	9.13E+04	2.56E+13
27	2.22E+12	2.60E+03	1.33E+01	4.32E+09	1.37E+09	1.59E+12	1.03E+05	2.59E+13
28	1.68E+12	2.57E+03	2.71E+01	5.94E+09	1.24E+09	1.82E+12	9.77E+04	2.55E+13
29	1.91E+12	2.53E+03	2.34E+01	6.39E+09	1.39E+09	1.71E+12	1.02E+05	2.81E+13
30	1.40E+12	2.59E+03	7.15E+00	4.47E+09	1.48E+09	1.58E+12	8.77E+04	2.07E+13
31	2.10E+12	2.77E+03	9.87E+00	4.63E+09	1.31E+09	1.54E+12	9.78E+04	2.58E+13
32	1.41E+12	2.49E+03	2.16E+01	4.93E+09	1.45E+09	1.76E+12	9.42E+04	2.14E+13
33	1.94E+12	2.83E+03	1.38E+01	4.71E+09	1.32E+09	1.81E+12	9.29E+04	2.48E+13
34	2.59E+12	2.56E+03	1.34E+01	5.49E+09	1.49E+09	1.57E+12	9.67E+04	3.10E+13
35	2.16E+12	2.84E+03	1.41E+01	6.00E+09	1.27E+09	1.75E+12	9.94E+04	2.91E+13
36	1.98E+12	2.61E+03	2.76E+01	4.35E+09	1.33E+09	1.57E+12	9.31E+04	2.42E+13
37	1.85E+12	2.75E+03	1.72E+01	5.84E+09	1.30E+09	1.80E+12	8.56E+04	2.65E+13
38	1.77E+12	2.60E+03	9.54E+00	4.53E+09	1.47E+09	1.62E+12	8.99E+04	2.33E+13
39	2.38E+12	2.89E+03	1.52E+01	5.28E+09	1.40E+09	1.52E+12	9.20E+04	2.91E+13
40	2.58E+12	2.49E+03	4.88E+00	6.48E+09	1.40E+09	1.66E+12	9.14E+04	3.39E+13
41	1.70E+12	2.58E+03	7.27E+00	4.28E+09	1.44E+09	1.63E+12	9.66E+04	2.25E+13
42	1.85E+12	2.75E+03	4.08E+00	5.54E+09	1.27E+09	1.81E+12	1.02E+05	2.73E+13
43	2.46E+12	2.56E+03	1.68E+01	4.84E+09	1.42E+09	1.69E+12	9.97E+04	2.87E+13
44	2.60E+12	2.53E+03	1.58E+01	5.79E+09	1.40E+09	1.77E+12	8.49E+04	3.18E+13
45	1.71E+12	2.73E+03	1.13E+01	4.97E+09	1.34E+09	1.67E+12	9.98E+04	2.38E+13
46	1.55E+12	2.67E+03	2.82E+01	4.41E+09	1.38E+09	1.50E+12	8.79E+04	2.12E+13
47	2.15E+12	2.71E+03	4.73E+00	4.74E+09	1.35E+09	1.76E+12	9.69E+04	2.73E+13
48	2.44E+12	2.85E+03	1.92E+01	5.55E+09	1.49E+09	1.64E+12	9.68E+04	3.00E+13
49	1.79E+12	2.49E+03	2.92E+01	6.04E+09	1.39E+09	1.53E+12	9.87E+04	2.64E+13
50	1.72E+12	2.53E+03	5.30E+00	4.44E+09	1.37E+09	1.71E+12	9.00E+04	2.34E+13

51	2.32E+12	2.73E+03	2.28E+01	6.15E+09	1.40E+09	1.57E+12	9.51E+04	3.05E+13	104	2.16E+12	2.79E+03	2.50E+00	4.30E+09	1.34E+09	1.60E+12	9.94E+04	2.92E+13
52	2.10E+12	2.78E+03	2.63E+01	6.44E+09	1.33E+09	1.63E+12	1.02E+05	2.95E+13	105	2.28E+12	2.88E+03	3.89E+00	5.30E+09	1.50E+09	1.64E+12	1.03E+05	2.99E+13
53	2.58E+12	2.56E+03	6.14E+00	4.32E+09	1.44E+09	1.57E+12	1.00E+05	2.89E+13	106	1.68E+12	2.80E+03	2.68E+00	6.04E+09	1.43E+09	1.77E+12	9.02E+04	2.91E+13
54	1.59E+12	2.61E+03	1.15E+00	6.27E+09	1.43E+09	1.65E+12	8.86E+04	4.39E+13	107	1.70E+12	2.77E+03	5.05E+00	4.29E+09	1.26E+09	1.63E+12	8.49E+04	2.30E+13
55	1.96E+12	2.41E+03	1.42E+01	5.41E+09	1.38E+09	1.58E+12	9.80E+04	2.64E+13	108	1.56E+12	2.76E+03	2.18E+01	6.24E+09	1.47E+09	1.77E+12	9.11E+04	2.53E+13
56	2.06E+12	2.70E+03	1.45E+01	6.11E+09	1.29E+09	1.69E+12	8.54E+04	2.86E+13	109	2.57E+12	2.82E+03	1.01E+01	4.89E+09	1.48E+09	1.56E+12	1.01E+05	2.97E+13
57	1.44E+12	2.74E+03	2.27E+01	4.85E+09	1.24E+09	1.77E+12	8.56E+04	2.15E+13	110	2.10E+12	2.48E+03	1.23E+01	6.36E+09	1.45E+09	1.56E+12	8.64E+04	2.95E+13
58	2.00E+12	2.89E+03	1.06E+01	5.38E+09	1.35E+09	1.71E+12	8.49E+04	2.67E+13	111	2.30E+12	2.77E+03	2.48E+01	4.36E+09	1.40E+09	1.63E+12	8.74E+04	2.65E+13
59	2.23E+12	2.56E+03	1.24E+01	6.15E+09	1.45E+09	1.83E+12	1.01E+05	3.00E+13	112	1.46E+12	2.71E+03	1.64E+01	6.42E+09	1.42E+09	1.61E+12	9.91E+04	2.50E+13
60	2.17E+12	2.69E+03	4.51E+00	5.76E+09	1.50E+09	1.80E+12	9.68E+04	2.97E+13	113	2.62E+12	2.52E+03	2.81E+01	6.09E+09	1.41E+09	1.72E+12	9.88E+04	3.24E+13
61	2.45E+12	2.69E+03	1.96E+00	5.81E+09	1.47E+09	1.65E+12	1.01E+05	3.70E+13	114	2.24E+12	2.54E+03	1.97E+00	4.78E+09	1.48E+09	1.62E+12	1.03E+05	3.31E+13
62	2.12E+12	2.51E+03	2.15E+01	5.08E+09	1.47E+09	1.77E+12	8.63E+04	2.68E+13	115	1.99E+12	2.68E+03	1.01E+01	4.04E+09	1.42E+09	1.61E+12	1.03E+05	2.38E+13
63	2.18E+12	2.70E+03	2.30E+01	4.09E+09	1.24E+09	1.52E+12	9.32E+04	2.51E+13	116	2.41E+12	2.45E+03	1.39E+01	6.09E+09	1.34E+09	1.75E+12	1.02E+05	3.10E+13
64	1.40E+12	2.89E+03	1.77E+01	4.84E+09	1.27E+09	1.72E+12	8.94E+04	2.12E+13	117	2.46E+12	2.73E+03	1.05E+01	4.53E+09	1.41E+09	1.63E+12	9.97E+04	2.82E+13
65	2.08E+12	2.87E+03	2.81E+01	4.35E+09	1.48E+09	1.82E+12	8.81E+04	2.49E+13	118	2.47E+12	2.68E+03	1.23E+01	6.25E+09	1.32E+09	1.53E+12	1.03E+05	3.18E+13
66	2.55E+12	2.79E+03	7.01E+00	5.19E+09	1.44E+09	1.63E+12	9.79E+04	3.05E+13	119	2.13E+12	2.85E+03	2.73E+01	5.85E+09	1.34E+09	1.81E+12	8.52E+04	2.85E+13
67	1.94E+12	2.74E+03	1.73E+01	4.57E+09	1.32E+09	1.58E+12	8.56E+04	2.44E+13	120	2.42E+12	2.50E+03	2.52E+01	5.51E+09	1.45E+09	1.50E+12	9.36E+04	2.98E+13
68	2.38E+12	2.84E+03	9.96E+00	6.50E+09	1.41E+09	1.82E+12	9.42E+04	3.19E+13	121	1.83E+12	2.73E+03	2.10E+00	4.27E+09	1.28E+09	1.60E+12	9.64E+04	2.84E+13
69	1.49E+12	2.64E+03	1.08E+01	4.59E+09	1.25E+09	1.64E+12	1.01E+05	2.14E+13	122	2.30E+12	2.50E+03	1.58E+01	6.03E+09	1.49E+09	1.70E+12	8.98E+04	3.01E+13
70	1.63E+12	2.61E+03	2.12E+01	4.85E+09	1.37E+09	1.73E+12	9.27E+04	2.28E+13	123	2.64E+12	2.89E+03	2.67E+01	6.70E+09	1.40E+09	1.64E+12	9.53E+04	3.39E+13
71	2.07E+12	2.83E+03	2.46E+01	4.62E+09	1.27E+09	1.80E+12	1.01E+05	2.55E+13	124	2.17E+12	2.42E+03	1.96E+01	6.31E+09	1.26E+09	1.60E+12	9.37E+04	2.97E+13
72	2.18E+12	2.41E+03	1.55E+01	4.19E+09	1.47E+09	1.68E+12	9.15E+04	2.53E+13	125	1.62E+12	2.72E+03	1.72E+01	4.96E+09	1.41E+09	1.65E+12	8.89E+04	2.30E+13
73	1.60E+12	2.81E+03	2.72E+01	4.90E+09	1.46E+09	1.50E+12	9.98E+04	2.27E+13	126	1.61E+12	2.58E+03	2.97E+01	5.28E+09	1.33E+09	1.79E+12	1.03E+05	2.36E+13
74	1.90E+12	2.77E+03	1.51E+01	4.83E+09	1.34E+09	1.80E+12	9.10E+04	2.48E+13	127	2.00E+12	2.82E+03	1.62E+01	4.94E+09	1.46E+09	1.64E+12	8.90E+04	2.57E+13
75	2.42E+12	2.73E+03	2.19E+00	4.46E+09	1.24E+09	1.76E+12	8.84E+04	3.26E+13	128	2.52E+12	2.79E+03	1.93E+01	6.52E+09	1.33E+09	1.80E+12	9.39E+04	3.27E+13
76	1.58E+12	2.50E+03	1.16E+01	5.93E+09	1.38E+09	1.57E+12	8.97E+04	2.49E+13	129	2.60E+12	2.70E+03	2.68E+01	4.61E+09	1.26E+09	1.55E+12	9.11E+04	2.91E+13
77	2.01E+12	2.52E+03	1.82E+01	6.19E+09	1.25E+09	1.51E+12	9.61E+04	2.84E+13	130	2.22E+12	2.49E+03	2.89E+01	6.61E+09	1.32E+09	1.69E+12	9.18E+04	3.07E+13
78	1.45E+12	2.75E+03	2.26E+01	4.33E+09	1.48E+09	1.63E+12	9.84E+04	2.05E+13	131	1.92E+12	2.46E+03	1.94E+01	6.49E+09	1.39E+09	1.53E+12	1.02E+05	2.83E+13
79	2.12E+12	2.83E+03	2.67E+01	4.97E+09	1.24E+09	1.57E+12	9.67E+04	2.65E+13	132	2.20E+12	2.80E+03	2.05E+01	5.79E+09	1.45E+09	1.57E+12	9.66E+04	2.88E+13
80	2.53E+12	2.72E+03	1.06E+01	6.10E+09	1.27E+09	1.56E+12	9.81E+04	3.20E+13	133	2.38E+12	2.82E+03	2.56E+01	5.51E+09	1.49E+09	1.71E+12	1.01E+05	2.95E+13
81	2.27E+12	2.72E+03	2.28E+01	4.21E+09	1.24E+09	1.81E+12	9.76E+04	2.60E+13	134	1.46E+12	2.46E+03	1.86E+01	6.42E+09	1.32E+09	1.67E+12	8.75E+04	2.50E+13
82	1.47E+12	2.46E+03	2.39E+01	4.44E+09	1.41E+09	1.55E+12	8.58E+04	2.07E+13	135	1.60E+12	2.59E+03	1.20E+01	6.56E+09	1.29E+09	1.62E+12	9.99E+04	2.64E+13
83	2.49E+12	2.43E+03	2.91E+01	6.29E+09	1.39E+09	1.80E+12	8.55E+04	3.19E+13	136	2.59E+12	2.43E+03	1.02E+01	4.68E+09	1.31E+09	1.75E+12	9.68E+04	2.94E+13
84	2.59E+12	2.55E+03	2.40E+01	4.22E+09	1.26E+09	1.56E+12	9.98E+04	2.82E+13	137	2.48E+12	2.73E+03	5.57E+00	6.34E+09	1.43E+09	1.58E+12	8.53E+04	3.27E+13
85	2.60E+12	2.41E+03	1.99E+01	6.60E+09	1.49E+09	1.71E+12	9.40E+04	3.34E+13	138	2.62E+12	2.56E+03	1.14E+01	4.79E+09	1.28E+09	1.55E+12	8.49E+04	2.98E+13
86	2.07E+12	2.60E+03	1.97E+01	5.65E+09	1.46E+09	1.80E+12	9.06E+04	2.76E+13	139	2.45E+12	2.41E+03	2.84E+01	4.56E+09	1.40E+09	1.66E+12	9.96E+04	2.79E+13
87	2.20E+12	2.82E+03	4.71E+00	5.66E+09	1.25E+09	1.74E+12	8.59E+04	2.96E+13	140	2.02E+12	2.48E+03	1.13E+01	5.34E+09	1.44E+09	1.82E+12	9.19E+04	2.68E+13
88	2.33E+12	2.76E+03	1.91E+01	5.72E+09	1.28E+09	1.66E+12	1.01E+05	2.97E+13	141	1.97E+12	2.58E+03	8.51E+00	4.03E+09	1.35E+09	1.52E+12	9.80E+04	2.37E+13
89	2.47E+12	2.87E+03	2.32E+00	4.18E+09	1.41E+09	1.73E+12	9.35E+04	3.18E+13	142	1.69E+12	2.55E+03	2.30E+01	6.12E+09	1.33E+09	1.70E+12	9.96E+04	2.60E+13
90	2.19E+12	2.66E+03	2.53E+01	5.11E+09	1.50E+09	1.76E+12	9.56E+04	2.74E+13	143	1.89E+12	2.70E+03	1.23E+01	5.07E+09	1.44E+09	1.75E+12	9.90E+04	2.52E+13
91	1.49E+12	2.76E+03	1.78E+01	6.57E+09	1.32E+09	1.71E+12	9.91E+04	2.56E+13	144	2.22E+12	2.58E+03	4.07E+00	5.04E+09	1.27E+09	1.69E+12	9.12E+04	2.88E+13
92	2.56E+12	2.82E+03	1.09E+01	6.27E+09	1.32E+09	1.55E+12	8.53E+04	3.26E+13	145	2.45E+12	2.66E+03	2.64E+01	6.53E+09	1.45E+09	1.56E+12	9.55E+04	3.21E+13
93	2.37E+12	2.64E+03	2.04E+01	5.73E+09	1.41E+09	1.55E+12	9.79E+04	2.99E+13	146	1.57E+12	2.42E+03	2.99E+01	4.42E+09	1.24E+09	1.81E+12	1.01E+05	2.14E+13
94	2.51E+12	2.54E+03	2.31E+01	4.00E+09	1.35E+09	1.81E+12	9.08E+04	2.72E+13	147	2.51E+12	2.88E+03	1.94E+01	6.53E+09	1.27E+09	1.67E+12	8.82E+04	3.26E+13
95	2.41E+12	2.53E+03	1.85E+01	4.35E+09	1.48E+09	1.59E+12	9.05E+04	2.72E+13	148	1.62E+12	2.68E+03	2.63E+01	6.40E+09	1.28E+09	1.77E+12	9.81E+04	2.61E+13
96	2.29E+12	2.86E+03	5.42E+00	4.52E+09	1.28E+09	1.59E+12	9.83E+04	2.75E+13	149	1.63E+12	2.72E+03	2.61E+01	6.63E+09	1.50E+09	1.65E+12	9.78E+04	2.66E+13
97	1.55E+12	2.64E+03	2.72E+01	5.32E+09	1.44E+09	1.80E+12	9.59E+04	2.33E+13	150	1.71E+12	2.60E+03	2.73E+01	4.94E+09	1.46E+09	1.78E+12	1.03E+05	2.35E+13
98	2.16E+12	2.79E+03	2.71E+00	5.35E+09	1.33E+09	1.79E+12	9.72E+04	3.09E+13	151	1.92E+12	2.76E+03	1.18E+01	6.02E+09	1.46E+09	1.54E+12	9.49E+04	2.75E+13
99	1.86E+12	2.81E+03	9.24E+00	5.63E+09	1.42E+09	1.68E+12	9.62E+04	2.64E+13	152	1.74E+12	2.69E+03	1.95E+01	6.55E+09	1.38E+09	1.65E+12	9.44E+04	2.72E+13
100	2.58E+12	2.48E+03	1.13E+01	4.31E+09	1.32E+09	1.66E+12	1.03E+05	2.85E+13	153	1.52E+12	2.63E+03	2.50E+01	6.34E+09	1.30E+09	1.68E+12	8.89E+04	2.52E+13
101	2.03E+12	2.68E+03	2.77E+01	6.37E+09	1.24E+09	1.53E+12	1.02E+05	2.89E+13	154	1.65E+12	2.77E+03	2.70E+01	5.80E+09	1.25E+09	1.71E+12	1.01E+05	2.49E+13
102	2.25E+12	2.75E+03	6.95E+00	4.69E+09	1.42E+09	1.58E+12	8.82E+04	2.73E+13	155	2.59E+12	2.49E+03	4.85E+00	6.59E+09	1.29E+09	1.79E+12	1.00E+05	3.43E+13
103	1.55E+12	2.44E+03	1.21E+01	4.71E+09	1.38E+09	1.61E+12	9.94E+04	2.21E+13	156	1.80E+12	2.81E+03	2.78E+01	4.38E+09	1.24E+09	1.73E+12	8.82E+04	2.30E+13

157	2.34E+12	2.85E+03	4.76E+00	6.17E+09	1.35E+09	1.54E+12	9.95E+04	3.17E+13	210	2.29E+12	2.45E+03	6.33E+00	3.96E+09	1.36E+09	1.78E+12	9.87E+04	2.61E+13
158	2.21E+12	2.41E+03	9.95E+00	6.64E+09	1.41E+09	1.58E+12	1.02E+05	3.09E+13	211	1.58E+12	2.87E+03	1.97E+01	5.01E+09	1.43E+09	1.64E+12	1.02E+05	2.28E+13
159	1.49E+12	2.49E+03	2.21E+01	3.97E+09	1.42E+09	1.67E+12	8.83E+04	1.99E+13	212	1.88E+12	2.52E+03	1.08E+01	5.47E+09	1.28E+09	1.71E+12	9.45E+04	2.61E+13
160	1.77E+12	2.67E+03	2.57E+01	4.73E+09	1.31E+09	1.64E+12	8.54E+04	2.35E+13	213	2.44E+12	2.78E+03	1.05E+01	4.70E+09	1.40E+09	1.74E+12	9.06E+04	2.84E+13
161	2.06E+12	2.54E+03	2.02E+01	4.36E+09	1.38E+09	1.80E+12	8.52E+04	2.48E+13	214	2.17E+12	2.40E+03	2.14E+01	4.00E+09	1.43E+09	1.56E+12	9.28E+04	2.48E+13
162	2.35E+12	2.89E+03	2.13E+01	5.93E+09	1.40E+09	1.55E+12	8.71E+04	3.02E+13	215	1.67E+12	2.87E+03	1.31E+01	5.64E+09	1.46E+09	1.50E+12	9.11E+04	2.48E+13
163	1.63E+12	2.75E+03	2.03E+01	5.33E+09	1.34E+09	1.53E+12	8.95E+04	2.38E+13	216	2.64E+12	2.72E+03	2.96E+01	6.63E+09	1.32E+09	1.57E+12	9.87E+04	3.37E+13
164	1.56E+12	2.80E+03	2.11E+01	5.27E+09	1.35E+09	1.61E+12	8.59E+04	2.32E+13	217	1.46E+12	2.81E+03	8.58E+00	5.31E+09	1.43E+09	1.61E+12	9.47E+04	2.29E+13
165	2.00E+12	2.71E+03	1.34E+01	4.39E+09	1.46E+09	1.64E+12	9.30E+04	2.46E+13	218	2.55E+12	2.71E+03	2.85E+01	3.93E+09	1.50E+09	1.55E+12	1.02E+05	2.73E+13
166	2.11E+12	2.62E+03	4.68E+00	5.95E+09	1.36E+09	1.70E+12	9.82E+04	2.96E+13	219	2.62E+12	2.59E+03	2.35E+01	5.36E+09	1.36E+09	1.75E+12	8.67E+04	3.09E+13
167	2.32E+12	2.69E+03	1.49E+01	4.77E+09	1.28E+09	1.70E+12	9.71E+04	2.76E+13	220	2.44E+12	2.88E+03	1.56E+01	4.42E+09	1.43E+09	1.50E+12	8.73E+04	2.77E+13
168	2.52E+12	2.55E+03	1.12E+00	5.39E+09	1.46E+09	1.64E+12	8.55E+04	4.95E+13	221	2.62E+12	2.62E+03	1.99E+00	6.17E+09	1.29E+09	1.54E+12	9.45E+04	3.87E+13
169	1.91E+12	2.64E+03	2.62E+01	6.72E+09	1.33E+09	1.51E+12	1.00E+05	2.88E+13	222	2.17E+12	2.83E+03	2.58E+01	6.11E+09	1.48E+09	1.75E+12	9.64E+04	2.94E+13
170	1.72E+12	2.44E+03	1.11E+01	5.77E+09	1.38E+09	1.58E+12	8.69E+04	2.55E+13	223	1.98E+12	2.55E+03	2.41E+01	5.02E+09	1.36E+09	1.74E+12	8.88E+04	2.56E+13
171	2.11E+12	2.50E+03	1.72E+01	4.13E+09	1.48E+09	1.60E+12	8.57E+04	2.47E+13	224	1.60E+12	2.44E+03	2.06E+00	6.40E+09	1.37E+09	1.77E+12	9.85E+04	3.16E+13
172	2.55E+12	2.57E+03	7.07E+00	6.22E+09	1.41E+09	1.76E+12	8.89E+04	3.27E+13	225	2.05E+12	2.41E+03	2.64E+01	5.57E+09	1.34E+09	1.57E+12	8.86E+04	2.73E+13
173	2.47E+12	2.62E+03	3.00E+01	6.08E+09	1.47E+09	1.77E+12	9.98E+04	3.14E+13	226	2.42E+12	2.87E+03	5.48E+00	4.69E+09	1.34E+09	1.73E+12	8.57E+04	2.88E+13
174	2.04E+12	2.47E+03	1.73E+01	4.31E+09	1.36E+09	1.79E+12	9.37E+04	2.46E+13	227	1.79E+12	2.55E+03	3.09E+00	6.25E+09	1.37E+09	1.53E+12	9.76E+04	2.76E+13
175	2.20E+12	2.51E+03	2.04E+01	6.65E+09	1.42E+09	1.83E+12	9.80E+04	3.07E+13	228	1.99E+12	2.81E+03	2.74E+01	4.63E+09	1.25E+09	1.51E+12	8.74E+04	2.48E+13
176	2.54E+12	2.81E+03	2.02E+01	3.95E+09	1.50E+09	1.54E+12	8.78E+04	2.73E+13	229	1.50E+12	2.45E+03	2.13E+01	6.49E+09	1.33E+09	1.83E+12	9.95E+04	2.54E+13
177	2.33E+12	2.79E+03	1.32E+01	4.01E+09	1.26E+09	1.77E+12	8.76E+04	2.60E+13	230	1.72E+12	2.41E+03	2.90E+01	6.47E+09	1.50E+09	1.52E+12	1.04E+05	2.68E+13
178	1.42E+12	2.44E+03	1.15E+01	5.25E+09	1.27E+09	1.73E+12	8.93E+04	2.23E+13	231	1.80E+12	2.52E+03	2.00E+01	6.22E+09	1.44E+09	1.72E+12	1.01E+05	2.69E+13
179	2.65E+12	2.45E+03	1.77E+01	6.54E+09	1.36E+09	1.62E+12	9.01E+04	3.36E+13	232	2.15E+12	2.76E+03	1.82E+01	6.68E+09	1.30E+09	1.83E+12	9.79E+04	3.04E+13
180	2.57E+12	2.87E+03	2.52E+01	6.67E+09	1.33E+09	1.79E+12	8.96E+04	3.34E+13	233	1.60E+12	2.50E+03	1.79E+01	6.46E+09	1.48E+09	1.66E+12	8.90E+04	2.60E+13
181	1.87E+12	2.41E+03	1.69E+01	5.84E+09	1.47E+09	1.62E+12	9.10E+04	2.66E+13	234	1.43E+12	2.79E+03	2.57E+01	4.10E+09	1.38E+09	1.59E+12	8.98E+04	1.97E+13
182	1.69E+12	2.89E+03	1.33E+01	4.11E+09	1.26E+09	1.69E+12	9.52E+04	2.18E+13	235	2.30E+12	2.59E+03	3.98E+00	6.57E+09	1.49E+09	1.53E+12	1.02E+05	3.27E+13
183	1.97E+12	2.56E+03	1.48E+01	5.54E+09	1.43E+09	1.76E+12	9.33E+04	2.68E+13	236	1.44E+12	2.50E+03	1.14E+01	4.81E+09	1.41E+09	1.61E+12	8.68E+04	2.15E+13
184	1.97E+12	2.82E+03	9.82E+00	4.51E+09	1.35E+09	1.58E+12	9.85E+04	2.46E+13	237	2.02E+12	2.47E+03	1.46E+01	4.05E+09	1.23E+09	1.53E+12	9.15E+04	2.39E+13
185	1.66E+12	2.69E+03	1.52E+01	5.69E+09	1.28E+09	1.72E+12	9.58E+04	2.49E+13	238	1.88E+12	2.52E+03	8.29E+00	4.13E+09	1.44E+09	1.75E+12	1.01E+05	2.34E+13
186	2.27E+12	2.70E+03	2.71E+01	6.68E+09	1.27E+09	1.68E+12	9.17E+04	3.12E+13	239	1.71E+12	2.51E+03	1.63E+01	5.74E+09	1.42E+09	1.72E+12	8.90E+04	2.53E+13
187	2.17E+12	2.42E+03	1.38E+01	4.91E+09	1.46E+09	1.61E+12	8.94E+04	2.68E+13	240	1.76E+12	2.48E+03	2.26E+01	5.67E+09	1.36E+09	1.51E+12	8.77E+04	2.55E+13
188	1.46E+12	2.56E+03	2.99E+01	4.92E+09	1.26E+09	1.83E+12	9.58E+04	2.17E+13	241	1.77E+12	2.80E+03	3.66E+00	4.17E+09	1.47E+09	1.77E+12	9.66E+04	2.41E+13
189	1.86E+12	2.78E+03	2.60E+01	4.52E+09	1.33E+09	1.68E+12	9.44E+04	2.37E+13	242	1.80E+12	2.57E+03	1.51E+01	5.00E+09	1.24E+09	1.57E+12	9.74E+04	2.44E+13
190	1.43E+12	2.68E+03	2.65E+01	4.72E+09	1.35E+09	1.83E+12	9.04E+04	2.11E+13	243	1.46E+12	2.86E+03	3.19E+00	5.18E+09	1.49E+09	1.75E+12	9.50E+04	2.47E+13
191	2.26E+12	2.42E+03	5.94E+00	6.15E+09	1.27E+09	1.67E+12	8.59E+04	3.07E+13	244	2.54E+12	2.43E+03	2.54E+00	4.46E+09	1.45E+09	1.61E+12	1.01E+05	3.20E+13
192	1.75E+12	2.67E+03	2.74E+01	4.67E+09	1.28E+09	1.61E+12	1.02E+05	2.32E+13	245	2.43E+12	2.52E+03	1.95E+01	4.61E+09	1.30E+09	1.68E+12	9.96E+04	2.80E+13
193	1.43E+12	2.86E+03	1.33E+01	6.25E+09	1.50E+09	1.75E+12	8.75E+04	2.45E+13	246	1.72E+12	2.52E+03	9.07E+00	6.49E+09	1.24E+09	1.66E+12	9.18E+04	2.72E+13
194	1.95E+12	2.42E+03	1.49E+01	6.69E+09	1.32E+09	1.64E+12	9.01E+04	2.91E+13	247	1.93E+12	2.65E+03	1.44E+01	6.36E+09	1.35E+09	1.78E+12	9.36E+04	2.83E+13
195	1.65E+12	2.62E+03	9.11E+00	4.51E+09	1.38E+09	1.73E+12	1.02E+05	2.25E+13	248	1.68E+12	2.44E+03	1.20E+00	5.50E+09	1.50E+09	1.64E+12	1.03E+05	4.14E+13
196	2.21E+12	2.82E+03	2.75E+01	5.21E+09	1.31E+09	1.74E+12	9.93E+04	2.77E+13	249	1.65E+12	2.43E+03	2.36E+00	5.50E+09	1.38E+09	1.83E+12	1.02E+05	2.87E+13
197	2.52E+12	2.54E+03	1.02E+01	4.11E+09	1.34E+09	1.79E+12	8.61E+04	2.77E+13	250	2.54E+12	2.88E+03	1.84E+01	6.14E+09	1.38E+09	1.66E+12	9.08E+04	3.20E+13
198	1.39E+12	2.89E+03	1.74E+01	4.14E+09	1.48E+09	1.67E+12	8.83E+04	1.97E+13	251	1.90E+12	2.89E+03	2.36E+01	5.77E+09	1.49E+09	1.57E+12	8.66E+04	2.67E+13
199	1.49E+12	2.54E+03	1.48E+01	4.49E+09	1.41E+09	1.76E+12	9.23E+04	2.11E+13	252	1.99E+12	2.51E+03	7.71E+00	5.13E+09	1.25E+09	1.80E+12	1.02E+05	2.63E+13
200	1.45E+12	2.61E+03	2.89E+01	5.27E+09	1.32E+09	1.65E+12	9.20E+04	2.24E+13	253	1.71E+12	2.59E+03	1.59E+00	6.50E+09	1.40E+09	1.55E+12	1.03E+05	3.65E+13
201	2.48E+12	2.52E+03	1.56E+01	3.96E+09	1.37E+09	1.73E+12	9.60E+04	2.69E+13	254	1.92E+12	2.41E+03	2.03E+01	4.08E+09	1.27E+09	1.62E+12	9.12E+04	2.32E+13
202	2.22E+12	2.45E+03	1.66E+01	4.33E+09	1.49E+09	1.53E+12	9.48E+04	2.59E+13	255	1.85E+12	2.67E+03	1.18E+01	6.00E+09	1.37E+09	1.67E+12	1.01E+05	2.69E+13
203	1.79E+12	2.78E+03	2.86E+01	5.51E+09	1.31E+09	1.51E+12	8.88E+04	2.53E+13	256	1.68E+12	2.41E+03	1.82E+01	5.96E+09	1.35E+09	1.65E+12	8.75E+04	2.75E+13
204	2.20E+12	2.78E+03	1.96E+01	5.50E+09	1.44E+09	1.61E+12	9.89E+04	2.83E+13	257	1.52E+12	2.41E+03	1.32E+01	5.69E+09	1.36E+09	1.66E+12	1.02E+05	2.39E+13
205	1.44E+12	2.72E+03	2.42E+01	5.97E+09	1.32E+09	1.63E+12	9.21E+04	2.38E+13	258	2.24E+12	2.80E+03	2.39E+01	3.99E+09	1.37E+09	1.59E+12	9.25E+04	2.52E+13
206	1.95E+12	2.58E+03	2.44E+01	5.15E+09	1.36E+09	1.72E+12	8.91E+04	2.57E+13	259	1.80E+12	2.66E+03	3.85E+00	5.81E+09	1.38E+09	1.59E+12	9.00E+04	2.76E+13
207	1.77E+12	2.45E+03	3.79E+00	5.44E+09	1.44E+09	1.53E+12	9.66E+04	2.67E+13	260	2.06E+12	2.87E+03	1.37E+01	5.59E+09	1.47E+09	1.80E+12	9.04E+04	2.76E+13
208	1.64E+12	2.63E+03	1.60E+01	5.19E+09	1.25E+09	1.63E+12	8.94E+04	2.36E+13	261	2.64E+12	2.68E+03	2.04E+01	6.06E+09	1.28E+09	1.58E+12	9.50E+04	3.25E+13
209	1.73E+12	2.57E+03	1.29E+01	4.77E+09	1.50E+09	1.78E+12	9.26E+04	2.35E+13	262	2.36E+12	2.61E+03	1.12E+01	6.23E+09	1.26E+09	1.78E+12	8.79E+04	3.11E+13

263	1.62E+12	2.51E+03	2.92E+01	6.34E+09	1.50E+09	1.65E+12	9.04E+04	2.59E+13	316	2.44E+12	2.63E+03	1.43E+01	4.66E+09	1.32E+09	1.70E+12	8.50E+04	2.82E+13
264	1.80E+12	2.80E+03	9.66E+00	4.18E+09	1.45E+09	1.72E+12	9.88E+04	2.28E+13	317	2.15E+12	2.68E+03	1.28E+01	4.92E+09	1.45E+09	1.74E+12	9.74E+04	2.68E+13
265	2.17E+12	2.41E+03	2.03E+01	5.46E+09	1.42E+09	1.51E+12	8.77E+04	2.79E+13	318	1.92E+12	2.64E+03	1.81E+01	5.59E+09	1.28E+09	1.78E+12	9.48E+04	2.65E+13
266	2.23E+12	2.48E+03	8.19E+00	4.50E+09	1.48E+09	1.50E+12	1.02E+05	2.66E+13	319	1.48E+12	2.45E+03	1.90E+01	5.72E+09	1.39E+09	1.78E+12	1.03E+05	2.36E+13
267	1.86E+12	2.53E+03	2.71E+00	4.87E+09	1.42E+09	1.58E+12	8.74E+04	2.77E+13	320	1.62E+12	2.68E+03	2.44E+01	6.28E+09	1.45E+09	1.52E+12	9.83E+04	2.58E+13
268	1.70E+12	2.44E+03	2.68E+01	4.89E+09	1.31E+09	1.56E+12	8.80E+04	2.33E+13	321	1.69E+12	2.76E+03	2.13E+00	5.61E+09	1.46E+09	1.82E+12	9.20E+04	3.02E+13
269	2.52E+12	2.43E+03	2.45E+01	4.64E+09	1.36E+09	1.70E+12	8.81E+04	2.86E+13	322	2.24E+12	2.69E+03	8.13E+00	6.03E+09	1.44E+09	1.60E+12	9.54E+04	2.99E+13
270	2.49E+12	2.42E+03	2.20E+01	6.41E+09	1.39E+09	1.52E+12	1.01E+05	3.22E+13	323	2.39E+12	2.87E+03	9.32E+00	4.93E+09	1.34E+09	1.70E+12	8.60E+04	2.86E+13
271	1.70E+12	2.57E+03	1.11E+01	6.51E+09	1.39E+09	1.60E+12	1.01E+05	2.70E+13	324	1.61E+12	2.90E+03	7.11E+00	5.86E+09	1.35E+09	1.53E+12	8.52E+04	2.53E+13
272	2.45E+12	2.53E+03	1.60E+01	5.80E+09	1.36E+09	1.77E+12	1.03E+05	3.07E+13	325	1.73E+12	2.43E+03	1.92E+01	5.40E+09	1.37E+09	1.56E+12	9.69E+04	2.47E+13
273	2.05E+12	2.80E+03	1.45E+01	4.70E+09	1.31E+09	1.72E+12	9.70E+04	2.55E+13	326	2.57E+12	2.47E+03	6.87E+00	5.66E+09	1.31E+09	1.59E+12	8.79E+04	3.16E+13
274	1.74E+12	2.42E+03	1.21E+01	6.51E+09	1.40E+09	1.70E+12	9.69E+04	2.73E+13	327	2.14E+12	2.76E+03	2.77E+01	6.29E+09	1.48E+09	1.71E+12	9.38E+04	2.95E+13
275	2.12E+12	2.84E+03	1.64E+01	5.16E+09	1.31E+09	1.72E+12	8.89E+04	2.70E+13	328	2.43E+12	2.49E+03	2.98E+01	4.58E+09	1.26E+09	1.70E+12	9.22E+04	2.78E+13
276	2.31E+12	2.84E+03	2.76E+01	4.77E+09	1.39E+09	1.76E+12	9.33E+04	2.74E+13	329	2.37E+12	2.40E+03	6.00E+00	6.67E+09	1.35E+09	1.67E+12	1.02E+05	3.25E+13
277	2.10E+12	2.79E+03	1.45E+01	5.64E+09	1.29E+09	1.51E+12	8.95E+04	2.78E+13	330	1.93E+12	2.88E+03	3.82E+00	4.12E+09	1.41E+09	1.75E+12	9.27E+04	2.50E+13
278	1.42E+12	2.84E+03	2.10E+01	5.75E+09	1.47E+09	1.64E+12	8.73E+04	2.33E+13	331	2.32E+12	2.73E+03	2.22E+01	4.29E+09	1.41E+09	1.72E+12	1.02E+05	2.65E+13
279	2.13E+12	2.88E+03	1.80E+01	6.52E+09	1.44E+09	1.80E+12	9.70E+04	3.00E+13	332	2.35E+12	2.85E+03	3.10E+00	6.58E+09	1.49E+09	1.75E+12	8.92E+04	3.41E+13
280	2.63E+12	2.58E+03	2.15E+01	5.84E+09	1.49E+09	1.62E+12	9.46E+04	3.20E+13	333	1.94E+12	2.61E+03	7.99E+00	4.26E+09	1.28E+09	1.79E+12	8.66E+04	2.41E+13
281	2.07E+12	2.64E+03	3.26E+00	4.99E+09	1.47E+09	1.62E+12	8.94E+04	2.84E+13	334	1.83E+12	2.78E+03	1.66E+01	5.74E+09	1.33E+09	1.60E+12	8.70E+04	2.61E+13
282	1.74E+12	2.69E+03	2.45E+01	5.30E+09	1.24E+09	1.75E+12	9.43E+04	2.45E+13	335	1.67E+12	2.51E+03	5.73E+00	6.13E+09	1.36E+09	1.79E+12	9.61E+04	2.66E+13
283	2.48E+12	2.82E+03	2.95E+01	5.89E+09	1.25E+09	1.54E+12	1.02E+05	3.10E+13	336	1.69E+12	2.64E+03	2.49E+01	4.62E+09	1.41E+09	1.62E+12	9.62E+04	2.27E+13
284	1.43E+12	2.75E+03	8.45E+00	5.77E+09	1.40E+09	1.60E+12	9.13E+04	2.37E+13	337	2.23E+12	2.84E+03	5.51E+00	6.40E+09	1.25E+09	1.66E+12	9.29E+04	3.11E+13
285	2.25E+12	2.90E+03	2.62E+01	4.81E+09	1.39E+09	1.69E+12	8.53E+04	2.71E+13	338	1.58E+12	2.58E+03	5.63E+00	5.23E+09	1.29E+09	1.78E+12	9.65E+04	2.40E+13
286	1.80E+12	2.48E+03	2.46E+00	5.32E+09	1.41E+09	1.61E+12	9.53E+04	2.89E+13	339	1.60E+12	2.86E+03	2.20E+01	4.43E+09	1.30E+09	1.74E+12	9.86E+04	2.17E+13
287	2.46E+12	2.78E+03	2.09E+01	4.27E+09	1.33E+09	1.61E+12	9.65E+04	2.74E+13	340	2.29E+12	2.80E+03	1.57E+01	4.12E+09	1.32E+09	1.50E+12	8.76E+04	2.60E+13
288	2.61E+12	2.49E+03	1.90E+01	6.43E+09	1.39E+09	1.57E+12	9.77E+04	3.31E+13	341	2.16E+12	2.83E+03	2.51E+01	6.54E+09	1.48E+09	1.53E+12	9.10E+04	3.01E+13
289	2.37E+12	2.74E+03	9.04E+00	5.08E+09	1.49E+09	1.82E+12	9.51E+04	2.88E+13	342	1.58E+12	2.61E+03	2.41E+01	6.03E+09	1.50E+09	1.53E+12	1.03E+05	2.50E+13
290	1.75E+12	2.63E+03	2.31E+01	5.63E+09	1.26E+09	1.67E+12	1.00E+05	2.53E+13	343	2.11E+12	2.47E+03	2.75E+00	5.56E+09	1.29E+09	1.75E+12	1.00E+05	3.09E+13
291	1.81E+12	2.68E+03	2.54E+01	6.24E+09	1.37E+09	1.57E+12	9.24E+04	2.70E+13	344	2.13E+12	2.74E+03	2.42E+01	4.16E+09	1.46E+09	1.79E+12	9.60E+04	2.49E+13
292	2.19E+12	2.54E+03	1.78E+01	6.64E+09	1.24E+09	1.70E+12	9.25E+04	3.06E+13	345	2.53E+12	2.42E+03	2.65E+01	6.72E+09	1.29E+09	1.64E+12	9.50E+04	3.31E+13
293	1.98E+12	2.68E+03	1.82E+01	5.06E+09	1.37E+09	1.52E+12	9.10E+04	2.57E+13	346	2.27E+12	2.59E+03	1.27E+01	4.10E+09	1.45E+09	1.79E+12	9.02E+04	2.59E+13
294	1.61E+12	2.57E+03	1.16E+01	5.09E+09	1.41E+09	1.54E+12	9.18E+04	2.32E+13	347	1.99E+12	2.65E+03	1.84E+01	4.44E+09	1.40E+09	1.74E+12	8.77E+04	2.45E+13
295	1.43E+12	2.73E+03	3.69E+00	5.45E+09	1.35E+09	1.69E+12	8.94E+04	2.44E+13	348	1.96E+12	2.48E+03	2.25E+01	4.33E+09	1.43E+09	1.60E+12	8.84E+04	2.40E+13
296	1.45E+12	2.57E+03	1.22E+01	6.13E+09	1.26E+09	1.78E+12	8.57E+04	2.44E+13	349	1.82E+12	2.72E+03	1.03E+00	5.74E+09	1.34E+09	1.52E+12	9.05E+04	4.87E+13
297	2.19E+12	2.53E+03	3.05E+00	5.64E+09	1.30E+09	1.60E+12	1.01E+05	3.10E+13	350	1.73E+12	2.50E+03	2.26E+01	4.76E+09	1.38E+09	1.68E+12	8.93E+04	2.33E+13
298	2.13E+12	2.44E+03	1.96E+01	5.00E+09	1.50E+09	1.65E+12	8.86E+04	2.66E+13	351	1.67E+12	2.72E+03	1.42E+01	4.02E+09	1.49E+09	1.76E+12	8.69E+04	2.14E+13
299	2.61E+12	2.45E+03	1.59E+01	4.94E+09	1.39E+09	1.69E+12	8.95E+04	3.00E+13	352	2.24E+12	2.83E+03	7.87E+00	5.96E+09	1.49E+09	1.69E+12	9.17E+04	2.99E+13
300	2.40E+12	2.47E+03	2.79E+01	4.40E+09	1.32E+09	1.72E+12	9.06E+04	2.73E+13	353	1.78E+12	2.88E+03	2.65E+01	6.60E+09	1.48E+09	1.81E+12	8.93E+04	2.76E+13
301	1.43E+12	2.62E+03	1.74E+01	5.53E+09	1.33E+09	1.51E+12	8.52E+04	2.29E+13	354	2.08E+12	2.82E+03	2.31E+01	5.17E+09	1.27E+09	1.69E+12	9.93E+04	2.67E+13
302	1.44E+12	2.84E+03	6.53E+00	5.47E+09	1.40E+09	1.65E+12	8.98E+04	2.33E+13	355	1.54E+12	2.79E+03	2.90E+01	5.11E+09	1.43E+09	1.63E+12	9.40E+04	2.27E+13
303	2.20E+12	2.83E+03	8.64E+00	5.72E+09	1.30E+09	1.67E+12	9.48E+04	2.90E+13	356	2.48E+12	2.47E+03	2.67E+01	6.43E+09	1.31E+09	1.74E+12	8.77E+04	3.22E+13
304	1.61E+12	2.47E+03	5.28E+00	6.44E+09	1.45E+09	1.79E+12	8.94E+04	2.69E+13	357	2.41E+12	2.61E+03	2.43E+01	5.36E+09	1.47E+09	1.68E+12	9.82E+04	2.94E+13
305	1.67E+12	2.45E+03	2.48E+01	4.02E+09	1.29E+09	1.62E+12	8.67E+04	2.13E+13	358	2.47E+12	2.75E+03	4.94E+00	4.36E+09	1.36E+09	1.77E+12	9.30E+04	2.86E+13
306	1.86E+12	2.71E+03	7.43E+00	5.78E+09	1.30E+09	1.80E+12	9.71E+04	2.69E+13	359	2.08E+12	2.66E+03	7.94E+00	5.67E+09	1.33E+09	1.54E+12	9.50E+04	2.81E+13
307	1.84E+12	2.77E+03	8.00E+00	6.00E+09	1.37E+09	1.60E+12	9.20E+04	2.71E+13	360	1.99E+12	2.78E+03	1.34E+01	6.14E+09	1.44E+09	1.64E+12	9.54E+04	2.82E+13
308	2.27E+12	2.65E+03	1.27E+01	4.41E+09	1.39E+09	1.67E+12	9.07E+04	2.65E+13	361	2.39E+12	2.73E+03	5.21E+00	5.94E+09	1.41E+09	1.78E+12	8.93E+04	3.14E+13
309	1.57E+12	2.51E+03	2.00E+01	4.72E+09	1.32E+09	1.58E+12	8.72E+04	2.21E+13	362	2.56E+12	2.69E+03	1.80E+01	5.44E+09	1.34E+09	1.53E+12	8.65E+04	3.07E+13
310	1.96E+12	2.44E+03	2.24E+01	5.90E+09	1.38E+09	1.80E+12	8.81E+04	2.74E+13	363	2.03E+12	2.50E+03	1.09E+01	6.42E+09	1.48E+09	1.50E+12	9.35E+04	2.91E+13
311	1.66E+12	2.71E+03	1.18E+01	4.67E+09	1.48E+09	1.63E+12	8.50E+04	2.28E+13	364	1.89E+12	2.78E+03	8.31E+00	5.27E+09	1.39E+09	1.58E+12	1.01E+05	2.58E+13
312	2.57E+12	2.43E+03	2.27E+01	6.05E+09	1.37E+09	1.56E+12	9.38E+04	3.20E+13	365	2.57E+12	2.71E+03	8.77E+00	5.71E+09	1.37E+09	1.63E+12	9.76E+04	3.15E+13
313	1.47E+12	2.90E+03	1.36E+01	4.87E+09	1.32E+09	1.81E+12	8.69E+04	2.19E+13	366	1.69E+12	2.86E+03	2.95E+01	4.21E+09	1.40E+09	1.60E+12	9.48E+04	2.19E+13
314	2.33E+12	2.40E+03	2.37E+01	4.16E+09	1.27E+09	1.52E+12	8.66E+04	2.62E+13	367	2.42E+12	2.48E+03	4.45E+00	5.11E+09	1.39E+09	1.80E+12	8.51E+04	3.01E+13
315	1.42E+12	2.47E+03	1.92E+01	5.26E+09	1.43E+09	1.78E+12	9.25E+04	2.22E+13	368	1.40E+12	2.87E+03	9.49E+00	4.04E+09	1.50E+09	1.74E+12	1.03E+05	1.97E+13

369	1.77E+12	2.75E+03	7.92E+00	4.22E+09	1.49E+09	1.65E+12	8.64E+04	2.28E+13	422	1.95E+12	2.75E+03	5.82E+00	4.18E+09	1.30E+09	1.57E+12	9.01E+04	2.43E+13
370	1.50E+12	2.74E+03	2.60E+01	5.26E+09	1.32E+09	1.55E+12	9.78E+04	2.28E+13	423	2.06E+12	2.47E+03	1.65E+01	5.05E+09	1.40E+09	1.51E+12	1.03E+05	2.62E+13
371	2.30E+12	2.63E+03	7.77E+00	5.19E+09	1.32E+09	1.83E+12	8.96E+04	2.86E+13	424	2.46E+12	2.59E+03	1.46E+00	5.78E+09	1.27E+09	1.71E+12	8.48E+04	4.19E+13
372	1.51E+12	2.86E+03	2.24E+01	5.62E+09	1.36E+09	1.54E+12	8.97E+04	2.36E+13	425	1.47E+12	2.89E+03	2.08E+01	6.14E+09	1.30E+09	1.54E+12	8.68E+04	2.44E+13
373	1.66E+12	2.65E+03	2.06E+01	4.65E+09	1.27E+09	1.75E+12	9.31E+04	2.26E+13	426	1.92E+12	2.82E+03	6.58E+00	6.75E+09	1.28E+09	1.57E+12	8.95E+04	2.94E+13
374	1.83E+12	2.70E+03	2.36E+01	3.99E+09	1.43E+09	1.71E+12	9.04E+04	2.24E+13	427	2.36E+12	2.54E+03	2.82E+01	4.08E+09	1.33E+09	1.77E+12	9.55E+04	2.63E+13
375	1.61E+12	2.85E+03	1.11E+00	6.18E+09	1.46E+09	1.62E+12	9.57E+04	4.53E+13	428	2.31E+12	2.74E+03	2.08E+01	5.13E+09	1.34E+09	1.77E+12	9.28E+04	2.83E+13
376	1.63E+12	2.73E+03	2.02E+01	5.17E+09	1.26E+09	1.66E+12	8.79E+04	2.35E+13	429	1.41E+12	2.68E+03	3.53E+00	4.83E+09	1.35E+09	1.76E+12	9.39E+04	2.32E+13
377	2.50E+12	2.77E+03	1.61E+01	5.26E+09	1.45E+09	1.54E+12	9.87E+04	2.98E+13	430	1.82E+12	2.89E+03	2.29E+01	5.73E+09	1.27E+09	1.62E+12	9.89E+04	2.60E+13
378	2.33E+12	2.64E+03	1.60E+01	5.12E+09	1.31E+09	1.81E+12	8.63E+04	2.84E+13	431	2.10E+12	2.40E+03	2.17E+00	4.26E+09	1.28E+09	1.70E+12	1.03E+05	3.00E+13
379	2.49E+12	2.75E+03	1.52E+01	4.60E+09	1.30E+09	1.58E+12	8.72E+04	2.84E+13	432	1.76E+12	2.74E+03	1.84E+01	6.07E+09	1.31E+09	1.54E+12	9.99E+04	2.63E+13
380	1.77E+12	2.70E+03	2.59E+01	4.22E+09	1.47E+09	1.81E+12	8.92E+04	2.24E+13	433	2.61E+12	2.80E+03	1.40E+01	5.21E+09	1.37E+09	1.66E+12	1.01E+05	3.06E+13
381	1.81E+12	2.56E+03	2.43E+00	4.42E+09	1.44E+09	1.67E+12	9.97E+04	2.72E+13	434	2.10E+12	2.62E+03	1.65E+00	6.17E+09	1.30E+09	1.74E+12	8.80E+04	3.77E+13
382	1.73E+12	2.67E+03	1.64E+01	5.94E+09	1.43E+09	1.62E+12	1.03E+05	2.58E+13	435	1.97E+12	2.46E+03	1.43E+01	5.33E+09	1.48E+09	1.69E+12	9.45E+04	2.63E+13
383	2.04E+12	2.65E+03	2.09E+01	6.30E+09	1.47E+09	1.67E+12	1.03E+05	2.88E+13	436	2.11E+12	2.67E+03	7.30E+00	5.23E+09	1.48E+09	1.52E+12	9.97E+04	2.74E+13
384	2.18E+12	2.55E+03	1.58E+01	5.87E+09	1.35E+09	1.64E+12	9.73E+04	2.89E+13	437	2.32E+12	2.71E+03	1.14E+01	5.95E+09	1.34E+09	1.62E+12	9.52E+04	3.02E+13
385	2.64E+12	2.63E+03	7.70E+00	5.97E+09	1.25E+09	1.66E+12	1.02E+05	3.27E+13	438	2.17E+12	2.78E+03	1.74E+01	4.07E+09	1.49E+09	1.76E+12	1.02E+05	2.50E+13
386	2.02E+12	2.73E+03	2.33E+01	5.32E+09	1.42E+09	1.69E+12	9.64E+04	2.66E+13	439	2.42E+12	2.49E+03	1.94E+01	6.56E+09	1.46E+09	1.69E+12	8.82E+04	3.21E+13
387	1.94E+12	2.65E+03	2.17E+01	6.62E+09	1.49E+09	1.61E+12	8.85E+04	2.88E+13	440	2.47E+12	2.54E+03	1.46E+01	4.79E+09	1.31E+09	1.81E+12	9.41E+04	2.87E+13
388	1.86E+12	2.41E+03	8.62E+00	4.44E+09	1.35E+09	1.79E+12	1.01E+05	2.39E+13	441	2.10E+12	2.90E+03	2.58E+01	6.53E+09	1.35E+09	1.78E+12	8.99E+04	2.98E+13
389	1.56E+12	2.71E+03	1.11E+01	5.70E+09	1.46E+09	1.73E+12	8.51E+04	2.43E+13	442	2.35E+12	2.77E+03	9.60E+00	6.07E+09	1.48E+09	1.62E+12	1.02E+05	3.07E+13
390	2.30E+12	2.60E+03	2.39E+01	6.20E+09	1.47E+09	1.82E+12	9.94E+04	3.05E+13	443	2.29E+12	2.78E+03	7.45E+00	5.99E+09	1.38E+09	1.63E+12	9.15E+04	3.03E+13
391	1.71E+12	2.84E+03	1.65E+01	5.88E+09	1.49E+09	1.58E+12	9.92E+04	2.56E+13	444	2.04E+12	2.79E+03	1.21E+00	6.29E+09	1.50E+09	1.60E+12	1.02E+05	4.52E+13
392	2.10E+12	2.49E+03	1.47E+01	4.74E+09	1.44E+09	1.76E+12	9.86E+04	2.60E+13	445	2.30E+12	2.62E+03	9.37E+00	5.82E+09	1.50E+09	1.57E+12	1.01E+05	2.99E+13
393	1.83E+12	2.58E+03	1.57E+01	5.58E+09	1.30E+09	1.80E+12	8.98E+04	2.58E+13	446	2.08E+12	2.70E+03	1.63E+00	5.49E+09	1.50E+09	1.69E+12	1.02E+05	3.65E+13
394	2.31E+12	2.67E+03	2.11E+01	4.76E+09	1.28E+09	1.61E+12	1.00E+05	2.74E+13	447	1.65E+12	2.42E+03	2.09E+01	6.33E+09	1.44E+09	1.51E+12	8.74E+04	2.61E+13
395	2.28E+12	2.74E+03	1.53E+01	4.68E+09	1.40E+09	1.80E+12	9.19E+04	2.71E+13	448	2.54E+12	2.67E+03	2.99E+01	5.06E+09	1.24E+09	1.74E+12	8.87E+04	2.97E+13
396	2.08E+12	2.50E+03	1.24E+00	5.86E+09	1.42E+09	1.68E+12	9.22E+04	4.38E+13	449	2.26E+12	2.69E+03	2.21E+01	4.45E+09	1.27E+09	1.74E+12	9.82E+04	2.64E+13
397	2.27E+12	2.71E+03	1.21E+01	4.71E+09	1.24E+09	1.57E+12	9.77E+04	2.71E+13	450	1.48E+12	2.64E+03	1.08E+01	3.94E+09	1.51E+09	1.65E+12	9.62E+04	2.00E+13
398	2.06E+12	2.50E+03	2.71E+01	5.48E+09	1.40E+09	1.78E+12	1.01E+05	2.72E+13	451	2.36E+12	2.51E+03	7.04E+00	5.41E+09	1.47E+09	1.61E+12	8.58E+04	2.96E+13
399	1.65E+12	2.81E+03	2.93E+01	4.17E+09	1.25E+09	1.68E+12	8.87E+04	2.15E+13	452	2.48E+12	2.89E+03	2.14E+01	6.12E+09	1.33E+09	1.72E+12	9.43E+04	3.16E+13
400	1.96E+12	2.85E+03	1.98E+01	5.96E+09	1.29E+09	1.66E+12	9.99E+04	2.75E+13	453	1.59E+12	2.87E+03	2.78E+01	4.92E+09	1.28E+09	1.59E+12	8.97E+04	2.27E+13
401	2.07E+12	2.53E+03	1.73E+01	5.21E+09	1.50E+09	1.62E+12	9.28E+04	2.67E+13	454	2.43E+12	2.87E+03	9.80E+00	6.37E+09	1.44E+09	1.70E+12	8.84E+04	3.20E+13
402	1.95E+12	2.56E+03	2.82E+01	5.04E+09	1.39E+09	1.77E+12	8.99E+04	2.55E+13	455	1.73E+12	2.60E+03	1.24E+01	6.64E+09	1.27E+09	1.70E+12	1.04E+05	2.75E+13
403	2.28E+12	2.74E+03	7.38E+00	6.47E+09	1.47E+09	1.55E+12	8.95E+04	3.12E+13	456	1.85E+12	2.61E+03	1.49E+01	6.16E+09	1.38E+09	1.59E+12	8.65E+04	2.72E+13
404	2.52E+12	2.76E+03	2.51E+01	6.35E+09	1.33E+09	1.62E+12	9.34E+04	3.23E+13	457	1.65E+12	2.52E+03	2.83E+01	5.39E+09	1.29E+09	1.82E+12	9.39E+04	2.41E+13
405	1.76E+12	2.84E+03	1.40E+01	6.20E+09	1.45E+09	1.52E+12	9.75E+04	2.67E+13	458	1.81E+12	2.52E+03	2.83E+01	5.18E+09	1.36E+09	1.58E+12	9.40E+04	2.48E+13
406	2.53E+12	2.90E+03	2.96E+01	6.26E+09	1.44E+09	1.82E+12	9.16E+04	3.22E+13	459	2.38E+12	2.53E+03	1.25E+01	4.91E+09	1.36E+09	1.52E+12	1.03E+05	2.83E+13
407	1.52E+12	2.58E+03	2.24E+01	4.74E+09	1.25E+09	1.73E+12	1.03E+05	2.18E+13	460	1.86E+12	2.40E+03	7.34E+00	6.39E+09	1.31E+09	1.54E+12	1.03E+05	2.81E+13
408	2.60E+12	2.86E+03	1.93E+01	5.75E+09	1.39E+09	1.53E+12	9.43E+04	3.16E+13	461	2.58E+12	2.80E+03	1.70E+00	5.87E+09	1.41E+09	1.71E+12	9.60E+04	4.01E+13
409	2.00E+12	2.68E+03	3.52E+00	6.33E+09	1.37E+09	1.63E+12	1.03E+05	3.05E+13	462	1.91E+12	2.77E+03	1.95E+01	6.14E+09	1.37E+09	1.72E+12	1.02E+05	2.76E+13
410	1.98E+12	2.71E+03	1.62E+01	4.53E+09	1.47E+09	1.68E+12	1.02E+05	2.46E+13	463	2.06E+12	2.72E+03	9.28E+00	6.70E+09	1.39E+09	1.53E+12	9.14E+04	3.00E+13
411	2.45E+12	2.81E+03	1.12E+01	6.17E+09	1.34E+09	1.73E+12	8.68E+04	3.16E+13	464	1.91E+12	2.82E+03	3.46E+00	4.14E+09	1.26E+09	1.67E+12	9.21E+04	2.52E+13
412	1.98E+12	2.45E+03	1.40E+00	5.21E+09	1.47E+09	1.62E+12	8.64E+04	3.82E+13	465	2.53E+12	2.71E+03	1.07E+01	3.99E+09	1.28E+09	1.54E+12	1.01E+05	2.74E+13
413	1.69E+12	2.63E+03	2.41E+01	4.12E+09	1.43E+09	1.53E+12	9.65E+04	2.17E+13	466	2.05E+12	2.75E+03	4.39E+00	4.69E+09	1.28E+09	1.74E+12	9.49E+04	2.66E+13
414	2.45E+12	2.75E+03	6.57E+00	4.13E+09	1.28E+09	1.67E+12	1.01E+05	2.75E+13	467	2.45E+12	2.69E+03	1.30E+01	6.20E+09	1.49E+09	1.64E+12	8.60E+04	3.16E+13
415	1.54E+12	2.47E+03	2.37E+01	4.86E+09	1.30E+09	1.72E+12	9.97E+04	2.22E+13	468	2.31E+12	2.84E+03	1.38E+01	5.28E+09	1.47E+09	1.77E+12	8.79E+04	2.86E+13
416	2.21E+12	2.51E+03	2.66E+01	4.15E+09	1.31E+09	1.76E+12	9.15E+04	2.54E+13	469	1.54E+12	2.74E+03	1.89E+00	6.21E+09	1.48E+09	1.75E+12	1.01E+05	3.18E+13
417	2.02E+12	2.46E+03	2.16E+01	4.49E+09	1.48E+09	1.54E+12	9.48E+04	2.48E+13	470	2.04E+12	2.53E+03	2.28E+01	5.16E+09	1.28E+09	1.67E+12	8.76E+04	2.64E+13
418	2.21E+12	2.44E+03	1.56E+01	5.73E+09	1.44E+09	1.79E+12	9.72E+04	2.88E+13	471	1.45E+12	2.45E+03	2.51E+01	5.05E+09	1.35E+09	1.69E+12	9.83E+04	2.19E+13
419	2.00E+12	2.81E+03	4.12E+00	6.28E+09	1.36E+09	1.58E+12	8.91E+04	2.98E+13	472	2.55E+12	2.42E+03	8.23E+00	4.89E+09	1.31E+09	1.71E+12	8.89E+04	2.97E+13
420	2.46E+12	2.54E+03	2.12E+01	6.12E+09	1.48E+09	1.68E+12	8.62E+04	3.14E+13	473	2.54E+12	2.55E+03	2.58E+01	5.00E+09	1.36E+09	1.61E+12	9.51E+04	2.95E+13
421	2.50E+12	2.56E+03	2.05E+01	6.63E+09	1.33E+09	1.72E+12	9.46E+04	3.27E+13	474	1.53E+12	2.66E+03	8.34E+00	6.63E+09	1.36E+09	1.69E+12	1.02E+05	2.62E+13

475	2.26E+12	2.74E+03	1.90E+01	5.61E+09	1.31E+09	1.52E+12	9.38E+04	2.89E+13	528	1.90E+12	2.57E+03	1.04E+01	4.67E+09	1.41E+09	1.55E+12	8.99E+04	2.45E+13
476	2.50E+12	2.84E+03	2.78E+01	6.55E+09	1.28E+09	1.64E+12	9.53E+04	3.26E+13	529	2.24E+12	2.84E+03	4.36E+00	5.75E+09	1.28E+09	1.80E+12	9.44E+04	3.03E+13
477	1.76E+12	2.82E+03	8.25E+00	5.30E+09	1.38E+09	1.55E+12	1.02E+05	2.50E+13	530	1.79E+12	2.80E+03	1.32E+01	6.21E+09	1.23E+09	1.77E+12	1.02E+05	2.70E+13
478	1.89E+12	2.87E+03	2.38E+01	6.38E+09	1.40E+09	1.72E+12	9.36E+04	2.79E+13	531	1.44E+12	2.78E+03	8.09E+00	5.78E+09	1.28E+09	1.78E+12	9.95E+04	2.38E+13
479	1.49E+12	2.74E+03	5.18E+00	6.16E+09	1.32E+09	1.79E+12	9.60E+04	2.55E+13	532	2.11E+12	2.86E+03	1.67E+01	5.51E+09	1.31E+09	1.65E+12	8.48E+04	2.76E+13
480	1.49E+12	2.79E+03	1.40E+01	6.09E+09	1.27E+09	1.69E+12	1.01E+05	2.46E+13	533	2.17E+12	2.71E+03	2.55E+01	5.02E+09	1.44E+09	1.64E+12	8.49E+04	2.69E+13
481	1.50E+12	2.87E+03	2.35E+01	6.73E+09	1.27E+09	1.56E+12	9.72E+04	2.59E+13	534	1.48E+12	2.72E+03	1.99E+01	5.90E+09	1.30E+09	1.72E+12	1.03E+05	2.40E+13
482	2.17E+12	2.81E+03	1.86E+01	4.03E+09	1.47E+09	1.81E+12	9.07E+04	2.50E+13	535	2.09E+12	2.90E+03	7.24E+00	5.37E+09	1.34E+09	1.68E+12	8.87E+04	2.76E+13
483	2.22E+12	2.44E+03	2.66E+01	3.98E+09	1.34E+09	1.75E+12	8.75E+04	2.51E+13	536	2.23E+12	2.77E+03	4.42E+00	5.41E+09	1.35E+09	1.62E+12	8.73E+04	2.94E+13
484	1.96E+12	2.72E+03	2.08E+01	5.49E+09	1.27E+09	1.69E+12	9.40E+04	2.66E+13	537	2.61E+12	2.65E+03	2.98E+00	6.28E+09	1.40E+09	1.77E+12	1.03E+05	3.55E+13
485	2.08E+12	2.45E+03	1.37E+01	5.45E+09	1.37E+09	1.73E+12	8.61E+04	2.73E+13	538	1.63E+12	2.87E+03	7.59E+00	4.86E+09	1.28E+09	1.60E+12	9.76E+04	2.32E+13
486	1.91E+12	2.44E+03	1.71E+01	4.32E+09	1.31E+09	1.82E+12	1.00E+05	2.37E+13	539	1.88E+12	2.89E+03	3.35E+00	4.38E+09	1.41E+09	1.69E+12	8.71E+04	2.57E+13
487	1.57E+12	2.71E+03	1.39E+01	4.77E+09	1.36E+09	1.68E+12	9.82E+04	2.23E+13	540	1.56E+12	2.54E+03	1.79E+01	6.69E+09	1.38E+09	1.56E+12	9.87E+04	2.63E+13
488	1.63E+12	2.75E+03	8.19E+00	4.82E+09	1.42E+09	1.58E+12	9.24E+04	2.31E+13	541	1.71E+12	2.70E+03	4.64E+00	6.55E+09	1.39E+09	1.58E+12	9.81E+04	2.81E+13
489	1.47E+12	2.51E+03	8.73E+00	6.16E+09	1.37E+09	1.81E+12	8.78E+04	2.48E+13	542	2.00E+12	2.86E+03	1.87E+01	5.45E+09	1.49E+09	1.63E+12	9.26E+04	2.67E+13
490	1.41E+12	2.70E+03	6.03E+00	4.38E+09	1.24E+09	1.67E+12	1.04E+05	2.09E+13	543	2.16E+12	2.48E+03	2.22E+01	5.66E+09	1.42E+09	1.81E+12	8.61E+04	2.83E+13
491	1.82E+12	2.65E+03	2.43E+01	5.69E+09	1.43E+09	1.54E+12	9.75E+04	2.59E+13	544	2.30E+12	2.49E+03	2.12E+01	4.64E+09	1.29E+09	1.55E+12	9.17E+04	2.70E+13
492	2.54E+12	2.63E+03	2.75E+01	4.72E+09	1.50E+09	1.61E+12	8.93E+04	2.89E+13	545	1.64E+12	2.84E+03	2.24E+01	5.07E+09	1.29E+09	1.65E+12	9.84E+04	2.33E+13
493	1.97E+12	2.73E+03	2.28E+00	5.43E+09	1.43E+09	1.59E+12	1.02E+05	3.10E+13	546	2.58E+12	2.58E+03	1.25E+01	4.05E+09	1.33E+09	1.68E+12	9.16E+04	2.79E+13
494	2.49E+12	2.74E+03	6.67E+00	4.89E+09	1.26E+09	1.57E+12	9.92E+04	2.95E+13	547	1.41E+12	2.63E+03	7.20E+00	4.72E+09	1.41E+09	1.66E+12	1.01E+05	2.14E+13
495	1.91E+12	2.63E+03	3.17E+00	4.24E+09	1.27E+09	1.53E+12	8.98E+04	2.58E+13	548	2.63E+12	2.72E+03	2.53E+01	6.15E+09	1.48E+09	1.54E+12	8.51E+04	3.27E+13
496	2.14E+12	2.78E+03	3.40E+00	5.14E+09	1.26E+09	1.80E+12	8.51E+04	2.91E+13	549	1.40E+12	2.53E+03	6.30E+00	4.80E+09	1.45E+09	1.68E+12	9.85E+04	2.17E+13
497	2.53E+12	2.61E+03	5.44E+00	4.20E+09	1.42E+09	1.57E+12	8.67E+04	2.85E+13	550	2.30E+12	2.57E+03	1.29E+01	4.33E+09	1.49E+09	1.54E+12	8.50E+04	2.65E+13
498	1.81E+12	2.80E+03	2.53E+01	6.19E+09	1.30E+09	1.65E+12	1.00E+05	2.70E+13	551	1.61E+12	2.65E+03	8.92E+00	4.95E+09	1.47E+09	1.74E+12	9.51E+04	2.31E+13
499	1.90E+12	2.58E+03	4.32E+00	6.31E+09	1.29E+09	1.69E+12	8.59E+04	2.91E+13	552	2.12E+12	2.74E+03	2.20E+01	5.10E+09	1.35E+09	1.63E+12	8.61E+04	2.68E+13
500	2.40E+12	2.88E+03	6.62E+00	4.59E+09	1.51E+09	1.81E+12	9.96E+04	2.83E+13	553	2.20E+12	2.89E+03	1.35E+01	6.07E+09	1.39E+09	1.71E+12	9.77E+04	2.96E+13
501	2.02E+12	2.41E+03	2.18E+01	4.97E+09	1.49E+09	1.70E+12	9.26E+04	2.58E+13	554	2.51E+12	2.54E+03	2.80E+01	6.61E+09	1.23E+09	1.59E+12	9.17E+04	3.27E+13
502	1.51E+12	2.49E+03	1.43E+01	5.52E+09	1.45E+09	1.67E+12	8.55E+04	2.35E+13	555	1.79E+12	2.64E+03	2.79E+01	6.02E+09	1.31E+09	1.52E+12	9.41E+04	2.64E+13
503	1.44E+12	2.59E+03	1.09E+01	6.26E+09	1.39E+09	1.54E+12	8.68E+04	2.46E+13	556	1.90E+12	2.43E+03	8.46E+00	6.74E+09	1.25E+09	1.82E+12	8.62E+04	2.91E+13
504	2.15E+12	2.51E+03	1.21E+01	4.88E+09	1.47E+09	1.76E+12	1.03E+05	2.67E+13	557	1.59E+12	2.62E+03	2.71E+01	5.03E+09	1.50E+09	1.68E+12	9.53E+04	2.29E+13
505	2.18E+12	2.69E+03	1.12E+01	5.54E+09	1.24E+09	1.57E+12	1.01E+05	2.83E+13	558	1.43E+12	2.65E+03	1.41E+01	5.17E+09	1.48E+09	1.57E+12	1.03E+05	2.22E+13
506	2.22E+12	2.76E+03	2.51E+00	6.30E+09	1.45E+09	1.53E+12	9.33E+04	3.38E+13	559	1.66E+12	2.58E+03	2.78E+01	4.37E+09	1.36E+09	1.56E+12	9.60E+04	2.20E+13
507	1.43E+12	2.88E+03	1.81E+01	6.51E+09	1.46E+09	1.50E+12	9.63E+04	2.50E+13	560	1.98E+12	2.52E+03	2.81E+01	5.37E+09	1.43E+09	1.66E+12	9.47E+04	2.64E+13
508	2.07E+12	2.46E+03	2.18E+01	6.33E+09	1.42E+09	1.71E+12	9.84E+04	2.90E+13	561	2.62E+12	2.53E+03	2.49E+01	5.45E+09	1.41E+09	1.74E+12	8.56E+04	3.11E+13
509	1.88E+12	2.47E+03	2.59E+01	4.54E+09	1.49E+09	1.58E+12	8.90E+04	2.39E+13	562	1.95E+12	2.72E+03	2.40E+00	4.37E+09	1.42E+09	1.74E+12	1.01E+05	2.82E+13
510	1.59E+12	2.81E+03	2.91E+01	5.15E+09	1.35E+09	1.52E+12	9.46E+04	2.31E+13	563	1.54E+12	2.50E+03	2.47E+01	4.39E+09	1.36E+09	1.67E+12	9.25E+04	2.11E+13
511	2.60E+12	2.74E+03	1.93E+01	5.16E+09	1.33E+09	1.68E+12	1.01E+05	3.04E+13	564	2.29E+12	2.64E+03	5.34E+00	4.75E+09	1.28E+09	1.71E+12	9.09E+04	2.80E+13
512	2.14E+12	2.42E+03	2.25E+01	5.78E+09	1.29E+09	1.73E+12	9.12E+04	2.84E+13	565	1.77E+12	2.52E+03	6.45E+00	4.98E+09	1.34E+09	1.64E+12	9.63E+04	2.46E+13
513	1.51E+12	2.60E+03	3.78E+00	4.00E+09	1.45E+09	1.75E+12	9.07E+04	2.18E+13	566	1.59E+12	2.72E+03	2.41E+01	4.23E+09	1.32E+09	1.66E+12	9.07E+04	2.12E+13
514	1.47E+12	2.45E+03	7.66E+00	5.54E+09	1.24E+09	1.79E+12	8.69E+04	2.35E+13	567	1.81E+12	2.76E+03	2.12E+01	5.22E+09	1.51E+09	1.75E+12	9.00E+04	2.49E+13
515	2.39E+12	2.89E+03	1.54E+01	5.18E+09	1.43E+09	1.53E+12	8.54E+04	2.89E+13	568	2.01E+12	2.57E+03	2.94E+01	5.22E+09	1.24E+09	1.71E+12	9.98E+04	2.62E+13
516	1.75E+12	2.53E+03	2.87E+01	6.18E+09	1.46E+09	1.76E+12	9.33E+04	2.65E+13	569	1.85E+12	2.62E+03	3.71E+00	4.19E+09	1.36E+09	1.78E+12	1.02E+05	2.47E+13
517	1.99E+12	2.41E+03	1.26E+01	5.83E+09	1.36E+09	1.66E+12	1.00E+05	2.75E+13	570	1.51E+12	2.40E+03	8.40E+00	4.75E+09	1.37E+09	1.52E+12	9.61E+04	2.20E+13
518	2.26E+12	2.89E+03	1.87E+01	4.63E+09	1.43E+09	1.55E+12	9.16E+04	2.68E+13	571	2.34E+12	2.85E+03	1.67E+01	5.14E+09	1.32E+09	1.72E+12	9.09E+04	2.85E+13
519	2.53E+12	2.67E+03	1.39E+01	5.76E+09	1.34E+09	1.72E+12	9.38E+04	3.12E+13	572	2.27E+12	2.51E+03	9.90E+00	5.03E+09	1.51E+09	1.77E+12	9.50E+04	2.79E+13
520	1.59E+12	2.53E+03	3.29E+00	6.21E+09	1.32E+09	1.78E+12	8.63E+04	2.77E+13	573	2.03E+12	2.47E+03	9.52E+00	5.61E+09	1.33E+09	1.78E+12	9.55E+04	2.75E+13
521	2.27E+12	2.83E+03	2.04E+00	4.93E+09	1.27E+09	1.81E+12	9.35E+04	3.33E+13	574	2.59E+12	2.83E+03	2.95E+01	4.60E+09	1.45E+09	1.59E+12	9.28E+04	2.90E+13
522	2.62E+12	2.48E+03	1.51E+01	4.59E+09	1.39E+09	1.70E+12	9.89E+04	2.93E+13	575	2.25E+12	2.86E+03	1.29E+01	6.37E+09	1.37E+09	1.67E+12	9.67E+04	3.05E+13
523	2.21E+12	2.65E+03	1.71E+01	5.09E+09	1.26E+09	1.76E+12	9.08E+04	2.75E+13	576	1.44E+12	2.46E+03	1.03E+01	6.22E+09	1.42E+09	1.62E+12	8.80E+04	2.45E+13
524	1.84E+12	2.60E+03	2.22E+01	4.84E+09	1.46E+09	1.61E+12	1.01E+05	2.42E+13	577	2.20E+12	2.55E+03	2.45E+01	5.52E+09	1.42E+09	1.50E+12	9.56E+04	2.82E+13
525	2.14E+12	2.43E+03	1.68E+01	6.18E+09	1.48E+09	1.61E+12	9.78E+04	2.92E+13	578	2.09E+12	2.81E+03	1.85E+01	6.43E+09	1.39E+09	1.54E+12	8.96E+04	2.95E+13
526	2.09E+12	2.88E+03	2.60E+01	4.27E+09	1.49E+09	1.69E+12	1.02E+05	2.48E+13	579	1.83E+12	2.75E+03	1.67E+01	5.97E+09	1.42E+09	1.79E+12	8.83E+04	2.67E+13
527	1.81E+12	2.55E+03	1.74E+00	5.26E+09	1.40E+09	1.54E+12	8.67E+04	3.29E+13	580	1.78E+12	2.56E+03	1.53E+01	6.75E+09	1.24E+09	1.66E+12	9.32E+04	2.80E+13

581	1.72E+12	2.56E+03	2.34E+01	5.92E+09	1.24E+09	1.82E+12	9.67E+04	2.58E+13	634	2.43E+12	2.87E+03	1.92E+00	5.83E+09	1.39E+09	1.69E+12	1.00E+05	3.71E+13
582	1.80E+12	2.51E+03	1.05E+01	5.13E+09	1.50E+09	1.61E+12	9.54E+04	2.48E+13	635	2.23E+12	2.74E+03	1.65E+01	4.54E+09	1.32E+09	1.50E+12	9.13E+04	2.64E+13
583	2.60E+12	2.51E+03	1.26E+01	5.36E+09	1.47E+09	1.62E+12	9.92E+04	3.08E+13	636	2.46E+12	2.47E+03	5.65E+00	4.26E+09	1.42E+09	1.65E+12	9.54E+04	2.81E+13
584	1.64E+12	2.55E+03	2.56E+01	5.82E+09	1.32E+09	1.66E+12	1.03E+05	2.49E+13	637	2.52E+12	2.84E+03	2.55E+01	6.69E+09	1.38E+09	1.81E+12	9.92E+04	3.31E+13
585	2.43E+12	2.40E+03	1.76E+00	6.38E+09	1.49E+09	1.56E+12	9.73E+04	3.95E+13	638	2.55E+12	2.70E+03	2.27E+01	5.48E+09	1.25E+09	1.55E+12	9.40E+04	3.06E+13
586	1.55E+12	2.44E+03	1.86E+01	5.71E+09	1.48E+09	1.51E+12	1.03E+05	2.41E+13	639	2.11E+12	2.60E+03	2.29E+01	4.41E+09	1.28E+09	1.74E+12	9.23E+04	2.53E+13
587	1.78E+12	2.90E+03	4.13E+00	5.82E+09	1.44E+09	1.80E+12	9.39E+04	2.74E+13	640	1.76E+12	2.59E+03	2.59E+00	4.88E+09	1.26E+09	1.51E+12	9.59E+04	2.73E+13
588	2.28E+12	2.63E+03	1.97E+01	5.14E+09	1.46E+09	1.63E+12	8.58E+04	2.80E+13	641	2.41E+12	2.65E+03	2.85E+01	5.37E+09	1.49E+09	1.78E+12	1.01E+05	2.95E+13
589	1.53E+12	2.41E+03	2.38E+01	5.95E+09	1.30E+09	1.65E+12	9.28E+04	2.44E+13	642	2.07E+12	2.65E+03	1.98E+01	6.00E+09	1.27E+09	1.81E+12	8.72E+04	2.84E+13
590	1.69E+12	2.58E+03	1.90E+01	6.31E+09	1.28E+09	1.51E+12	9.36E+04	2.63E+13	643	1.53E+12	2.63E+03	1.27E+00	6.36E+09	1.46E+09	1.71E+12	9.24E+04	4.02E+13
591	1.87E+12	2.68E+03	5.39E+00	3.95E+09	1.43E+09	1.80E+12	1.03E+05	2.34E+13	644	1.88E+12	2.43E+03	2.28E+01	5.24E+09	1.43E+09	1.62E+12	9.70E+04	2.54E+13
592	1.76E+12	2.82E+03	3.75E+00	5.87E+09	1.40E+09	1.63E+12	8.71E+04	2.76E+13	645	2.56E+12	2.52E+03	1.79E+01	4.56E+09	1.40E+09	1.51E+12	9.66E+04	2.87E+13
593	1.42E+12	2.87E+03	9.71E+00	5.03E+09	1.25E+09	1.52E+12	9.88E+04	2.19E+13	646	1.87E+12	2.46E+03	6.64E+00	4.35E+09	1.25E+09	1.63E+12	9.79E+04	2.39E+13
594	1.78E+12	2.56E+03	1.99E+01	5.57E+09	1.35E+09	1.54E+12	1.01E+05	2.54E+13	647	1.74E+12	2.42E+03	1.07E+01	4.85E+09	1.32E+09	1.53E+12	8.60E+04	2.37E+13
595	1.70E+12	2.77E+03	1.48E+01	5.09E+09	1.27E+09	1.58E+12	9.30E+04	2.39E+13	648	2.34E+12	2.64E+03	2.65E+01	4.30E+09	1.48E+09	1.63E+12	9.23E+04	2.66E+13
596	2.39E+12	2.55E+03	6.72E+00	6.65E+09	1.29E+09	1.56E+12	9.15E+04	3.25E+13	649	1.70E+12	2.71E+03	1.89E+01	4.16E+09	1.36E+09	1.78E+12	1.00E+05	2.19E+13
597	2.56E+12	2.66E+03	2.56E+01	6.44E+09	1.38E+09	1.73E+12	9.57E+04	3.28E+13	650	2.14E+12	2.83E+03	2.59E+01	4.56E+09	1.25E+09	1.68E+12	9.76E+04	2.58E+13
598	2.02E+12	2.61E+03	3.92E+00	6.60E+09	1.29E+09	1.65E+12	9.09E+04	3.08E+13	651	1.95E+12	2.76E+03	1.03E+01	4.78E+09	1.40E+09	1.70E+12	8.79E+04	2.51E+13
599	2.05E+12	2.47E+03	5.88E+00	5.60E+09	1.30E+09	1.78E+12	9.03E+04	2.81E+13	652	2.50E+12	2.54E+03	8.99E+00	5.04E+09	1.36E+09	1.64E+12	9.19E+04	2.96E+13
600	1.93E+12	2.89E+03	2.06E+01	5.76E+09	1.34E+09	1.79E+12	9.66E+04	2.70E+13	653	1.66E+12	2.71E+03	1.84E+01	4.14E+09	1.48E+09	1.61E+12	9.43E+04	2.15E+13
601	2.28E+12	2.79E+03	9.02E+00	4.34E+09	1.24E+09	1.59E+12	1.01E+05	2.66E+13	654	2.23E+12	2.79E+03	5.00E+00	5.06E+09	1.37E+09	1.71E+12	8.73E+04	2.84E+13
602	2.56E+12	2.77E+03	9.45E+00	4.39E+09	1.31E+09	1.60E+12	9.38E+04	2.86E+13	655	2.16E+12	2.78E+03	1.31E+00	5.80E+09	1.43E+09	1.64E+12	9.80E+04	4.27E+13
603	1.75E+12	2.85E+03	2.87E+01	6.65E+09	1.42E+09	1.70E+12	9.65E+04	2.75E+13	656	2.56E+12	2.51E+03	2.94E+01	4.48E+09	1.27E+09	1.78E+12	8.64E+04	2.85E+13
604	2.15E+12	2.43E+03	2.30E+01	4.65E+09	1.50E+09	1.76E+12	9.81E+04	2.60E+13	657	2.01E+12	2.76E+03	2.91E+01	5.47E+09	1.30E+09	1.73E+12	9.64E+04	2.68E+13
605	1.82E+12	2.84E+03	2.72E+01	6.29E+09	1.41E+09	1.56E+12	9.16E+04	2.72E+13	658	1.48E+12	2.54E+03	7.36E+00	4.45E+09	1.32E+09	1.70E+12	9.29E+04	2.13E+13
606	1.87E+12	2.62E+03	1.41E+00	5.70E+09	1.35E+09	1.67E+12	8.70E+04	3.84E+13	659	2.41E+12	2.59E+03	4.27E+00	4.51E+09	1.41E+09	1.59E+12	8.84E+04	2.88E+13
607	1.75E+12	2.63E+03	5.25E+00	5.99E+09	1.37E+09	1.58E+12	8.76E+04	2.69E+13	660	1.63E+12	2.62E+03	2.47E+01	5.90E+09	1.44E+09	1.79E+12	1.00E+05	2.51E+13
608	1.77E+12	2.44E+03	8.68E+00	6.45E+09	1.38E+09	1.60E+12	9.01E+04	2.75E+13	661	2.56E+12	2.88E+03	1.34E+01	4.91E+09	1.32E+09	1.72E+12	8.92E+04	2.96E+13
609	2.07E+12	2.73E+03	2.29E+01	4.55E+09	1.39E+09	1.55E+12	8.85E+04	2.53E+13	662	1.60E+12	2.58E+03	2.33E+01	6.39E+09	1.50E+09	1.57E+12	9.90E+04	2.59E+13
610	2.01E+12	2.52E+03	2.90E+01	4.49E+09	1.24E+09	1.63E+12	9.84E+04	2.47E+13	663	2.27E+12	2.53E+03	2.23E+01	5.73E+09	1.28E+09	1.54E+12	1.00E+05	2.92E+13
611	1.95E+12	2.46E+03	9.88E+00	5.57E+09	1.30E+09	1.78E+12	8.87E+04	2.68E+13	664	2.16E+12	2.48E+03	3.43E+00	5.56E+09	1.35E+09	1.65E+12	8.54E+04	3.01E+13
612	2.40E+12	2.61E+03	3.31E+00	5.08E+09	1.39E+09	1.55E+12	9.03E+04	3.09E+13	665	1.45E+12	2.85E+03	2.89E+01	4.25E+09	1.41E+09	1.77E+12	9.31E+04	2.02E+13
613	2.42E+12	2.84E+03	2.18E+01	5.37E+09	1.51E+09	1.75E+12	9.35E+04	2.95E+13	666	1.64E+12	2.69E+03	2.94E+01	4.96E+09	1.41E+09	1.72E+12	9.33E+04	2.31E+13
614	2.28E+12	2.58E+03	2.76E+01	3.99E+09	1.45E+09	1.70E+12	9.02E+04	2.55E+13	667	1.84E+12	2.70E+03	2.88E+01	4.58E+09	1.43E+09	1.51E+12	9.93E+04	2.37E+13
615	2.52E+12	2.47E+03	3.99E+00	4.80E+09	1.24E+09	1.81E+12	9.51E+04	3.05E+13	668	1.99E+12	2.54E+03	1.10E+01	4.99E+09	1.26E+09	1.75E+12	9.68E+04	2.58E+13
616	2.37E+12	2.62E+03	1.96E+01	6.73E+09	1.24E+09	1.82E+12	1.01E+05	3.21E+13	669	2.27E+12	2.62E+03	6.07E+00	4.20E+09	1.27E+09	1.59E+12	1.02E+05	2.65E+13
617	2.29E+12	2.60E+03	2.61E+01	4.55E+09	1.28E+09	1.51E+12	8.50E+04	2.68E+13	670	2.38E+12	2.49E+03	1.07E+01	4.95E+09	1.32E+09	1.73E+12	9.29E+04	2.85E+13
618	2.03E+12	2.51E+03	8.88E+00	5.91E+09	1.27E+09	1.82E+12	1.03E+05	2.82E+13	671	1.58E+12	2.67E+03	8.85E+00	5.24E+09	1.33E+09	1.83E+12	8.65E+04	2.36E+13
619	2.39E+12	2.54E+03	7.55E+00	6.71E+09	1.31E+09	1.65E+12	1.00E+05	3.25E+13	672	1.99E+12	2.53E+03	1.50E+01	5.07E+09	1.24E+09	1.77E+12	9.49E+04	2.59E+13
620	2.01E+12	2.56E+03	2.61E+01	6.05E+09	1.50E+09	1.79E+12	9.80E+04	2.81E+13	673	2.21E+12	2.85E+03	8.79E+00	6.37E+09	1.30E+09	1.52E+12	9.68E+04	3.04E+13
621	2.61E+12	2.57E+03	2.40E+01	6.28E+09	1.28E+09	1.68E+12	9.44E+04	3.28E+13	674	1.97E+12	2.85E+03	6.36E+00	6.20E+09	1.40E+09	1.63E+12	9.09E+04	2.87E+13
622	2.12E+12	2.43E+03	2.86E+01	4.34E+09	1.36E+09	1.68E+12	1.02E+05	2.51E+13	675	1.83E+12	2.78E+03	2.77E+00	6.27E+09	1.34E+09	1.52E+12	9.19E+04	3.03E+13
623	2.61E+12	2.61E+03	1.58E+01	5.20E+09	1.30E+09	1.53E+12	1.02E+05	3.05E+13	676	1.96E+12	2.73E+03	1.30E+01	6.58E+09	1.43E+09	1.64E+12	8.73E+04	2.90E+13
624	2.09E+12	2.72E+03	2.32E+01	5.43E+09	1.43E+09	1.68E+12	9.43E+04	2.73E+13	677	2.57E+12	2.70E+03	2.14E+01	4.24E+09	1.25E+09	1.62E+12	9.90E+04	2.81E+13
625	2.33E+12	2.49E+03	5.08E+00	5.25E+09	1.30E+09	1.58E+12	8.59E+04	2.95E+13	678	2.06E+12	2.78E+03	1.46E+01	5.49E+09	1.42E+09	1.81E+12	1.02E+05	2.73E+13
626	1.92E+12	2.76E+03	2.03E+01	4.99E+09	1.29E+09	1.83E+12	9.41E+04	2.52E+13	679	1.53E+12	2.85E+03	2.86E+01	5.17E+09	1.46E+09	1.55E+12	9.05E+04	2.28E+13
627	2.50E+12	2.57E+03	4.04E+00	4.37E+09	1.37E+09	1.74E+12	8.57E+04	2.94E+13	680	1.73E+12	2.75E+03	2.32E+01	5.10E+09	1.45E+09	1.83E+12	8.96E+04	2.41E+13
628	1.47E+12	2.42E+03	1.88E+01	6.32E+09	1.44E+09	1.64E+12	8.71E+04	2.48E+13	681	1.72E+12	2.63E+03	1.00E+01	6.48E+09	1.38E+09	1.65E+12	8.63E+04	2.71E+13
629	1.75E+12	2.81E+03	8.91E+00	4.06E+09	1.48E+09	1.51E+12	9.70E+04	2.22E+13	682	2.37E+12	2.82E+03	2.76E+01	4.91E+09	1.49E+09	1.79E+12	9.11E+04	2.82E+13
630	1.54E+12	2.64E+03	1.80E+01	6.62E+09	1.29E+09	1.63E+12	9.56E+04	2.60E+13	683	2.18E+12	2.79E+03	1.48E+00	6.07E+09	1.26E+09	1.66E+12	9.02E+04	4.03E+13
631	1.63E+12	2.87E+03	2.19E+01	5.02E+09	1.46E+09	1.67E+12	8.56E+04	2.32E+13	684	1.42E+12	2.49E+03	1.53E+01	5.12E+09	1.50E+09	1.81E+12	9.57E+04	2.20E+13
632	1.76E+12	2.52E+03	1.53E+00	6.71E+09	1.35E+09	1.78E+12	9.49E+04	3.80E+13	685	1.85E+12	2.55E+03	8.71E+00	6.10E+09	1.44E+09	1.68E+12	9.69E+04	2.73E+13
633	1.90E+12	2.44E+03	1.04E+01	6.39E+09	1.38E+09	1.80E+12	8.92E+04	2.82E+13	686	2.41E+12	2.85E+03	2.15E+01	4.20E+09	1.26E+09	1.60E+12	8.78E+04	2.70E+13

687	2.13E+12	2.88E+03	4.60E+00	6.41E+09	1.28E+09	1.64E+12	8.60E+04	3.08E+13	740	1.82E+12	2.45E+03	1.37E+01	6.22E+09	1.31E+09	1.75E+12	1.03E+05	2.72E+13
688	2.29E+12	2.54E+03	1.28E+01	5.89E+09	1.47E+09	1.65E+12	9.70E+04	2.98E+13	741	2.58E+12	2.43E+03	1.26E+01	4.29E+09	1.32E+09	1.79E+12	9.11E+04	2.84E+13
689	2.13E+12	2.61E+03	4.59E+00	5.57E+09	1.30E+09	1.71E+12	9.73E+04	2.89E+13	742	1.51E+12	2.78E+03	3.60E+00	5.29E+09	1.38E+09	1.55E+12	9.27E+04	2.47E+13
690	2.30E+12	2.58E+03	1.61E+01	3.96E+09	1.44E+09	1.81E+12	9.22E+04	2.57E+13	743	2.46E+12	2.65E+03	1.71E+01	5.56E+09	1.45E+09	1.82E+12	1.01E+05	3.03E+13
691	2.19E+12	2.41E+03	2.31E+01	5.87E+09	1.28E+09	1.76E+12	9.83E+04	2.90E+13	744	1.87E+12	2.89E+03	3.23E+00	5.79E+09	1.45E+09	1.71E+12	1.00E+05	2.88E+13
692	2.36E+12	2.60E+03	2.16E+01	4.40E+09	1.37E+09	1.73E+12	9.45E+04	2.70E+13	745	2.26E+12	2.85E+03	6.90E+00	4.10E+09	1.29E+09	1.73E+12	1.02E+05	2.61E+13
693	2.14E+12	2.86E+03	1.49E+00	4.06E+09	1.47E+09	1.52E+12	9.39E+04	3.55E+13	746	1.54E+12	2.55E+03	2.69E+01	6.04E+09	1.32E+09	1.75E+12	8.88E+04	2.47E+13
694	2.51E+12	2.64E+03	5.16E+00	4.14E+09	1.41E+09	1.56E+12	1.02E+05	2.84E+13	747	2.29E+12	2.82E+03	1.78E+01	4.29E+09	1.26E+09	1.71E+12	9.75E+04	2.63E+13
695	2.42E+12	2.76E+03	2.63E+00	5.69E+09	1.25E+09	1.56E+12	8.67E+04	3.36E+13	748	1.45E+12	2.81E+03	2.95E+00	5.98E+09	1.27E+09	1.68E+12	9.73E+04	2.67E+13
696	2.25E+12	2.57E+03	1.24E+01	4.15E+09	1.33E+09	1.83E+12	9.93E+04	2.58E+13	749	2.45E+12	2.67E+03	1.02E+01	5.59E+09	1.45E+09	1.82E+12	1.03E+05	3.04E+13
697	2.40E+12	2.45E+03	9.40E+00	5.23E+09	1.31E+09	1.72E+12	8.78E+04	2.93E+13	750	1.53E+12	2.89E+03	2.36E+01	6.49E+09	1.50E+09	1.76E+12	1.01E+05	2.56E+13
698	2.33E+12	2.64E+03	1.50E+01	6.35E+09	1.46E+09	1.60E+12	9.19E+04	3.10E+13	751	1.87E+12	2.69E+03	1.06E+01	5.01E+09	1.33E+09	1.80E+12	8.80E+04	2.51E+13
699	2.02E+12	2.79E+03	4.50E+00	5.42E+09	1.50E+09	1.83E+12	8.59E+04	2.80E+13	752	1.73E+12	2.49E+03	1.54E+01	6.66E+09	1.42E+09	1.66E+12	8.82E+04	2.75E+13
700	2.36E+12	2.82E+03	8.15E+00	5.70E+09	1.29E+09	1.51E+12	9.21E+04	3.01E+13	753	1.83E+12	2.64E+03	6.84E+00	5.10E+09	1.48E+09	1.55E+12	9.37E+04	2.52E+13
701	1.93E+12	2.62E+03	1.68E+01	5.90E+09	1.34E+09	1.69E+12	8.88E+04	2.72E+13	754	2.45E+12	2.55E+03	1.27E+01	5.11E+09	1.46E+09	1.77E+12	1.01E+05	2.85E+13
702	2.63E+12	2.55E+03	1.19E+01	6.57E+09	1.46E+09	1.75E+12	9.86E+04	3.37E+13	755	2.33E+12	2.51E+03	1.56E+01	6.74E+09	1.30E+09	1.67E+12	8.70E+04	3.18E+13
703	1.94E+12	2.81E+03	2.53E+01	6.47E+09	1.32E+09	1.64E+12	8.85E+04	2.85E+13	756	1.65E+12	2.86E+03	2.97E+01	6.06E+09	1.46E+09	1.78E+12	9.93E+04	2.56E+13
704	1.82E+12	2.58E+03	1.31E+01	5.76E+09	1.45E+09	1.74E+12	9.72E+04	2.62E+13	757	2.32E+12	2.49E+03	1.70E+01	6.46E+09	1.27E+09	1.65E+12	8.66E+04	3.11E+13
705	2.24E+12	2.59E+03	2.46E+01	4.48E+09	1.47E+09	1.78E+12	9.42E+04	2.64E+13	758	1.62E+12	2.66E+03	2.37E+01	5.22E+09	1.25E+09	1.51E+12	9.37E+04	2.35E+13
706	2.35E+12	2.41E+03	2.23E+01	4.07E+09	1.42E+09	1.74E+12	9.52E+04	2.62E+13	759	2.52E+12	2.85E+03	1.63E+01	4.60E+09	1.45E+09	1.77E+12	8.87E+04	2.86E+13
707	1.84E+12	2.46E+03	1.47E+01	4.69E+09	1.36E+09	1.77E+12	9.40E+04	2.40E+13	760	1.50E+12	2.66E+03	2.79E+01	4.01E+09	1.31E+09	1.64E+12	1.02E+05	2.01E+13
708	1.73E+12	2.68E+03	7.47E+00	5.53E+09	1.45E+09	1.57E+12	8.77E+04	2.53E+13	761	2.47E+12	2.86E+03	2.11E+01	5.44E+09	1.40E+09	1.78E+12	8.65E+04	3.00E+13
709	1.65E+12	2.75E+03	2.93E+01	5.43E+09	1.26E+09	1.61E+12	9.86E+04	2.42E+13	762	1.66E+12	2.86E+03	1.37E+00	5.14E+09	1.42E+09	1.55E+12	1.03E+05	3.66E+13
710	1.92E+12	2.48E+03	2.33E+01	4.18E+09	1.50E+09	1.51E+12	9.10E+04	2.34E+13	763	1.81E+12	2.77E+03	1.76E+01	4.74E+09	1.34E+09	1.60E+12	9.56E+04	2.39E+13
711	2.00E+12	2.60E+03	9.20E+00	4.02E+09	1.37E+09	1.65E+12	8.90E+04	2.39E+13	764	2.53E+12	2.82E+03	2.07E+01	4.21E+09	1.48E+09	1.77E+12	1.01E+05	2.79E+13
712	1.84E+12	2.56E+03	2.20E+01	6.50E+09	1.31E+09	1.62E+12	9.06E+04	2.78E+13	765	1.41E+12	2.73E+03	5.60E+00	4.17E+09	1.33E+09	1.82E+12	1.03E+05	2.05E+13
713	1.71E+12	2.90E+03	6.99E+00	6.64E+09	1.30E+09	1.71E+12	9.67E+04	2.76E+13	766	2.19E+12	2.65E+03	2.46E+01	4.49E+09	1.39E+09	1.71E+12	9.22E+04	2.60E+13
714	1.95E+12	2.67E+03	6.24E+00	5.66E+09	1.35E+09	1.63E+12	8.99E+04	2.73E+13	767	2.31E+12	2.79E+03	2.84E+00	5.68E+09	1.44E+09	1.68E+12	9.81E+04	3.23E+13
715	1.55E+12	2.41E+03	1.11E+01	4.70E+09	1.47E+09	1.72E+12	9.37E+04	2.20E+13	768	2.58E+12	2.46E+03	2.39E+01	4.27E+09	1.38E+09	1.59E+12	1.00E+05	2.82E+13
716	2.35E+12	2.86E+03	2.92E+01	3.95E+09	1.42E+09	1.56E+12	9.69E+04	2.59E+13	769	2.31E+12	2.70E+03	5.11E+00	6.66E+09	1.47E+09	1.66E+12	9.72E+04	3.24E+13
717	2.12E+12	2.60E+03	2.54E+01	4.61E+09	1.41E+09	1.77E+12	9.54E+04	2.57E+13	770	1.58E+12	2.83E+03	2.66E+01	5.88E+09	1.40E+09	1.61E+12	8.72E+04	2.46E+13
718	2.64E+12	2.58E+03	6.18E+00	5.88E+09	1.46E+09	1.56E+12	9.88E+04	3.27E+13	771	1.97E+12	2.44E+03	1.87E+01	4.66E+09	1.29E+09	1.73E+12	9.32E+04	2.48E+13
719	1.51E+12	2.88E+03	4.97E+00	4.86E+09	1.35E+09	1.54E+12	8.70E+04	2.29E+13	772	1.40E+12	2.75E+03	2.46E+01	4.81E+09	1.44E+09	1.80E+12	1.03E+05	2.11E+13
720	2.56E+12	2.49E+03	1.89E+01	6.30E+09	1.32E+09	1.76E+12	9.03E+04	3.25E+13	773	2.40E+12	2.84E+03	2.23E+01	4.04E+09	1.26E+09	1.57E+12	9.34E+04	2.65E+13
721	2.36E+12	2.60E+03	2.21E+01	5.53E+09	1.29E+09	1.53E+12	9.99E+04	2.94E+13	774	1.52E+12	2.59E+03	5.76E+00	3.94E+09	1.50E+09	1.51E+12	1.03E+05	2.07E+13
722	1.55E+12	2.48E+03	1.22E+01	4.43E+09	1.25E+09	1.76E+12	9.64E+04	2.14E+13	775	1.57E+12	2.68E+03	4.56E+00	5.55E+09	1.26E+09	1.54E+12	9.95E+04	2.50E+13
723	2.32E+12	2.88E+03	1.33E+01	4.10E+09	1.44E+09	1.60E+12	1.03E+05	2.62E+13	776	1.52E+12	2.46E+03	1.44E+01	5.40E+09	1.24E+09	1.59E+12	8.76E+04	2.33E+13
724	2.07E+12	2.75E+03	2.15E+01	4.76E+09	1.24E+09	1.56E+12	8.55E+04	2.57E+13	777	1.41E+12	2.88E+03	2.69E+01	5.52E+09	1.39E+09	1.79E+12	9.89E+04	2.27E+13
725	2.19E+12	2.62E+03	1.89E+01	5.19E+09	1.46E+09	1.73E+12	1.00E+05	2.75E+13	778	1.60E+12	2.75E+03	5.12E+00	5.40E+09	1.35E+09	1.50E+12	8.85E+04	2.46E+13
726	1.68E+12	2.62E+03	1.88E+01	4.55E+09	1.47E+09	1.66E+12	1.02E+05	2.26E+13	779	2.23E+12	2.89E+03	6.40E+00	4.97E+09	1.27E+09	1.73E+12	9.42E+04	2.78E+13
727	2.00E+12	2.67E+03	1.36E+01	4.51E+09	1.46E+09	1.66E+12	9.30E+04	2.48E+13	780	1.54E+12	2.50E+03	1.78E+01	5.91E+09	1.42E+09	1.59E+12	9.87E+04	2.45E+13
728	1.43E+12	2.79E+03	1.20E+01	4.38E+09	1.46E+09	1.55E+12	8.97E+04	2.05E+13	781	2.12E+12	2.66E+03	2.56E+01	5.30E+09	1.29E+09	1.56E+12	1.02E+05	2.72E+13
729	1.96E+12	2.87E+03	1.27E+01	5.74E+09	1.23E+09	1.51E+12	8.98E+04	2.71E+13	782	2.21E+12	2.88E+03	9.68E+00	4.59E+09	1.28E+09	1.66E+12	1.03E+05	2.66E+13
730	1.94E+12	2.44E+03	5.69E+00	5.15E+09	1.34E+09	1.69E+12	8.75E+04	2.63E+13	783	2.51E+12	2.40E+03	1.40E+01	5.68E+09	1.42E+09	1.51E+12	9.14E+04	3.09E+13
731	1.84E+12	2.59E+03	2.94E+01	5.71E+09	1.42E+09	1.70E+12	8.80E+04	2.62E+13	784	1.80E+12	2.43E+03	1.10E+01	4.05E+09	1.33E+09	1.56E+12	9.24E+04	2.24E+13
732	1.89E+12	2.50E+03	1.38E+01	6.01E+09	1.41E+09	1.52E+12	1.03E+05	2.72E+13	785	2.33E+12	2.69E+03	1.34E+00	4.73E+09	1.29E+09	1.56E+12	8.80E+04	4.09E+13
733	1.87E+12	2.86E+03	6.46E+00	4.15E+09	1.39E+09	1.61E+12	9.96E+04	2.35E+13	786	2.23E+12	2.55E+03	2.67E+01	6.45E+09	1.41E+09	1.54E+12	1.03E+05	3.04E+13
734	1.57E+12	2.71E+03	1.87E+01	5.85E+09	1.38E+09	1.81E+12	9.70E+04	2.46E+13	787	1.62E+12	2.80E+03	5.54E+00	3.94E+09	1.47E+09	1.70E+12	9.44E+04	2.15E+13
735	1.40E+12	2.76E+03	2.62E+01	4.03E+09	1.41E+09	1.64E+12	9.26E+04	1.94E+13	788	1.79E+12	2.90E+03	1.88E+01	6.62E+09	1.31E+09	1.73E+12	8.64E+04	2.78E+13
736	1.64E+12	2.44E+03	9.23E+00	6.70E+09	1.23E+09	1.62E+12	9.61E+04	2.71E+13	789	1.45E+12	2.43E+03	1.61E+01	6.19E+09	1.47E+09	1.82E+12	8.90E+04	2.44E+13
737	1.50E+12	2.59E+03	1.30E+01	4.37E+09	1.30E+09	1.72E+12	8.53E+04	2.09E+13	790	2.49E+12	2.72E+03	2.01E+01	6.08E+09	1.42E+09	1.68E+12	9.22E+04	3.15E+13
738	2.18E+12	2.48E+03	1.72E+01	4.49E+09	1.45E+09	1.76E+12	9.20E+04	2.59E+13	791	2.44E+12	2.87E+03	4.23E+00	4.86E+09	1.44E+09	1.59E+12	9.59E+04	2.98E+13
739	1.68E+12	2.82E+03	1.58E+01	5.67E+09	1.47E+09	1.73E+12	1.01E+05	2.50E+13	792	2.41E+12	2.80E+03	1.19E+01	4.06E+09	1.28E+09	1.52E+12	1.02E+05	2.67E+13

793	1.52E+12	2.67E+03	2.73E+01	4.21E+09	1.24E+09	1.70E+12	1.02E+05	2.06E+13	846	2.64E+12	2.82E+03	2.63E+01	6.52E+09	1.43E+09	1.55E+12	9.92E+04	3.35E+13
794	1.55E+12	2.48E+03	6.51E+00	5.42E+09	1.42E+09	1.75E+12	1.00E+05	2.40E+13	847	2.49E+12	2.72E+03	1.98E+01	6.03E+09	1.31E+09	1.69E+12	1.01E+05	3.14E+13
795	1.88E+12	2.66E+03	5.96E+00	4.82E+09	1.33E+09	1.81E+12	1.02E+05	2.52E+13	848	2.11E+12	2.75E+03	1.52E+01	6.35E+09	1.35E+09	1.51E+12	1.02E+05	2.94E+13
796	2.40E+12	2.52E+03	2.95E+01	5.29E+09	1.46E+09	1.60E+12	1.03E+05	2.91E+13	849	2.60E+12	2.60E+03	8.07E+00	6.08E+09	1.31E+09	1.50E+12	9.45E+04	3.26E+13
797	1.90E+12	2.90E+03	2.68E+01	6.24E+09	1.49E+09	1.62E+12	8.83E+04	2.76E+13	850	2.51E+12	2.85E+03	2.23E+00	6.40E+09	1.25E+09	1.66E+12	9.84E+04	3.72E+13
798	2.61E+12	2.68E+03	1.77E+01	6.60E+09	1.49E+09	1.74E+12	9.00E+04	3.35E+13	851	2.59E+12	2.70E+03	2.07E+01	4.28E+09	1.29E+09	1.50E+12	1.03E+05	2.83E+13
799	1.51E+12	2.58E+03	1.59E+01	4.64E+09	1.23E+09	1.52E+12	1.01E+05	2.15E+13	852	2.62E+12	2.52E+03	5.71E+00	5.68E+09	1.43E+09	1.81E+12	9.91E+04	3.23E+13
800	2.59E+12	2.52E+03	8.81E+00	4.03E+09	1.34E+09	1.52E+12	9.14E+04	2.81E+13	853	2.48E+12	2.77E+03	4.78E+00	5.52E+09	1.27E+09	1.70E+12	9.83E+04	3.13E+13
801	2.23E+12	2.42E+03	1.65E+01	6.38E+09	1.39E+09	1.51E+12	8.71E+04	3.03E+13	854	2.31E+12	2.49E+03	2.01E+01	4.24E+09	1.28E+09	1.55E+12	9.18E+04	2.63E+13
802	2.01E+12	2.46E+03	2.52E+01	6.31E+09	1.24E+09	1.72E+12	1.03E+05	2.86E+13	855	2.47E+12	2.51E+03	2.39E+00	4.66E+09	1.49E+09	1.69E+12	8.91E+04	3.25E+13
803	1.89E+12	2.73E+03	1.16E+01	6.72E+09	1.26E+09	1.81E+12	1.01E+05	2.88E+13	856	1.67E+12	2.51E+03	1.19E+01	5.29E+09	1.34E+09	1.72E+12	9.55E+04	2.41E+13
804	1.76E+12	2.65E+03	2.80E+01	5.89E+09	1.43E+09	1.58E+12	1.00E+05	2.59E+13	857	1.89E+12	2.47E+03	2.00E+01	4.34E+09	1.35E+09	1.64E+12	9.90E+04	2.35E+13
805	2.53E+12	2.41E+03	1.17E+01	4.66E+09	1.46E+09	1.60E+12	1.02E+05	2.89E+13	858	2.44E+12	2.46E+03	2.84E+01	5.01E+09	1.33E+09	1.60E+12	9.77E+04	2.89E+13
806	1.93E+12	2.54E+03	1.80E+00	3.97E+09	1.44E+09	1.59E+12	9.75E+04	3.04E+13	859	2.39E+12	2.55E+03	1.91E+01	6.10E+09	1.45E+09	1.67E+12	9.34E+04	3.09E+13
807	1.68E+12	2.59E+03	2.92E+00	4.79E+09	1.25E+09	1.58E+12	1.00E+05	2.58E+13	860	1.93E+12	2.48E+03	4.19E+00	4.40E+09	1.41E+09	1.61E+12	8.48E+04	2.53E+13
808	1.61E+12	2.66E+03	1.44E+01	5.95E+09	1.26E+09	1.78E+12	1.01E+05	2.51E+13	861	2.25E+12	2.54E+03	1.70E+01	5.86E+09	1.36E+09	1.73E+12	8.68E+04	2.94E+13
809	1.84E+12	2.63E+03	1.70E+01	5.43E+09	1.34E+09	1.82E+12	9.73E+04	2.56E+13	862	1.44E+12	2.67E+03	1.35E+01	5.92E+09	1.25E+09	1.74E+12	8.73E+04	2.39E+13
810	1.67E+12	2.85E+03	2.83E+01	5.02E+09	1.40E+09	1.60E+12	1.03E+05	2.34E+13	863	2.44E+12	2.66E+03	1.24E+01	6.34E+09	1.47E+09	1.59E+12	9.52E+04	3.18E+13
811	1.46E+12	2.43E+03	7.22E+00	4.47E+09	1.40E+09	1.53E+12	1.00E+05	2.12E+13	864	1.42E+12	2.59E+03	1.70E+00	4.31E+09	1.30E+09	1.55E+12	1.03E+05	2.85E+13
812	1.48E+12	2.70E+03	1.31E+01	4.57E+09	1.26E+09	1.59E+12	9.91E+04	2.12E+13	865	2.01E+12	2.81E+03	2.38E+01	4.87E+09	1.25E+09	1.62E+12	8.61E+04	2.55E+13
813	1.52E+12	2.50E+03	1.04E+01	6.25E+09	1.29E+09	1.51E+12	9.06E+04	2.52E+13	866	2.26E+12	2.66E+03	2.97E+01	6.67E+09	1.30E+09	1.60E+12	9.35E+04	3.11E+13
814	1.66E+12	2.47E+03	2.05E+01	5.23E+09	1.24E+09	1.61E+12	8.65E+04	2.38E+13	867	2.12E+12	2.40E+03	7.56E+00	5.93E+09	1.43E+09	1.53E+12	9.99E+04	2.89E+13
815	2.38E+12	2.78E+03	1.62E+01	6.05E+09	1.33E+09	1.73E+12	9.49E+04	3.07E+13	868	2.25E+12	2.83E+03	2.70E+01	6.68E+09	1.41E+09	1.73E+12	9.78E+04	3.11E+13
816	2.46E+12	2.53E+03	1.04E+01	5.63E+09	1.39E+09	1.71E+12	1.01E+05	3.05E+13	869	2.63E+12	2.78E+03	2.82E+01	6.01E+09	1.49E+09	1.57E+12	9.93E+04	3.23E+13
817	2.28E+12	2.52E+03	1.25E+01	4.82E+09	1.25E+09	1.63E+12	9.08E+04	2.74E+13	870	2.24E+12	2.70E+03	6.81E+00	4.98E+09	1.32E+09	1.59E+12	1.01E+05	2.79E+13
818	2.63E+12	2.46E+03	2.01E+01	5.35E+09	1.38E+09	1.52E+12	1.02E+05	3.09E+13	871	1.70E+12	2.61E+03	1.82E+00	5.55E+09	1.34E+09	1.81E+12	9.47E+04	3.20E+13
819	2.55E+12	2.62E+03	1.20E+01	6.02E+09	1.31E+09	1.79E+12	8.85E+04	3.19E+13	872	2.11E+12	2.47E+03	1.36E+01	5.93E+09	1.48E+09	1.72E+12	8.48E+04	2.86E+13
820	1.93E+12	2.50E+03	7.64E+00	3.97E+09	1.34E+09	1.50E+12	1.01E+05	2.34E+13	873	1.78E+12	2.54E+03	3.64E+00	6.70E+09	1.39E+09	1.58E+12	9.85E+04	2.96E+13
821	1.53E+12	2.57E+03	2.80E+01	5.62E+09	1.43E+09	1.55E+12	9.46E+04	2.37E+13	874	2.34E+12	2.69E+03	5.79E+00	4.43E+09	1.24E+09	1.77E+12	9.79E+04	2.76E+13
822	1.90E+12	2.54E+03	1.81E+01	4.61E+09	1.41E+09	1.70E+12	9.62E+04	2.42E+13	875	2.51E+12	2.71E+03	1.47E+01	4.90E+09	1.25E+09	1.57E+12	9.21E+04	2.92E+13
823	1.94E+12	2.83E+03	2.27E+01	4.67E+09	1.32E+09	1.74E+12	9.06E+04	2.46E+13	876	1.63E+12	2.64E+03	2.69E+01	5.10E+09	1.35E+09	1.63E+12	8.97E+04	2.33E+13
824	2.38E+12	2.67E+03	2.08E+01	5.60E+09	1.36E+09	1.69E+12	9.77E+04	2.97E+13	877	1.75E+12	2.86E+03	7.79E+00	6.33E+09	1.24E+09	1.79E+12	9.63E+04	2.72E+13
825	1.72E+12	2.74E+03	4.46E+00	4.63E+09	1.30E+09	1.55E+12	9.68E+04	2.41E+13	878	2.05E+12	2.88E+03	2.88E+00	5.84E+09	1.26E+09	1.70E+12	9.31E+04	3.08E+13
826	1.45E+12	2.63E+03	2.44E+01	6.54E+09	1.44E+09	1.69E+12	9.00E+04	2.52E+13	879	2.04E+12	2.44E+03	1.09E+01	6.42E+09	1.38E+09	1.58E+12	9.59E+04	2.92E+13
827	2.55E+12	2.69E+03	2.55E+01	4.31E+09	1.30E+09	1.59E+12	9.57E+04	2.81E+13	880	2.24E+12	2.48E+03	2.43E+01	5.81E+09	1.35E+09	1.78E+12	9.47E+04	2.92E+13
828	1.75E+12	2.61E+03	2.98E+01	5.25E+09	1.42E+09	1.71E+12	9.03E+04	2.45E+13	881	1.42E+12	2.76E+03	6.79E+00	6.41E+09	1.38E+09	1.54E+12	8.69E+04	2.51E+13
829	1.55E+12	2.86E+03	2.54E+01	6.26E+09	1.30E+09	1.62E+12	9.25E+04	2.53E+13	882	1.97E+12	2.66E+03	2.61E+00	5.84E+09	1.25E+09	1.67E+12	9.61E+04	3.08E+13
830	1.56E+12	2.46E+03	2.97E+01	6.73E+09	1.29E+09	1.69E+12	9.71E+04	2.64E+13	883	1.67E+12	2.83E+03	1.07E+01	3.96E+09	1.39E+09	1.82E+12	1.03E+05	2.14E+13
831	2.15E+12	2.74E+03	2.19E+01	4.94E+09	1.35E+09	1.74E+12	9.84E+04	2.67E+13	884	1.41E+12	2.63E+03	2.64E+01	5.82E+09	1.43E+09	1.81E+12	8.67E+04	2.34E+13
832	1.65E+12	2.79E+03	1.75E+01	6.51E+09	1.34E+09	1.73E+12	9.82E+04	2.66E+13	885	2.04E+12	2.84E+03	2.32E+01	4.62E+09	1.37E+09	1.72E+12	1.00E+05	2.52E+13
833	2.57E+12	2.47E+03	7.52E+00	6.52E+09	1.30E+09	1.80E+12	8.63E+04	3.34E+13	886	1.78E+12	2.84E+03	2.96E+01	6.57E+09	1.46E+09	1.62E+12	9.64E+04	2.76E+13
834	1.82E+12	2.50E+03	1.20E+01	5.46E+09	1.48E+09	1.82E+12	9.92E+04	2.56E+13	887	2.22E+12	2.66E+03	8.51E+00	4.52E+09	1.40E+09	1.75E+12	9.81E+04	2.66E+13
835	2.50E+12	2.71E+03	1.83E+01	4.23E+09	1.29E+09	1.70E+12	8.96E+04	2.77E+13	888	2.13E+12	2.80E+03	7.82E+00	4.08E+09	1.45E+09	1.79E+12	8.70E+04	2.51E+13
836	2.15E+12	2.67E+03	1.15E+01	5.31E+09	1.24E+09	1.80E+12	9.58E+04	2.76E+13	889	1.66E+12	2.67E+03	1.03E+01	6.56E+09	1.30E+09	1.50E+12	9.05E+04	2.68E+13
837	1.67E+12	2.56E+03	2.75E+01	5.42E+09	1.37E+09	1.53E+12	9.99E+04	2.43E+13	890	2.14E+12	2.66E+03	2.80E+01	4.57E+09	1.34E+09	1.74E+12	9.86E+04	2.58E+13
838	2.37E+12	2.77E+03	2.25E+00	4.84E+09	1.50E+09	1.79E+12	9.47E+04	3.28E+13	891	2.08E+12	2.73E+03	1.91E+01	5.58E+09	1.37E+09	1.73E+12	9.31E+04	2.76E+13
839	1.59E+12	2.58E+03	1.60E+01	5.46E+09	1.26E+09	1.57E+12	1.00E+05	2.38E+13	892	2.25E+12	2.47E+03	2.38E+01	4.46E+09	1.23E+09	1.60E+12	1.03E+05	2.64E+13
840	2.35E+12	2.83E+03	2.34E+01	4.58E+09	1.43E+09	1.64E+12	8.91E+04	2.73E+13	893	1.58E+12	2.63E+03	1.61E+01	5.89E+09	1.45E+09	1.63E+12	8.84E+04	2.47E+13
841	1.53E+12	2.57E+03	1.47E+01	5.38E+09	1.26E+09	1.61E+12	9.33E+04	2.33E+13	894	1.61E+12	2.69E+03	1.55E+01	6.23E+09	1.42E+09	1.56E+12	1.00E+05	2.78E+13
842	1.71E+12	2.59E+03	2.35E+01	4.00E+09	1.32E+09	1.65E+12	9.26E+04	2.16E+13	895	2.63E+12	2.66E+03	1.01E+01	6.08E+09	1.42E+09	1.61E+12	9.10E+04	3.27E+13
843	1.56E+12	2.82E+03	6.38E+00	5.39E+09	1.37E+09	1.56E+12	9.60E+04	2.40E+13	896	2.49E+12	2.80E+03	6.25E+00	5.97E+09	1.24E+09	1.82E+12	9.14E+04	3.19E+13
844	2.42E+12	2.43E+03	2.93E+01	4.81E+09	1.43E+09	1.65E+12	9.28E+04	2.83E+13	897	1.61E+12	2.86E+03	1.16E+01	6.58E+09	1.46E+09	1.56E+12	9.03E+04	2.65E+13
845	2.59E+12	2.53E+03	2.62E+01	4.41E+09	1.38E+09	1.65E+12	1.02E+05	2.86E+13	898	2.43E+12	2.83E+03	9.41E+00	6.48E+09	1.36E+09	1.79E+12	9.73E+04	3.22E+13

899	2.36E+12	2.83E+03	8.05E+00	4.95E+09	1.40E+09	1.77E+12	9.31E+04	2.85E+13	952	1.86E+12	2.55E+03	6.93E+00	5.31E+09	1.41E+09	1.77E+12	9.97E+04	2.58E+13
900	2.09E+12	2.76E+03	3.47E+00	4.55E+09	1.37E+09	1.66E+12	8.62E+04	2.74E+13	953	2.05E+12	2.70E+03	2.35E+01	5.63E+09	1.38E+09	1.75E+12	1.03E+05	2.74E+13
901	2.03E+12	2.72E+03	1.18E+01	4.22E+09	1.36E+09	1.81E+12	9.95E+04	2.44E+13	954	1.71E+12	2.40E+03	2.48E+01	4.79E+09	1.29E+09	1.52E+12	1.01E+05	2.32E+13
902	1.87E+12	2.42E+03	2.25E+01	5.65E+09	1.33E+09	1.50E+12	9.94E+04	2.62E+13	955	2.06E+12	2.88E+03	2.57E+01	6.02E+09	1.45E+09	1.60E+12	9.07E+04	2.83E+13
903	2.41E+12	2.85E+03	1.63E+01	4.01E+09	1.45E+09	1.55E+12	9.16E+04	2.66E+13	956	2.34E+12	2.84E+03	2.89E+00	4.03E+09	1.44E+09	1.56E+12	9.34E+04	2.89E+13
904	2.13E+12	2.89E+03	1.23E+01	5.65E+09	1.49E+09	1.72E+12	9.58E+04	2.82E+13	957	1.89E+12	2.42E+03	1.75E+01	4.08E+09	1.34E+09	1.54E+12	8.57E+04	2.30E+13
905	1.41E+12	2.57E+03	1.76E+01	4.28E+09	1.38E+09	1.75E+12	9.23E+04	2.01E+13	958	1.56E+12	2.68E+03	2.50E+01	6.16E+09	1.28E+09	1.53E+12	9.52E+04	2.51E+13
906	1.47E+12	2.76E+03	6.75E+00	4.30E+09	1.29E+09	1.60E+12	9.34E+04	2.09E+13	959	1.68E+12	2.87E+03	1.92E+01	4.98E+09	1.29E+09	1.62E+12	8.52E+04	2.35E+13
907	1.47E+12	2.57E+03	2.17E+01	4.88E+09	1.37E+09	1.58E+12	9.27E+04	2.17E+13	960	2.35E+12	2.56E+03	1.30E+01	4.25E+09	1.39E+09	1.74E+12	1.03E+05	2.67E+13
908	1.84E+12	2.76E+03	1.41E+01	5.98E+09	1.43E+09	1.72E+12	8.56E+04	2.68E+13	961	1.93E+12	2.45E+03	8.95E+00	5.04E+09	1.31E+09	1.59E+12	8.62E+04	2.56E+13
909	1.48E+12	2.65E+03	1.69E+01	5.47E+09	1.37E+09	1.58E+12	8.72E+04	2.31E+13	962	2.03E+12	2.51E+03	2.68E+01	5.58E+09	1.49E+09	1.80E+12	8.55E+04	2.72E+13
910	2.43E+12	2.65E+03	8.38E+00	4.09E+09	1.27E+09	1.53E+12	8.62E+04	2.71E+13	963	2.04E+12	2.69E+03	1.02E+01	4.16E+09	1.25E+09	1.70E+12	1.02E+05	2.45E+13
911	1.60E+12	2.69E+03	2.09E+00	4.09E+09	1.35E+09	1.70E+12	9.89E+04	2.65E+13	964	1.52E+12	2.77E+03	2.77E+01	5.05E+09	1.38E+09	1.76E+12	1.03E+05	2.25E+13
912	2.08E+12	2.63E+03	2.84E+01	5.20E+09	1.39E+09	1.69E+12	8.52E+04	2.67E+13	965	2.40E+12	2.74E+03	2.88E+01	4.54E+09	1.49E+09	1.76E+12	9.20E+04	2.76E+13
913	2.09E+12	2.74E+03	1.80E+01	4.23E+09	1.50E+09	1.66E+12	9.12E+04	2.48E+13	966	1.69E+12	2.71E+03	1.87E+00	6.54E+09	1.40E+09	1.80E+12	1.03E+05	3.38E+13
914	1.57E+12	2.68E+03	2.42E+01	6.01E+09	1.44E+09	1.52E+12	9.22E+04	2.48E+13	967	2.54E+12	2.62E+03	2.74E+01	5.15E+09	1.49E+09	1.64E+12	9.91E+04	2.99E+13
915	2.60E+12	2.77E+03	5.93E+00	6.23E+09	1.51E+09	1.67E+12	8.87E+04	3.33E+13	968	2.51E+12	2.79E+03	1.68E+01	6.65E+09	1.46E+09	1.66E+12	9.62E+04	3.29E+13
916	1.68E+12	2.62E+03	1.71E+01	5.67E+09	1.50E+09	1.53E+12	1.02E+05	2.49E+13	969	1.53E+12	2.53E+03	1.08E+00	5.48E+09	1.45E+09	1.62E+12	8.85E+04	4.68E+13
917	2.38E+12	2.66E+03	9.58E+00	4.90E+09	1.44E+09	1.61E+12	8.92E+04	2.84E+13	970	2.01E+12	2.60E+03	9.76E+00	5.35E+09	1.41E+09	1.67E+12	9.30E+04	2.68E+13
918	1.74E+12	2.60E+03	1.41E+01	5.60E+09	1.47E+09	1.82E+12	9.90E+04	2.53E+13	971	1.49E+12	2.62E+03	1.66E+01	4.75E+09	1.34E+09	1.67E+12	8.84E+04	2.16E+13
919	1.87E+12	2.42E+03	1.02E+00	5.60E+09	1.33E+09	1.51E+12	9.24E+04	4.92E+13	972	1.88E+12	2.59E+03	2.89E+01	6.68E+09	1.31E+09	1.56E+12	9.63E+04	2.85E+13
920	2.55E+12	2.52E+03	2.07E+01	6.11E+09	1.25E+09	1.82E+12	9.13E+04	3.20E+13	973	1.93E+12	2.60E+03	3.13E+00	4.65E+09	1.33E+09	1.65E+12	8.82E+04	2.69E+13
921	1.78E+12	2.80E+03	2.88E+01	4.73E+09	1.26E+09	1.60E+12	9.37E+04	2.36E+13	974	2.25E+12	2.69E+03	2.58E+01	5.00E+09	1.29E+09	1.65E+12	9.00E+04	2.75E+13
922	1.98E+12	2.43E+03	5.86E+00	6.32E+09	1.38E+09	1.53E+12	8.64E+04	2.90E+13	975	1.56E+12	2.85E+03	2.59E+01	3.98E+09	1.36E+09	1.68E+12	9.32E+04	2.05E+13
923	2.03E+12	2.65E+03	4.81E+00	4.82E+09	1.38E+09	1.80E+12	1.02E+05	2.66E+13	976	1.40E+12	2.59E+03	3.01E+00	4.45E+09	1.43E+09	1.58E+12	9.42E+04	2.29E+13
924	2.34E+12	2.67E+03	2.84E+01	5.20E+09	1.34E+09	1.71E+12	1.02E+05	2.85E+13	977	1.50E+12	2.45E+03	1.85E+01	4.12E+09	1.48E+09	1.76E+12	8.50E+04	2.03E+13
925	2.47E+12	2.56E+03	2.06E+01	5.62E+09	1.42E+09	1.79E+12	8.81E+04	3.04E+13	978	1.48E+12	2.72E+03	2.52E+01	6.71E+09	1.29E+09	1.66E+12	9.57E+04	2.57E+13
926	2.21E+12	2.76E+03	1.00E+01	4.75E+09	1.38E+09	1.72E+12	9.26E+04	2.69E+13	979	2.50E+12	2.72E+03	2.19E+01	6.61E+09	1.40E+09	1.83E+12	1.04E+05	3.28E+13
927	2.50E+12	2.44E+03	7.74E+00	5.42E+09	1.26E+09	1.74E+12	9.09E+04	3.05E+13	980	2.49E+12	2.88E+03	2.01E+01	6.45E+09	1.33E+09	1.74E+12	9.75E+04	3.24E+13
928	2.38E+12	2.60E+03	1.97E+01	6.59E+09	1.43E+09	1.76E+12	8.91E+04	3.19E+13	981	1.79E+12	2.46E+03	1.55E+00	4.69E+09	1.46E+09	1.54E+12	9.21E+04	3.35E+13
929	2.35E+12	2.57E+03	1.14E+01	5.07E+09	1.34E+09	1.57E+12	8.69E+04	2.85E+13	982	1.79E+12	2.64E+03	2.81E+00	5.92E+09	1.44E+09	1.79E+12	9.45E+04	2.93E+13
930	2.63E+12	2.45E+03	2.00E+01	6.05E+09	1.26E+09	1.51E+12	8.88E+04	3.24E+13	983	1.85E+12	2.83E+03	4.29E+00	5.86E+09	1.30E+09	1.83E+12	8.58E+04	2.78E+13
931	2.37E+12	2.48E+03	2.85E+01	5.25E+09	1.25E+09	1.83E+12	9.12E+04	2.89E+13	984	1.64E+12	2.55E+03	1.76E+01	5.99E+09	1.44E+09	1.82E+12	9.08E+04	2.54E+13
932	2.18E+12	2.81E+03	1.64E+01	4.96E+09	1.25E+09	1.65E+12	1.02E+05	2.70E+13	985	2.58E+12	2.81E+03	2.86E+01	4.05E+09	1.45E+09	1.59E+12	9.59E+04	2.78E+13
933	2.03E+12	2.61E+03	9.63E+00	5.34E+09	1.48E+09	1.76E+12	8.61E+04	2.69E+13	986	2.32E+12	2.77E+03	8.57E+00	4.24E+09	1.34E+09	1.75E+12	1.03E+05	2.67E+13
934	1.81E+12	2.73E+03	1.50E+01	5.33E+09	1.28E+09	1.52E+12	1.01E+05	2.51E+13	987	2.02E+12	2.61E+03	3.57E+00	4.83E+09	1.43E+09	1.51E+12	9.36E+04	2.73E+13
935	1.83E+12	2.81E+03	1.50E+01	5.33E+09	1.26E+09	1.80E+12	9.17E+04	2.53E+13	988	1.51E+12	2.86E+03	1.49E+01	6.46E+09	1.47E+09	1.68E+12	9.49E+04	2.55E+13
936	2.60E+12	2.50E+03	2.40E+01	5.80E+09	1.39E+09	1.77E+12	1.00E+05	3.17E+13	989	1.57E+12	2.60E+03	2.48E+01	4.47E+09	1.26E+09	1.82E+12	9.04E+04	2.16E+13
937	1.86E+12	2.50E+03	1.83E+01	6.06E+09	1.35E+09	1.76E+12	9.05E+04	2.70E+13	990	2.40E+12	2.57E+03	6.70E+00	4.48E+09	1.50E+09	1.68E+12	9.46E+04	2.79E+13
938	1.76E+12	2.70E+03	1.26E+01	4.50E+09	1.39E+09	1.67E+12	8.53E+04	2.31E+13	991	2.48E+12	2.64E+03	2.10E+01	5.03E+09	1.30E+09	1.75E+12	9.29E+04	2.92E+13
939	1.48E+12	2.80E+03	2.74E+01	4.07E+09	1.31E+09	1.59E+12	1.01E+05	2.01E+13	992	2.36E+12	2.64E+03	4.18E+00	6.71E+09	1.26E+09	1.61E+12	9.76E+04	3.33E+13
940	2.19E+12	2.88E+03	2.10E+01	5.24E+09	1.50E+09	1.75E+12	9.71E+04	2.77E+13	993	1.98E+12	2.68E+03	3.00E+01	4.96E+09	1.38E+09	1.81E+12	9.53E+04	2.55E+13
941	2.16E+12	2.67E+03	2.17E+01	6.23E+09	1.25E+09	1.75E+12	8.83E+04	2.95E+13	994	2.39E+12	2.61E+03	5.36E+00	5.36E+09	1.36E+09	1.57E+12	9.02E+04	3.00E+13
942	1.49E+12	2.65E+03	1.42E+01	6.45E+09	1.33E+09	1.73E+12	8.60E+04	2.53E+13	995	1.83E+12	2.50E+03	1.75E+01	4.58E+09	1.50E+09	1.82E+12	9.03E+04	2.37E+13
943	2.20E+12	2.50E+03	7.13E+00	5.28E+09	1.27E+09	1.82E+12	9.58E+04	2.82E+13	996	1.62E+12	2.46E+03	1.69E+01	3.93E+09	1.50E+09	1.60E+12	9.24E+04	2.08E+13
944	1.50E+12	2.55E+03	9.15E+00	5.99E+09	1.25E+09	1.76E+12	9.85E+04	2.46E+13	997	2.62E+12	2.42E+03	9.77E+00	4.54E+09	1.24E+09	1.55E+12	8.86E+04	2.93E+13
945	2.05E+12	2.79E+03	3.36E+00	5.97E+09	1.33E+09	1.54E+12	8.66E+04	3.02E+13	998	1.48E+12	2.46E+03	2.88E+01	4.42E+09	1.46E+09	1.63E+12	9.01E+04	2.08E+13
946	1.74E+12	2.83E+03	6.21E+00	5.58E+09	1.42E+09	1.50E+12	9.74E+04	2.57E+13	999	1.54E+12	2.45E+03	3.94E+00	5.12E+09	1.40E+09	1.56E+12	1.01E+05	2.42E+13
947	1.46E+12	2.42E+03	1.28E+01	3.95E+09	1.39E+09	1.70E+12	9.42E+04	1.98E+13	1000	2.31E+12	2.53E+03	2.45E+01	6.45E+09	1.37E+09	1.73E+12	8.51E+04	3.10E+13
948	2.09E+12	2.61E+03	1.13E+01	5.91E+09	1.24E+09	1.55E+12	9.52E+04	2.85E+13	1001	2.34E+12	2.59E+03	2.50E+01	4.78E+09	1.29E+09	1.50E+12	1.02E+05	2.76E+13
949	2.37E+12	2.48E+03	1.74E+01	4.46E+09	1.37E+09	1.58E+12	9.59E+04	2.72E+13	1002	1.58E+12	2.42E+03	1.15E+01	5.39E+09	1.26E+09	1.74E+12	1.01E+05	2.38E+13
950	1.92E+12	2.77E+03	2.07E+01	6.59E+09	1.40E+09	1.50E+12	9.15E+04	2.85E+13	1003	1.40E+12	2.79E+03	5.00E+00	4.89E+09	1.32E+09	1.80E+12	9.27E+04	2.22E+13
951	2.05E+12	2.56E+03	6.09E+00	5.62E+09	1.36E+09	1.78E+12	1.00E+05	2.80E+13	1004	2.44E+12	2.83E+03	2.70E+01	5.34E+09	1.45E+09	1.57E+12	8.75E+04	2.96E+13

1005	1.57E+12	2.80E+03	1.56E+01	6.74E+09	1.27E+09	1.50E+12	9.88E+04	2.64E+13
1006	2.14E+12	2.43E+03	1.35E+01	6.72E+09	1.36E+09	1.55E+12	9.12E+04	3.05E+13
1007	1.61E+12	2.63E+03	1.43E+01	6.66E+09	1.40E+09	1.70E+12	1.04E+05	2.66E+13
1008	2.54E+12	2.68E+03	2.50E+01	4.52E+09	1.34E+09	1.59E+12	1.00E+05	2.85E+13
1009	1.81E+12	2.80E+03	7.86E+00	4.28E+09	1.28E+09	1.63E+12	9.41E+04	2.32E+13

K.2 Data for Geometry Sensitivity Analysis

<ID>	Height	HoleDiam	Thickness	Width	Energy	Mass	PartCost	Utilization	Volume
0	69.50	7.07	6.84	52.83	8.92E+12	0.0448	2.79	0.84	4.48E-05
1	50.41	6.45	3.34	31.39	4.51E+12	0.0159	1.28	0.89	1.59E-05
2	58.59	5.42	5.76	58.31	6.84E+12	0.0350	2.11	0.85	3.50E-05
3	33.48	2.61	2.82	30.16	3.64E+12	0.0106	0.98	0.91	1.06E-05
4	54.81	7.38	7.86	32.01	8.29E+12	0.0396	2.58	0.81	3.96E-05
5	69.17	2.72	4.41	56.25	5.94E+12	0.0294	1.80	0.88	2.94E-05
6	43.46	3.20	6.67	38.88	6.64E+12	0.0307	2.02	0.83	3.07E-05
7	61.70	2.98	6.30	43.92	6.70E+12	0.0369	2.09	0.85	3.69E-05
8	69.25	3.96	3.66	47.77	5.35E+12	0.0235	1.58	0.89	2.35E-05
9	40.48	5.16	7.83	56.98	8.09E+12	0.0388	2.51	0.83	3.88E-05
10	41.52	2.40	1.88	51.24	3.48E+12	0.0091	0.92	0.93	9.13E-06
11	51.92	5.12	5.80	33.53	6.10E+12	0.0286	1.85	0.85	2.86E-05
12	46.88	6.00	5.26	43.27	5.81E+12	0.0259	1.74	0.86	2.59E-05
13	64.77	5.93	2.79	32.04	4.28E+12	0.0158	1.21	0.91	1.58E-05
14	54.38	4.16	2.12	44.57	3.84E+12	0.0115	1.05	0.91	1.15E-05
15	66.64	6.79	5.36	39.34	6.57E+12	0.0321	2.01	0.85	3.21E-05
16	37.95	2.26	4.39	52.75	4.94E+12	0.0206	1.44	0.87	2.06E-05
17	55.25	4.57	4.00	34.38	5.01E+12	0.0207	1.47	0.88	2.07E-05
18	38.84	3.92	7.06	50.37	7.43E+12	0.0329	2.27	0.83	3.29E-05
19	46.07	3.64	6.33	56.25	6.58E+12	0.0334	2.02	0.85	3.34E-05
20	30.13	4.31	2.65	36.62	3.60E+12	0.0099	0.97	0.90	9.88E-06
21	51.56	6.56	3.26	36.96	4.57E+12	0.0163	1.30	0.88	1.63E-05
22	30.59	3.01	5.89	41.54	5.44E+12	0.0230	1.61	0.84	2.30E-05
23	47.97	6.92	3.98	37.94	4.83E+12	0.0192	1.40	0.89	1.92E-05
24	68.19	4.10	4.10	47.61	5.58E+12	0.0260	1.67	0.88	2.60E-05
25	53.74	7.32	4.02	51.20	5.22E+12	0.0224	1.54	0.88	2.24E-05
26	48.41	4.50	7.53	34.17	7.75E+12	0.0357	2.39	0.83	3.57E-05
27	45.65	5.91	4.78	49.51	5.61E+12	0.0241	1.66	0.88	2.41E-05
28	43.05	4.37	3.17	37.07	4.34E+12	0.0143	1.22	0.88	1.43E-05
29	61.09	8.00	4.60	44.61	5.99E+12	0.0267	1.79	0.87	2.67E-05
30	68.12	3.09	2.02	57.39	3.98E+12	0.0134	1.10	0.92	1.34E-05
31	39.86	4.20	2.56	34.21	3.72E+12	0.0109	1.01	0.90	1.09E-05
32	44.20	6.16	1.53	46.33	3.34E+12	0.0074	0.87	0.93	7.44E-06
33	63.95	3.99	4.77	40.31	6.06E+12	0.0280	1.82	0.88	2.80E-05
34	69.47	3.27	4.51	49.92	5.96E+12	0.0293	1.81	0.87	2.93E-05
35	40.13	6.06	3.44	40.89	4.41E+12	0.0153	1.25	0.90	1.53E-05
36	35.13	5.26	7.75	35.18	7.13E+12	0.0308	2.17	0.83	3.08E-05
37	54.26	5.63	1.80	38.65	3.55E+12	0.0094	0.95	0.92	9.42E-06
38	63.52	7.51	5.41	48.33	6.65E+12	0.0327	2.04	0.85	3.27E-05
39	41.74	3.37	7.94	52.59	7.50E+12	0.0389	2.34	0.83	3.89E-05
40	41.00	3.44	2.06	35.37	3.53E+12	0.0090	0.94	0.91	8.98E-06
41	59.35	6.03	6.36	53.90	8.19E+12	0.0381	2.53	0.84	3.81E-05
42	51.48	6.68	7.09	56.41	8.30E+12	0.0396	2.58	0.83	3.96E-05
43	67.32	4.13	2.34	34.96	4.08E+12	0.0139	1.13	0.92	1.39E-05
44	36.95	4.50	1.04	55.24	3.05E+12	0.0049	0.77	0.93	4.86E-06
45	47.33	2.25	4.30	45.87	5.05E+12	0.0217	1.48	0.88	2.17E-05

46	51.76	5.36	4.27	52.43	5.31E+12	0.0235	1.57	0.87	2.35E-05
47	32.23	5.84	6.11	38.63	5.57E+12	0.0238	1.66	0.83	2.38E-05
48	50.20	7.62	3.31	45.07	4.67E+12	0.0171	1.33	0.88	1.71E-05
49	57.41	3.87	3.58	54.41	5.07E+12	0.0212	1.48	0.89	2.12E-05
50	55.63	5.40	1.75	50.65	3.61E+12	0.0099	0.97	0.92	9.92E-06
51	63.61	5.52	1.27	50.90	3.42E+12	0.0078	0.90	0.91	7.80E-06
52	54.72	3.22	5.90	42.99	6.40E+12	0.0318	1.96	0.86	3.18E-05
53	54.11	5.66	6.43	30.58	7.38E+12	0.0320	2.25	0.84	3.20E-05
54	30.41	7.81	4.94	38.99	5.03E+12	0.0187	1.46	0.85	1.87E-05
55	53.13	7.40	7.41	35.49	8.07E+12	0.0374	2.50	0.81	3.74E-05
56	66.96	6.77	2.50	44.11	4.25E+12	0.0153	1.20	0.92	1.53E-05
57	47.47	6.07	5.07	36.28	5.64E+12	0.0240	1.68	0.85	2.40E-05
58	62.21	7.16	3.01	57.71	4.64E+12	0.0189	1.34	0.90	1.89E-05
59	31.94	5.00	3.28	36.04	4.09E+12	0.0125	1.13	0.89	1.25E-05
60	37.97	4.45	5.78	39.94	5.63E+12	0.0248	1.68	0.86	2.48E-05
61	51.24	7.08	6.44	36.58	7.40E+12	0.0320	2.25	0.84	3.20E-05
62	55.60	2.09	4.52	33.57	5.06E+12	0.0234	1.50	0.88	2.34E-05
63	35.86	7.22	7.50	41.39	7.27E+12	0.0314	2.21	0.82	3.14E-05
64	46.94	6.24	4.28	39.49	4.99E+12	0.0206	1.46	0.86	2.06E-05
65	63.08	5.87	1.22	34.42	3.27E+12	0.0069	0.85	0.93	6.86E-06
66	35.99	3.33	3.68	51.40	4.55E+12	0.0167	1.30	0.88	1.67E-05
67	48.04	3.65	5.29	52.79	6.03E+12	0.0280	1.82	0.86	2.80E-05
68	32.20	6.33	6.25	35.43	5.55E+12	0.0238	1.65	0.83	2.38E-05
69	52.34	7.28	7.24	40.00	8.05E+12	0.0372	2.49	0.82	3.72E-05
70	64.88	5.96	3.37	52.20	5.12E+12	0.0211	1.49	0.89	2.11E-05
71	57.84	5.73	6.04	31.91	6.43E+12	0.0316	1.97	0.85	3.16E-05
72	32.71	2.65	6.70	35.73	6.01E+12	0.0259	1.80	0.84	2.59E-05
73	66.34	2.09	7.64	55.04	8.77E+12	0.0494	2.79	0.84	4.94E-05
74	66.98	4.02	6.58	32.23	8.11E+12	0.0382	2.51	0.84	3.82E-05
75	68.98	2.05	5.59	59.46	6.84E+12	0.0378	2.13	0.86	3.78E-05
76	52.64	4.17	5.48	49.07	6.24E+12	0.0299	1.89	0.86	2.99E-05
77	56.56	6.82	1.83	47.17	3.65E+12	0.0103	0.98	0.93	1.03E-05
78	59.02	6.39	5.27	48.33	6.38E+12	0.0306	1.94	0.85	3.06E-05
79	65.07	7.65	1.30	33.02	3.36E+12	0.0074	0.88	0.91	7.38E-06
80	56.87	5.10	6.76	43.75	7.98E+12	0.0374	2.46	0.85	3.74E-05
81	32.62	6.34	4.96	57.57	5.43E+12	0.0223	1.60	0.86	2.23E-05
82	67.23	6.94	3.49	54.35	5.30E+12	0.0226	1.56	0.89	2.26E-05
83	60.62	5.10	5.79	49.42	6.76E+12	0.0344	2.08	0.85	3.44E-05
84	66.39	3.50	6.20	30.62	6.91E+12	0.0355	2.14	0.83	3.55E-05
85	62.65	3.67	5.35	35.62	6.30E+12	0.0302	1.92	0.86	3.02E-05
86	57.59	7.58	2.15	35.35	3.85E+12	0.0114	1.05	0.90	1.14E-05
87	35.78	4.79	7.20	45.48	7.23E+12	0.0312	2.20	0.83	3.12E-05
88	54.34	6.55	1.25	44.73	3.26E+12	0.0068	0.84	0.92	6.77E-06
89	45.28	6.89	2.98	48.69	4.16E+12	0.0149	1.17	0.91	1.49E-05
90	67.30	3.12	3.40	33.82	4.96E+12	0.0200	1.44	0.90	2.00E-05
91	48.71	5.48	7.51	54.78	8.32E+12	0.0404	2.59	0.83	4.04E-05
92	57.76	6.21	2.59	38.48	4.10E+12	0.0141	1.14	0.91	1.41E-05

46	51.76	5.36	4.27	52.43	5.31E+12	0.0235	1.57	0.87	2.35E-05
47	32.23	5.84	6.11	38.63	5.57E+12	0.0238	1.66	0.83	2.38E-05
48	50.20	7.62	3.31	45.07	4.67E+12	0.0171	1.33	0.88	1.71E-05
49	57.41	3.87	3.58	54.41	5.07E+12	0.0212	1.48	0.89	2.12E-05
50	55.63	5.40	1.75	50.65	3.61E+12	0.0099	0.97	0.92	9.92E-06
51	63.61	5.52	1.27	50.90	3.42E+12	0.0078	0.90	0.91	7.80E-06
52	54.72	3.22	5.90	42.99	6.40E+12	0.0318	1.96	0.86	3.18E-05
53	54.11	5.66	6.43	30.58	7.38E+12	0.0320	2.25	0.84	3.20E-05
54	30.41	7.81	4.94	38.99	5.03E+12	0.0187	1.46	0.85	1.87E-05
55	53.13	7.40	7.41	35.49	8.07E+12	0.0374	2.50	0.81	3.74E-05
56	66.96	6.77	2.50	44.11	4.25E+12	0.0153	1.20	0.92	1.53E-05
57	47.47	6.07	5.07	36.28	5.64E+12	0.0240	1.68	0.85	2.40E-05
58	62.21	7.16	3.01	57.71	4.64E+12	0.0189	1.34	0.90	1.89E-05
59	31.94	5.00	3.28	36.04	4.09E+12	0.0125	1.13	0.89	1.25E-05
60	37.97	4.45	5.78	39.94	5.63E+12	0.0248	1.68	0.86	2.48E-05
61	51.24	7.08	6.44	36.58	7.40E+12	0.0320	2.25	0.84	3.20E-05
62	55.60	2.09	4.52	33.57	5.06E+12	0.0234	1.50	0.88	2.34E-05
63	35.86	7.22	7.50	41.39	7.27E+12	0.0314	2.21	0.82	3.14E-05
64	46.94	6.24	4.28	39.49	4.99E+12	0.0206	1.46	0.86	2.06E-05
65	63.08	5.87	1.22	34.42	3.27E+12	0.0069	0.85	0.93	6.86E-06
66	35.99	3.33	3.68	51.40	4.55E+12	0.0167	1.30	0.88	1.67E-05
67	48.04	3.65	5.29	52.79	6.03E+12	0.0280	1.82	0.86	2.80E-05
68	32.20	6.33	6.25	35.43	5.55E+12	0.0238	1.65	0.83	2.38E-05
69	52.34	7.28	7.24	40.00	8.05E+12	0.0372	2.49	0.82	3.72E-05
70	64.88	5.96	3.37	52.20	5.12E+12	0.0211	1.49	0.89	2.11E-05
71	57.84	5.73	6.04	31.91	6.43E+12	0.0316	1.97	0.85	3.16E-05
72	32.71	2.65	6.70	35.73	6.01E+12	0.0259	1.80	0.84	2.59E-05
73	66.34	2.09	7.64	55.04	8.77E+12	0.0494	2.79	0.84	4.94E-05
74	66.98	4.02	6.58	32.23	8.11E+12	0.0382	2.51	0.84	3.82E-05
75	68.98	2.05	5.59	59.46	6.84E+12	0.0378	2.13	0.86	3.78E-05
76	52.64	4.17	5.48	49.07	6.24E+12	0.0299	1.89	0.86	2.99E-05
77	56.56	6.82	1.83	47.17	3.65E+12	0.0103	0.98	0.93	1.03E-05
78	59.02	6.39	5.27	48.33	6.38E+12	0.0306	1.94	0.85	3.06E-05
79	65.07	7.65	1.30	33.02	3.36E+12	0.0074	0.88	0.91	7.38E-06
80	56.87	5.10	6.76	43.75	7.98E+12	0.0374	2.46	0.85	3.74E-05
81	32.62	6.34	4.96	57.57	5.43E+12	0.0223	1.60	0.86	2.23E-05
82	67.23	6.94	3.49	54.35	5.30E+12	0.0226	1.56	0.89	2.26E-05
83	60.62	5.10	5.79	49.42	6.76E+12	0.0344	2.08	0.85	3.44E-05
84	66.39	3.50	6.20	30.62	6.91E+12	0.0355	2.14	0.83	3.55E-05
85	62.65	3.67	5.35	35.62	6.30E+12	0.0302	1.92	0.86	3.02E-05
86	57.59	7.58	2.15	35.35	3.85E+12	0.0114	1.05	0.90	1.14E-05
87	35.78	4.79	7.20	45.48	7.23E+12	0.0312	2.20	0.83	3.12E-05
88	54.34	6.55	1.25	44.73	3.26E+12	0.0068	0.84	0.92	6.77E-06
89	45.28	6.89	2.98	48.69	4.16E+12	0.0149	1.17	0.91	1.49E-05
90	67.30	3.12	3.40	33.82	4.96E+12	0.0200	1.44	0.90	2.00E-05
91	48.71	5.48	7.51	54.78	8.32E+12	0.0404	2.59	0.83	4.04E-05
92	57.76	6.21	2.59	38.48	4.10E+12	0.0141	1.14	0.91	1.41E-05

93	34.96	2.55	3.69	38.41	4.33E+12	0.0151	1.22	0.89	1.51E-05
94	53.61	6.85	1.40	33.89	3.27E+12	0.0071	0.85	0.92	7.07E-06
95	57.94	7.96	1.69	45.72	3.59E+12	0.0096	0.96	0.92	9.56E-06
96	40.18	6.66	1.33	52.95	3.20E+12	0.0064	0.82	0.92	6.39E-06
97	39.90	6.30	2.05	32.83	3.50E+12	0.0086	0.93	0.91	8.60E-06
98	36.55	6.23	5.93	55.34	5.97E+12	0.0276	1.80	0.85	2.76E-05
99	67.40	7.25	3.33	41.30	5.07E+12	0.0202	1.48	0.87	2.02E-05
100	52.88	2.92	3.93	56.37	5.18E+12	0.0224	1.52	0.89	2.24E-05
101	59.68	6.41	6.82	34.94	7.94E+12	0.0370	2.45	0.85	3.70E-05
102	31.49	5.89	4.75	56.85	5.25E+12	0.0209	1.53	0.87	2.09E-05
103	69.10	3.51	7.47	53.58	8.74E+12	0.0491	2.78	0.84	4.91E-05
104	56.65	3.81	1.30	40.40	3.29E+12	0.0071	0.85	0.93	7.09E-06
105	48.55	5.55	3.24	31.80	4.43E+12	0.0152	1.25	0.89	1.52E-05
106	61.58	2.64	4.00	52.98	5.40E+12	0.0245	1.61	0.89	2.45E-05
107	63.92	6.13	3.32	36.64	4.89E+12	0.0191	1.41	0.89	1.91E-05
108	63.14	5.55	3.84	54.33	5.37E+12	0.0239	1.59	0.90	2.39E-05
109	54.58	7.14	7.23	50.03	8.38E+12	0.0403	2.61	0.83	4.03E-05
110	62.47	3.41	7.03	47.49	8.04E+12	0.0422	2.53	0.83	4.22E-05
111	43.09	6.05	1.36	33.04	3.13E+12	0.0060	0.80	0.93	5.96E-06
112	59.91	3.14	4.56	53.33	5.77E+12	0.0275	1.74	0.85	2.75E-05
113	69.84	7.90	7.22	59.61	9.38E+12	0.0488	2.96	0.84	4.88E-05
114	54.02	2.35	5.55	54.05	6.13E+12	0.0316	1.87	0.87	3.16E-05
115	37.82	5.77	4.96	41.26	5.29E+12	0.0214	1.55	0.87	2.14E-05
116	36.78	4.22	7.74	44.04	7.46E+12	0.0337	2.28	0.83	3.37E-05
117	50.31	6.91	4.74	41.63	5.64E+12	0.0240	1.67	0.87	2.40E-05
118	66.05	6.47	5.23	57.19	6.74E+12	0.0339	2.07	0.86	3.39E-05
119	68.13	5.62	7.34	36.25	8.81E+12	0.0439	2.76	0.83	4.39E-05
120	56.49	3.00	7.69	57.88	8.42E+12	0.0458	2.67	0.82	4.58E-05
121	45.52	2.96	5.58	57.39	6.17E+12	0.0295	1.87	0.86	2.95E-05
122	55.42	6.89	5.83	50.47	6.57E+12	0.0329	2.01	0.86	3.29E-05
123	61.52	7.10	6.88	47.91	8.55E+12	0.0408	2.66	0.82	4.08E-05
124	32.34	2.62	5.22	55.88	5.50E+12	0.0232	1.63	0.85	2.32E-05
125	35.60	4.39	3.65	57.22	4.60E+12	0.0171	1.31	0.88	1.71E-05
126	68.54	2.36	3.09	37.53	4.85E+12	0.0188	1.40	0.91	1.88E-05
127	65.52	5.99	2.31	55.85	4.21E+12	0.0148	1.18	0.92	1.48E-05
128	68.95	3.85	3.64	38.36	5.23E+12	0.0223	1.54	0.88	2.23E-05
129	63.27	2.18	7.59	37.11	8.09E+12	0.0436	2.55	0.83	4.36E-05
130	50.97	2.76	3.35	45.51	4.70E+12	0.0176	1.35	0.88	1.76E-05
131	47.52	4.43	2.95	31.08	4.00E+12	0.0136	1.11	0.91	1.36E-05
132	39.14	3.79	6.24	53.13	6.22E+12	0.0298	1.90	0.83	2.98E-05
133	45.99	5.61	3.65	42.76	4.69E+12	0.0177	1.34	0.88	1.77E-05
134	56.30	4.07	1.72	40.80	3.54E+12	0.0093	0.94	0.93	9.32E-06
135	63.33	5.28	7.28	58.43	9.06E+12	0.0463	2.85	0.84	4.63E-05
136	35.34	2.14	7.83	34.17	6.58E+12	0.0311	2.01	0.83	3.11E-05
137	65.78	7.65	5.43	56.66	6.87E+12	0.0350	2.12	0.86	3.50E-05
138	36.81	5.24	6.93	55.40	7.36E+12	0.0325	2.24	0.85	3.25E-05
139	37.65	5.93	7.11	59.72	7.69E+12	0.0346	2.36	0.82	3.46E-05

140	40.34	4.40	7.21	41.77	7.37E+12	0.0324	2.25	0.83	3.24E-05
141	46.65	6.53	3.75	53.06	4.88E+12	0.0195	1.42	0.89	1.95E-05
142	41.06	5.44	5.49	57.90	5.96E+12	0.0275	1.79	0.86	2.75E-05
143	34.34	4.70	6.73	54.67	7.14E+12	0.0304	2.16	0.84	3.04E-05
144	37.12	6.42	7.15	48.84	7.37E+12	0.0321	2.25	0.83	3.21E-05
145	68.06	2.99	1.77	57.50	3.85E+12	0.0118	1.05	0.92	1.18E-05
146	43.18	6.73	7.38	33.64	7.43E+12	0.0324	2.27	0.82	3.24E-05
147	59.21	7.54	2.05	53.67	3.95E+12	0.0122	1.08	0.92	1.22E-05
148	55.31	2.22	3.23	59.02	4.87E+12	0.0191	1.41	0.90	1.91E-05
149	33.83	3.09	6.14	30.89	5.49E+12	0.0232	1.63	0.83	2.32E-05
150	42.63	5.02	6.99	38.06	7.29E+12	0.0316	2.22	0.83	3.16E-05
151	52.64	3.35	5.55	34.75	5.98E+12	0.0279	1.80	0.86	2.79E-05
152	60.95	7.83	6.05	51.57	7.02E+12	0.0362	2.18	0.84	3.62E-05
153	37.12	6.31	5.82	44.51	5.70E+12	0.0254	1.70	0.86	2.54E-05
154	35.84	6.71	5.94	43.80	5.71E+12	0.0253	1.71	0.85	2.53E-05
155	50.08	5.74	4.05	35.71	4.91E+12	0.0198	1.43	0.88	1.98E-05
156	52.41	4.69	1.84	51.52	3.64E+12	0.0101	0.98	0.92	1.01E-05
157	59.07	5.41	4.29	38.44	5.32E+12	0.0237	1.57	0.87	2.37E-05
158	66.49	3.70	1.06	46.16	3.28E+12	0.0065	0.84	0.93	6.55E-06
159	45.11	5.14	7.21	59.70	8.13E+12	0.0383	2.52	0.82	3.83E-05
160	40.82	2.51	3.56	49.55	4.57E+12	0.0170	1.30	0.89	1.70E-05
161	53.53	3.24	5.08	32.91	5.75E+12	0.0255	1.72	0.86	2.55E-05
162	67.96	3.91	2.40	54.62	4.31E+12	0.0157	1.22	0.90	1.57E-05
163	64.85	4.63	7.99	54.01	9.63E+12	0.0506	3.06	0.81	5.06E-05
164	50.96	2.72	4.80	34.11	5.52E+12	0.0236	1.63	0.88	2.36E-05
165	56.25	3.22	5.53	59.29	6.64E+12	0.0331	2.04	0.85	3.31E-05
166	67.47	6.93	5.85	30.96	6.70E+12	0.0338	2.06	0.85	3.38E-05
167	60.46	6.39	3.81	30.04	4.98E+12	0.0203	1.45	0.89	2.03E-05
168	30.66	2.28	3.47	43.04	4.20E+12	0.0138	1.17	0.89	1.38E-05
169	69.98	2.58	5.07	57.57	6.78E+12	0.0343	2.08	0.86	3.43E-05
170	68.41	7.37	6.69	58.66	8.88E+12	0.0446	2.78	0.85	4.46E-05
171	45.62	2.16	4.95	51.13	5.44E+12	0.0253	1.62	0.87	2.53E-05
172	39.42	7.83	3.90	30.96	4.48E+12	0.0159	1.27	0.86	1.59E-05
173	49.16	3.86	4.26	47.65	5.19E+12	0.0222	1.53	0.85	2.22E-05
174	47.51	7.17	3.22	35.84	4.45E+12	0.0152	1.26	0.88	1.52E-05
175	38.40	5.33	4.34	47.90	4.87E+12	0.0198	1.42	0.87	1.98E-05
176	57.66	5.53	7.25	58.13	8.76E+12	0.0436	2.74	0.83	4.36E-05
177	55.38	2.21	4.20	41.35	5.17E+12	0.0227	1.53	0.89	2.27E-05
178	32.09	3.79	7.78	39.76	6.12E+12	0.0307	1.91	0.82	3.07E-05
179	44.85	6.51	7.01	35.80	7.42E+12	0.0320	2.26	0.82	3.20E-05
180	31.90	5.02	6.97	38.13	6.69E+12	0.0270	2.00	0.84	2.70E-05
181	57.84	2.04	2.22	52.59	4.00E+12	0.0131	1.10	0.91	1.31E-05
182	40.42	5.35	7.33	37.21	7.30E+12	0.0319	2.22	0.83	3.19E-05
183	32.88	7.32	3.93	55.64	4.67E+12	0.0174	1.34	0.86	1.74E-05
184	47.59	2.23	4.42	58.78	5.34E+12	0.0241	1.59	0.87	2.41E-05
185	37.88	4.71	2.85	36.18	3.81E+12	0.0119	1.04	0.91	1.19E-05
186	55.75	7.02	7.29	43.08	8.31E+12	0.0396	2.58	0.82	3.96E-05

187	66.75	3.43	3.17	31.63	4.79E+12	0.0183	1.38	0.90	1.83E-05
188	30.04	7.77	5.03	33.12	4.97E+12	0.0180	1.43	0.84	1.80E-05
189	33.56	3.52	4.27	36.31	4.50E+12	0.0168	1.28	0.88	1.68E-05
190	31.61	4.44	7.72	43.67	6.77E+12	0.0311	2.10	0.82	3.11E-05
191	64.67	3.42	4.40	30.44	5.43E+12	0.0247	1.62	0.87	2.47E-05
192	56.34	2.78	4.93	35.54	5.82E+12	0.0260	1.74	0.87	2.60E-05
193	42.21	6.58	7.84	46.13	7.92E+12	0.0370	2.45	0.82	3.70E-05
194	55.70	6.66	5.57	47.33	6.39E+12	0.0310	1.95	0.85	3.10E-05
195	31.14	5.86	6.65	51.26	6.88E+12	0.0280	2.07	0.84	2.80E-05
196	48.39	3.98	6.59	42.71	7.45E+12	0.0330	2.27	0.85	3.30E-05
197	41.55	2.77	1.82	46.69	3.44E+12	0.0086	0.91	0.92	8.62E-06
198	37.36	4.69	4.64	42.18	5.15E+12	0.0201	1.50	0.87	2.01E-05
199	41.97	3.96	3.80	40.35	4.60E+12	0.0173	1.32	0.89	1.73E-05
200	58.64	2.56	2.09	30.40	3.78E+12	0.0110	1.03	0.91	1.10E-05
201	35.71	7.80	5.56	41.99	5.52E+12	0.0233	1.64	0.85	2.33E-05
202	45.06	3.40	3.26	45.62	4.50E+12	0.0160	1.28	0.89	1.60E-05
203	63.84	6.43	3.24	38.54	4.87E+12	0.0188	1.40	0.89	1.88E-05
204	54.73	2.15	6.08	31.58	6.01E+12	0.0308	1.84	0.86	3.08E-05
205	38.89	7.76	4.16	48.95	4.83E+12	0.0191	1.40	0.87	1.91E-05
206	69.43	6.02	7.95	58.15	9.88E+12	0.0534	3.15	0.82	5.34E-05
207	32.26	6.99	2.91	45.26	3.82E+12	0.0119	1.05	0.90	1.19E-05
208	66.43	6.01	7.76	30.14	8.77E+12	0.0442	2.75	0.83	4.42E-05
209	69.53	4.11	6.40	44.96	8.41E+12	0.0406	2.61	0.85	4.06E-05
210	63.50	7.82	4.70	35.68	5.95E+12	0.0267	1.78	0.87	2.67E-05
211	68.45	4.69	1.38	53.08	3.51E+12	0.0090	0.93	0.93	9.00E-06
212	55.54	7.11	6.89	54.44	8.31E+12	0.0397	2.58	0.84	3.97E-05
213	49.43	3.70	6.53	41.32	7.42E+12	0.0328	2.26	0.85	3.28E-05
214	36.43	2.39	1.16	56.08	3.09E+12	0.0055	0.78	0.94	5.46E-06
215	50.74	2.17	7.27	47.04	7.53E+12	0.0384	2.35	0.83	3.84E-05
216	63.17	7.46	2.10	37.79	3.93E+12	0.0120	1.08	0.91	1.20E-05
217	33.99	3.95	1.64	54.50	3.31E+12	0.0074	0.86	0.92	7.37E-06
218	48.45	6.97	7.56	36.22	7.84E+12	0.0362	2.42	0.83	3.62E-05
219	33.09	2.52	5.67	56.90	5.46E+12	0.0256	1.64	0.85	2.56E-05
220	39.94	2.46	7.90	58.22	7.55E+12	0.0393	2.36	0.83	3.93E-05
221	43.03	3.55	5.53	54.90	5.99E+12	0.0280	1.80	0.86	2.80E-05
222	53.78	6.20	4.90	58.61	6.13E+12	0.0284	1.85	0.87	2.84E-05
223	37.47	3.16	5.15	57.72	5.70E+12	0.0248	1.70	0.85	2.48E-05
224	31.11	6.70	7.03	31.81	6.58E+12	0.0254	1.97	0.82	2.54E-05
225	58.06	4.52	1.87	59.14	3.76E+12	0.0114	1.02	0.93	1.14E-05
226	32.00	3.19	3.60	39.85	4.25E+12	0.0142	1.19	0.88	1.42E-05
227	49.26	2.94	4.44	30.10	4.96E+12	0.0208	1.45	0.87	2.08E-05
228	45.79	3.47	2.63	32.74	3.84E+12	0.0120	1.06	0.91	1.20E-05
229	40.76	3.30	4.68	49.74	5.40E+12	0.0223	1.59	0.88	2.23E-05
230	41.85	3.06	6.41	48.25	6.66E+12	0.0307	2.03	0.84	3.07E-05
231	42.88	6.79	1.52	33.45	3.19E+12	0.0067	0.82	0.93	6.67E-06
232	41.69	4.19	4.47	40.08	4.91E+12	0.0202	1.43	0.86	2.02E-05
233	33.14	7.43	1.49	44.39	3.14E+12	0.0061	0.80	0.93	6.13E-06

234	66.09	2.54	1.41	36.39	3.40E+12	0.0083	0.89	0.93	8.31E-06
235	62.33	3.51	5.42	36.73	6.33E+12	0.0307	1.93	0.86	3.07E-05
236	40.25	3.40	2.92	55.92	4.07E+12	0.0144	1.14	0.92	1.44E-05
237	47.32	4.85	4.14	55.52	5.14E+12	0.0220	1.52	0.88	2.20E-05
238	39.19	2.71	1.03	47.96	3.03E+12	0.0048	0.76	0.93	4.77E-06
239	38.35	2.30	1.15	46.83	3.07E+12	0.0052	0.78	0.93	5.20E-06
240	66.90	7.72	5.21	53.55	6.74E+12	0.0334	2.07	0.85	3.34E-05
241	46.72	7.92	6.64	50.62	7.66E+12	0.0339	2.35	0.83	3.39E-05
242	48.33	3.38	2.39	41.73	3.83E+12	0.0119	1.05	0.92	1.19E-05
243	39.02	4.48	1.22	57.67	3.15E+12	0.0060	0.80	0.94	5.99E-06
244	46.51	2.02	5.69	30.78	5.51E+12	0.0259	1.65	0.85	2.59E-05
245	43.92	5.31	3.57	52.08	4.71E+12	0.0179	1.35	0.89	1.79E-05
246	48.21	2.01	5.19	51.43	5.69E+12	0.0273	1.72	0.86	2.73E-05
247	33.87	2.28	3.91	48.80	4.53E+12	0.0170	1.29	0.88	1.70E-05
248	57.08	6.88	6.61	30.68	7.64E+12	0.0340	2.34	0.84	3.40E-05
249	43.12	5.10	1.77	49.93	3.46E+12	0.0087	0.92	0.92	8.66E-06
250	52.78	7.48	3.99	48.54	5.12E+12	0.0216	1.50	0.89	2.16E-05
251	69.90	5.44	5.75	51.98	7.16E+12	0.0378	2.23	0.85	3.78E-05
252	61.23	4.25	3.34	53.35	5.06E+12	0.0204	1.47	0.88	2.04E-05
253	38.01	3.31	7.89	56.75	7.39E+12	0.0379	2.30	0.83	3.79E-05
254	43.30	6.87	3.04	33.40	3.99E+12	0.0134	1.11	0.90	1.34E-05
255	54.97	2.10	5.91	46.63	6.20E+12	0.0327	1.90	0.87	3.27E-05
256	55.90	3.22	2.90	37.00	4.19E+12	0.0154	1.18	0.91	1.54E-05
257	45.26	3.55	1.57	40.50	3.32E+12	0.0075	0.86	0.93	7.46E-06
258	39.61	2.44	7.36	39.61	6.78E+12	0.0323	2.08	0.83	3.23E-05
259	66.19	2.19	6.66	37.41	7.72E+12	0.0395	2.41	0.84	3.95E-05
260	64.15	2.53	6.22	56.58	7.01E+12	0.0397	2.20	0.86	3.97E-05
261	38.92	4.22	3.48	57.65	4.61E+12	0.0170	1.31	0.89	1.70E-05
262	63.37	3.61	4.46	49.86	5.70E+12	0.0273	1.71	0.88	2.73E-05
263	50.71	6.83	4.19	37.72	5.03E+12	0.0208	1.48	0.87	2.08E-05
264	41.16	2.19	3.64	57.62	4.72E+12	0.0183	1.36	0.89	1.83E-05
265	53.49	7.13	4.64	42.39	5.71E+12	0.0245	1.69	0.87	2.45E-05
266	59.81	7.24	7.34	39.30	8.42E+12	0.0408	2.62	0.83	4.08E-05
267	51.67	6.69	4.45	47.40	5.30E+12	0.0237	1.57	0.88	2.37E-05
268	31.47	7.19	5.91	50.20	5.66E+12	0.0248	1.69	0.85	2.48E-05
269	53.84	7.71	4.99	58.36	6.19E+12	0.0288	1.87	0.86	2.88E-05
270	69.68	4.28	6.03	51.34	7.34E+12	0.0395	2.29	0.85	3.95E-05
271	52.09	4.89	1.65	42.11	3.45E+12	0.0086	0.91	0.93	8.58E-06
272	40.85	5.34	6.54	43.46	7.16E+12	0.0299	2.17	0.83	2.99E-05
273	63.48	7.25	7.93	49.74	9.31E+12	0.0483	2.95	0.82	4.83E-05
274	31.05	6.16	2.87	49.84	3.82E+12	0.0120	1.05	0.91	1.20E-05
275	58.29	7.86	7.13	39.56	8.29E+12	0.0390	2.58	0.82	3.90E-05
276	42.74	3.03	1.41	45.09	3.21E+12	0.0067	0.83	0.93	6.71E-06
277	63.64	6.63	5.82	33.42	6.57E+12	0.0327	2.02	0.85	3.27E-05
278	68.67	3.31	5.40	56.77	6.92E+12	0.0359	2.14	0.87	3.59E-05
279	61.85	5.98	2.82	43.40	4.36E+12	0.0164	1.24	0.91	1.64E-05
280	40.60	4.82	6.27	47.12	6.14E+12	0.0293	1.86	0.84	2.93E-05

281	42.71	5.37	6.96	54.39	7.64E+12	0.0349	2.34	0.85	3.49E-05
282	54.93	3.61	5.01	57.52	6.22E+12	0.0293	1.88	0.86	2.93E-05
283	48.68	5.47	5.33	42.01	5.88E+12	0.0266	1.76	0.86	2.66E-05
284	36.62	4.14	3.73	42.79	4.46E+12	0.0160	1.27	0.88	1.60E-05
285	31.17	5.83	1.63	45.76	3.22E+12	0.0066	0.83	0.92	6.59E-06
286	32.55	3.84	3.62	52.41	4.45E+12	0.0158	1.26	0.88	1.58E-05
287	53.98	3.74	1.52	47.62	3.38E+12	0.0083	0.89	0.94	8.34E-06
288	54.16	2.47	5.62	42.47	5.98E+12	0.0301	1.82	0.85	3.01E-05
289	69.13	2.52	4.59	41.00	6.14E+12	0.0285	1.85	0.88	2.85E-05
290	62.08	2.76	7.44	34.55	7.87E+12	0.0416	2.47	0.83	4.16E-05
291	31.00	4.65	5.14	46.54	5.25E+12	0.0210	1.54	0.85	2.10E-05
292	32.14	7.29	2.34	46.60	3.60E+12	0.0096	0.96	0.91	9.64E-06
293	55.46	7.22	2.80	48.40	4.28E+12	0.0156	1.21	0.90	1.56E-05
294	38.54	2.66	1.96	57.32	3.51E+12	0.0095	0.94	0.93	9.54E-06
295	39.05	2.57	6.78	30.23	6.24E+12	0.0277	1.88	0.84	2.77E-05
296	44.90	5.65	2.37	49.11	3.84E+12	0.0118	1.05	0.91	1.18E-05
297	44.04	6.44	2.76	52.08	4.06E+12	0.0138	1.13	0.91	1.38E-05
298	58.42	4.88	3.83	35.25	4.98E+12	0.0206	1.45	0.90	2.06E-05
299	35.68	3.32	5.71	37.97	5.50E+12	0.0235	1.63	0.85	2.35E-05
300	49.11	2.32	6.06	51.10	6.25E+12	0.0322	1.92	0.83	3.22E-05
301	39.64	5.58	3.72	38.73	4.48E+12	0.0162	1.27	0.89	1.62E-05
302	67.13	2.42	6.34	52.54	7.15E+12	0.0408	2.25	0.85	4.08E-05
303	33.73	7.97	3.91	39.66	4.44E+12	0.0156	1.26	0.87	1.56E-05
304	59.63	2.00	6.62	31.36	7.18E+12	0.0354	2.21	0.85	3.54E-05
305	31.43	2.74	5.25	44.61	5.24E+12	0.0213	1.53	0.86	2.13E-05
306	63.80	4.59	4.22	37.31	5.40E+12	0.0244	1.61	0.88	2.44E-05
307	54.28	5.32	3.79	41.49	4.93E+12	0.0201	1.44	0.90	2.01E-05
308	46.80	4.78	4.98	46.91	5.72E+12	0.0251	1.70	0.87	2.51E-05
309	32.46	2.57	5.10	49.30	5.31E+12	0.0217	1.56	0.86	2.17E-05
310	36.67	5.56	6.81	55.67	7.31E+12	0.0319	2.22	0.85	3.19E-05
311	40.56	6.08	1.17	48.61	3.11E+12	0.0055	0.79	0.93	5.51E-06
312	57.13	5.54	2.78	52.88	4.34E+12	0.0162	1.23	0.91	1.62E-05
313	62.36	7.49	3.00	40.45	4.46E+12	0.0173	1.28	0.90	1.73E-05
314	37.31	7.99	2.67	50.15	3.88E+12	0.0121	1.07	0.91	1.21E-05
315	40.39	2.49	5.46	45.47	5.41E+12	0.0252	1.62	0.86	2.52E-05
316	67.65	2.83	2.51	47.75	4.28E+12	0.0159	1.21	0.92	1.59E-05
317	54.41	6.29	7.43	56.04	8.66E+12	0.0427	2.71	0.82	4.27E-05
318	62.78	3.07	7.90	35.88	8.25E+12	0.0448	2.61	0.82	4.48E-05
319	60.38	2.07	2.16	58.97	4.07E+12	0.0135	1.13	0.91	1.35E-05
320	47.73	7.64	1.58	32.31	3.33E+12	0.0073	0.86	0.93	7.33E-06
321	59.29	6.09	6.05	34.46	6.57E+12	0.0327	2.02	0.84	3.27E-05
322	61.76	7.24	1.47	59.11	3.51E+12	0.0092	0.93	0.94	9.23E-06
323	48.16	4.25	2.54	32.77	3.84E+12	0.0119	1.05	0.92	1.19E-05
324	44.04	6.46	4.86	48.74	5.58E+12	0.0239	1.65	0.88	2.39E-05
325	39.34	3.32	2.02	53.40	3.54E+12	0.0097	0.94	0.92	9.70E-06
326	39.53	4.88	6.80	37.74	7.02E+12	0.0294	2.12	0.84	2.94E-05
327	56.01	7.30	2.11	55.06	3.96E+12	0.0123	1.09	0.90	1.23E-05

328	35.93	4.14	2.01	43.11	3.41E+12	0.0086	0.90	0.92	8.58E-06
329	36.21	7.55	5.96	34.77	5.54E+12	0.0239	1.64	0.85	2.39E-05
330	58.36	6.77	4.73	31.50	5.74E+12	0.0248	1.71	0.86	2.48E-05
331	54.65	7.26	6.98	58.70	8.38E+12	0.0407	2.60	0.85	4.07E-05
332	35.46	4.73	6.72	53.63	7.23E+12	0.0306	2.19	0.83	3.06E-05
333	52.60	2.86	1.26	46.65	3.26E+12	0.0068	0.85	0.92	6.81E-06
334	54.05	6.01	6.45	33.23	7.44E+12	0.0326	2.26	0.85	3.26E-05
335	65.42	2.27	7.16	59.20	8.47E+12	0.0467	2.68	0.85	4.67E-05
336	59.09	4.08	3.78	32.57	4.93E+12	0.0202	1.44	0.90	2.02E-05
337	50.16	4.82	5.17	35.58	5.73E+12	0.0253	1.71	0.86	2.53E-05
338	48.26	2.88	6.29	34.80	5.97E+12	0.0300	1.83	0.83	3.00E-05
339	43.41	5.90	1.08	49.02	3.10E+12	0.0053	0.78	0.93	5.28E-06
340	41.15	3.20	6.18	39.10	5.93E+12	0.0276	1.79	0.85	2.76E-05
341	40.46	5.64	4.18	32.14	4.62E+12	0.0176	1.33	0.88	1.76E-05
342	57.97	7.09	2.67	52.71	4.29E+12	0.0157	1.21	0.92	1.57E-05
343	43.99	7.56	7.06	59.19	7.96E+12	0.0368	2.46	0.83	3.68E-05
344	51.02	7.00	6.26	42.39	6.51E+12	0.0321	2.00	0.84	3.21E-05
345	35.28	6.72	7.81	43.07	7.44E+12	0.0329	2.28	0.82	3.29E-05
346	65.17	2.62	7.11	55.96	8.43E+12	0.0456	2.67	0.83	4.56E-05
347	62.27	4.59	6.60	46.08	8.36E+12	0.0392	2.60	0.82	3.92E-05
348	64.53	6.07	1.89	34.60	3.70E+12	0.0108	1.00	0.92	1.08E-05
349	51.23	5.30	2.77	48.02	4.16E+12	0.0148	1.17	0.91	1.48E-05
350	49.31	6.59	4.04	54.18	5.14E+12	0.0218	1.51	0.88	2.18E-05
351	62.57	5.69	1.94	51.79	3.82E+12	0.0119	1.04	0.92	1.19E-05
352	67.17	5.45	5.31	45.54	6.63E+12	0.0330	2.03	0.86	3.30E-05
353	49.95	3.45	3.61	57.30	4.95E+12	0.0200	1.44	0.88	2.00E-05
354	44.95	6.76	2.81	44.25	4.02E+12	0.0136	1.12	0.91	1.36E-05
355	67.11	5.75	2.90	48.96	4.56E+12	0.0183	1.31	0.91	1.83E-05
356	39.72	7.63	7.94	33.28	7.45E+12	0.0331	2.28	0.82	3.31E-05
357	64.01	2.66	1.76	42.74	3.66E+12	0.0105	0.98	0.94	1.05E-05
358	30.50	7.68	2.99	32.61	3.71E+12	0.0108	1.01	0.88	1.08E-05
359	43.53	6.08	2.76	34.10	3.87E+12	0.0123	1.06	0.91	1.23E-05
360	32.42	6.28	7.17	43.62	7.01E+12	0.0291	2.12	0.82	2.91E-05
361	59.50	4.59	2.47	42.88	4.09E+12	0.0141	1.14	0.92	1.41E-05
362	33.77	7.58	6.31	47.80	5.89E+12	0.0268	1.77	0.84	2.68E-05
363	38.59	4.91	5.63	36.84	5.53E+12	0.0239	1.64	0.86	2.39E-05
364	44.75	5.50	6.45	31.23	6.96E+12	0.0286	2.10	0.84	2.86E-05
365	37.25	7.43	1.01	54.71	NaN	0.0047	0.00	NaN	4.73E-06
366	37.42	5.84	5.63	42.22	5.58E+12	0.0243	1.66	0.86	2.43E-05
367	64.96	6.60	4.78	44.73	6.22E+12	0.0289	1.88	0.86	2.89E-05
368	60.76	4.66	4.48	42.03	5.51E+12	0.0257	1.64	0.88	2.57E-05
369	65.02	6.22	4.56	36.55	5.63E+12	0.0265	1.69	0.87	2.65E-05
370	43.77	5.36	6.94	33.90	7.22E+12	0.0309	2.19	0.83	3.09E-05
371	42.98	4.04	1.35	35.91	3.14E+12	0.0061	0.80	0.93	6.06E-06
372	40.28	5.39	4.72	52.13	5.49E+12	0.0227	1.62	0.86	2.27E-05
373	50.48	5.06	5.77	56.07	6.44E+12	0.0319	1.97	0.86	3.19E-05
374	54.80	3.92	4.55	50.41	5.52E+12	0.0256	1.65	0.87	2.56E-05

375	69.82	4.89	2.53	50.84	4.38E+12	0.0166	1.25	0.91	1.66E-05
376	50.15	6.04	6.39	45.24	7.53E+12	0.0331	2.30	0.84	3.31E-05
377	48.04	5.03	6.10	59.51	6.70E+12	0.0335	2.06	0.83	3.35E-05
378	44.61	2.18	2.66	35.28	3.85E+12	0.0121	1.06	0.91	1.21E-05
379	36.89	5.57	3.45	49.46	4.44E+12	0.0156	1.26	0.89	1.56E-05
380	59.59	4.26	6.38	54.99	8.20E+12	0.0386	2.53	0.84	3.86E-05
381	39.78	7.44	4.81	51.72	5.48E+12	0.0228	1.61	0.87	2.28E-05
382	52.91	3.04	4.23	39.71	5.15E+12	0.0220	1.51	0.86	2.20E-05
383	44.41	3.93	4.35	46.86	5.02E+12	0.0213	1.47	0.88	2.13E-05
384	58.39	5.30	5.83	38.28	6.43E+12	0.0319	1.96	0.86	3.19E-05
385	58.94	5.92	4.32	38.24	5.33E+12	0.0237	1.58	0.87	2.37E-05
386	52.12	3.25	1.07	50.87	3.17E+12	0.0059	0.81	0.93	5.86E-06
387	56.99	5.78	3.75	37.15	4.94E+12	0.0200	1.43	0.89	2.00E-05
388	51.19	3.18	7.14	46.73	7.46E+12	0.0378	2.32	0.83	3.78E-05
389	38.47	6.84	7.80	31.28	7.31E+12	0.0315	2.23	0.81	3.15E-05
390	47.01	7.47	5.52	51.06	6.11E+12	0.0284	1.85	0.85	2.84E-05
391	52.04	3.65	5.02	44.86	5.89E+12	0.0266	1.77	0.86	2.66E-05
392	48.62	3.73	7.46	41.85	7.34E+12	0.0373	2.28	0.84	3.73E-05
393	58.50	6.11	2.73	57.84	4.39E+12	0.0165	1.25	0.90	1.65E-05
394	65.65	6.35	6.85	55.22	8.78E+12	0.0438	2.74	0.85	4.38E-05
395	41.25	7.52	4.33	54.74	5.04E+12	0.0213	1.47	0.88	2.13E-05
396	67.56	7.79	7.73	55.42	9.53E+12	0.0503	3.02	0.83	5.03E-05
397	33.07	4.23	6.00	37.82	5.54E+12	0.0237	1.65	0.83	2.37E-05
398	68.51	7.61	5.54	49.56	6.88E+12	0.0354	2.12	0.86	3.54E-05
399	48.28	5.50	1.56	55.46	3.45E+12	0.0084	0.91	0.93	8.39E-06
400	48.90	5.85	4.62	37.26	5.45E+12	0.0225	1.60	0.87	2.25E-05
401	64.38	6.72	3.40	53.39	5.15E+12	0.0213	1.51	0.90	2.13E-05
402	49.50	2.59	1.21	44.41	3.18E+12	0.0062	0.82	0.93	6.23E-06
403	39.29	4.96	6.73	32.53	6.83E+12	0.0279	2.05	0.84	2.79E-05
404	62.82	6.25	2.23	31.30	3.92E+12	0.0123	1.08	0.92	1.23E-05
405	34.29	2.89	6.37	39.53	6.08E+12	0.0260	1.82	0.84	2.60E-05
406	56.59	3.19	7.08	31.66	7.37E+12	0.0366	2.29	0.82	3.66E-05
407	50.01	2.81	6.15	36.91	6.02E+12	0.0304	1.84	0.84	3.04E-05
408	56.82	2.36	4.36	49.77	5.43E+12	0.0250	1.62	0.88	2.50E-05
409	49.32	6.95	1.89	54.76	3.63E+12	0.0102	0.98	0.92	1.02E-05
410	65.09	3.60	5.93	54.29	7.09E+12	0.0377	2.20	0.86	3.77E-05
411	65.27	3.82	5.65	58.18	6.98E+12	0.0367	2.16	0.86	3.67E-05
412	47.27	6.22	2.29	31.93	3.70E+12	0.0105	1.00	0.91	1.05E-05
413	49.86	3.10	4.85	42.36	5.64E+12	0.0247	1.67	0.88	2.47E-05
414	64.20	4.08	1.09	48.65	3.29E+12	0.0067	0.85	0.92	6.70E-06
415	32.31	7.82	5.92	52.74	5.75E+12	0.0255	1.72	0.85	2.55E-05
416	46.41	7.00	2.41	59.95	3.99E+12	0.0130	1.10	0.91	1.30E-05
417	61.06	3.53	7.40	31.45	7.69E+12	0.0402	2.40	0.84	4.02E-05
418	59.86	5.98	5.66	42.45	6.47E+12	0.0321	1.98	0.86	3.21E-05
419	30.76	5.22	1.48	39.57	3.08E+12	0.0057	0.78	0.93	5.69E-06
420	42.31	7.90	6.32	48.42	6.30E+12	0.0302	1.92	0.83	3.02E-05
421	51.49	2.13	1.20	32.90	3.13E+12	0.0059	0.80	0.94	5.90E-06

422	40.68	6.26	5.28	52.35	5.78E+12	0.0255	1.73	0.85	2.55E-05
423	68.58	6.83	4.12	43.68	5.62E+12	0.0257	1.68	0.86	2.57E-05
424	52.70	4.47	1.11	53.14	3.21E+12	0.0062	0.82	0.93	6.18E-06
425	48.78	2.80	4.24	45.89	5.09E+12	0.0218	1.49	0.87	2.18E-05
426	52.26	5.42	2.69	44.84	4.12E+12	0.0143	1.15	0.91	1.43E-05
427	59.20	5.73	3.50	51.32	5.04E+12	0.0207	1.47	0.89	2.07E-05
428	55.07	6.58	4.85	32.87	5.71E+12	0.0247	1.70	0.87	2.47E-05
429	63.32	2.93	5.48	58.54	6.80E+12	0.0350	2.09	0.87	3.50E-05
430	64.42	3.49	4.15	38.82	5.41E+12	0.0243	1.61	0.88	2.43E-05
431	53.26	7.96	6.86	57.42	8.29E+12	0.0391	2.57	0.83	3.91E-05
432	59.98	6.63	3.12	53.95	4.91E+12	0.0188	1.42	0.89	1.88E-05
433	58.72	6.49	2.61	52.02	4.26E+12	0.0154	1.20	0.92	1.54E-05
434	50.11	6.88	1.09	56.17	3.20E+12	0.0060	0.82	0.93	5.99E-06
435	58.79	4.83	3.11	51.18	4.83E+12	0.0183	1.39	0.89	1.83E-05
436	51.96	5.65	1.13	47.83	3.21E+12	0.0061	0.82	0.92	6.06E-06
437	38.23	2.38	5.98	55.81	5.77E+12	0.0287	1.75	0.86	2.87E-05
438	66.72	5.08	8.00	40.70	9.39E+12	0.0483	2.98	0.80	4.83E-05
439	57.30	5.48	5.99	34.66	6.50E+12	0.0317	1.99	0.83	3.17E-05
440	33.19	4.93	3.38	30.76	4.09E+12	0.0126	1.13	0.90	1.26E-05
441	61.62	3.27	2.59	46.45	4.23E+12	0.0153	1.19	0.92	1.53E-05
442	64.96	7.84	5.85	53.01	7.02E+12	0.0367	2.18	0.86	3.67E-05
443	36.19	7.67	7.57	39.90	7.30E+12	0.0315	2.23	0.82	3.15E-05
444	63.70	7.52	3.14	56.38	5.04E+12	0.0198	1.46	0.88	1.98E-05
445	40.00	4.40	3.67	57.98	4.71E+12	0.0182	1.35	0.89	1.82E-05
446	44.59	4.43	4.48	53.81	5.21E+12	0.0229	1.54	0.87	2.29E-05
447	38.48	3.27	7.38	44.77	6.89E+12	0.0330	2.12	0.82	3.30E-05
448	42.84	3.60	7.67	43.18	7.19E+12	0.0360	2.23	0.83	3.60E-05
449	60.13	3.90	3.89	40.56	5.16E+12	0.0220	1.51	0.88	2.20E-05
450	42.92	2.04	2.60	55.57	3.98E+12	0.0132	1.10	0.91	1.32E-05
451	68.33	6.81	1.13	50.96	3.38E+12	0.0073	0.88	0.92	7.29E-06
452	46.14	6.53	5.39	53.51	6.08E+12	0.0279	1.83	0.85	2.79E-05
453	50.86	5.90	3.16	59.55	4.79E+12	0.0178	1.37	0.88	1.78E-05
454	46.03	6.90	1.54	31.12	3.28E+12	0.0069	0.85	0.92	6.94E-06
455	64.59	5.95	3.39	30.08	4.84E+12	0.0189	1.40	0.90	1.89E-05
456	50.65	6.13	1.74	37.29	3.46E+12	0.0086	0.91	0.92	8.64E-06
457	64.30	5.34	4.03	55.01	5.60E+12	0.0255	1.68	0.87	2.55E-05
458	60.68	7.12	4.09	45.05	5.38E+12	0.0237	1.59	0.87	2.37E-05
459	34.99	6.12	1.15	55.17	3.08E+12	0.0053	0.78	0.93	5.26E-06
460	51.38	3.46	6.34	43.97	6.54E+12	0.0331	2.01	0.85	3.31E-05
461	31.22	2.65	6.75	41.70	6.13E+12	0.0267	1.84	0.83	2.67E-05
462	67.40	2.12	2.72	39.66	4.36E+12	0.0165	1.24	0.90	1.65E-05
463	66.26	3.88	7.05	41.24	8.63E+12	0.0426	2.70	0.83	4.26E-05
464	34.04	5.23	2.68	58.52	3.89E+12	0.0124	1.07	0.92	1.24E-05
465	56.92	6.26	5.44	47.21	6.37E+12	0.0307	1.94	0.85	3.07E-05
466	64.69	7.28	7.47	56.96	9.26E+12	0.0477	2.92	0.83	4.77E-05
467	40.96	7.23	2.84	44.66	3.96E+12	0.0130	1.10	0.90	1.30E-05
468	46.29	7.61	6.44	56.11	7.62E+12	0.0338	2.33	0.85	3.38E-05

469	32.97	6.03	1.87	53.26	3.39E+12	0.0082	0.89	0.93	8.19E-06
470	32.07	6.65	4.06	52.23	4.63E+12	0.0174	1.33	0.87	1.74E-05
471	31.83	7.75	6.50	59.83	7.07E+12	0.0292	2.13	0.84	2.92E-05
472	56.75	6.74	5.10	32.10	5.93E+12	0.0264	1.78	0.85	2.64E-05
473	57.40	2.37	7.12	30.21	7.39E+12	0.0369	2.29	0.82	3.69E-05
474	47.96	5.79	5.70	45.60	6.11E+12	0.0288	1.85	0.86	2.88E-05
475	52.50	2.46	4.06	45.91	5.09E+12	0.0218	1.49	0.88	2.18E-05
476	46.57	2.41	4.67	33.84	5.37E+12	0.0217	1.58	0.85	2.17E-05
477	35.74	5.76	4.09	39.09	4.55E+12	0.0169	1.30	0.87	1.69E-05
478	37.60	6.33	2.86	40.06	3.85E+12	0.0122	1.06	0.91	1.22E-05
479	33.51	3.18	2.74	53.73	3.84E+12	0.0122	1.05	0.91	1.22E-05
480	30.29	5.74	2.14	33.79	3.38E+12	0.0078	0.89	0.91	7.80E-06
481	43.22	5.18	6.76	49.34	7.52E+12	0.0331	2.30	0.83	3.31E-05
482	67.27	4.79	7.53	39.46	8.92E+12	0.0455	2.80	0.83	4.55E-05
483	47.68	6.13	1.40	46.52	3.27E+12	0.0071	0.85	0.93	7.07E-06
484	64.07	6.25	2.41	39.20	4.12E+12	0.0141	1.15	0.91	1.41E-05
485	45.96	4.86	1.67	32.28	3.33E+12	0.0076	0.87	0.93	7.58E-06
486	54.62	6.32	1.43	41.76	3.36E+12	0.0076	0.88	0.91	7.64E-06
487	66.67	4.52	2.27	33.24	4.02E+12	0.0132	1.11	0.92	1.32E-05
488	42.40	6.91	6.79	53.30	7.56E+12	0.0336	2.31	0.84	3.36E-05
489	46.47	3.99	1.83	54.18	3.56E+12	0.0096	0.95	0.92	9.59E-06
490	62.90	7.65	2.19	38.39	3.97E+12	0.0125	1.09	0.91	1.25E-05
491	50.62	2.06	6.01	42.20	6.12E+12	0.0309	1.88	0.83	3.09E-05
492	34.42	2.95	4.32	47.49	4.72E+12	0.0187	1.36	0.87	1.87E-05
493	31.57	4.26	3.59	54.84	4.42E+12	0.0157	1.25	0.89	1.57E-05
494	54.22	3.35	3.58	41.16	4.84E+12	0.0190	1.40	0.88	1.90E-05
495	53.37	5.56	3.47	46.04	4.82E+12	0.0187	1.39	0.89	1.87E-05
496	56.16	6.52	1.53	55.70	3.53E+12	0.0089	0.93	0.93	8.92E-06
497	30.87	7.89	5.34	58.25	5.55E+12	0.0234	1.64	0.85	2.34E-05
498	51.13	2.74	5.97	55.72	6.31E+12	0.0333	1.94	0.85	3.33E-05
499	46.24	2.91	7.18	37.41	7.02E+12	0.0340	2.16	0.82	3.40E-05
500	35.55	7.04	7.92	42.65	7.49E+12	0.0333	2.30	0.82	3.33E-05
501	68.28	6.11	5.35	42.83	6.66E+12	0.0331	2.04	0.86	3.31E-05
502	53.59	2.12	6.09	48.89	6.41E+12	0.0336	1.98	0.83	3.36E-05
503	34.39	4.21	1.59	31.60	3.15E+12	0.0061	0.81	0.93	6.11E-06
504	33.02	2.34	2.49	45.94	3.64E+12	0.0104	0.98	0.92	1.04E-05
505	62.19	7.98	4.66	43.72	6.02E+12	0.0271	1.81	0.87	2.71E-05
506	42.33	3.49	7.60	54.63	7.41E+12	0.0380	2.30	0.84	3.80E-05
507	48.50	2.24	3.76	50.07	4.86E+12	0.0198	1.41	0.90	1.98E-05
508	57.71	7.95	5.38	38.04	6.21E+12	0.0290	1.88	0.85	2.90E-05
509	66.15	5.19	4.07	49.24	5.61E+12	0.0255	1.68	0.86	2.55E-05
510	37.21	3.37	1.45	53.57	3.22E+12	0.0068	0.83	0.93	6.75E-06
511	58.21	6.95	1.12	39.92	3.23E+12	0.0061	0.83	0.91	6.15E-06
512	69.05	3.00	4.37	37.34	5.64E+12	0.0266	1.69	0.87	2.66E-05
513	56.46	4.84	4.77	41.46	5.85E+12	0.0260	1.75	0.87	2.60E-05
514	43.74	4.48	6.17	40.77	6.09E+12	0.0288	1.85	0.84	2.88E-05
515	53.21	2.48	4.88	54.89	6.00E+12	0.0277	1.80	0.87	2.77E-05

516	52.00	7.86	7.04	35.01	7.74E+12	0.0349	2.38	0.83	3.49E-05
517	43.37	3.83	1.36	44.13	3.19E+12	0.0065	0.82	0.92	6.49E-06
518	46.18	4.16	3.46	38.17	4.52E+12	0.0164	1.29	0.90	1.64E-05
519	57.51	7.11	1.65	48.56	3.59E+12	0.0094	0.96	0.92	9.43E-06
520	42.05	6.84	3.74	52.93	4.74E+12	0.0184	1.36	0.89	1.84E-05
521	30.98	6.55	2.51	48.93	3.66E+12	0.0104	0.99	0.91	1.04E-05
522	53.12	7.40	4.80	46.08	5.87E+12	0.0257	1.75	0.86	2.57E-05
523	55.82	5.58	6.99	41.97	8.06E+12	0.0379	2.49	0.84	3.79E-05
524	31.69	5.86	5.46	50.51	5.47E+12	0.0231	1.62	0.85	2.31E-05
525	52.46	7.94	2.50	44.91	4.01E+12	0.0132	1.11	0.91	1.32E-05
526	57.02	6.37	1.91	45.38	3.68E+12	0.0107	0.99	0.92	1.07E-05
527	68.85	5.07	1.34	55.27	3.50E+12	0.0089	0.93	0.93	8.88E-06
528	36.40	7.74	2.62	39.25	3.74E+12	0.0109	1.02	0.91	1.09E-05
529	46.22	7.87	1.58	35.16	3.32E+12	0.0073	0.86	0.93	7.29E-06
530	34.83	3.80	5.22	59.46	5.64E+12	0.0245	1.68	0.86	2.45E-05
531	39.72	5.71	1.97	57.93	3.55E+12	0.0097	0.95	0.93	9.73E-06
532	49.75	7.56	5.32	47.26	6.05E+12	0.0276	1.82	0.85	2.76E-05
533	55.66	2.75	6.02	48.86	6.41E+12	0.0340	1.98	0.85	3.40E-05
534	58.10	3.11	6.00	36.78	6.52E+12	0.0325	2.00	0.85	3.25E-05
535	37.04	7.32	6.12	41.59	5.81E+12	0.0261	1.74	0.84	2.61E-05
536	68.24	4.12	3.77	31.01	5.14E+12	0.0221	1.51	0.91	2.21E-05
537	30.25	4.91	2.47	39.02	3.53E+12	0.0094	0.95	0.91	9.40E-06
538	69.94	5.88	7.07	54.46	9.12E+12	0.0470	2.87	0.84	4.70E-05
539	30.33	3.66	2.24	40.21	3.46E+12	0.0087	0.92	0.92	8.65E-06
540	59.53	4.07	4.11	35.41	5.20E+12	0.0225	1.53	0.87	2.25E-05
541	37.56	4.93	2.86	41.90	3.86E+12	0.0124	1.06	0.91	1.24E-05
542	53.34	5.96	6.15	42.25	6.50E+12	0.0325	1.99	0.85	3.25E-05
543	56.08	7.86	3.97	53.23	5.26E+12	0.0228	1.55	0.89	2.28E-05
544	64.63	3.69	7.56	57.12	8.72E+12	0.0485	2.77	0.83	4.85E-05
545	41.83	4.99	7.62	51.61	7.92E+12	0.0371	2.45	0.83	3.71E-05
546	46.72	2.07	2.64	59.08	4.10E+12	0.0143	1.15	0.92	1.43E-05
547	36.99	4.71	7.32	42.69	7.28E+12	0.0316	2.22	0.82	3.16E-05
548	30.73	5.25	4.28	44.24	4.57E+12	0.0171	1.31	0.86	1.71E-05
549	38.10	4.29	7.54	34.63	7.18E+12	0.0313	2.18	0.83	3.13E-05
550	49.21	3.43	7.55	45.78	7.60E+12	0.0389	2.37	0.82	3.89E-05
551	69.76	3.38	6.71	46.50	8.66E+12	0.0430	2.70	0.85	4.30E-05
552	47.70	5.81	1.25	35.23	3.15E+12	0.0059	0.80	0.93	5.93E-06
553	34.74	3.17	6.68	34.87	6.10E+12	0.0265	1.83	0.83	2.65E-05
554	58.55	4.84	2.04	38.19	3.81E+12	0.0112	1.03	0.92	1.12E-05
555	41.68	3.48	2.28	40.95	3.67E+12	0.0104	0.99	0.91	1.04E-05
556	36.70	5.71	6.56	32.70	6.65E+12	0.0262	1.99	0.84	2.62E-05
557	44.53	6.24	5.84	44.91	6.04E+12	0.0282	1.82	0.85	2.82E-05
558	48.83	4.09	7.72	42.54	8.05E+12	0.0388	2.49	0.84	3.88E-05
559	44.47	4.67	1.47	32.81	3.19E+12	0.0066	0.82	0.91	6.57E-06
560	32.87	2.21	2.93	39.06	3.76E+12	0.0117	1.03	0.91	1.17E-05
561	60.71	7.35	4.71	42.30	5.97E+12	0.0269	1.79	0.88	2.69E-05
562	58.86	3.30	3.10	42.95	4.72E+12	0.0175	1.35	0.89	1.75E-05

563	50.50	2.79	2.94	47.44	4.21E+12	0.0155	1.18	0.91	1.55E-05
564	68.72	7.20	7.97	37.88	9.26E+12	0.0483	2.93	0.82	4.83E-05
565	57.34	7.59	3.85	55.77	5.27E+12	0.0228	1.55	0.88	2.28E-05
566	31.73	2.67	3.36	54.51	4.32E+12	0.0147	1.21	0.89	1.47E-05
567	55.21	4.06	6.87	47.35	8.09E+12	0.0382	2.50	0.84	3.82E-05
568	51.96	6.93	5.36	56.71	6.33E+12	0.0301	1.92	0.85	3.01E-05
569	45.18	6.04	4.71	52.19	5.62E+12	0.0240	1.66	0.87	2.40E-05
570	42.03	3.89	4.42	59.66	5.18E+12	0.0227	1.53	0.87	2.27E-05
571	40.52	3.75	6.19	50.06	6.20E+12	0.0295	1.89	0.83	2.95E-05
572	43.27	3.50	3.38	43.92	4.48E+12	0.0160	1.27	0.90	1.60E-05
573	68.62	3.56	3.83	46.20	5.38E+12	0.0242	1.60	0.91	2.42E-05
574	36.75	3.93	6.82	49.60	7.17E+12	0.0308	2.17	0.84	3.08E-05
575	62.95	2.05	1.34	57.04	3.44E+12	0.0085	0.91	0.92	8.47E-06
576	34.53	2.83	5.37	49.99	5.50E+12	0.0237	1.63	0.87	2.37E-05
577	43.52	7.91	1.66	50.70	3.42E+12	0.0082	0.90	0.93	8.17E-06
578	58.90	4.75	5.67	43.52	6.47E+12	0.0321	1.98	0.86	3.21E-05
579	34.23	2.14	6.49	50.93	6.41E+12	0.0286	1.94	0.83	2.86E-05
580	38.39	4.24	5.47	54.22	5.81E+12	0.0260	1.74	0.85	2.60E-05
581	45.46	5.37	1.92	30.46	3.43E+12	0.0086	0.90	0.92	8.55E-06
582	42.40	7.01	1.73	50.76	3.43E+12	0.0084	0.90	0.93	8.41E-06
583	30.09	7.78	3.20	40.67	4.09E+12	0.0122	1.13	0.88	1.22E-05
584	41.28	4.12	5.68	47.40	5.85E+12	0.0268	1.76	0.86	2.68E-05
585	39.26	6.54	4.43	41.57	4.83E+12	0.0195	1.40	0.87	1.95E-05
586	61.19	3.91	2.48	58.03	4.25E+12	0.0155	1.20	0.92	1.55E-05
587	67.75	5.04	6.84	56.83	8.90E+12	0.0451	2.79	0.85	4.51E-05
588	49.57	4.42	1.68	57.45	3.54E+12	0.0093	0.94	0.92	9.30E-06
589	51.29	2.69	2.06	47.04	3.78E+12	0.0110	1.03	0.91	1.10E-05
590	47.37	7.80	5.60	49.28	6.15E+12	0.0286	1.86	0.85	2.86E-05
591	57.12	6.80	2.96	33.35	4.23E+12	0.0155	1.19	0.91	1.55E-05
592	66.85	6.48	3.13	34.47	4.84E+12	0.0183	1.39	0.89	1.83E-05
593	41.56	7.39	7.66	59.24	8.20E+12	0.0388	2.55	0.82	3.88E-05
594	54.54	2.30	6.25	38.96	6.26E+12	0.0330	1.93	0.85	3.30E-05
595	43.61	7.35	7.48	55.31	8.11E+12	0.0379	2.51	0.82	3.79E-05
596	45.68	4.51	1.16	48.68	3.15E+12	0.0058	0.80	0.93	5.82E-06
597	41.38	4.81	2.18	51.86	3.73E+12	0.0106	1.01	0.90	1.06E-05
598	42.17	2.51	2.94	56.81	4.14E+12	0.0149	1.16	0.91	1.49E-05
599	51.81	5.94	6.48	36.72	7.42E+12	0.0325	2.26	0.85	3.25E-05
600	48.72	3.56	7.70	34.89	7.32E+12	0.0369	2.27	0.82	3.69E-05
601	48.10	2.50	3.06	46.81	4.47E+12	0.0157	1.27	0.91	1.57E-05
602	61.75	4.62	1.71	42.52	3.61E+12	0.0099	0.97	0.93	9.90E-06
603	63.59	7.13	5.97	46.43	6.92E+12	0.0358	2.14	0.85	3.58E-05
604	58.81	4.01	7.42	31.55	8.18E+12	0.0393	2.54	0.83	3.93E-05
605	65.81	2.69	1.45	38.25	3.43E+12	0.0086	0.90	0.94	8.62E-06
606	60.88	4.61	5.30	58.92	6.67E+12	0.0331	2.05	0.85	3.31E-05
607	58.19	4.38	7.28	35.78	8.19E+12	0.0392	2.54	0.83	3.92E-05
608	49.71	3.34	2.64	50.26	4.08E+12	0.0140	1.14	0.92	1.40E-05
609	60.73	3.73	2.52	59.42	4.27E+12	0.0158	1.21	0.92	1.58E-05

610	50.57	3.85	6.95	53.79	8.01E+12	0.0380	2.47	0.85	3.80E-05
611	68.75	3.94	6.51	54.06	8.68E+12	0.0428	2.71	0.85	4.28E-05
612	52.53	2.42	7.58	34.58	7.40E+12	0.0380	2.30	0.84	3.80E-05
613	67.69	4.73	4.62	42.91	6.16E+12	0.0285	1.86	0.87	2.85E-05
614	52.21	5.88	6.40	46.37	7.65E+12	0.0341	2.34	0.84	3.41E-05
615	59.73	3.02	2.09	43.24	3.89E+12	0.0119	1.07	0.91	1.19E-05
616	47.05	6.17	5.45	40.63	5.86E+12	0.0264	1.76	0.86	2.64E-05
617	66.31	3.86	1.64	34.71	3.58E+12	0.0096	0.95	0.93	9.58E-06
618	33.39	2.14	5.32	55.76	5.31E+12	0.0240	1.58	0.85	2.40E-05
619	41.32	7.15	3.10	32.63	4.22E+12	0.0132	1.17	0.88	1.32E-05
620	34.52	4.94	5.12	57.79	5.58E+12	0.0237	1.66	0.85	2.37E-05
621	38.73	7.49	6.11	42.13	5.94E+12	0.0268	1.79	0.83	2.68E-05
622	42.09	3.36	1.01	59.73	NaN	0.0052	0.00	NaN	5.22E-06
623	46.99	2.31	3.14	56.13	4.62E+12	0.0168	1.32	0.89	1.68E-05
624	62.71	7.73	1.18	50.32	3.33E+12	0.0072	0.87	0.93	7.18E-06
625	56.16	6.18	4.92	35.97	5.83E+12	0.0258	1.74	0.86	2.58E-05
626	64.12	2.90	2.20	34.07	3.95E+12	0.0125	1.09	0.91	1.25E-05
627	66.01	7.27	6.71	59.39	8.83E+12	0.0438	2.76	0.84	4.38E-05
628	65.94	5.68	6.28	45.27	7.29E+12	0.0385	2.28	0.82	3.85E-05
629	52.96	4.29	6.17	34.30	6.32E+12	0.0310	1.93	0.85	3.10E-05
630	40.78	4.46	1.49	39.12	3.18E+12	0.0066	0.82	0.93	6.63E-06
631	62.84	4.92	7.50	46.59	8.90E+12	0.0449	2.80	0.83	4.49E-05
632	52.31	4.72	5.41	51.07	6.22E+12	0.0297	1.89	0.86	2.97E-05
633	35.03	4.76	1.07	56.55	3.06E+12	0.0050	0.77	0.92	4.95E-06
634	45.38	2.49	6.35	44.45	6.66E+12	0.0310	2.03	0.85	3.10E-05
635	66.46	3.67	5.24	36.97	6.36E+12	0.0311	1.94	0.87	3.11E-05
636	44.20	2.82	2.32	33.56	3.66E+12	0.0104	0.99	0.91	1.04E-05
637	41.03	2.27	3.51	39.37	4.43E+12	0.0157	1.25	0.89	1.57E-05
638	60.59	4.90	7.26	35.12	8.34E+12	0.0400	2.60	0.82	4.00E-05
639	39.82	5.66	5.09	32.46	5.28E+12	0.0213	1.55	0.86	2.13E-05
640	53.08	7.14	6.94	35.64	7.80E+12	0.0351	2.40	0.82	3.51E-05
641	48.87	6.16	3.25	39.43	4.53E+12	0.0160	1.28	0.89	1.60E-05
642	65.54	3.71	2.97	41.65	4.48E+12	0.0178	1.28	0.92	1.78E-05
643	38.78	5.75	5.29	33.20	5.33E+12	0.0219	1.57	0.86	2.19E-05
644	57.78	6.49	1.99	41.87	3.71E+12	0.0110	1.01	0.92	1.10E-05
645	54.45	6.67	1.10	50.40	3.21E+12	0.0061	0.82	0.93	6.14E-06
646	67.76	3.15	7.71	34.84	8.42E+12	0.0457	2.67	0.82	4.57E-05
647	49.53	6.27	7.65	45.68	8.24E+12	0.0394	2.56	0.82	3.94E-05
648	32.77	3.64	2.46	34.99	3.54E+12	0.0095	0.95	0.91	9.46E-06
649	62.41	4.27	1.98	36.34	3.73E+12	0.0112	1.01	0.92	1.12E-05
650	38.17	4.53	6.55	51.73	7.18E+12	0.0305	2.17	0.84	3.05E-05
651	67.82	7.60	3.95	39.97	5.40E+12	0.0240	1.61	0.89	2.40E-05
652	36.36	4.33	6.53	57.34	7.29E+12	0.0309	2.21	0.82	3.09E-05
653	56.37	3.75	6.21	48.30	6.79E+12	0.0351	2.10	0.85	3.51E-05
654	55.01	2.89	1.60	46.96	3.50E+12	0.0089	0.92	0.93	8.86E-06
655	32.66	7.33	7.60	33.75	6.97E+12	0.0286	2.11	0.81	2.86E-05
656	38.61	5.39	7.79	41.42	7.54E+12	0.0340	2.31	0.82	3.40E-05

657	43.65	5.77	7.86	37.49	7.79E+12	0.0358	2.40	0.81	3.58E-05
658	49.14	3.57	3.28	40.32	4.56E+12	0.0163	1.30	0.88	1.63E-05
659	56.43	4.78	2.23	32.03	3.82E+12	0.0115	1.04	0.92	1.15E-05
660	61.42	2.94	3.23	40.50	4.81E+12	0.0185	1.38	0.89	1.85E-05
661	37.35	4.95	2.75	43.35	3.84E+12	0.0120	1.05	0.90	1.20E-05
662	49.04	3.40	4.25	40.90	5.03E+12	0.0212	1.47	0.87	2.12E-05
663	54.88	7.53	3.00	55.17	4.46E+12	0.0172	1.28	0.90	1.72E-05
664	49.02	7.42	2.31	54.24	3.94E+12	0.0124	1.08	0.91	1.24E-05
665	43.36	6.64	1.57	54.55	3.40E+12	0.0079	0.89	0.93	7.93E-06
666	48.99	5.97	3.97	58.58	5.15E+12	0.0219	1.52	0.88	2.19E-05
667	66.54	5.64	5.88	32.30	6.70E+12	0.0339	2.06	0.85	3.39E-05
668	51.44	6.56	4.13	46.98	5.15E+12	0.0219	1.52	0.88	2.19E-05
669	34.78	7.44	7.82	43.99	7.45E+12	0.0328	2.28	0.81	3.28E-05
670	42.13	5.91	6.23	43.22	6.12E+12	0.0289	1.86	0.84	2.89E-05
671	40.92	4.68	3.27	57.03	4.56E+12	0.0163	1.30	0.88	1.63E-05
672	62.07	6.85	7.36	41.47	8.63E+12	0.0424	2.70	0.83	4.24E-05
673	55.12	6.59	1.12	51.84	3.26E+12	0.0063	0.84	0.92	6.34E-06
674	31.24	2.98	4.31	43.87	4.56E+12	0.0173	1.31	0.87	1.73E-05
675	44.69	3.87	2.88	53.83	4.14E+12	0.0147	1.16	0.90	1.47E-05
676	62.01	7.31	6.02	31.75	6.66E+12	0.0329	2.05	0.83	3.29E-05
677	53.47	7.70	1.92	55.38	3.71E+12	0.0109	1.00	0.92	1.09E-05
678	58.46	3.80	3.89	51.90	5.26E+12	0.0229	1.55	0.88	2.29E-05
679	52.93	4.54	1.81	46.77	3.59E+12	0.0098	0.96	0.92	9.78E-06
680	60.30	3.97	4.54	30.87	5.40E+12	0.0244	1.61	0.86	2.44E-05
681	55.20	2.08	6.20	49.63	6.50E+12	0.0349	2.02	0.85	3.49E-05
682	61.16	4.34	5.88	35.09	6.54E+12	0.0326	2.00	0.85	3.26E-05
683	53.69	7.74	1.31	32.37	3.23E+12	0.0065	0.83	0.93	6.53E-06
684	64.50	5.07	2.11	32.67	3.90E+12	0.0120	1.07	0.92	1.20E-05
685	61.93	6.36	1.50	47.57	3.48E+12	0.0089	0.92	0.93	8.94E-06
686	57.52	3.98	3.55	31.96	4.80E+12	0.0186	1.38	0.88	1.86E-05
687	62.30	2.49	2.97	43.15	4.42E+12	0.0174	1.26	0.92	1.74E-05
688	60.25	4.94	4.53	56.50	5.75E+12	0.0278	1.73	0.88	2.78E-05
689	51.86	6.43	1.78	46.78	3.58E+12	0.0095	0.96	0.91	9.46E-06
690	60.33	7.19	2.84	48.09	4.38E+12	0.0167	1.24	0.91	1.67E-05
691	47.19	4.46	4.79	50.79	5.73E+12	0.0248	1.71	0.86	2.48E-05
692	69.29	3.75	3.53	58.87	5.40E+12	0.0238	1.60	0.89	2.38E-05
693	47.80	6.80	6.90	56.44	7.92E+12	0.0370	2.44	0.85	3.70E-05
694	44.13	4.17	3.87	50.31	4.83E+12	0.0193	1.40	0.88	1.93E-05
695	58.02	4.18	6.57	36.76	7.78E+12	0.0355	2.39	0.84	3.55E-05
696	60.98	2.02	6.06	32.09	6.29E+12	0.0331	1.94	0.85	3.31E-05
697	44.51	2.67	4.21	38.10	4.82E+12	0.0196	1.40	0.88	1.96E-05
698	41.11	5.28	2.73	47.71	3.95E+12	0.0129	1.09	0.90	1.29E-05
699	37.06	6.30	7.81	44.80	7.56E+12	0.0342	2.32	0.82	3.42E-05
700	46.92	3.14	6.63	33.77	6.63E+12	0.0309	2.02	0.84	3.09E-05
701	49.46	4.36	3.02	31.11	4.09E+12	0.0143	1.15	0.90	1.43E-05
702	43.82	3.88	6.13	56.70	6.43E+12	0.0316	1.97	0.84	3.16E-05
703	40.00	7.99	2.38	58.01	3.85E+12	0.0117	1.05	0.91	1.17E-05

704	47.82	5.19	2.30	48.12	3.85E+12	0.0118	1.05	0.91	1.18E-05
705	35.63	2.11	3.41	39.24	4.24E+12	0.0142	1.19	0.90	1.42E-05
706	60.22	7.62	7.91	30.50	8.53E+12	0.0421	2.67	0.82	4.21E-05
707	53.29	4.31	6.74	37.69	7.68E+12	0.0347	2.36	0.84	3.47E-05
708	69.66	4.34	2.38	51.48	4.30E+12	0.0156	1.21	0.90	1.56E-05
709	33.60	7.84	2.15	39.73	3.50E+12	0.0086	0.93	0.90	8.61E-06
710	67.62	2.99	5.16	54.58	6.73E+12	0.0337	2.07	0.86	3.37E-05
711	59.66	4.55	6.18	46.38	6.91E+12	0.0358	2.14	0.84	3.58E-05
712	34.89	2.82	3.54	34.28	4.23E+12	0.0140	1.18	0.89	1.40E-05
713	59.15	7.93	4.01	32.70	5.12E+12	0.0214	1.51	0.87	2.14E-05
714	51.11	6.18	6.07	37.84	6.28E+12	0.0304	1.91	0.85	3.04E-05
715	55.79	4.61	5.21	44.30	6.12E+12	0.0286	1.85	0.86	2.86E-05
716	39.36	4.85	5.25	37.58	5.42E+12	0.0226	1.60	0.86	2.26E-05
717	49.77	5.25	4.12	36.90	4.92E+12	0.0202	1.43	0.88	2.02E-05
718	31.37	6.72	3.86	35.52	4.29E+12	0.0145	1.20	0.87	1.45E-05
719	47.11	7.68	4.01	47.98	4.98E+12	0.0203	1.46	0.88	2.03E-05
720	47.90	2.32	2.16	42.62	3.72E+12	0.0108	1.01	0.92	1.08E-05
721	44.98	4.19	7.87	49.40	8.11E+12	0.0394	2.52	0.84	3.94E-05
722	44.84	3.46	4.23	52.49	5.05E+12	0.0216	1.48	0.88	2.16E-05
723	44.68	7.70	2.33	32.51	3.68E+12	0.0103	0.99	0.91	1.03E-05
724	36.10	5.54	5.03	50.55	5.47E+12	0.0226	1.62	0.85	2.26E-05
725	30.06	6.38	7.14	31.52	6.14E+12	0.0254	1.87	0.82	2.54E-05
726	36.51	2.60	2.98	58.50	4.05E+12	0.0142	1.13	0.92	1.42E-05
727	33.93	4.03	3.88	34.01	4.35E+12	0.0151	1.23	0.87	1.51E-05
728	56.00	2.84	4.84	36.67	5.77E+12	0.0256	1.72	0.87	2.56E-05
729	39.51	7.10	4.46	49.49	5.00E+12	0.0208	1.46	0.86	2.08E-05
730	42.51	2.61	3.92	53.88	4.85E+12	0.0196	1.41	0.88	1.96E-05
731	68.25	2.16	3.69	33.50	5.12E+12	0.0219	1.50	0.90	2.19E-05
732	33.66	6.61	1.73	44.48	3.28E+12	0.0072	0.85	0.92	7.19E-06
733	64.34	5.01	4.69	48.17	6.17E+12	0.0287	1.86	0.88	2.87E-05
734	45.22	7.89	1.46	50.53	3.29E+12	0.0073	0.86	0.92	7.32E-06
735	57.20	7.50	2.27	31.22	3.86E+12	0.0117	1.06	0.91	1.17E-05
736	35.38	3.63	7.18	51.88	7.35E+12	0.0323	2.24	0.83	3.23E-05
737	58.24	6.96	4.94	32.94	5.85E+12	0.0261	1.75	0.87	2.61E-05
738	30.90	6.97	1.44	51.02	3.14E+12	0.0060	0.80	0.93	6.01E-06
739	63.97	5.17	3.04	48.50	4.59E+12	0.0186	1.32	0.90	1.86E-05
740	34.85	7.88	6.36	58.39	7.13E+12	0.0295	2.15	0.84	2.95E-05
741	46.10	5.21	3.18	41.06	4.45E+12	0.0153	1.26	0.88	1.53E-05
742	41.43	3.01	4.50	59.32	5.17E+12	0.0230	1.53	0.88	2.30E-05
743	43.95	4.98	2.56	43.48	3.88E+12	0.0122	1.06	0.91	1.22E-05
744	60.42	3.76	3.74	43.55	5.09E+12	0.0215	1.49	0.90	2.15E-05
745	59.95	3.25	4.49	59.93	5.76E+12	0.0280	1.73	0.88	2.80E-05
746	38.81	7.45	7.77	53.68	7.94E+12	0.0368	2.46	0.81	3.68E-05
747	59.40	3.05	4.90	55.99	6.26E+12	0.0298	1.90	0.87	2.98E-05
748	36.02	5.21	6.60	42.59	6.86E+12	0.0281	2.06	0.85	2.81E-05
749	67.01	7.29	4.61	37.90	6.07E+12	0.0274	1.82	0.87	2.74E-05
750	32.59	5.27	7.48	30.64	6.81E+12	0.0276	2.05	0.81	2.76E-05

751	65.62	7.36	5.74	46.23	6.85E+12	0.0351	2.11	0.86	3.51E-05
752	37.51	7.79	1.18	43.31	3.06E+12	0.0051	0.77	0.93	5.12E-06
753	42.86	6.52	5.04	38.57	5.52E+12	0.0229	1.63	0.85	2.29E-05
754	66.81	6.98	5.64	34.04	6.59E+12	0.0329	2.02	0.86	3.29E-05
755	30.45	6.00	1.94	32.20	3.23E+12	0.0070	0.84	0.92	6.98E-06
756	55.95	4.86	6.65	36.18	7.70E+12	0.0350	2.36	0.85	3.50E-05
757	59.25	6.74	1.42	49.20	3.44E+12	0.0083	0.91	0.92	8.30E-06
758	67.50	2.84	6.58	33.94	7.67E+12	0.0388	2.39	0.83	3.88E-05
759	59.46	5.69	2.03	59.81	3.88E+12	0.0125	1.07	0.92	1.25E-05
760	36.58	7.18	7.30	50.81	7.50E+12	0.0329	2.30	0.82	3.29E-05
761	48.57	2.39	5.14	37.10	5.43E+12	0.0250	1.62	0.86	2.50E-05
762	30.36	6.19	6.51	40.26	6.52E+12	0.0250	1.94	0.84	2.50E-05
763	61.28	7.34	6.22	30.24	6.66E+12	0.0335	2.05	0.84	3.35E-05
764	33.34	4.56	2.33	30.91	3.47E+12	0.0087	0.92	0.91	8.74E-06
765	34.59	5.46	1.96	46.25	3.39E+12	0.0084	0.89	0.93	8.38E-06
766	34.10	2.75	4.34	44.22	4.66E+12	0.0182	1.34	0.87	1.82E-05
767	30.71	7.72	7.10	47.13	7.03E+12	0.0287	2.13	0.81	2.87E-05
768	36.12	6.29	2.21	45.20	3.60E+12	0.0096	0.96	0.91	9.55E-06
769	56.22	7.77	2.17	40.19	3.88E+12	0.0117	1.06	0.90	1.17E-05
770	34.61	3.43	5.11	51.68	5.46E+12	0.0228	1.61	0.85	2.28E-05
771	51.78	5.29	6.92	43.86	7.83E+12	0.0362	2.41	0.84	3.62E-05
772	54.90	7.92	3.02	36.45	4.27E+12	0.0157	1.21	0.90	1.57E-05
773	65.33	2.04	4.38	49.03	5.52E+12	0.0273	1.66	0.88	2.73E-05
774	42.45	2.47	3.54	31.04	4.38E+12	0.0153	1.24	0.88	1.53E-05
775	59.79	5.45	1.19	38.00	3.25E+12	0.0066	0.84	0.93	6.61E-06
776	55.36	4.03	7.32	57.10	8.58E+12	0.0429	2.68	0.84	4.29E-05
777	38.15	6.75	2.13	30.52	3.49E+12	0.0085	0.92	0.90	8.54E-06
778	43.59	7.91	5.18	57.77	5.94E+12	0.0266	1.78	0.85	2.66E-05
779	33.23	2.10	4.52	54.82	4.75E+12	0.0202	1.39	0.85	2.02E-05
780	65.60	5.79	5.60	53.45	6.91E+12	0.0356	2.13	0.86	3.56E-05
781	63.12	7.76	1.90	40.61	3.73E+12	0.0110	1.01	0.93	1.10E-05
782	60.86	7.06	3.71	30.71	4.93E+12	0.0199	1.43	0.89	1.99E-05
783	33.29	5.23	7.23	31.89	6.77E+12	0.0273	2.03	0.82	2.73E-05
784	35.29	3.04	2.19	46.29	3.57E+12	0.0095	0.96	0.91	9.52E-06
785	45.04	5.04	2.00	39.41	3.51E+12	0.0094	0.94	0.92	9.41E-06
786	61.33	3.67	7.89	45.33	8.34E+12	0.0463	2.64	0.84	4.63E-05
787	46.78	7.95	7.37	55.49	8.19E+12	0.0387	2.54	0.83	3.87E-05
788	69.60	5.17	4.98	59.25	6.75E+12	0.0337	2.07	0.87	3.37E-05
789	31.76	4.42	4.68	36.40	4.92E+12	0.0179	1.42	0.86	1.79E-05
790	67.97	3.62	3.06	30.82	4.76E+12	0.0179	1.37	0.90	1.79E-05
791	56.60	2.34	4.92	55.93	5.87E+12	0.0291	1.77	0.88	2.91E-05
792	48.18	2.85	6.68	53.99	7.28E+12	0.0357	2.25	0.83	3.57E-05
793	45.55	5.95	3.30	58.99	4.72E+12	0.0175	1.35	0.88	1.75E-05
794	41.21	5.23	7.58	51.49	7.84E+12	0.0366	2.42	0.83	3.66E-05
795	65.89	2.33	3.62	38.72	5.11E+12	0.0215	1.49	0.89	2.15E-05
796	46.62	3.77	1.28	31.17	3.13E+12	0.0058	0.80	0.93	5.84E-06
797	37.76	4.44	1.51	38.32	3.15E+12	0.0064	0.81	0.93	6.39E-06

798	36.31	5.11	4.07	50.72	4.75E+12	0.0184	1.37	0.86	1.84E-05
799	44.29	4.64	4.66	45.71	5.46E+12	0.0226	1.61	0.87	2.26E-05
800	38.29	7.60	7.61	41.79	7.48E+12	0.0330	2.29	0.82	3.30E-05
801	30.94	2.63	2.62	36.02	3.58E+12	0.0099	0.96	0.91	9.86E-06
802	31.29	5.68	3.94	35.99	4.33E+12	0.0149	1.22	0.87	1.49E-05
803	33.71	3.29	3.43	53.73	4.38E+12	0.0153	1.24	0.90	1.53E-05
804	38.28	2.80	5.79	42.49	5.40E+12	0.0255	1.62	0.86	2.55E-05
805	61.38	6.47	4.57	52.27	5.78E+12	0.0277	1.74	0.87	2.77E-05
806	63.74	3.58	3.18	48.36	4.97E+12	0.0194	1.44	0.88	1.94E-05
807	57.90	3.47	3.80	38.50	4.98E+12	0.0207	1.45	0.90	2.07E-05
808	68.90	2.97	5.73	45.17	6.92E+12	0.0362	2.14	0.86	3.62E-05
809	67.54	4.48	3.51	51.59	5.27E+12	0.0226	1.55	0.89	2.26E-05
810	45.89	3.57	2.75	30.29	3.87E+12	0.0123	1.06	0.90	1.23E-05
811	34.27	4.15	7.67	48.45	7.43E+12	0.0332	2.27	0.83	3.32E-05
812	46.36	3.63	5.09	37.64	5.58E+12	0.0241	1.66	0.87	2.41E-05
813	47.85	7.06	6.14	37.35	6.21E+12	0.0294	1.89	0.84	2.94E-05
814	61.24	5.27	5.70	47.69	6.66E+12	0.0338	2.05	0.86	3.38E-05
815	40.06	6.28	1.95	36.82	3.40E+12	0.0084	0.90	0.93	8.42E-06
816	32.72	4.65	6.66	58.27	7.11E+12	0.0302	2.15	0.84	3.02E-05
817	66.21	5.52	6.93	33.60	8.32E+12	0.0401	2.58	0.84	4.01E-05
818	42.28	4.32	7.95	44.37	7.89E+12	0.0373	2.44	0.83	3.73E-05
819	35.20	7.51	6.90	54.11	7.33E+12	0.0312	2.23	0.82	3.12E-05
820	35.19	2.70	7.85	59.98	7.32E+12	0.0372	2.28	0.83	3.72E-05
821	53.95	6.09	5.95	40.72	6.37E+12	0.0313	1.94	0.86	3.13E-05
822	38.05	6.64	4.88	57.25	5.57E+12	0.0234	1.65	0.86	2.34E-05
823	68.37	2.55	2.44	56.94	4.33E+12	0.0162	1.23	0.92	1.62E-05
824	44.27	3.13	3.49	47.28	4.61E+12	0.0171	1.31	0.89	1.71E-05
825	65.75	5.59	5.12	32.37	6.24E+12	0.0294	1.89	0.86	2.94E-05
826	53.64	5.06	3.29	43.60	4.71E+12	0.0176	1.35	0.89	1.76E-05
827	37.77	4.14	7.52	45.83	7.52E+12	0.0336	2.30	0.82	3.36E-05
828	61.99	6.36	1.24	41.03	3.31E+12	0.0072	0.86	0.93	7.16E-06
829	35.08	4.35	4.65	45.31	5.12E+12	0.0200	1.49	0.88	2.00E-05
830	61.00	7.03	6.49	37.52	7.94E+12	0.0362	2.44	0.84	3.62E-05
831	34.14	4.01	4.37	44.32	4.68E+12	0.0184	1.35	0.87	1.84E-05
832	40.23	4.28	6.42	30.55	6.71E+12	0.0267	2.01	0.84	2.67E-05
833	35.09	7.20	2.36	45.43	3.64E+12	0.0101	0.98	0.91	1.01E-05
834	63.01	2.38	7.87	40.15	8.30E+12	0.0458	2.63	0.84	4.58E-05
835	67.90	3.69	7.09	35.19	8.64E+12	0.0422	2.70	0.82	4.22E-05
836	69.57	7.17	7.24	58.06	9.37E+12	0.0486	2.96	0.83	4.86E-05
837	64.18	5.82	5.49	51.77	6.74E+12	0.0342	2.07	0.86	3.42E-05
838	51.57	6.46	4.58	55.54	5.87E+12	0.0255	1.75	0.85	2.55E-05
839	67.88	4.54	2.83	52.50	4.56E+12	0.0183	1.31	0.91	1.83E-05
840	64.46	7.41	1.28	55.14	3.44E+12	0.0081	0.91	0.92	8.07E-06
841	66.78	5.89	5.87	33.32	6.70E+12	0.0341	2.06	0.86	3.41E-05
842	69.39	3.39	2.01	49.20	3.93E+12	0.0130	1.08	0.92	1.30E-05
843	64.26	6.41	1.86	45.96	3.75E+12	0.0112	1.02	0.93	1.12E-05
844	58.73	3.13	5.73	32.45	6.27E+12	0.0306	1.91	0.86	3.06E-05

845	65.70	3.23	1.39	38.90	3.40E+12	0.0083	0.89	0.94	8.27E-06
846	38.69	3.28	3.56	44.05	4.46E+12	0.0159	1.26	0.89	1.59E-05
847	45.35	2.97	5.61	34.38	5.72E+12	0.0257	1.71	0.86	2.57E-05
848	62.60	2.86	7.64	41.10	8.17E+12	0.0444	2.58	0.84	4.44E-05
849	61.91	3.77	5.38	53.92	6.62E+12	0.0331	2.03	0.86	3.31E-05
850	47.60	2.93	1.91	35.33	3.46E+12	0.0090	0.92	0.93	9.05E-06
851	58.15	3.53	4.83	50.22	6.08E+12	0.0281	1.83	0.87	2.81E-05
852	31.86	4.97	3.96	50.18	4.53E+12	0.0168	1.30	0.89	1.68E-05
853	63.24	5.20	3.87	56.31	5.44E+12	0.0244	1.61	0.88	2.44E-05
854	30.19	4.56	1.23	33.66	2.96E+12	0.0045	0.74	0.93	4.50E-06
855	49.68	6.82	6.55	38.94	7.45E+12	0.0324	2.27	0.84	3.24E-05
856	57.21	5.18	7.97	58.44	9.23E+12	0.0478	2.92	0.82	4.78E-05
857	52.39	2.20	2.71	52.05	4.19E+12	0.0150	1.18	0.91	1.50E-05
858	57.62	7.21	7.19	59.60	8.75E+12	0.0434	2.74	0.83	4.34E-05
859	69.23	6.75	7.68	53.18	9.49E+12	0.0503	3.01	0.83	5.03E-05
860	55.86	5.80	2.44	40.81	4.00E+12	0.0132	1.11	0.91	1.32E-05
861	40.10	4.36	1.06	46.93	3.05E+12	0.0049	0.77	0.93	4.92E-06
862	54.16	2.73	4.10	52.31	5.28E+12	0.0232	1.56	0.87	2.32E-05
863	41.91	3.81	1.69	59.87	3.46E+12	0.0087	0.91	0.93	8.67E-06
864	60.01	5.41	1.99	34.25	3.68E+12	0.0108	0.99	0.93	1.08E-05
865	64.75	5.70	4.40	39.32	5.55E+12	0.0259	1.66	0.88	2.59E-05
866	37.70	4.80	7.31	42.29	7.28E+12	0.0318	2.22	0.83	3.18E-05
867	41.63	7.47	2.46	54.12	3.88E+12	0.0121	1.07	0.91	1.21E-05
868	50.81	7.66	1.38	49.13	3.31E+12	0.0073	0.86	0.92	7.32E-06
869	49.83	2.61	3.46	56.58	4.83E+12	0.0191	1.40	0.90	1.91E-05
870	57.27	2.89	6.47	49.81	7.48E+12	0.0373	2.32	0.84	3.73E-05
871	30.83	6.40	2.55	56.20	3.76E+12	0.0111	1.03	0.91	1.11E-05
872	47.41	5.13	1.32	49.16	3.25E+12	0.0068	0.84	0.92	6.79E-06
873	39.11	7.07	3.08	30.34	4.13E+12	0.0125	1.15	0.89	1.25E-05
874	31.32	4.56	7.00	50.44	7.08E+12	0.0295	2.15	0.82	2.95E-05
875	50.33	7.26	6.28	37.47	6.38E+12	0.0310	1.95	0.84	3.10E-05
876	42.57	7.41	7.96	58.86	8.40E+12	0.0407	2.62	0.81	4.07E-05
877	56.79	5.05	2.71	36.46	4.14E+12	0.0144	1.16	0.90	1.44E-05
878	55.14	6.62	2.57	32.43	4.00E+12	0.0131	1.11	0.91	1.31E-05
879	37.90	5.33	3.42	57.18	4.55E+12	0.0164	1.30	0.89	1.64E-05
880	53.42	5.12	7.39	36.52	8.04E+12	0.0378	2.49	0.82	3.78E-05
881	52.18	5.81	5.26	47.53	6.10E+12	0.0283	1.84	0.86	2.83E-05
882	55.49	3.08	6.47	34.53	6.98E+12	0.0336	2.14	0.85	3.36E-05
883	36.86	4.77	4.74	51.38	5.33E+12	0.0217	1.56	0.87	2.17E-05
884	45.84	5.60	4.58	54.94	5.67E+12	0.0239	1.68	0.85	2.39E-05
885	69.73	5.15	3.31	53.48	5.26E+12	0.0219	1.54	0.88	2.19E-05
886	65.22	6.60	2.08	50.59	4.05E+12	0.0130	1.12	0.91	1.30E-05
887	37.16	7.53	3.70	58.89	4.70E+12	0.0177	1.35	0.88	1.77E-05
888	63.42	7.01	2.89	57.08	4.56E+12	0.0182	1.31	0.91	1.82E-05
889	61.49	7.03	2.58	41.21	4.20E+12	0.0148	1.18	0.91	1.48E-05
890	53.03	6.21	1.62	36.49	3.42E+12	0.0083	0.90	0.93	8.25E-06
891	50.40	5.72	3.42	33.10	4.56E+12	0.0165	1.30	0.90	1.65E-05

892	43.88	2.53	6.32	48.06	6.09E+12	0.0310	1.87	0.83	3.10E-05
893	62.50	7.47	4.82	31.72	5.92E+12	0.0265	1.77	0.87	2.65E-05
894	53.81	7.93	3.70	49.38	5.02E+12	0.0204	1.46	0.88	2.04E-05
895	30.60	3.95	4.91	33.99	4.88E+12	0.0181	1.40	0.87	1.81E-05
896	31.66	6.34	2.42	33.38	3.51E+12	0.0090	0.93	0.90	8.99E-06
897	32.36	4.05	6.09	40.11	5.57E+12	0.0242	1.66	0.84	2.42E-05
898	45.42	6.14	4.19	52.38	5.08E+12	0.0214	1.49	0.88	2.14E-05
899	32.93	4.99	5.00	46.28	5.24E+12	0.0209	1.53	0.86	2.09E-05
900	62.76	5.09	2.92	30.74	4.28E+12	0.0161	1.21	0.92	1.61E-05
901	36.24	5.43	1.21	31.70	3.00E+12	0.0048	0.75	0.93	4.76E-06
902	52.73	4.67	7.62	43.59	8.28E+12	0.0403	2.58	0.83	4.03E-05
903	52.82	6.10	5.18	34.35	5.82E+12	0.0260	1.74	0.86	2.60E-05
904	35.51	5.46	6.77	52.68	7.17E+12	0.0306	2.17	0.84	3.06E-05
905	69.33	6.38	2.25	55.60	4.24E+12	0.0149	1.19	0.92	1.49E-05
906	38.68	5.00	5.02	49.68	5.54E+12	0.0233	1.64	0.85	2.33E-05
907	61.83	5.15	3.20	40.84	4.81E+12	0.0184	1.38	0.89	1.84E-05
908	41.94	4.30	4.02	48.77	4.85E+12	0.0193	1.41	0.87	1.93E-05
909	44.33	2.40	1.02	47.24	3.06E+12	0.0050	0.77	0.94	5.02E-06
910	67.05	3.26	5.57	52.15	6.86E+12	0.0358	2.12	0.87	3.58E-05
911	41.79	6.86	7.71	37.68	7.62E+12	0.0342	2.34	0.81	3.42E-05
912	48.96	2.45	2.39	55.08	3.96E+12	0.0130	1.09	0.91	1.30E-05
913	50.25	5.02	1.75	39.82	3.47E+12	0.0088	0.92	0.92	8.81E-06
914	59.42	5.31	7.50	43.44	8.62E+12	0.0426	2.70	0.83	4.26E-05
915	65.31	3.72	5.64	48.18	6.81E+12	0.0349	2.10	0.86	3.49E-05
916	56.89	6.32	3.15	39.16	4.68E+12	0.0170	1.33	0.88	1.70E-05
917	65.39	2.34	2.53	44.67	4.23E+12	0.0154	1.19	0.92	1.54E-05
918	62.15	4.20	5.51	58.63	6.79E+12	0.0348	2.09	0.86	3.48E-05
919	60.49	4.04	3.63	41.92	5.03E+12	0.0207	1.46	0.89	2.07E-05
920	69.01	2.68	5.76	51.65	6.83E+12	0.0376	2.13	0.86	3.76E-05
921	61.48	2.78	7.41	42.85	8.07E+12	0.0430	2.54	0.83	4.30E-05
922	53.90	7.05	4.63	40.03	5.66E+12	0.0242	1.68	0.87	2.42E-05
923	51.63	4.23	3.07	46.02	4.56E+12	0.0163	1.30	0.90	1.63E-05
924	41.44	6.15	4.49	44.09	5.01E+12	0.0208	1.47	0.85	2.08E-05
925	44.09	6.69	4.22	43.79	4.93E+12	0.0201	1.44	0.88	2.01E-05
926	68.82	3.21	6.41	50.10	8.49E+12	0.0414	2.64	0.85	4.14E-05
927	45.16	3.16	5.05	52.46	5.81E+12	0.0258	1.74	0.86	2.58E-05
928	42.78	5.52	3.85	36.14	4.58E+12	0.0172	1.31	0.89	1.72E-05
929	31.54	6.98	7.39	31.19	6.75E+12	0.0268	2.03	0.81	2.68E-05
930	56.70	7.67	5.72	45.01	6.48E+12	0.0317	1.98	0.85	3.17E-05
931	54.50	4.97	5.86	53.20	6.57E+12	0.0333	2.02	0.86	3.33E-05
932	33.55	4.80	4.18	56.33	4.77E+12	0.0189	1.38	0.88	1.89E-05
933	56.04	3.10	2.26	43.34	3.91E+12	0.0124	1.08	0.92	1.24E-05
934	32.84	3.71	2.79	50.98	3.83E+12	0.0121	1.05	0.91	1.21E-05
935	50.90	6.69	1.71	51.29	3.54E+12	0.0092	0.94	0.92	9.23E-06
936	40.70	7.39	2.43	48.08	3.79E+12	0.0114	1.03	0.91	1.14E-05
937	32.48	2.26	3.81	30.03	4.19E+12	0.0141	1.18	0.89	1.41E-05
938	51.08	4.63	3.52	49.97	4.83E+12	0.0190	1.39	0.89	1.90E-05

939	60.82	3.07	5.05	35.55	6.09E+12	0.0280	1.84	0.85	2.80E-05
940	46.37	6.57	5.95	58.35	6.45E+12	0.0317	1.97	0.85	3.17E-05
941	50.80	3.84	2.08	47.86	3.79E+12	0.0111	1.03	0.91	1.11E-05
942	44.76	3.78	2.28	45.12	3.75E+12	0.0111	1.02	0.92	1.11E-05
943	50.56	5.62	6.29	48.23	6.65E+12	0.0333	2.05	0.83	3.33E-05
944	38.97	2.01	6.83	38.68	6.46E+12	0.0296	1.96	0.84	2.96E-05
945	51.33	7.71	7.04	52.82	8.19E+12	0.0384	2.54	0.83	3.84E-05
946	60.19	7.37	1.61	31.85	3.49E+12	0.0087	0.92	0.92	8.65E-06
947	45.85	2.29	5.14	31.35	5.24E+12	0.0233	1.55	0.85	2.33E-05
948	34.68	5.51	6.87	52.92	7.20E+12	0.0308	2.18	0.84	3.08E-05
949	39.56	7.57	5.43	40.42	5.56E+12	0.0238	1.65	0.86	2.38E-05
950	60.55	4.00	3.77	33.71	4.97E+12	0.0206	1.45	0.90	2.06E-05
951	47.20	2.58	3.05	41.13	4.38E+12	0.0149	1.24	0.91	1.49E-05
952	51.71	3.10	7.17	48.60	7.56E+12	0.0387	2.36	0.83	3.87E-05
953	49.90	5.60	3.08	31.43	4.37E+12	0.0147	1.23	0.90	1.47E-05
954	33.90	6.50	7.30	42.09	7.08E+12	0.0299	2.14	0.83	2.99E-05
955	63.00	5.99	7.63	37.59	8.70E+12	0.0436	2.73	0.83	4.36E-05
956	39.47	5.67	1.05	58.11	3.09E+12	0.0052	0.78	0.93	5.16E-06
957	66.59	4.77	7.44	44.16	8.99E+12	0.0456	2.83	0.83	4.56E-05
958	65.85	6.65	4.82	59.58	6.53E+12	0.0315	1.99	0.86	3.15E-05
959	46.52	3.54	1.00	47.09	NaN	0.0050	0.00	NaN	5.04E-06
960	49.98	4.37	3.11	45.41	4.55E+12	0.0161	1.29	0.89	1.61E-05
961	33.26	4.60	4.76	38.79	5.02E+12	0.0189	1.45	0.86	1.89E-05
962	44.38	4.38	7.79	58.72	8.36E+12	0.0409	2.61	0.82	4.09E-05
963	47.12	4.32	1.55	37.19	3.32E+12	0.0074	0.86	0.93	7.37E-06
964	57.47	5.38	6.96	40.56	8.12E+12	0.0381	2.51	0.83	3.81E-05
965	35.90	7.36	7.02	30.37	6.80E+12	0.0271	2.04	0.82	2.71E-05
966	30.21	4.41	1.61	36.12	3.13E+12	0.0060	0.80	0.93	5.98E-06
967	34.65	2.43	5.20	32.97	4.86E+12	0.0203	1.42	0.86	2.03E-05
968	32.00	5.78	6.78	59.05	7.17E+12	0.0305	2.17	0.84	3.05E-05
969	65.48	5.83	5.81	58.81	7.15E+12	0.0378	2.22	0.85	3.78E-05
970	65.14	7.69	5.51	56.47	6.86E+12	0.0352	2.11	0.86	3.52E-05
971	42.67	2.92	1.32	38.79	3.13E+12	0.0060	0.80	0.93	6.03E-06
972	43.69	4.74	1.29	51.94	3.21E+12	0.0065	0.83	0.93	6.47E-06
973	45.73	6.92	1.68	49.65	3.45E+12	0.0085	0.91	0.92	8.45E-06
974	39.21	3.59	4.87	52.63	5.48E+12	0.0232	1.62	0.87	2.32E-05
975	68.00	7.04	7.74	32.18	8.86E+12	0.0452	2.78	0.84	4.52E-05
976	58.98	6.44	2.70	33.16	4.15E+12	0.0144	1.16	0.91	1.44E-05
977	49.62	4.63	1.79	40.26	3.49E+12	0.0089	0.92	0.93	8.94E-06
978	34.17	7.56	4.38	57.81	4.90E+12	0.0201	1.43	0.87	2.01E-05
979	36.44	4.11	6.52	34.73	6.73E+12	0.0264	2.02	0.82	2.64E-05
980	62.52	4.06	2.36	37.04	4.04E+12	0.0134	1.12	0.91	1.34E-05
981	64.81	4.74	5.68	40.95	6.65E+12	0.0337	2.04	0.86	3.37E-05
982	60.11	4.96	1.79	58.76	3.77E+12	0.0111	1.02	0.91	1.11E-05
983	49.38	5.14	7.98	41.17	8.18E+12	0.0400	2.54	0.84	4.00E-05
984	61.66	4.57	2.22	44.98	4.01E+12	0.0130	1.11	0.91	1.30E-05
985	45.57	3.05	4.89	38.10	5.47E+12	0.0230	1.61	0.87	2.30E-05

986	37.64	2.88	5.00	30.32	5.12E+12	0.0200	1.49	0.86	2.00E-05
987	68.79	2.23	3.21	35.04	4.92E+12	0.0193	1.42	0.89	1.93E-05
988	33.43	2.71	7.77	36.06	6.55E+12	0.0304	2.00	0.82	3.04E-05
989	34.03	2.86	1.82	42.97	3.30E+12	0.0076	0.86	0.93	7.56E-06
990	60.08	3.34	6.62	56.64	8.48E+12	0.0406	2.64	0.82	4.06E-05
991	58.61	4.49	6.91	38.59	8.09E+12	0.0380	2.50	0.83	3.80E-05
992	35.43	2.24	3.36	44.53	4.29E+12	0.0145	1.20	0.89	1.45E-05
993	30.55	6.51	1.85	39.78	3.26E+12	0.0071	0.85	0.92	7.09E-06
994	63.79	7.16	7.45	45.65	8.95E+12	0.0446	2.81	0.82	4.46E-05
995	34.47	7.09	4.59	59.88	5.36E+12	0.0214	1.57	0.86	2.14E-05
996	53.17	2.44	4.16	59.76	5.36E+12	0.0242	1.59	0.89	2.42E-05
997	36.04	4.87	4.14	59.36	4.87E+12	0.0197	1.42	0.88	1.97E-05
998	66.00	5.49	6.86	35.87	8.29E+12	0.0401	2.57	0.85	4.01E-05
999	42.54	6.78	2.68	33.07	3.82E+12	0.0116	1.05	0.91	1.16E-05

Appendix L Design Alternatives with Emergy Results

Alternative	Picture	Description of Change(s)	DFM / DFA Principles Used
Original		N/A	N/A
A		- Combined base and supports into a single bent part	- Reduced part count by combining parts - Reduced number of welds
B		- Combined lugs and stiffener into single bent part	- Reduced part count by combining parts

C		<ul style="list-style-type: none"> - Replaced stiffener with a smaller, thicker part that could be made with a channel bending tool, but maintain the stiffness required 	<ul style="list-style-type: none"> - Reduce number of bend actions required for stiffener (can complete with channel tool) - Reduce weld length
D		<ul style="list-style-type: none"> - Split side flanges into two parts each to allow for better nesting 	<ul style="list-style-type: none"> - Improve sheet utilization and reduce in-part waste
E		<ul style="list-style-type: none"> - Merge combined parts from A and B together for a two part assembly 	<ul style="list-style-type: none"> - Reduce part count

F		<ul style="list-style-type: none"> - Merged all parts into a single bent part with no welds 	<ul style="list-style-type: none"> - Reduce part count - Remove all welds
G		<ul style="list-style-type: none"> - Retained changes from D - Split lug into two parts to all for better nesting - Combined half of lug with bracket replacement 	<ul style="list-style-type: none"> - Combine parts - Improve sheet utilization
H		<ul style="list-style-type: none"> - Reduced size, and removed bends for stiffener by thickening material for the base 	<ul style="list-style-type: none"> - Reduce number of bend actions required for stiffener (can complete with channel tool) - Reduce weld length - Improve nesting count - Reduce part (stiffener) mass

I		<ul style="list-style-type: none"> -Modified merged lugs and stiffener to removed bend by thickening part - Changed internal shape 	<ul style="list-style-type: none"> - Reduced part count by combining parts - Reduced number of welds - Reduce bend count
J		<ul style="list-style-type: none"> - Combined smaller stiffener from H with single part base from A 	<ul style="list-style-type: none"> - Reduced part count by combining parts - Reduced number of welds and weld length - Reduce mass of stiffener - Reduce number of bends

L.1 Alternative A Emergy

Figure L.1. The emergy values for design alternative A

L.2 Alternative B Emergy

(a) The emergy values for entire assembly.

(b) The emergy values for base merge part.

(c) The emergy values for side flange left hand part. (d) The emergy values for side flange right hand part.

Figure L.2. The emergy values for design alternative B.

(e) The emergy values for stiffener lugs merge part.

Continued Figure~L.2. The emergy values for design alternative B.

L.3 Alternative C Emergy

(a) The emergy values for entire assembly.

(b) The emergy values for base part.

(c) The emergy values for side flange left hand part.

(d) The emergy values for side flange right hand part.

Figure L.3. The emergy values for design alternative C.

(e) The emergy values for stiffener part.

(f) The emergy values for lug part.

Continued Figure~L.3. The emergy values for design alternative C.

L.4 Alternative D Emergy

(a) The emergy values for entire assembly.

(b) The emergy values for base part.

(c) The emergy values for brace left hand part.

(d) The emergy values for brace right hand part.

Figure L.4. The emergy values for design alternative D.

(e) The emergy values for stiffener part.

(f) The emergy values for lug part.

(g) The emergy values for bracket left hand part. (h) The emergy values for bracket right hand part.

Continued Figure~L.4. The emergy values for design alternative D.

L.5 Alternative E Emergy

(a) The emery values for entire assembly

(b) The emery values for stiffener lugs merge part.

(c) The emery values for base merge part

Figure L.5. The emery values for design alternative E.

L.6 Alternative F Emergy

Figure L.6. The emergy values for design alternative F.

L.7 Alternative G Emergy

(a) The emergy values for entire assembly.

(b) The emergy values for base part.

(c) The emergy values for brace left hand part. (d) The emergy values for brace right hand part.

Figure L.7. The emergy values for design alternative G.

Continued Figure~L.7. The emergy values for design alternative G.

L.8 Alternative H Emergy

(a) The emergy values for entire assembly.

(b) The emergy values for base part

(c) The emergy values for side flange left hand part. (d) The emergy values for side flange right hand part.

Figure L.8. The emergy values for design alternative H.

(e) The emergy values for stiffener part.

(f) The emergy values for lug part.

Continued Figure~L.8. The emergy values for design alternative H.

L.9 Alternative I Emergy

(a) The emergy values for entire assembly

(b) The emergy values for stiffener lugs merge part.

(c) The emergy values for base merge part

Figure L.9. The emergy values for design alternative I.

L.10 Alternative J Emergy

Figure L.10. The emergy values for design alternative J

Appendix M Workshop Screening Survey

Thank you for your interest in participating in this study on Real-Time Geometry-Based Feedback for Design Engineers on the Environmental Impact of Manufacturing. To determine eligibility, please provide the following information (please write legibly):

Full Name:

Email Address:

What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

If you are currently an undergraduate student, what year are you?

Freshman

Sophomore

Junior

Senior

5+ Year

Are you 18 years old or over?

Yes

No

You will be contacted by email regarding your eligibility for this study and to schedule your participation in the workshop if you are selected. Please return this completed eligibility form to Amanda Bligh or Manbir Sodhi in person or via email: <abligh@uri.edu>.

Appendix N Workshop Supporting Presentations

This section includes the presentations used during the experimental workshop. Three presentation are included. The first contains the material provided for the first survey related to the design alternatives. The second was used to provide an introduction to emergy for participants. The final presentation provides a short training for using the emergy extension for aPriori.

N.1 Design Alternatives for Participants

Part 1

- Review Materials as Group: 10 minutes
- Complete Survey Individually: 15 minutes
- You Should Have:

Introduction

- Survey asks to rank designs by sustainability
- You are given
 - Basic Manufacturing Data for an Original Design & 6 Design Alternatives
 - Definition of Data available
 - Directions for completing survey
- **Cannot** answer questions about designs or how to rank them
- **Can** answer questions about survey

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Sheet Utilization

Based on number of unfolded parts that fit on the sheet

Measure of the amount of the sheet used for parts

Material: Steel, Cold Worked, AISI 1020
[3.04 mm x 1,219.20 mm x 3,048.00 mm]

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Includes sheet waste divided by number of parts on sheet

Rough Mass

Includes internal scrap from holes

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Additional Notes

- All parts are same material – 1020 Steel
- All welding is same size & type – 3mm fillet

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How to Complete Survey

1. Complete questions 1 through 6
2. Open CAD_Designs.pdf and review the alternatives
3. Rank the designs for sustainability by listing them on line from least to most sustainable manufacturing
4. Hand in Survey when Complete

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

Ranked by Participant as Least Sustainable Design

Least sustainable

Q S R Z

Most sustainable

Ranked by Participant as Most Sustainable Design

Design Alternatives "R" and "Z" have been Ranked by Participant as equal in sustainability

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Designs

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Starting Design (S)

	Part Name	QTY	Rough Mass (kg)	Sheet Utilization	Routing	Cycle Time
1	BASE FLANGE	1	0.61	88%	Laser / Bend	24
2	SIDE FLANGE LH	1	0.41	76%	Laser / Bend	37
3	SIDE FLANGE RH	1	0.43	75%	Laser / Bend	37
4	LUG	2	0.19	72%	Laser / Bend	48
5	STIFFENER	1	0.28	95%	Laser / Bend	27
ASSY	BRACKET FITTING	1	1.75	-	Welding	298

Finished Assembly Mass: 1.75 kg

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Alternative A

	Part Name	QTY	Rough Mass (kg)	Sheet Utilization	Routing	Cycle Time
1	BASE MERGE_A	1	1.44	73%	Laser / Bend	102
2	LUG_A	2	0.19	72%	Laser / Bend	24
3	STIFFENER_A	1	0.30	94%	Laser / Bend	27
ASSY	BRACKET FITTING_A	1	-	-	Welding	161

Finished Assembly Mass: 1.75 kg

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Alternative B

	Part Name	QTY	Rough Mass (kg)	Sheet Utilization	Routing	Cycle Time
1	BASE FLANGE_B	1	0.61	88%	Laser / Bend	24
2	SIDE FLANGE LH_B	1	0.41	76%	Laser / Bend	37
3	SIDE FLANGE RH_B	1	0.43	75%	Laser / Bend	37
4	STIFFENER LUGS MERGED_B	1	0.85	65%	Laser / Bend	58
ASSY	BRACKET FITTING_B	1	-	-	Welding	309

Finished Assembly Mass: 1.76 kg

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Alternative D

	Part Name	QTY	Rough Mass (kg)	Sheet Utilization	Routing	Cycle Time
1	BASE FLANGE_D	1	0.61	88%	Laser / Bend	24
2	BRACKET LH_D	1	0.22	52%	Laser / Bend	27
3	BRACKET RH_D	1	0.25	58%	Laser / Bend	27
4	LUG_D	2	0.19	72%	Laser / Bend	48
5	STIFFENER_D	1	0.28	95%	Laser / Bend	27
6	BRACE LH_D	1	0.12	87%	Laser / Bend	18
7	BRACE RH_D	1	0.12	88%	Laser / Bend	18
ASSY	BRACKET FITTING_D	1	-	-	Welding	377

Finished Assembly Mass: 1.59 kg

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Alternative F

	Part Name	QTY	Rough Mass (kg)	Sheet Utilization	Routing	Cycle Time
1	BASE MERGE_F	1	2.8	56%	Laser / Bend	132

Finished Mass: 1.58 kg

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Alternative G

	Part Name	QTY	Rough Mass (kg)	Sheet Utilization	Routing	Cycle Time
1	BASE FLANGE_G	1	0.61	88%	Laser / Bend	24
2	BRACKET LUG MERGE LH_G	1	0.33	57%	Laser / Bend	32
3	BRACKET LUG MERGE RH_G	1	0.34	58%	Laser / Bend	32
4	LUG FOR WELD_G	2	0.11	71%	Laser / Bend	8
5	STIFFENER_G	1	0.28	95%	Laser / Bend	27
6	BRACE LH_G	1	0.12	87%	Laser / Bend	18
7	BRACE RH_G	1	0.12	88%	Laser / Bend	18
ASSY	BRACKET FITTING_G	1	-	-	Welding	377

Finished Assembly Mass: 2.04 kg THINK BIG WE DO™

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Alternative J

	Part Name	QTY	Rough Mass (kg)	Sheet Utilization	Routing	Cycle Time
1	BASE MERGE_J	1	1.44	73%	Laser / Bend	102
2	LUG_J	2	0.19	72%	Laser / Bend	24
3	STIFFENER_J	1	0.37	81%	Laser / Bend	8
ASSY	BRACKET FITTING_J	1	-	-	Welding	152

Finished Assembly Mass: 1.42 kg

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N.2 Emergy Introduction

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Part 2 Emergy Accounting Introduction

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Amanda Bligh
MISE PhD Candidate

Part 2

- Review Materials as Group: 30 minutes
- Complete Survey Individually: 30 minutes
- You Should Have:

Software_Training.pdf

PDF

On Computer

Start_aPriori.bat

C:/aPrioriQ/

1_Start_aPriori.bat

2_Start_admin_client.bat

Second Survey

Number for Study XX

Match your Number

Hardcopy

1. Rank the designs provided by manufacturing sustainable by putting their letters on the axis below, b toolset.

Least sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

Opening Software

- Double-click on 1_Start_aPriori.bat

- Login
 - User Name: apriori
 - Password: apriori

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Agenda

- Energy as a Sustainability Metric
- Energy Introduction
- Application to Designs

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Energy Metrics

Consumed Energy Sum of produced energy used by a system

- **Common Application:** Life Cycle Analysis
- Covers only produced energy inputs (electricity, fossil fuel heat, etc.)

Exergy Available energy to do useful work

- **Common Application:** Measure energy efficiency of manufacturing processes
- No measurement of work done by earth
- Limited methods to measure human impact

Energy Cumulative sum of all work done in a system

- **Common Application:** Impact to earth systems of human based activities
- Includes all work done in a system based on earth impact
- Can be formulated to measure any system—organic or non-organic; money; etc.

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Odum

Emergy

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Almeida
et al.

Emergy Manufacturing Example

How to ensure we are capturing everything?

Description								% (sej/sej) ^b
Implantation								
1	Concrete	g	F	3.54×10^6	1.34×10^6	9.13×10^{15}	3.53%	0.42%
2	Steel	g	F	1.60×10^6	2.77×10^9	4.43×10^{15}	2.68%	0.21%
3	Polypropylene	g	F	1.37×10^5	5.87×10^9	8.04×10^{14}	0.49%	<0.10%
4	Equipment	g	F	5.30×10^4	4.10×10^9	2.17×10^{14}	0.13%	<0.10%
5	Labor	J	F	5.02×10^7	4.30×10^9	2.16×10^{14}	0.13%	<0.10%
6	Machinery	g	F	2.22×10^4	4.10×10^9	9.10×10^{13}	<0.10%	<0.10%
7	PVC	g	F	1.15×10^4	5.87×10^9	6.75×10^{13}	<0.10%	<0.10%
8	Water	g	N	2.70×10^7	2.25×10^5	6.08×10^{12}	<0.10%	<0.10%
9	Rubber	g	F	1.00×10^3	4.30×10^9	4.30×10^{12}	<0.10%	<0.10%
Operation								
10	Electricity	J	F	4.95×10^{11}	1.65×10^5	8.17×10^{16}	49.52%	3.78%
11	Labor	J	F	9.80×10^9	4.30×10^6	4.21×10^{16}	25.52%	1.95%
12	Chemicals	g	F	2.55×10^7	1.00×10^9	2.55×10^{16}	15.45%	1.18%
13	Water	g	N	3.67×10^9	2.25×10^5	8.26×10^{14}	0.50%	<0.10%
14	Energy (process)	kg	Y1	7.2×10^3	2.29×10^{13}	1.65×10^{17}	100.00%	—
	Steel	g	N	7.20×10^8	2.77×10^9	1.99×10^{18}	—	92.13%
	Energy (fasteners)	kg	Y2	7.27×10^5	2.97×10^{12}	2.16×10^{18}	—	100.00%

^a Considering items from 1 to 13.
^b Considering items from 1 to 14.

Analogy to Cost

Analogy to Cost

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Analogy to Cost

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Analogy to Cost

Cost	Energy
$m_{rough}c_{kg}$	$T_{mat}m_{rough}$
$t_c n_p h_p$	$T_l t_l n_p$
$\frac{c_{mach}(1+f_{inst}) + c_{mach}f_{maint}}{t_{life}} t_c$	$\frac{E_{mach} + c_{mach}f_{inst}T_s + c_{mach}f_{maint}T_s}{t_{life}} t_c$
$\frac{(A_{mach} + A_{gap} + A_{space})(R_A)}{t_{earn}} t_c$	$\frac{(A_{mach} + A_{gap} + A_{space})(\frac{T_A}{t_{life}})}{t_{earn}} t_c$

Factory Building

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The Full Emergy Model

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Output in Software -- Assembly

Output in Software -- Part

Compare Energy in Two Designs

Next – Software Training

Next >>

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N.3 Software Introduction

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Part 2

Software Training & Survey Directions

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Amanda Bligh
MISE PhD Candidate

Part 2

- Review Materials as Group: 30 minutes
- Complete Survey Individually: 30 minutes
- You Should Have:

Software_Training.pdf

PDF

On Computer

Start_aPriori

On Computer

Second Survey

Match your Number

Hardcopy

Number for Study XX

1. Rank the designs provided by manufacturing sustainable by putting their letters on the axis below, b toolset.

Least sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

Agenda

- How to open software
- Finding assemblies
- Evaluating energy results
- Completing Survey
- Extra: Viewing cost for parts & assemblies

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Opening Software

- Double-click on aPriori Desktop icon

- Login
 - User Name: apriori
 - Password: apriori

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Opening Rollup & Design Alternatives

1. Click on magnifying glass

2. In Search window and enter:

- “energy” in Name/Part #
- Roll-up in Component Type

3. Click “Find”

4. Double-click on “ENERGY WORKSHOP” to open the rollup

Component Scenarios: 1 found.

Thumb Name/Part #	Scenario Name	Piece Part Cost (USD)	Total Capital Investments (USD)
ENERGY WORKSHOP	Initial		

Opening Rollup & Design Alternatives

5. Open design alternative by double-clicking

5a. In lower-right, opening indicator will appear

6. The newly opened alternative appears as a tab – return to the rollup by clicking on its tab

Roll-up Details

Status	Level	Name	Scenario
●	1	BRACKET FITTING_C	bulk-initial
●	1	BRACKET FITTING_G	bulk-initial
●	1	BASEMERGE_F	bulk-initial
●	1	BRACKET FITTING_B	bulk-initial
●	1	BRACKET FITTING	bulk-initial
●	1	BRACKET FITTING_J	bulk-initial
●	1	BRACKET FITTING_A	bulk-initial
●	1	BRACKET FITTING_E	bulk-initial
●	1	BRACKET FITTING_I	bulk-initial

Machine

Displaying Assembly-BRACKET FITTING.bulk-initial

aPrioRi

File Scenario Cost View Tools Reports Help

Cost Guide

1	2	3
Production Scenario	GCD Tolerances	Process and Machine Options

Evaluating Energy Results for Design Alternative

The image shows two screenshots of the aPrioRI software interface. The left screenshot shows the main menu with the 'Energy' button highlighted and a yellow box with the text '1. Click on Energy button'. The right screenshot shows the 'Energy Summary' window with a yellow box labeled '2. Review Summary Results' pointing to the summary data and another yellow box labeled '3. Review Detailed Results' pointing to the detailed component energy breakdown.

Energy Summary Data:

Energy Summary	
Total Energy (eq):	6.036 E 13
Material:	2.551 E 13 42.27%
Welding:	1.89 E 13 31.31%
Component:	1.595 E 13 26.43%

Component Material Energy Data:

Component Material Energy	
Material:	1.16 E 13
Material Labor + Services:	1.391 E 13
Welding Energy:	
Operator:	1.445 E 13
Equipment:	5.045 E 10
Equipment Installation:	5.035 E 9
Equipment Maintenance:	1.259 E 10
Machine Power:	2.743 E 11
Machine Setup:	2.181 E 11
Indirect Overhead:	3.817 E 12
Supplies:	6.351 E 10
Component Energy:	
Operator:	1.096 E 13
Equipment:	8.959 E 11
Equipment Installation:	1.695 E 11
Equipment Maintenance:	4.237 E 11
Machine Power:	2.138 E 11
Machine Setup:	9.055 E 11
Indirect Overhead:	2.381 E 12
Supplies:	1.597 E 8

How to Complete Survey

1. Review Emergy of Designs in Software
2. Rank the designs for based on emergy by listing them on line from least to most sustainable manufacturing
3. Answer remaining questions
4. Hand in Survey when Complete

Ranked by Participant as Least Sustainable Design

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

Least sustainable

W R Q S Z N

Most sustainable

Ranked by Participant as Most Sustainable Design

Starting / original design

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Extra: Reviewing Cost

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Viewing Cost -- Assembly

Welding Summary

	Current (USD)	Previous (USD)	Last Saved (USD)
Material Cost	0.00	0.00	0.00
Labor	2.05	2.05	2.05
Direct Overhead	0.09	0.09	0.09
Amortized Batch Setup	0.04	0.04	0.04
Logistics	0.00	0.00	0.00
Other Direct Costs	0.80	0.80	0.80
Total Variable Costs	2.98	2.98	2.98
Period Cost			
Indirect Overhead	0.74	0.74	0.74
SG&A	0.29	0.29	0.29
Margin	0.00	0.00	0.00
Piece Part Cost	4.01	4.01	4.01
Fixed Costs			
Total Amortized Investments	0.00	0.00	0.00
Fully Burdened Cost of Subcomponents	11.54	11.54	11.54
Fully Burdened Cost	15.55	15.55	15.55
Capital Costs			
Total Capital Investments	0.00	0.00	0.00

Total Cost of Parts in Ass'y

Manufacturing Process

Status	Process Step	VPE	Machine
●	BRACKET FITTING	Energy Analysis	Machine
●	Assembly	Energy Analysis	
●	Pick and Place	Energy Analysis	Default Pick and Place
●	Welding	Energy Analysis	
●	Manual MIG Welding	Energy Analysis	Deltaweld 653 (Miller)

Geometric Cost Drivers

Show	Name
●	Component
●	Joining

Viewing Cost -- Assembly

Cost Summary Assembly Details Assembly Tracker Investment

Edit Table View Options All Data - Current - Full Cost - Tree

Part Details

Status	Level	Cost Object Name	Scenario	Q	Material Cost (USD)	Labor (USD)	Direct Overhead (USD)	Amortized Batch Setup (USD)	Logistics (USD)	Other Direct Costs (USD)	Total Variable Costs (USD)
●	0	BRACKET FITTING	bulk-initial	1	7.43	3.48	0.89	0.19	0.00	0.97	12.96
●	1	Assembly Processes			0.00	2.05	0.09	0.04	0.00	0.80	2.98
●	1	BASE FLANGE	bulk-initial	1	2.13	0.21	0.14	0.03	0.00	0.05	2.55
●	1	SIDE FLANGE LH	bulk-initial	1	1.44	0.30	0.14	0.03	0.00	0.03	1.94
●	1	STIFFENER	bulk-initial	1	1.04	0.22	0.10	0.03	0.00	0.02	1.41
●	1	LUG	bulk-initial	2	1.31	0.41	0.28	0.03	0.00	0.03	2.06
●	1	SIDE FLANGE RH	bulk-initial	1	1.52	0.30	0.14	0.03	0.00	0.04	2.02
-		Component Subtotal		6	7.43	1.43	0.80	0.15	0.00	0.18	9.99
-		Assembly Processes Subtotal			0.00	2.05	0.09	0.04	0.00	0.80	2.98
-		GRAND TOTAL			7.43	3.48	0.89	0.19	0.00	0.97	12.96

Double-click to open parts

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Viewing Cost -- Part

Validation Part Summary Design to Cost Cost Summary Part Details Investment

Cost information for part

How Part is Made

	Current (USD)	Previous (USD)	Last Saved (USD)
Variable Costs			
Material Cost	9.82	9.82	9.82
Labor	1.08	1.08	1.08
Direct Overhead	0.56	0.56	0.56
Amortized Batch Setup	0.03	0.03	0.03
Logistics	0.00	0.00	0.00
Other Direct Costs	0.24	0.24	0.24
Total Variable Costs	11.73	11.73	11.73
Period Costs			
Indirect Overhead	0.39	0.39	0.39
SG&A	1.16	1.16	1.16
Margin	0.00	0.00	0.00
Piece Part Cost	13.29	13.29	13.29
Fixed Costs			
Total Amortized Investments	0.00	0.00	0.00
Fully Burdened Cost	13.29	13.29	13.29
Capital Costs			
Total Capital Investments	0.00	0.00	0.00

Manufacturing Process

Edit View Primary Process Group: Sheet Metal Material: Steel, Cold Worked, AISI 1020 (Emergency Analysis) [X]

Status	Process Step	VPE	Machine
●	BASEMERGE_F	Emergency Analysis	
●	Sheet Metal	Emergency Analysis	
●	Material Stock	Emergency Analysis	Default Material Stock
●	Laser Cut	Emergency Analysis	Cincinnati CL850
●	Bend Brake	Emergency Analysis	SPH-60C (Amada)
●	No Cost Feature	Emergency Analysis	

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Appendix O Workshop Initial Survey

Number for Study _____

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

Least sustainable

Most sustainable

Appendix P Workshop Final Survey

Number for Study _____

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

Least sustainable

Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments:

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient
Information Information

Comments:

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

Change 2:

Change 3:

Q.1 Summary of Results

383

384

Number for Study 1

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

S F D B G J A
Least sustainable Most sustainable

2	3	6	5	4	1	7
J	G	F	D	B	A	S
1.4	.93	1.77	1.13	1.3	1.1	2.8
152	377	132	377	309	161	298

Number for Study 1

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

D G B S A J F

Least sustainable Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments:

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 7 8 9 10
Very Easy Very Hard

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient
Information Information

Comments:

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

A WAY TO INCLUDE YOUR OWN VALUES
ie. what you see as more important a variable
AN OPTIONAL toggle

Change 2:

A WAY TO GIVE IMPORTANCE TO YOU FOR EACH VALUE

Change 3:

A WAY TO CHANGE WHAT IS CALCULATED FOR PROJECT
ie. only consider specific values for specific projects

4 S - 4.94 6 G - 5.24
3 A - 4.23 2 J - 3.88
5 B - 5.07 1 F 3.85
7 D - 5.32

Number for Study 2

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

G D B F B A S J
Least sustainable Most sustainable

81.2

79.6

76.0

77.1

56.0

77.7

75.3

$S: 4.936 \times 10^{-3}$
 $A: 4.225 \times 10^{-3}$
 $B: 5.062 \times 10^{-3}$
 $G: 5.349 \times 10^{-3}$
 $J: 5.24 \times 10^{-3}$
 $F: 3.877 \times 10^{-3}$

Number for Study 2

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

Comments:

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

Comments:

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: Potential change of material. A large portion of the energy (76.39%) comes from material energy.

Change 2: Find cheaper machines to operate bend process as the bend and bend operator uses a substantial portion of energy.

Change 3: Make material in part thinner, or ~~or~~ make larger holes in part to minimize material used.

Number for Study 3

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify ocean Engineering)

Other (Please Specify _____)

2. Are you currently a student?

☒ Yes

☐ No

3. If you are currently a student, what year are you?

☒ Freshman

☐ Sophomore

☐ Junior

☐ Senior or beyond (5+ year)

☐ Graduate Student

4. Are you 18 years old or over?

☒ Yes

☐ No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

☐ None

☒ I have taken a class about sustainability

☐ I have evaluated the environmental sustainability of a manufactured part or product

$$\begin{aligned} A &\approx 1.9 - 1.42 \approx .5 & D &\approx 1.80 - 1.59 \approx .2 & J &\approx 1.9 - 1.75 \approx .15 \\ B &\approx 2.4 - 2.04 \approx .4 & E &\approx 2.2 - 1.76 \approx .4 & & \\ F &\approx 2.8 - 1.58 \approx 1.3 & G &\approx 1.9 - 1.75 \approx .15 & & \end{aligned}$$

☐ I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

☐ I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

☐ I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

☒ None

☐ I have designed parts or products within class projects

☐ I currently design parts or products within class projects

☐ I have designed parts or products as part of my job or research

☐ I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F G J B D S A
Least sustainable Most sustainable

Number for Study 3

④ $5: 4.936 \times 10^{13}$
 ③ $A: 4.222 \times 10^{13}$
 ⑤ $B: 5.008 \times 10^{13}$
 ⑥ $D: 5.319 \times 10^{13}$
 ⑦ $G: 5.24 \times 10^{13}$
 ② $J: 3.887 \times 10^{13}$
 ① $F: 3.546 \times 10^{13}$

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

D G B A S J F
 Least sustainable Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

① 2 3 4 5 6 7 8 9 10
 Much Easier Similar Much Harder

Comments: the software was very simple to use

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 ④ 5 6 7 8 9 10
 Very Easy Very Hard

Comments: The general concept of the metric of energy was easy to understand, but it was difficult to follow where the specific values came from and how they were calculated.

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 ⑧ 9 10
 Not Enough Sufficient Information

Comments: There was sufficient information to compare the general designs, but it was hard to trace how the information came together to create the quantitative value of energy for a specific design.

material: 76.39 N

bend: 13.65

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: The 76.39 N of the energy in design F can be attributed to the materials. The rough mass used in producing a component is 2.8 kg compared to a finish mass of 1.58 kg. The discrepancy between these numbers suggests a lot of waste. ~~Arranging the parts more uniformly would allow the parts to be cut more efficiently and would greatly increase sustainability.~~

Change 2: use water/solar power to run machinery

Change 3: reuse the discarded/waste material for the welding process

Number for Study 4

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify Electrical and Computer)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

Number for Study 4

$$\begin{aligned} S &= 4.936 E13 & G &= 5.24 E13 \\ A &= 4.225 E13 & J &= 3.877 E13 \\ B &= 5.068 E13 & F &= 3.846 E13 \\ D &= 5.319 E13 & & \end{aligned}$$

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

Comments:

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

Comments:

Since I'm not very knowledgeable on the topic, the energy calculation was easier to grasp than ~~the~~ calculating sustainability just with quantity of materials used and time.

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

Comments:

Yes, however if I wanted to ~~make~~ make a more in-depth analysis, I would need to know how these calculations were obtained.

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: maybe one could use a different material that does not require as much energy.

Change 2: Not only could one change the material, but he or she may also obtain materials acquired through a more sustainable means.

Change 3: group
If humanity (as a whole) could find a way to live in a more sustainable manner then the energy from the operator would decrease in all systems.

Number for Study 5

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

G D F B S J A

Least sustainable

Most sustainable

Number for Study 5

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

G D B S A J F
Least sustainable Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments: Easy instructions to understand what parts needed to be evaluated in the software

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments: Explained well ^{for} what components are counted for in energy

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient
Information Information

Comments: The metric of energy displayed how much energy & resources were needed to create this product and allowed easy comparisons b/w alternatives

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: Reduce machine setup time in the laser energy & bend energy - time study

Change 2: Reduce the amount of sheet waste in alternative F
- choose a different type of metal that could be repurposed in ~~the~~ another part of production

Change 3: Reduce the amount of bending of alternative F, produce the product w/ minimal bending

Number for Study 6

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify Civil Engineering)

Other (Please Specify _____)

2. Are you currently a student?

☒ Yes

☐ No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

☒ Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

☒ Yes

☐ No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

☒ None

☐ I have taken a class about sustainability

☐ I have evaluated the environmental sustainability of a manufactured part or product

☐ I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

☐ I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

☐ I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

☒ None

☐ I have designed parts or products within class projects

☐ I currently design parts or products within class projects

☐ I have designed parts or products as part of my job or research

☐ I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F D J A B S

Least sustainable Most sustainable

Number for Study 6

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

Least sustainable D G B S A J F Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments: *Not sure how individual components are received initially, but the whole process and this software makes sense.*

3. How easy was the metric of emergy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments:

4. Did the metric of emergy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient
Information Information

Comments:

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: *Find a way to utilize more of the steel sheet.*

Change 2: *Change material of bracket to one that is more easy utilize at a higher percent.*

Change 3: *Make "F" by using more steps so that the sheet can be utilized further.*

Number for Study 7

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

G S ~~0~~ ~~9~~ ~~4~~ A J F
Least sustainable Most sustainable

Number for Study 7

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

Comments:

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

Comments:

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

Change 2:

Change 3:

Number for Study 8

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

Number for Study 8

A	B	D	S
4.225 € 13	5.06 € 13	5.319 € 13	4.936
G	J	F	
5.24 € 13	3.877 € 13	3.846 € 13	

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

Least sustainable D G B S A J F Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments: - Have not used a sustainability software before, but this was very simple to use

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments: if done correctly, very easy

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient Information

Comments: From my knowledge there is enough information.

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: - The material 'cost' is about 76% of the total energy. ~~XXXXXXXXXX~~ This design would be more sustainable if a different material were to be used.

Change 2: - Sheet utilization is only 56% for this part, if this were to increase maybe the total energy would decrease.

Change 3: - Decrease in cycle time total

Number for Study 9

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F B D A G
J S
Least sustainable Most sustainable

9

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

D G B S A J F

Least sustainable Most sustainable

Least sustainable

Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Much Easier

Similar

Much Harder

Comments:

Comments:
Very simple and straightforward to find information, nice that the set up is like a website (tabs)

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Very Easy

Very Hard

Comments:

Very interesting, when doing the first ranking I was only thinking about the wasted material, not wasted energy

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1	2	3	4	5	6	7	8	9	10
Not Enough Information									Sufficient Information

Not Enough Information

Sufficient
Information

Comments:

Comments:
Definitely, much easier and more accurate to compare instead of trying to determine which part of the manufacturing process might be more/less sustainable

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

change the material to some material that takes less energy to create because material has the second highest amount of energy (1.316×10^{13})

Change 2:

Change or improve the way the material is transported and the labor and services that goes into it because material labor and services has the highest amount of energy (1.622×10^{13})

Change 3:

Try to automate the process even more and involve less of the operator because in both the laser and bend energy, the operator is the highest amount of energy (2.418×10^{12} for laser and 3.92×10^{12} for bend)

Number for Study 40

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

D F G S B J A
Least sustainable Most sustainable

Number for Study 10

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

D G B S A J F
Least sustainable Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 ④ 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments:

To use it for our survey application it was easy but from the complexity of the options, it looks like it could be a maze of tabs.

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 ④ 5 6 7 8 9 10
Very Easy Very Hard

Comments:

To my understanding, energy is a quantified value based on the input of energy into a product to create it through multiple steps.

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 ③ 4 5 6 7 8 9 10
Not Enough Sufficient Information

Comments:

Based on the software outputs, it was clear which products used less/more energy.

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

→ produce less waste, only 56% of the sheet metal was used (F)
→ recycle old scraps to melt and make more

Change 2:

→ decrease the holes or non essential cuts (simplify)

Change 3:

Find more energy efficient equipment to produce the product using the same steps.

Number for Study 11

1. What major are you or have you most recently completed:

☒ Mechanical Engineering

☐ Industrial and Systems Engineering

☐ Other Engineering (Please Specify _____)

☐ Other (Please Specify _____)

2. Are you currently a student?

☒ Yes

☐ No

3. If you are currently a student, what year are you?

☐ Freshman

☒ Sophomore

☐ Junior

☐ Senior or beyond (5+ year)

☐ Graduate Student

4. Are you 18 years old or over?

☒ Yes

☐ No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

☒ None

☐ I have taken a class about sustainability

☐ I have evaluated the environmental sustainability of a manufactured part or product

☐ I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

☐ I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

☐ I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

☒ None

☐ I have designed parts or products within class projects

☐ I currently design parts or products within class projects

☐ I have designed parts or products as part of my job or research

☐ I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F G S D A B
Least sustainable Most sustainable

~~F~~ ~~G~~ ~~S~~ ~~D~~ ~~A~~ ~~B~~

Number for Study 11

S = 4.936
A = 3.225
B = 5.065
D = 5.319
E = 5.340
S = 3.877
F = 5.846

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

Least sustainable D ~~D~~ G B S A J F Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments:

It gives a lot of information without me having to look for it too hard. The information is easy to understand.

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments:

I think, if I ^{can} pull up the energy summary of multiple designs it would make it easier to compare ~~with~~ the sustainability metrics.

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient
Information Information

Comments:

Yes, It gave me a number I could compare with other designs making it easy to understand what more sustainable and more environmentally friendly.

5. Give three additional changes that you would make to the design you noted as most sustainable in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

→ have the price/design produce less waste
Try less big parts with odd angles and holes
which ~~don't~~ need to be cut

Change 2:

→ less parts needed to make the design.
- It seemed like 3 was a good number

Change 3:

→ Make the cut out parts shape fit ~~each~~ easily together to create less waste from the sheet metal.

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

(Senior or beyond (5+ year))

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

A J D G F B S

Least sustainable Most sustainable

Number for Study 12

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

Least sustainable D A F G B E Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments:

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient
Information Information

Comments:

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

Lower fixed cost if possible

Change 2:

Material use had the highest energy
we'll look at the report for design f
then look at the number three for energy

Change 3:

material and material load + services had
the highest energy levels so that should be
decreased

Number for Study 13

1. What major are you or have you most recently completed:

Mechanical Engineering

✓ Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify + Math (Applied))

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F J D B A S G

Least sustainable Most sustainable

Number for Study 13

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

D G B S A J F
Least sustainable Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments: Be able to open multiple windows of energy summary to better compare results, also display design name on energy summary window

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient Information

Comments: The presentation was sufficient, but was curious how values of energy were originally obtained

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: Increase sheet utilization, since it had the lowest rating, and the highest value of energy for materials category compared to the other designs.

Change 2: Determine a way to install the equipment for the process more efficiently. Compared to the other designs, the most sustainable design F had the highest value of energy for equipment installation.

Change 3: Focus on optimizing material labor + services. Design F had the highest value for energy in this category, compared to the other designs.

Number for Study 14

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F ^D J B G A S
Least sustainable Most sustainable

Number for Study 14

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

Least sustainable D G B S A J F Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments: Simple yet effective. ~~Given~~ Given only a few minutes to practice, it was easy to navigate

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments: Although, at first, the explanation of energy seemed strenuous, pictures and analogies made it easy to figure out the true effectiveness of energy

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient
Information Information

Comments: Because of the lack of time, I mis understood the meaning of sustainability (more so strength vs cost and manufacturing time) in the first survey. However, given the program and a thorough explanation, I was (hopefully) able to understand the reasoning of energy

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: Since Figure "F" was my #1 choice, I would try to reduce the amount of sharp corners and flanges used in bending to increase the effectiveness of the sheet usage and decreasing cost

Change 2: For strength concerns, it may be necessary to add welds to the screw brackets. Although this may increase cycle time, the base weld would be easier to form and bend because it is a much simpler shape without the brackets

Change 3:
Use a stamping and bending method of cut instead of laser to decrease cycle time and base energy

Number for Study 15

1. What major are you or have you most recently completed:

Mechanical Engineering

☒ Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

☒ Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

☒ Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

☒ Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

☒ I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

☒ I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F _____ J B D G A S _____
Least sustainable Most sustainable

Number for Study 15

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

Comments:

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

Comments: Only issue is that they are only comparable to each other, but not to a global benchmark

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

Using software to slightly alter the design in a way that has a higher sheet utilization percentage.

Change 2:

Experiment with/research new materials that ^{would give} a lower total energy to the product without sacrificing performance or integrity

Change 3:

Using a solar/wind/ or otherwise renewable ^{energy} focused factory would help to lower the sustainability of the overall process.

Number for Study 16

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F D G B S A J
Least sustainable Most sustainable

Most
✓ J A
150 161
1.42 1.75

✓ S
298

Least Least
✓ B G D F
309 377 377 132
1.76 2.04 1.59 1.58

Number for Study 16

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

D G B S A F F

Least sustainable Most sustainable

higher energy $A = 4.225 \times 10^{13}$ $B = 5.068 \times 10^{13}$ lower energy $S = 4.44 \times 10^{13}$ $D = 5.319 \times 10^{13}$ $G = 5.24 \times 10^{13}$ $F = 3.877 \times 10^{13}$ $F = 3.846 \times 10^{13}$

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments:

I have never used other engineering software that calculates the sustainability of a product. However, this manufacturing sustainability software was very easy to use.

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments:

I would like to learn more about how they generated a transformity constant to assign to each material since there are a lot of factors that go into it.

4. Did the metric of energy provide you with a way to meaningfully compare the designs?

In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Information Sufficient Information

Comments:

Energy is a great metric to meaningfully compare designs, however, it is not obvious as to how environmentally friendly a product is. We do not have an idea of the direct implications the specific manufactured product has on the environment.

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: I would look at ways of trying to use recycled metal (assuming that it would be cheaper to purchase) as long as it does not affect the quality of the product being manufactured.

Change 2:

Decreasing the process / service time considering the fact that material labor / services had the highest energy. Trying to make the process more lean by observing where changes could be made to decrease the idle time or time wasted.

Change 3:

Utilizing a different material to manufacture this product as long as the product's functionality is not affected.

Number for Study 17

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

☒ Yes

☐ No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

☒ Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

☒ Yes

☐ No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

☒ I have taken a class about sustainability

☐ I have evaluated the environmental sustainability of a manufactured part or product

☐ I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

☐ I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

☐ I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

☒ I have designed parts or products within class projects

☐ I currently design parts or products within class projects

☐ I have designed parts or products as part of my job or research

☐ I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F G DS B J

Least sustainable Most sustainable

J → >70% utilization
hot liquid

F → 56% sheet utilization

S-4.936 E13 A-4.225 E13 B-5.068 E13 D-5.741 E13 G-5.29 E13
J-8.877 E13 F-3.846 E13

Number for Study 17

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

Comments:

It seems like it could be easy to get used to and logical after spending a few hours with it.

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

Comments:

Very well explained - seems like a complicated topic that was very broken down into a digestible concept.

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

Comments:

Yes - however I wasn't positive on if certain categories of energy (such as laser vs material) are technically worse or better, or if they have all been equalized essentially.

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1:

The majority of the energy produced can be sourced back to the material - potentially using less material or thinner material if the design allows.

Change 2:

Redesign the part with less holes to lower the energy contribution from cutting holes.

Change 3:

Create the product out of recycled material in order to lower energy of creating that material - although I'm not sure if this would technically increase the energy, because it may include the original production of that material plus the energy required to handle it as a recyclable and get it ready as a raw material again.

Number for Study 18

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

G D B S A F J
Least sustainable Most sustainable

G D B S F A J

Number for Study 18

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

D G B S A J F
Least sustainable Most sustainable

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 3 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments: *easy and good overview about needed links*

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 2 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments: *not so easy to understand; never heard the concept of energy before*

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 10
Not Enough Sufficient Information

Comments: *good, fundamental information to understand the concepts and the provided informations for the designs*

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: ~~reduce weight by using thinner material~~
reduce weight by using less materials at the sides of the workpiece

Change 2: *remove the small bar at the end of the ground space to save material & (like version A); also avoid a welding process*

Change 3: *smaller bar at the top of the workpiece*

1. 4.236
A. 4.225
B. 5.068
D. 5.319
G. 5.24
J. 2.877
F. 3.846
3
D G B A J F
3.57
9.56
13.16

Number for Study 19

1. What major are you or have you most recently completed:

Mechanical Engineering

Industrial and Systems Engineering

Other Engineering (Please Specify _____)

Other (Please Specify _____)

2. Are you currently a student?

Yes

No

3. If you are currently a student, what year are you?

Freshman

Sophomore

Junior

Senior or beyond (5+ year)

Graduate Student

4. Are you 18 years old or over?

Yes

No

5. What experience do you have in evaluating the manufacturing sustainability of a part or product (circle all that apply)?

None

I have taken a class about sustainability

I have evaluated the environmental sustainability of a manufactured part or product

I have evaluated the environmental sustainability of a manufactured part or product based on its geometry

I currently evaluate the environmental sustainability of manufactured parts or products as part of my research or job.

I currently evaluate the environmental sustainability of manufactured parts or products based on its geometry

6. What experience do you have designing parts or products (select all that apply)?

None

I have designed parts or products within class projects

I currently design parts or products within class projects

I have designed parts or products as part of my job or research

I currently design parts or products as part of my job or research

7. Rank the designs shown on the projector (or provided) by manufacturing sustainability from least to most sustainable by putting their letters on the axis below.

F J A B S G D
Least sustainable Most sustainable

Number for Study 19

1. Rank the designs provided by manufacturing sustainability from least to most sustainable by putting their letters on the axis below, based on your analysis in the software toolset.

2. How easy was the software tool to learn how to use for evaluating manufacturing sustainability compared to other engineering softwares you have used?

1 2 (3) 4 5 6 7 8 9 10
Much Easier Similar Much Harder

Comments: Took a moment to locate tabs but it was simple to repeat the process for each assembly. Curious if other tools in the software are simple to use.

3. How easy was the metric of energy to understand in evaluating the manufacturing sustainability of manufacturing parts and assemblies?

1 (2) 3 4 5 6 7 8 9 10
Very Easy Very Hard

Comments:

4. Did the metric of energy provide you with a way to meaningfully compare the designs? In other words, was there enough information provided to understand why a design was more or less environmentally friendly?

1 2 3 4 5 6 7 8 9 (10)
Not Enough Sufficient
Information Information

Comments: The less energy, the more sustainable.

5. Give three additional changes that you would make to the design you noted as *most sustainable* in question #1, that would be likely to further increase the sustainability of this assembly. Be clear in your description and feel free to use pictures to illustrate.

Change 1: ~~Decrease energy accounted for by the laser by using a more energy efficient one.~~

Decrease energy accounted for by the laser by using a more energy efficient one.

Change 2: Decrease materials used to the minimum level while the part remains structurally sound.

Change 3: Ease of operating or make it autonomous so the cost of hiring operators is reduced.

Appendix R UEVs Used in this Study

Table R.1 is a list of UEVs used in this study. All UEVs have been converted to the 1.2E25 baseline.

Table R.1. List of UEVs used in this study in 1.2E+25 seJ/yr baseline

Title	Units	UEV w/L&S	UEV no L&S	Source(s)
Structural Steel (all virgin)	sej/g	5.47E+09	4.69E+09	[126]
Structural Steel (with recycle)	sej/g	4.81E+09	4.02E+09	[126]
Copper	sej/g		2.30E+11	[125, 171]
Electricity - Coal	sej/J	2.18E+05		[131]
Electricity - Hydro	sej/J	8.51E+04		[131]
Electricity - Natural Gas	sej/J	2.17E+05		[131]
Electricity - Nuclear	sej/J	2.55E+05		[131]
Electricity - Peat	sej/J	2.27E+05		[131]
Electricity - Wind	sej/J	8.35E+04		[131]
Emergy to dollar ratio	sej/USD		2.02E+12	[127]
Natural Gas	sej/J	5.64E+04		[153]
Fuel Oil	sej/g	3.45E+09	3.09E+09	[151]
Propane	sej/g	4.03E+09	3.61E+09	[151]
Gasoline	sej/g	3.78E+09	3.38E+09	[151]
PET plastic Preform	sej/g	4.79E+10		[98]
Silver	sej/g		3.42E+11	[172]
Gold	sej/g		3.83E+11	[172]
Palladium	sej/g		9.34E+10	[172]
Aluminium	sej/g		4.11E+09	[172]
Beryllium	sej/g		8.35E+11	[172]
Bismuth	sej/g		2.43E+14	[172]

Title	Units	UEV w/L&S	UEV no L&S	Source(s)
Chromium	sej/g		1.15E+11	[172]
Tin	sej/g		1.28E+12	[172]
Zinc	sej/g		5.47E+10	[172]
Antimony	sej/g		3.19E+12	[172]
Arsenic	sej/g		3.46E+12	[172]
Bromine	sej/g		2.63E+12	[172]
Cadmium	sej/g		2.58E+13	[172]
Chlorine	sej/g		8.49E+09	[160]
Lead	sej/g		3.65E+11	[172]
Nickel	sej/g		1.52E+11	[172]
Plastics	sej/g	4.17E+09	4.00E+09	[132]
Industrial Ceramics	sej/g		1.09E+11	This Study
Glass	sej/g		1.07E+09	[173]
Liquid Crystals	sej/g	1.70E+10	1.53E+10	This Study
Silicon	sej/g		1.37E+09	[172]
Brass	sej/g		1.68639E+11	This study
Concrete	sej/g	1.37E+09	1.37E+09	[208]
Land Erosion	sej/J		9.42E+04	[94]
Landfill	sej/g	8.73E+08		[123]
Helium	sej/g		3.97E+11	[127]
Nitrogen (N)	sej/g		8.86E+09	[127]
CO ₂	sej/g		3.05E+07	[213]
Oxygen (O ₂)	sej/g		1.22E+06	[213]
N ₂	sej/g		2.95E+10	[213]
Other Petroleum Oils	sej/g	3.40E+09	3.07E+09	[151]

Title	Units	UEV w/L&S	UEV no L&S	Source(s)
Barium	sej/g		1.68E+11	[127]
Titanium	sej/g		4.87E+10	[172]
Oxygen (O)	sej/g		6.11E+05	This study
Steel, EAF Process (virgin)	sej/g	5.28E+09	5.21E+09	[132]
Steel, EAF Process (100% post-consumer scrap)	sej/g	5.61E+09	5.56E+09	[132]
Steel, EAF Process (30% post-consumer & 70% in-house scrap)	sej/g	5.39E+09	5.33E+09	[132]
Steel, BOF Process (virgin)	sej/g	6.80E+09	6.75E+09	[132]
Steel, BOF Process (25% in-house scrap)	sej/g	6.80E+09	6.75E+09	[132]
Steel, 1998 China	sej/g	9.94E+09		[133]
Steel, 1999 China	sej/g	8.68E+09		[133]
Steel, 2000 China	sej/g	6.44E+09		[133]
Steel, 2001 China	sej/g	6.44E+09		[133]
Steel, 2002 China	sej/g	5.03E+09		[133]
Steel, 2003 China	sej/g	5.08E+09		[133]
Steel, 2004 China	sej/g	5.39E+09		[133]
Steel, 2016 China	sej/g	3.52E+09		[134]
Steel, CR Sheet	sej/g		3.93E+09	[135]
Barium Titanate	sej/g		1.09E+11	This study
Epoxy	sej/g		1.27E+10	This study
Chlorine	sej/g		1.70E+10	[160]
Chlorine - Cl ₂	sej/g		8.49E+09	[160]

Title	Units	UEV w/L&S	UEV no L&S	Source(s)
Ammonia - pre-industrial	sej/g		9.65E+08	[213]
Methanol	sej/g		3.25E+09	[235]
Hydrogen from steam refinement of natural gas	sej/g		1.47E+10	[229]
Ammonia - post-industrial	sej/g		4.47E+09	[213]

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