AN ABSTRACT OF THE THESIS OF

Michael D. Eastwood for the degree of Master of Science in Mechanical Engineering presented on June 3, 2014

Title: Assessing Steel Bevel Gear Design Alternatives for Sustainability Performance through Unit Manufacturing Process Modeling

Abstract approved:

Karl R. Haapala

As the growth in demand for sustainable manufacturing continues, companies must begin to make conscious design decisions with regard to the sustainability of their products. This means balancing economics of production with environmental and social performance. Thus, design and manufacturing engineers must consider economic, environmental, and social aspects simultaneously when developing products and process plans. The purpose of this research is to unify unit process-based modeling with sustainability assessment approaches to create a unit manufacturing process-based methodology for product sustainability assessment. Combining these approaches allows for conducting sustainability assessment of components and assemblies at the process level by quantifying a selected set of sustainability metrics. The methodology both improves upon existing approaches in identifying the sustainability impacts of a product and assists manufacturing decision makers. A demonstration of the methodology to assess and compare the sustainability performance of three design alternatives for a bevel gear is presented, first for lightweighting and, second, for improving performance of the

induction hardening process through an alloy change. For each bevel gear alternative in the lightweighting demonstration, the findings showed that the turning, vapor degreasing, and cadmium plating processes had the greatest impacts on the sustainability performance. In the induction hardening demonstration, a unit manufacturing process model is constructed and applied to hardening the teeth of a bevel gear made from three different steel alloys to improve the sustainability performance of the process. The model is composed of mathematical equations which are functions of process and component design parameters to quantify the economic, environmental, and social metrics of interest. The findings showed that the electrical resistivity of the steel alloy had the most influence on the sustainability performance of the induction hardening process. The addition of a tempering process is included in the assessment to achieve functional equivalence between the three steel alloys, and it was found to significantly alter the sustainability assessment results. The presented unit process-based sustainability assessment methodology and construction of unit process models can be applied to aid the investigation of tradeoffs during the design decision making process for a wide range of products.

ASSESSING STEEL BEVEL GEAR DESIGN ALTERNATIVES FOR SUSTAINABILITY PERFORMANCE THROUGH UNIT MANUFACTURING PROCESS MODELING

by
Michael D. Eastwood

A THESIS

Submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 3, 2014
Commencement June 2015

Master of Science thesis of Michael D. Eastwood presented on June 3, 2014

APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial and Manufacturing Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Michael D. Eastwood, Author

ACKNOWLEDGEMENTS

This work would not have been possible without the continuous support and technical guidance that I received from my advisor Dr. Karl Haapala. I would like to thank Dr. Chris Hoyle, Dr. Hector Vergara, and Dr. Leslie Burns for serving as my thesis examination committee members. I would also like to thank the Boeing Company and the Oregon Metals Initiative for funding this research. Special thanks goes to Matt Carter, Ann Simmons, Paul Liner, and Jason Marr of Boeing Portland for providing assistance with this research. Acknowledgements goes to my fellow Industrial Sustainability Laboratory students for their inputs and advice, especially Ian Garretson for his continuous assistance of this research. Additionally, I would like to thank my friends and family for all of their love and support.

CONTRIBUTION OF AUTHORS

Chapter 3: Manuscript 1

Dr. Karl Haapala contributed to the writing of the manuscript and development of the unit process-based product sustainability assessment methodology. Matt Carter and Ann Simmons of Boeing Portland contributed by providing manufacturing process data for the unit process models. Ian Garretson contributed by constructing the natural gas heat treatment unit process model for use in assessing the sustainability performance of the bevel gear.

Chapter 4: Manuscript 2

Dr. Karl Haapala contributed to the writing of the manuscript and guidance in constructing the induction hardening unit process model and formulating the analyses. Matt Carter and Ann Simmons of Boeing Portland contributed by providing induction hardening process data for the unit process model. Ian Garretson contributed by constructing the natural gas heat treatment unit process model for use in assessing the sustainability performance of the bevel gear.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX TABLES

NOMENCLATURE

A	magnetic vector potential
A_r	cross sectional area of material removed
A_S	hardened workpiece surface area
A_{ST}	exposed surface area of tank
B	magnetic field density
C	coefficient variable for penetration depth
C_f	feed factor
c_c	coolant cost
c_{CH4}	natural gas cost
c_{cp}	cost of cadmium plating chemicals
c_{con}	consumable cost
c_d	degreaser cost
c_e	electrical energy cost
c_L	labor cost
c_p	specific heat
c_q	quenchant cost
c_w	water cost
D	distance from center of the induction coil to workpiece surface
D_i	initial diameter
D_f	final diameter
E_{CH4}	natural gas energy consumption
E_{on}	on-site energy consumption
E_p	energy carried off by the part
f	alternating current frequency
f_c	cutter speed
f_r	feed rate
GWP_{CH4}	CH_4 global warming potential

GWP_{NO2}	NO_2 global warming potential
H	magnetic field intensity
H_S	surface magnetic field intensity
I	AC current in the induction coil
ID	inner diameter
I_M	part moment of inertia
I_{stk}	strike current
K_{Cd}	gas-mass transfer coefficient
K_p	machine power constant
M_{Cd}	molecular weight of cadmium
m_{CH4}	mass of natural gas burned
m_{con}	mass of consumable item
m_d	mass of degreaser
m_{de}	mass of degreaser emissions
m_r	mass of material removed
m_p	part mass
OD	outer diameter
P_c	power lost from induction coil
P_{Cd}	vapor pressure of cadmium
P_i	idle power
P_m	motor power
P_o	workpiece surface power density
P_p	pump power
P_r	radiation power losses
P_{r1}	run 1 power
P_{r2}	run 2 power
P_s	standby power
P_{stk}	strike power
P_w	workpiece power

p_c	coolant concentration percent
p_{cp}	cadmium plating chemical concentration percent
p_q	quenchant concentration percent
p_{red}	percent emission reduction
Q	material removal rate
q_{c_loss}	natural convection heat lost
q_{f_loss}	heat lost in flue gas
R	radius of the induction coil
R_g	universal gas constant
r_{AH}	aromatic hydrocarbons generation rate
r_{Cd}	cadmium emission generation rate
r_{CH4}	CH_4 generation rate
r_{CN}	cyanide emission generation rate
r_{CO2}	CO_2 generation rate
r_{HE}	heat energy rate
r_{Hg}	mercury generation rate
r_{ill}	illness incident rate
r_{inj}	injury incident rate
r_{lwd}	lost work day rate
r_{NO2}	NO_2 generation rate
r_{NOx}	NO_x generation rate
r_{Pb}	lead generation rate
r_{PM}	particulate matter generation rate
r_q	quenchant flow rate
r_{rec}	production rate of recyclable waste
r_{SOx}	SO_x generation rate
r_w	input water flow rate
r_{wd}	output water discharge rate
T	heated workpiece temperature

T_f	final temperature
T_i	initial temperature
T_∞	ambient temperature
t_i	idle time
t_m	machining time
t_p	total process time
t_q	time duration of quench
t_{ref}	time between tank refills
t_{run}	heating run time
t_s	standby time
t_w	water flow time
V_c	volume of coolant consumed
V_{cp}	volume of cadmium plating chemicals
V_d	volume of degreaser consumed
V_{dis}	volume of tank discharged
V_f	final part volume
V_{haz}	volume of hazardous waste
V_i	initial part volume
V_{pv}	plating voltage
V_q	volume of quenchant lost/consumed
V_r	volume of material removed
V_s	stock material volume
V_{sd}	volume of sludge discharged
V_T	volume of quenchant tank
V_{T_low}	volume of quenchant tank when low
V_{WL}	volume of water lost/consumed
V_{WT}	volume of water in the tank
W	tool wear factor
W_e	working mode emission rate

α	electrical resistivity temperature coefficient
δ	current penetration depth
ε	emissivity
η_c	coupling efficiency
η_m	motor efficiency
η_{vd}	vapor degreaser heating efficiency
θ	angle from the center of the induction coil to workpiece surface
μ_o	magnetic permeability of free space
μ_r	relative magnetic permeability
ρ	electrical resistivity
ρ_c	density of coolant
ρ_{CH4}	density of natural gas
ρ_d	density of degreaser
ρ_{haz}	density of hazardous waste
ρ_r	density of material removed
ρ_s	density of sludge
ρ_∞	electrical resistivity at ambient temperature
σ	Stefan-Boltzmann constant
$\omega_{\mathbf{b}}$	angular speed of gear blank
$\omega_{\mathbf{r}}$	rotational speed

CHAPTER 1: INTRODUCTION

1.1 Overview

The integration of the economic, environmental, and social aspects have been denoted as the three pillars of sustainability [1]. The economic aspect focuses on financial performance, the environmental aspect deals with the effects on the natural environment, and the social aspect focuses on the well-being of people. There are many methods and definitions for assessing these three aspects individually or jointly; however, it is widely agreed that all three must be simultaneously considered in order to assess the sustainability performance of a product or process [2], [3].

The degradation of the environment caused by economic advancement led to the discussion of the notion of sustainable development on an international level at the 1992 United Nations Conference on Environment and Development. The conference covered several issues including the growing scarcity of water, the depletion of non-renewable sources of energy, and human health problems in the workplace and the community [4]. A major contributor to these issues was found to be the unsustainable production patterns in industry. The conference resulted in creating three major agreements including Agenda 21, The Rio Declaration on Environment and Development, and The Statement of Forest Principles [4]. These agreements comprise of a program of action and a series of principles to address all areas of sustainable development.

Since then, the market has changed and more regulations relating to sustainability have emerged. In the United States, regulations are documented within the US Code of Federal

Regulations [5], and includes regulations such as the Clean Air Act, the Clean Water Act, and the Resource Conservation and Recovery Act. The United States Environmental Protection Agency (EPA) enforces these regulations to ensure the protection of human health and the environment [6]. Regulations have forced companies to face the challenge of balancing economics with environmental and social aspects.

As consumers are becoming aware of sustainability in a broad sense, they are placing value on economic, environmental, and social responsibility. Thus, they are generating demand for more sustainable products and practices. Retailers are recognizing the cost benefits of reducing material consumption and eliminating wastes, and are demanding it from their suppliers. In some instances, retailers are requiring documentation from their suppliers to reduce energy use, greenhouse gas (GHG) emissions, and wastes [7]. The trend of implementing sustainability goals continues to grow as companies experience these pressures from their customers.

The product manufacturing industry is starting to incorporate economic, environmental, and social aspects of sustainability into design decision making processes. It is a difficult task to reduce energy and natural resource consumption and ensure the well-being of employees, customers, and the community, all the while remaining economically competitive. This research is motivated by the need for companies and engineers to assess the sustainability performance of their products and processes to make sustainable conscious decisions. They require a reliable method for quantifying and comparing performance measures between product and process alternatives to identify improvement areas and select the most sustainable alternative.

1.2 Background

Previous research on developing methodologies for sustainability assessments have focused on each of the aspects of sustainability. Life cycle assessment (LCA) is a widely used and internationally standardized method for conducting environmental assessments of manufactured products by measuring emissions, energy consumption, material consumption, and waste generation. In the literature, there is much work that utilizes the LCA method for environmentally assessing products and processes, and further extends it through integration with other methods and software tools to enable faster assessments, greater analyses, and stronger decision making [8]–[11]. Although there is not an internationally standardized economic assessment method, a lot of the research utilizes the LCA method framework and apply its concepts to economic assessments [12]–[14]. This type of work measures a product’s incurred and saved costs from material extraction, production, use, and disposal for making design comparisons or improvements from implementing environmentally friendly techniques. Methods for social assessments are limited primarily due to the disagreements and challenges for measuring social performance [15]. Similar to methods for economic assessments, research for social assessments utilize the concepts from LCA to measure the social implications of manufacturing a product such as occupational illnesses and injuries, wages, and benefits [16], [17].

Manufacturing process models for quantifying sustainability metrics are often developed to assist sustainability assessments. General manufacturing models have been developed to approximate the sustainability performance of a facility or even a category of manufacturing processes such as machining [18]–[21]. More recent work has focused on developing methodologies for collecting data and constructing unit manufacturing process models to measure environmental performance [22], [23].

One focus of this work is the induction hardening process for steel alloy components. A majority of the research and modeling efforts for induction hardening can be divided into experimental studies, mathematical models, and finite element analyses. The previous research analyzes the electromagnetic, thermodynamic, and microstructural transformations that occurs during the induction hardening process to predict the temperature distribution, hardness profile, and residual stresses in the workpiece [24]–[27]. Research for constructing a unit manufacturing process model for induction hardening to measure sustainability performance has not yet been reported in literature.

1.3 Research Objective

The objective of this research is to provide design and manufacturing engineers the ability to reliably assess the economic, environmental, and social performance of their products and processes. In order to assist decision making during design for manufacturing activities in identifying efficiency improvements and determining the most sustainable product alternatives, unifying unit manufacturing process modeling with sustainability assessment approaches is needed.

1.4 Research Tasks

Several research tasks were undertaken to fulfill the objective of this research. The first task is to unify unit manufacturing process modeling with sustainability assessment approaches to develop a unit process-based methodology to assist product sustainability assessment. Subtasks include defining the methodology steps and how they can be implemented to assess the sustainability performance of a product and demonstrating the methodology for quantifying a selected set of sustainability metrics for bevel gear design alternatives.

The second task is to develop an induction hardening unit manufacturing process model to assist the sustainability assessment for a bevel gear. Subtasks include conducting background research for understanding the process's functionality, collecting process data, applying theoretical equations to quantify sustainability metrics, and analyzing the assessment results.

1.5 Thesis Outline

This research is reported in the manuscript format and includes five chapters. Chapter 1 provides the overview, motivation, and tasks of this research. Chapter 2 reviews the literature on sustainable manufacturing, sustainability assessments, manufacturing process models, and the types of models applied to induction hardening. Chapter 3 is a journal article submitted to the *Journal of Cleaner Production* and titled "A Unit Process Model Based Methodology to Assist Product Sustainability Assessment during Design for Manufacturing." This article develops a product sustainability assessment methodology to select, quantify, and aggregate metrics for unit manufacturing processes. The methodology is demonstrated for comparing the sustainability performance of three design alternatives for the production of a bevel gear. Chapter 4 is a journal article to be submitted to the *International Journal of Advanced Manufacturing Technology* and titled "An Induction Hardening Process Model to Assist Sustainability Assessment of a Bevel Gear." This article applies the methodology developed in Chapter 3 to construct a unit manufacturing process model specifically for induction hardening. The model is demonstrated for comparing the sustainability performance of an induction hardened bevel gear using three different steel alloy design alternatives. Chapter 5 presents the summary, conclusions, and contributions of this research, and proposes opportunities for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Sustainability and Manufacturing

The Brundtland Report [28] defines sustainable development as the “development which meets the needs of the present without compromising the ability of future generations to meet their own needs.” Although this definition is widely accepted, it is not applicable for businesses and engineering decision makers in manufacturing. The U.S. Department of Commerce [29] defines sustainable manufacturing as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound.” This definition neglects the entire life cycle of the product and focuses on the manufacturing phase. A more complete definition of sustainable manufacturing was presented by Zhang et al. [30] as the “set of systems and activities for the creation and provision of manufactured products that balance benefits for ecological systems, social systems, and economic systems.” This definition includes the entire life cycle of the product from cradle-to-grave as well as all aspects of sustainability.

Manufacturing plays an important economic role by providing jobs and helping an economy to grow [31]. With the growth of manufacturing, also comes the disruptive and often harmful effects on humans and the environment. This is due to the unsustainable production patterns in manufacturing of high energy consumption and pollutants emitted. The manufacturing industry is responsible for approximately 33% of the energy consumption globally [32], with over 90% of its energy use originating from fossil fuels

[33]. The industrializing countries lacking environmental laws are significantly impacted by the effects of pollution. For the countries that have addressed environmental issues, average life expectancies have improved [31].

The emergence of regulations has placed pressure on all industry sectors to improve their sustainability performance [34]. This has caused the product manufacturing industry to incorporate economic, environmental, and social considerations during the decision making process. The number of manufacturing companies making fundamental changes toward sustainability goals is increasing worldwide [35]. These companies face the difficult challenge of balancing economic with environmental and social aspects.

To evaluate and improve the sustainability performance of manufacturing products and processes, metrics are commonly used [36]. Developing and defining metrics for sustainable manufacturing aids decision makers to improve a process or system by comparing performance [37]. Measurable, useful, and meaningful metrics will be relevant, understandable, manageable, reliable, cost-effective, and flexible [38]. Lu et al. [39] presented a framework for developing sustainable manufacturing metrics which encompass all aspects of sustainability. A list of potential metrics were developed and grouped into the categories of environmental impact, energy consumption, economic cost, worker safety, worker health, and waste management. The proposed metrics are for measuring the sustainability performance of a product or process, and are quantified by analytical calculations, experimental measurements, or collected on-site.

The following section presents the research efforts for developing methods and tools for performing sustainability assessment of product design and manufacturing processes and process plans.

2.2 Sustainability Assessment

Ness et al. [40] categorized sustainability assessment methods and tools into the three categories: indicators and indices, product-related assessments, and integrated assessments. Indicators and indices are most often quantitative measurements of the economic, environmental, and/or social performance. Product-related assessments focus on evaluating the different flows related to a product or process through its life cycle. Integrated assessments are for supporting decisions related to a policy or a project by combining sustainability assessments with traditional company assessments. There are various methods and tools for conducting sustainability assessments, but only a few of them take into account economic, environmental, and social aspects holistically. Economic assessments are widely used in industry with several types of methods, environmental assessments most often utilize the internationally standardized life cycle assessment (LCA) method, and social assessments are generally considered to be in the early stages of development [41].

Common software tools for performing environmental assessments (e.g., SimaPro and GaBi) rely on various LCI databases, such as ecoinvent, U.S. Life Cycle Inventory (USLCI), and European Reference Life Cycle Database (ELCD) [42]. LCA tools have uncertainties in the assessment results due to the uncertainties within the LCI databases, as well as not containing the necessary details for assigning the environmental impacts to individual manufacturing processes [42]–[44]. Development of methods and tools is an ongoing effort in research and industry to provide more accurate sustainability assessments of products and processes. The following sections present recent research in methods and tools for environmental, economic, and social assessments.

2.2.1 Environmental Assessment

Environmental assessments focus on the impacts made by negative changes to the natural environment (land, air, and water) and public health [45]. In general, it is necessary to measure the efficient use of production inputs (materials, energy, and water resources) and the fate of outputs (emissions, effluents, and wastes).

LCA is a widely used, standardized method for conducting environmental assessments of manufactured products. The framework of the LCA method includes four iterative phases as described by ISO 14040 [46]: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation. The goal and scope definition defines the purpose of assessment, the needed information that adds value to the decision making process, and the boundaries of the product life cycle [47], [48]. Inventory analysis involves the creation of life cycle inventory (LCI) databases by collecting information on the inputs and outputs for the processes within the defined system boundary. Impact assessment is the evaluation of the effect of inputs and outputs on environmental impacts. Common environmental impacts considered include global warming potential, acidification, smog, ozone layer depletion, eutrophication, toxic pollutants, habitat destruction, and depletion of minerals and fossil fuels [44]. Interpretation involves the analysis and validation of the results from the other phases, and the effective communication of the results, analysis, and recommendations.

A collaborative computer-based method was developed by Borland et al. [10] for generating responsive environmental impact assessments for product designers. The goal was to speed up the process compared to standard LCAs, which are time consuming and difficult because they require high quality data and environmental expertise. The method utilized the Internet to share only the necessary data between environmental, stress analysis, CAD, and product design experts. The results showed the approach was feasible and the environmental assessment can be completed in a timely manner. A major concern was the lack of detailed relationships between design changes and the environmental assessment for the designer to make knowledgeable decisions. Haapala et al. [8] proposed a method for automating environmental impact assessments during the conceptual phase of product design. The method consists of a morphological matrix to develop a functional model for a desired product, a concept generator that transforms the functional model into possible assemblies of components, and a life cycle impact assessment (LCIA) method for generating the environmental impact assessment. The method could enable the evaluation and reduction of environmental impacts during the early stages of product design, compared to common sustainability assessments methods which evaluate the sustainability performance of existing products.

An LCA based methodology proposed by Le Bourhis et al. [9] evaluated the environmental impact of a direct additive laser manufacturing process from a CAD model. The methodology focused on the electrical energy, fluid, and material consumption of the manufacturing process. The geometry of the part was obtained from the CAD model and applied in analytic, mathematical models for quantifying the environmental impacts associated with each of the sub-processes involved in direct additive laser manufacturing process. The methodology was validated against experimental results, and was able to identify the influences of the process parameters on the environmental impacts. Jiang et al. [11] developed an environmental performance assessment method for manufacturing processes and process plans. The method involved constructing input-output diagrams for determining key material and energy flows for each manufacturing process, developing mathematical models to quantify environmental metrics, and aggregating the information for the manufacturing process plan to assess the environmental performance. In order to compare alternative products, the analytical hierarchy process (AHP) was used to provide a weighted environmental performance score for each alternative.

2.2.2 Economic Assessment

In the manufacturing industry, the measurement of economic performance is a familiar topic since manufacturing is a business function, and thus, it is generally easy to analyze [49]. In a majority of applications, the economic performance is represented in dollar amounts. It is a measure of the costs throughout a product's life cycle, and should reflect the impacts on the local, regional, and national level.

The economic input-output life cycle assessment (EIO LCA) method was developed by Hendrickson et al. [12] for conducting an economy wide product manufacturing economic and environmental assessment. The method utilized the economic general equilibrium model proposed by Leontief [50], which assumed an increase in output goods to any sector of an economy requires a proportional increase in each input received from all other sectors. Using available U.S. economy data, the method was used to conduct an assessment for steel-reinforced concrete production. They quantified the costs of production, the hazardous waste generated, and the toxic emissions released for the US economy for producing steel-reinforced concrete. Kumar and Sutherland [51] developed a material flow and economic exchange model for assessing the economic performance of material recovery for end of life vehicles. The model was used to assess various strategies implemented within the U.S. automotive recovery infrastructure. They found that in order to achieve higher material recovery rates from vehicles, the recovery businesses need to employ new strategies, which ends up hindering their economic sustainability. To prevent the economic burden on increasing material recovery rates, potential profit-enhancement strategies were proposed.

Kim et al. [13] conducted a life cycle economic assessment for the reduction of greenhouse gas emissions by reducing the weight of a vehicle. The costs of producing alternative vehicles made from various percentages of aluminum and high-strength steel were compared. Relevant cost data from literature was compiled to estimate the economic performance of the vehicle alternatives. They found that lightweighting vehicles using aluminum was the most cost effective option to reduce greenhouse gas emissions per kilogram. Beaver [14] combined LCA techniques with total cost assessment (TCA) and developed a TCA tool to estimate the incurred and saved costs of implementing environmental goals within a company. The tool used data from in-house databases, publicly available data such as from literature, the EPA, and LCI databases if available. The tool also incorporated conventional costs such as raw materials and utilities, as well as potential overlooked costs associated with improving environmental performance. These costs included those due to designing environmentally sustainable products, qualification of suppliers, and evaluating pollution control equipment.

2.2.3 Social Assessment

Approaches for economic and environmental assessments have been at the center of attention for sustainable manufacturing, and the development of approaches for social assessments have so far been largely neglected [16], [52]. It is often uncertain how to best assess social sustainability. This is primarily due to varying perceptions of social impacts and the mix between qualitative and quantitative measurements [15]. There are disagreements on whether social impacts are related to manufacturing processes or company conduct. Understanding and incorporating the social aspect of sustainability is a challenging task, but it is necessary for design and manufacturing engineers to understand the social implications of their work and decisions.

Schmidt et al. [16] presented a new LCA tool for measuring the social performance of products and processes. They discussed the many challenges for conducting social sustainability assessments, which include the absence of databases for social aspects and the complexity for defining and measuring social indicators. The authors proposed a preliminary set of social indicators, which were categorized by stakeholder groups who may be affected during the life cycle of a product. A weighting scheme was applied in the tool in order to aggregate and compare product alternatives based on their respective social impacts. Dreyer et al. [17] developed a methodology for conducting a social LCIA. The goal was to enable companies to conduct their business in a socially responsible manner by identifying the impacts of their products on people. The methodology combined bottom-up and top-down approaches to relate the social implications to the manufacturing processes. The findings showed the impacts on people were primarily related to the conduct of the company rather than the individual manufacturing processes.

2.2.4 Sustainability Decision Making

Sustainability assessments measure the sustainability performance of products and processes, but do not compare metrics or product alternatives. To make sustainability design and manufacturing decisions, decision making methods need to be incorporated with sustainability assessment methods. Previous work for combining these approaches includes weighting schemes and multi-criteria decision analyses, and are presented below.

A multi-criteria decision making framework developed by Munda [53] ranks countries, cities, or regions based on their sustainability performance. Economic, environmental, and social metrics were selected based on the available data and their applicability to the country, city, or region. The metrics were weighted using a pairwise comparison method, and aggregated using a normalization rule. A fuzzy preference relation was used to rank the country, city, or region based on its sustainability performance.

Eastlick and Haapala [54] developed a decision making method for comparing product alternative sustainability metrics values. The method used a fixed sum method to weight the metrics and organize them by relative importance into a value tree. Four multi-criteria decision analyses were investigated for generating sustainability performance rankings: a simple weighted sum method using MS Excel and three advanced methods using commercial software. The weighted sum method was found to be more time efficient and provided the transparency needed to support decision making. Similarly, to compare product alternatives, Zhang and Haapala [55] utilized the analytic hierarchy process, a pairwise comparison method, to develop product sustainability metric weightings. The PROMETHEE method was used to rank the product alternatives for decision making. The approach was demonstrated for ranking three different machining parameter scenarios for producing a stainless steel knife.

Many of the previously described sustainability assessment methods and tools incorporate manufacturing process modeling to quantify metrics and measure sustainability performance. Research and work for manufacturing process modeling is presented in the following section.

2.3 Manufacturing Process Models

Manufacturing processes add value to a product by transforming inputs into outputs. Examples of common modeling languages for building process-specific models include Integration Definition and Function Modeling (IDEF0), Business Process Model and Notation (BPMN), and Process Specification Language (PSL) [42]. These models focus on the flow of materials and services between manufacturing processes, and do not explicitly detail how the processes are related to sustainability performance. Due to the multiple and complex tradeoffs in sustainable product and process design, it is necessary to develop manufacturing process models for measuring their sustainability performance.

Jawahir and Jayal [56] described some common process modeling techniques for evaluating product and process sustainability performance, these include analytical, empirical, and computational models, as well as optimization methods. Analytical models utilize theoretical equations for predicting performance. Empirical models incorporate experimental studies to validate and refine analytical models. Computational models use computer programs for conducting finite element analyses. Optimization methods are used for determining the most efficient process parameters. Prior work for developing manufacturing process models also varies by the system level. The reported research presented below has been categorized into high-level and low-level unit manufacturing process models. The high-level manufacturing process models focus on the company level through the generalized manufacturing processes level, and the low-level unit manufacturing process models focus on individual manufacturing processes.

2.3.1 High-Level (Top Down) Manufacturing Process Models

The following work covers high-level manufacturing process models. These models measure the economic and/or environmental sustainability performance at the company level down to the generalized manufacturing processes level.

Tornberg et al. [19] developed an activity-based process model to estimate the cost from initial product design through product manufacturing. The model calculated the costs on a per activity basis. Activities are the individual job functions such as creating the product drawing, designing the tooling, machine programming, material handling, and machining. The model was implemented for a manufacturing company and was effective in providing cost information for product designers. Choi et al. [20] developed general manufacturing process models to assess a product's environmental impact. Based on the concept of material balance to connect the inputs to the outputs, equations were constructed for calculating the solid waste generation, electrical energy consumption, waste water produced, and the level of noise created from a manufacturing process. The models were applied to several alternative manufacturing production methods of a toy train. The assessment compared each alternative to obtain the toy train alternative with the lowest environmental impact.

An input-output model for manufacturing companies was developed by Lin and Polenske [18] to provide information and analyses for making business decisions. The model utilized matrices to track the flow of input materials to the final product as well as solid waste byproducts from all of the manufacturing processes within a facility. The model was primarily used for measuring a company's economic performance, but also has the capabilities of providing aid in environmental management by tracking the solid wastes generated. Li and Yuan [21] developed a model for predicting the energy consumption of any general machining process, such as turning and milling. The energy consumption model was a function of the spindle power and material removal rate. The model was developed by first starting with a rough estimate and refined through experimental results. It was found to be 97% accurate for low material removal rates in cases such as manual or micro machining.

2.3.2 Low-Level (Bottom Up) Unit Manufacturing Process Models

Manufacturing process flows are composed of several processes and sub-processes. These are known as unit manufacturing processes, which are the individual steps that convert raw materials into the final product [57]. In order to accurately assess the sustainability of a product, it is necessary to decompose the flow and analyze the effects of each individual, low-level unit manufacturing process from the bottom up. Unit manufacturing process models for quantifying sustainability metrics can account for the variances in the manufacturing process flow due to the physical part design and the resulting process design [58]. They can provide a descriptive prediction of a process by relating the material and energy inputs to the waste and effluent outputs. Process modeling takes product and process information and produces results in the form of economic, environmental, and social metrics. Sustainability assessments conducted for a final product rarely link the sustainability performance results to unit manufacturing processes. Typically, the methods used to measure sustainability metrics and collect data are not well documented. In recent years, however, methods for evaluating the sustainability of unit manufacturing processes have become more prevalent. A standard method is currently being developed by ASTM International for characterizing the sustainability of manufacturing processes [59].

The Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) is an international group which has focused its efforts on documenting, analyzing, and reducing the environmental footprint for a range of manufacturing processes [22]. The key objective of the CO2PE! is to study the energy consumption and CO_2 emissions of discrete part manufacturing processes. Similarly, Overcash et al. [60] developed a unit process life cycle inventory (UPLCI) for a drilling process. An estimation of the process energy use and the material and cutting fluid losses for drilling a set of holes were calculated using theoretical equations and data from a selected computer numerical controlled (CNC) machine under high production mode. Duflou et al. [61] developed a UPLCI for laser cutting processes, specifically for a CO_2 laser cutting machine and a selective laser melting machine. Several measurement studies were conducted in order to determine the energy use, process gas consumption, produced waste, and air emissions for the laser cutting machines.

As part of the CO2PE!-Initiative, Kellens et al. [43] documented the UPLCI methodology to aid in the collection of data for unit manufacturing processes and the construction of unit process models. The methodology contains two approaches to generate reports with different levels of detail referred to as the screening approach and in-depth approach. The screening approach utilizes publicly available data and engineering calculations to estimate the energy use and material losses, which leads to an approximate LCI. The in-depth approach includes a time, power, consumables, and emissions study to provide more accurate LCI data that better characterizes the environmental impacts associated with manufacturing processes. Overcash and Twomey [62] have used the screening approach to generate and collect data for unit manufacturing process models. They have produced UPLCI reports for several common manufacturing processes, including material removal, mass conservation, joining, and heat treating processes.

The Smart Manufacturing Program at the U.S. National Institute of Standards and Technology (NIST) aims to develop methods for evaluating and improving resource efficiency and waste reduction for manufacturing processes and product assemblies [23]. A method developed by Feng et al. [63] of NIST calculates energy metrics for a general product assembly process. Specifically, the authors presented the metrics and equations for quantifying the energy consumption and energy efficiency for both the main equipment and auxiliary equipment that are necessary for an assembly process. A study for a hybrid laser welding process was conducted to estimate the energy consumption and efficiency for the individual sub-process as well as for the overall assembly process. Madan et al. [64] presented a guideline for characterizing the energy consumption for an injection molding process. The goal of the work was to stray away from high level analyses which do not accurately estimate the energy performance at the process level and to incorporate the pre and post operations. Similarly, Watkins et al. [65] described a method for characterizing the sustainability performance for a die casting process. The method developed was comprised of three parts: defining sustainability performance indicators, developing information models to quantify the indicators, and applying process-specific data sets to support and use in the information models. A die casting process was studied and theoretical energy consumption equations were compiled for each sub-process.

Gediga et al. [66] constructed theoretical equations to form unit manufacturing process models for several joining processes including laser beam welding, gas metal arc welding, resistance spot welding, punch riveting, and screwing. An assessment was conducted for quantifying the energy consumption to join aluminum and steel sheets with a functional unit of joining a one meter length of material. The boundaries of assessment included raw material extraction through end-of-life for the metal sheets, as well as the input materials required for joining such as welding wire and inert gas. Input data from an automotive industry partner were used to validate the models. Haapala et al. [67] developed unit manufacturing process models for electric arc furnace steelmaking and sand casting for evaluating environmental performance. The models were demonstrated on a steel component to quantify electrical energy consumption and greenhouse gas and pollutant emissions for different alloys. Results identified several possible areas of improvement in the processes to reduce the environmental impacts for producing the steel component. Fratila [68] combined theoretical equations with experimental results for modeling a gear milling process. An environmental assessment was conducted to compare the effects of dry cutting, minimal quantity lubricating, and flood lubricating on cutting tool wear, energy consumption, and generation of pollutant emissions when machining a 16MnCr5 steel helical gear. The results were able to conclude dry cutting and minimal quantity lubrication offers many possibilities for improved efficiency and reduction of environmental impacts and process costs.

The previous mentioned work for unit manufacturing process modeling covers many types of manufacturing process, but models for surface hardening processes are limited. The manufacturing process of interest for this research is induction hardening, due to its increase in application within the manufacturing industry for its energy efficiency, short processing times, and repeatability [69], [70]. The induction hardening process enhances the mechanical properties at the surface of a material by changing its microstructure [69], [71]. This is achieved by rapidly heating the workpiece through inducing high frequency alternating currents from a generated magnetic field. Prior models developed for the induction hardening process are discussed in the following section.

2.4 Induction Hardening Models

Most of the recent research and modeling for induction hardening has studied the effects of process and design parameters on the magnetic field, temperature distribution, phase transformations, and workpiece properties such as hardness profile, hardness depth, and microstructure. An overview of the relevant work on experimental studies, mathematical models, and finite element analyses (FEA) is presented below.

2.4.1 Experimental Studies

An experimental study conducted by Kurek et al. [72] observed the influence of manufacturing process and design parameters on the temperature distribution in steel gears during an induction hardening process. The study investigated the effects of varying the alternating current (AC) frequency in the induction coil, gear radius, number of teeth, tooth length, tooth height, and inductor distance from the tooth. For each parameter, they were able to conclude the value that achieved the most desirable temperature distribution. Kristoffersen and Vomacka [73] conducted an experimental study to observe the influence of process parameters on the residual stresses for induction hardening a cylindrical steel part. The process parameters examined included frequency, power, and heating time, as well as the microstructure prior to induction hardening. They concluded that for the same case depth, each process parameter and initial microstructure affected the residual stress state of the part due to their impacts on temperature distribution within the part during heating.

2.4.2 Mathematical Models

Hömberg [74] constructed mathematical models for the heating and hardening that occur during induction hardening of a steel workpiece. The electromagnetic and thermomechanical effects were studied for development of the heating and hardening models. The findings showed that the rise in temperature of the workpiece is dependent upon both the electrical conductivity of the workpiece and the heating caused by the Joule Effect from the induced current.

Bokota and Iskierka [75] constructed numerical models from theoretical equations to analyze the resultant phase transformations and residual stresses from induction hardening cone-shaped steel parts. Maxwell's equations and the Fourier-Kirchhoff equation were used to calculate the electromagnetic field and the thermal field, respectively. These equations were then implemented into the constructed numerical models for predicting the phase transformation and residual stresses. Similar to the previous work, Chaboudez et al. [76] constructed mathematical models for the electromagnetic and thermal field from theoretical equations. Numerical simulation code was developed based on the mathematical models to analyze the time dependent electromagnetic and thermal field from an induction hardening process for long steel and stainless steel workpieces. Experimental measurements were able to validate the models and simulation with minimal error. The aim of the previous works was to avoid the numerous costly and time consuming experimental studies typically involved with predicting the behavior and identifying the optimal parameters for induction hardening.

2.4.3 Finite Element Analysis and Computer Simulation

Model development for induction hardening has also incorporated the construction of mathematical models for analyzing electromagnetic, thermodynamic, and microstructural transformations. Cajner et al. [24] developed a computer simulation to measure the surface hardness and hardening depths of cylindrical parts made of 42CrMo4 steel. The induction hardening model included input parameters from the power supply, quenchant, and heating time. Experimental results were able to validate their simulation. Detailed mathematical models were constructed by Melander [25] to calculate the temperature distribution, hardness profile, and residual stresses for the static and progressive induction hardening of an AISI 4142 steel cylinder bar. A finite difference method (FDM) was used to solve for the magnetic field, temperatures, and phase transformations in the static case, where the workpiece does not move with respect to the induction coil. A finite element modeling (FEM) program was used to solve for the magnetic field in the progressive case, where the workpiece moves through the coil. Only minor deviations were found between the calculations and the measured results.

An FEA model developed by Yuan et al. [26] was used to predict the current and temperature distributions within an AISI 1070 steel part to determine the phase transformation and hardness profile. The model analyzed all of the key aspects of the process including the current in the coil to the quenching of the workpiece. The results of the model were found to be a close match to the experimental results. Barka et al. [27] developed an axisymmetric model for an FEA simulation to conduct a sensitivity study on the hardness profile for an AISI 4340 steel flat cylinder heated by induction hardening. The sensitivity study determined the significance of the frequency, power, and heating time on the resulting hardness profile. It was found that the heating time was the predominant factor in determining the hardened case depth, and that there were no interactions between the three parameters.

2.5 Limitations of Prior Research

The reviewed research provides an immense knowledge base for each respective field. Despite the contributions of the reviewed research to sustainable manufacturing, sustainability assessments, unit manufacturing process models, and induction hardening, there are some limitations which are identified below:

i. A majority of sustainability assessments focus on the environmental aspect, economic aspect, or a combination of the two, and do not simultaneously consider all aspects of sustainability, i.e., the economic, environmental, and social dimensions.

ii. Most of the reported research efforts on developing unit manufacturing process models only focus on the environmental aspect rather than all three aspects of sustainability. Typically, the models quantify one or two metrics such as energy consumption, emissions, or material losses. Sustainability assessment requires evaluation of a broader set of metrics.

iii. An induction hardening sustainability unit process model to quantify metrics such as water use, energy consumption, emissions, injuries, and other sustainability metrics has yet to be developed.

It could be argued that the assessment approaches for each aspect are complementary to each other, but sustainability involves more than the aggregation of the information and issues. It is also about the interconnections and effects each aspect has on one another within a product or process system [77]. A complete sustainability assessment for making informed product design and manufacturing decisions should include economic, environmental, and social aspects [41], [78], [79].

This research attempts to address the identified gaps by developing a methodology to assist product sustainability assessment that simultaneously considers all three aspects of sustainability. The unit manufacturing process models developed as part of the methodology will quantify economic, environmental, and social metrics to obtain the product's sustainability performance. An induction hardening model is constructed for quantifying a selected set of sustainability metrics. The goal for the methodology and unit manufacturing process models is to develop more robust product sustainability assessments; these in turn will assist design and manufacturing engineers during design and process evaluation and decision making.

Chapter 3: A Unit Process Model Based Methodology to Assist Product Sustainability Assessment during Design for Manufacturing

by
Michael D. Eastwood, Karl R. Haapala, Matthew D. Carter, and Ann E. Simmons

Submitted to the Journal of Cleaner Production
http://www.journals.elsevier.com/journal-of-cleaner-production/

CHAPTER 3: A UNIT PROCESS MODEL BASED METHODOLOGY TO ASSIST PRODUCT SUSTAINABILITY ASSESSMENT DURING DESIGN FOR MANUFACTURING

3.1 Abstract

As the growth in demand for sustainable manufacturing continues, companies must begin to make conscious decisions with regard to the sustainability of their products. Thus, design and manufacturing engineers must consider economic, environmental, and social aspects simultaneously when developing products and process flows. The purpose of this research is to develop a sustainable assessment methodology to both improve the accuracy of existing approaches in identifying the sustainability impacts of a product and to assist manufacturing decision makers. The methodology developed utilizes unit process modeling and life cycle inventory techniques. Combining these approaches allows for conducting product sustainability assessment at the process level by quantifying a selected set of sustainability metrics. A demonstration of the methodology to assess three design alternatives for a bevel gear is presented. The developed methodology is capable of quantifying the sustainability metrics by aggregating information from the process level. It was found that the various metrics require different aggregation methods from the manufacturing process to the manufacturing system level. The general approach can be applied to aid the investigation of tradeoffs during the design decision making process for a wide range of products.

3.2 Introduction

The product manufacturing industry is starting to incorporate economic, environmental, and social aspects of sustainability into design decision making processes. The degradation of the environment caused by economic advancement led to the discussion of the notion of sustainable development on an international level at the 1992 United Nations Conference on Environment and Development. The conference covered several issues including the growing scarcity of water, the depletion of non-renewable sources of energy, and human health problems in the workplace and the community [4]. A major contributor to these issues was found to be the unsustainable production patterns in industry. The conference resulted in creating three major agreements including Agenda 21, The Rio Declaration on Environment and Development, and The Statement of Forest Principles [4]. These agreements comprise of a program of action and a series of principles to address all areas of sustainable development.

Since then, the market has changed and more regulations relating to sustainability have emerged. In the United States, regulations are documented within the US Code of Federal Regulations [5], and includes regulations such as the Clean Air Act, the Clean Water Act, and the Resource Conservation and Recovery Act. The United States Environmental Protection Agency (EPA) enforces these regulations to ensure the protection of human health and the environment [6]. Regulations have forced companies to face the challenge of balancing economics with environmental and social aspects. It is a difficult task to reduce energy and natural resource consumption and ensure the well-being of employees, customers, and the community, all the while remaining economically competitive.

As consumers are becoming aware of sustainability in a broad sense, they are placing value on economic, environmental, and social responsibility. Thus, they are generating demand for more sustainable products and practices. Retailers are recognizing the cost benefits of reducing material consumption and eliminating wastes, and are demanding it from their suppliers. In some instances, retailers are requiring documentation from their suppliers to reduce energy use, greenhouse gas (GHG) emissions, and wastes [7]. The trend of implementing sustainability goals continues to grow as companies experience these pressures from their customers.

In order to quantify the sustainability performance of a manufactured product, the economic, environmental, and social aspects must be simultaneously considered. When assessing the sustainability of a product, one must define the goal and scope of the study, select and quantify applicable sustainability metrics, identify the key unit manufacturing processes, develop mathematical unit process models to quantify the sustainability metrics, and analyze and interpret the results. This is a challenging set of tasks due to the extent of sustainability aspects to consider. According to Chiu and Kremer [80], a majority of research and tools to assess the sustainability performance of a manufactured product at the design and process level focus just on the environmental aspect, and mathematical models to assess all aspects of sustainability are non-existent.

The objective of this work is to develop a product sustainability assessment methodology to improve the accuracy of quantifying metrics related to the economy, environment, and society during the design for manufacturing process. The six-step methodology developed as part of this research utilizes unit process modeling and life cycle inventory (LCI) approaches to quantify sustainability metrics for cradle-to-gate product sustainability assessment. It can be applied to assess the sustainability performance of alternative product designs from the process level. In the discussion below, current sustainability assessment approaches are first presented including metrics/indicators, life cycle inventory methods, and unit process modeling. Second, the six-step sustainability assessment methodology developed is explained in detail. Third, the methodology is demonstrated for design and manufacturing alternatives using a bevel gear manufacturing case study. Finally, the results of the case study and the conclusions discovered from this research are discussed.

3.3 Background

Sustainable manufacturing is defined by Haapala et al. [49] as the "manufacturing of products that address sustainability goals in their use (e.g., renewable energy and green building products), as well as sustainable manufacturing processes and systems for all products." In order to achieve sustainability, decision makers must take into consideration the entire life cycle of a product and identify the impacts on the economy, environment, and society. Each decision that is made has implications for each aspect of sustainability and affects the present and future generations [3].

3.3.1 Sustainability Metrics

When conducting a sustainability assessment, one of the initial tasks is to define quantifiable metrics. The most commonly used sustainability metrics in practice are categorized into the three basic sustainability domains: economic, environmental, and social [45]. The purpose of applying sustainability metrics to assess a product is to both measure sustainability performance and drive the advancement toward sustainability goals [81].

In a majority of applications, economic metrics are represented in terms of dollars. They are a measure of the capital incurred throughout a product's life cycle, and should reflect the impacts on the local, regional, and national level. Environmental metrics focus on the impacts made by negative changes to the natural environment. They target the impacts on the land, air, water, and public health [45]. In general, it is necessary to measure the efficient use of production inputs (materials, energy, and water resources) and the fate of outputs (emissions, effluents, and wastes). It is often uncertain how to best measure social metrics, which is primarily due to varying perceptions of social impacts and the mix between qualitative and quantitative measurements [15]. Developing social metrics is a challenging task, but necessary to bring awareness to design and manufacturing engineers of the social implications of their work and decisions.

The purpose of sustainability metrics is to measure the status or performance of a product relative to a particular category [82]. Measurable, useful, and meaningful metrics will be relevant, understandable, manageable, reliable, cost-effective, and flexible [38]. It is important to note that the measurement of the metric values should be used to guide for interpretation of sustainability performance. Furthermore, overall sustainability performance assessment must take into account all of the metrics simultaneously.

Standardizing metrics is required in order to compare the sustainability performance of different products. Utilizing publicly available metric sets is a beneficial way of accomplishing this task. Currently available metric sets range from a high level for corporate metrics to the individual product level. By far, most metric sets report the sustainability at the company level. Example company level metric sets have been established by the Global Reporting Initiative (GRI) [83], Dow Jones Sustainability Index (DJSI) [84], and ISO 14031 [85]. There are two process-level metric sets that have identified by Feng et al. [38], which are the Organization for Economic Co-operation and Development (OECD) toolkit [86] and Ford's Product Sustainability Index (PSI) [87]. Although the identified metric sets are useful in many ways, none of them provide the level of technical detail, accuracy, or relevancy required to make product and manufacturing design decisions based on sustainability performance.

3.3.2 Life Cycle Inventory

Life cycle inventory is one of the four iterative phases of a life cycle assessment (LCA) [46]. An LCI analysis involves modeling a system's flows and compiling the input and output data for all of the activities within the system boundary [88]. LCA uses the data collected from the LCI phase for assessing the environmental impacts associated with a product, process, service, or system. The boundaries of an LCA study for a product are typically selected within the range of cradle-to-grave stages which include raw material extraction and processing, manufacturing, use and maintenance, end of life, and transportation required within and between each life cycle stage [48]. Once the system boundaries and the environmental metrics of interest are selected and the materials, energy, and wastes are quantified for each relevant stage of the life cycle, the associated environmental impacts can be evaluated through the application of impact assessment methods [44]. Currently, one limitation of LCA studies for sustainability assessment is they do not address economic and social concerns.

Due to resource (time and money) constraints involved with collecting necessary data, and the uncertainties of current LCI databases, comprehensive analysis over the product life cycle often leads to uncertainty in the data and generalized results [89]. Specific unit manufacturing processes are often not included in such studies, since models and data are not readily available due to intellectual property concerns of companies [90]. A high level product life cycle description often does not incorporate sufficient detail to yield an accurate representation of manufacturing related impacts nor allow for concurrent design for sustainability. The fact that similar components can be created using different processes, which entail different impacts, further complicates analysis. Thus, early design stage choices can substantially impact the resulting product sustainability performance. It has been shown that the early product design stage establishes up to 80% of life cycle costs [91]. A similar level of dependence on the life cycle environmental and social impacts would also be expected.

An example of a methodology utilizing LCI data for conducting a sustainability analysis at the process level was developed by Culaba and Purvis [92]. Their methodology incorporates the use of an expert system software model that takes in process LCI data to produce the analysis, and it provides feedback on how to increase the efficiency of the process. The focus of their methodology is assessing a singular process rather than for a product, and the sustainability analysis only assessed the environmental impacts of the process.

3.3.3 Unit Process Modeling

Manufacturing process flows are composed of several processes and sub-processes. In order to accurately assess the sustainability of a product, it is necessary to decompose the flow and analyze the effects of each individual unit process. Unit process models for quantifying sustainability metrics can account for the variances in the manufacturing process flow due to the physical part design and the resulting process design [58]. They can provide a descriptive prediction of a process by relating the material and energy inputs to the waste and effluent outputs. Process modeling takes product and process information and produces results in the form of economic, environmental, and social metrics. Evaluating unit process effects on the overall sustainability metrics would provide greater certainty of product and process design attributes that require improvement.

Kellens et al. [43] developed a methodology for developing manufacturing unit process life cycle inventories (UPLCI). They describe two approaches for collecting data and modeling a unit process: the screening approach and the in-depth approach. The screening approach relies on publicly available data and engineering calculations, whereas the in-depth approach includes a time, power, consumables, and emissions study to more accurately describe a process. Overcash and Twomey [62] have used the screening approach to generate unit process models. They have produced UPLCI reports for several common manufacturing processes, including material removal, mass conservation, joining, and heat treating processes. Research by the U.S. National Institute of Standards and Technology (NIST) has focused on developing methods to assist in-depth manufacturing process sustainability assessment [63]–[65]. The two approaches previously described provide detail at the process level, but focus on the environmental impacts of energy, material use, and emissions.

3.4 Sustainability Assessment Methodology

The research reported here further develops the methodology reported by Eastlick et al. [93] and Eastwood et al. [94]. It improves upon the previously mentioned work by refining the approach for conducting a sustainability assessment, formatting it into a procedural process, and increasing the applicability to a wider range of products including individual components and assemblies of components. The methodology combines LCI techniques with unit process modeling to provide a detailed sustainability assessment. The integration of these approaches addresses unit manufacturing operations and identifies the economic, environmental, and social metrics for each respective process from cradle-to-gate. The methodology accounts for the component and process design to establish a unit process model for each relevant manufacturing and assembly process. The component design includes physical part parameters, materials used, and the amount of each material, as well as other metrics as described below. A process design consists of the set of manufacturing and assembly steps experienced by the components. Figure 3.1 illustrates the major steps of the developed sustainability assessment methodology. The steps are described in more detail in the following sections.

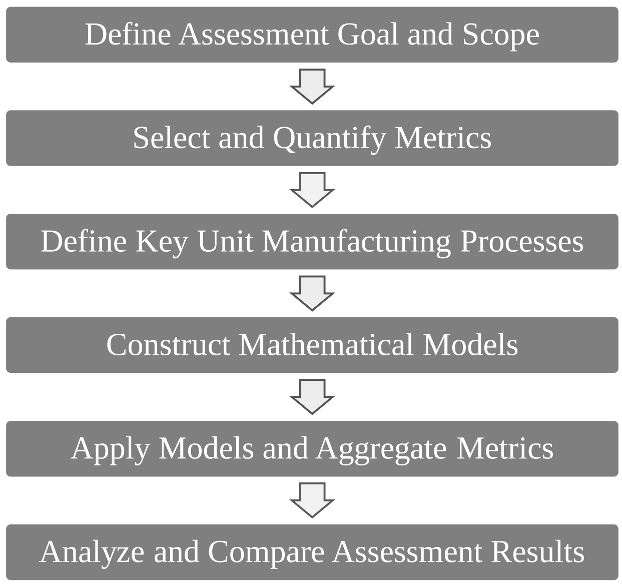


Figure 3.1: Sustainability Assessment Methodology

3.4.1 Define Assessment Goal and Scope

The first step, defining the goal and scope of the sustainability assessment, is similar to the first of the four iterative phases of the LCA framework as described by ISO 14040 [46]. Defining the study goal provides a guideline through the rest of the steps. Initially establishing the goal of the assessment drives the type of data that will be collected, the specificity of the data, the type of results and how the results will be displayed, and how the assessment will be carried out. This is ultimately done to obtain meaningful results to determine the design alternative with the best sustainability performance.

Defining the system boundary assists in guiding the assessment of the various life cycle stages and activities. Determining which stages (e.g., raw material extraction and processing, manufacturing, use, and end of life) and processes to include depends on several conditions such as the required accuracy and completeness of the results, and time and resource constraints.

3.4.2 Select and Quantify Metrics

Once the goal and scope have been defined, the appropriate metrics to be quantified to evaluate sustainability performance are selected. There are several key factors to consider when choosing metrics for sustainability assessment. First, the metrics should provide ample coverage across the three sustainability domains. Next, the metrics should provide sufficient detail within each of the domains to provide an accurate indication of performance. Finally, if the assessment will be used for comparing alternatives, the metrics must be commonly used or follow standard guidelines [95].

3.4.3 Define Key Unit Manufacturing Processes

The unit manufacturing processes to consider in the sustainability assessment are determined by the scope of the study. The goal defines the level of detail to be used for evaluating supply chain and manufacturing facility processes and activities from an aggregated set of processes down to in-depth analysis of an individual machine. If the scope of the assessment were from cradle to gate, then it would include upstream processes such as those used in mining and refining all the way through in-house manufacturing processes.

One task is to identify the processes that impact the economy, environment, and society, as well as the processes that have relatively low impacts. This helps to reduce the time for collecting data and generating unit process models that would not contribute to the assessment results. Attributes to consider when identifying the impacts of a process are "where" and "which" [49]. "Where" a process takes place is important because sustainability priorities vary for different companies and communities. Depending on the design alternatives or location, "which" processes are needed to produce a product change.

3.4.4 Construct Mathematical Models

After defining the key unit manufacturing processes, generating the models for each process can begin. This step consumes the most amount of time and resources. Gathering data and developing mathematical equations for each of the selected metrics are the two key factors for generating unit process models. The mathematical models should be in an input-output (IO) based format in order to decrease the time of generating results [88]. The equations should be a function of design and process specific parameters, and output the values for the corresponding sustainability metrics. There are two types of data to collect. The first data type is information about the process through interviewing experts and literature research. This is done to obtain an understanding of the process of how it impacts the sustainability aspects, and helps to develop the mathematical models. The second type of data to collect is the process specific parameters. The parameter data are used by the mathematical models to quantify the sustainability performance metrics of the product for each specific process.

3.4.5 Apply Models and Aggregate Metrics

Next, applying the mathematical models and aggregating the sustainability metric values is necessary to analyze the assessment results. The economic, environmental, and social metrics need to be quantified and compiled for a single process. The metrics for all of the processes then need to be aggregated into a summary table to analyze the performance of the entire process flow for the product (component or assembly). Moving from conducting a sustainability assessment for a single component to an assembly can be a difficult task. Many of the metrics can be summed, but metrics which are a percentage or an average require different methods for aggregating an assembly assessment. Extra data must be tracked to accurately quantify these types of metrics. The summary assessment table can be examined to determine which processes have the highest contribution to the various sustainability metrics. The unit processes with the greatest impacts and areas for improvement can also be identified.

3.4.6 Analyze and Compare Assessment Results

The final step of the method is to analyze the results and compare the alternatives. A straightforward way to compare product alternatives is to normalize the assessment results. This is done by selecting an alternative as a baseline for the other alternatives to be compared against. The metric totals for the baseline alternative are set to a value of one, and the metric totals for the other alternatives are divided by the baseline alternative metric totals. Finally, the normalized metric values can be graphed either using a radar chart or stacked bar graph for example. The graphical representation makes it easier to assess the sustainability performance of all the product alternatives.

There has been previous research in developing weighting schemes and multi-criteria decision making in order to compare metrics and product alternatives [53]–[55]. The previous work provides well developed methods for condensing the metrics onto a single scale, but the actual weights have yet to be standardized. Developing a weighting scheme and decision making process is outside of the scope of the research reported herein.

3.5 Demonstration of the Methodology

The sustainability assessment methodology detailed previously will be demonstrated to evaluate and compare three alternative bevel gear designs. The purpose is to illustrate the ability of the methodology in assisting design for manufacturing and assembly (DFMA), and highlight the differences in the respective sustainability performance for each design alternative.

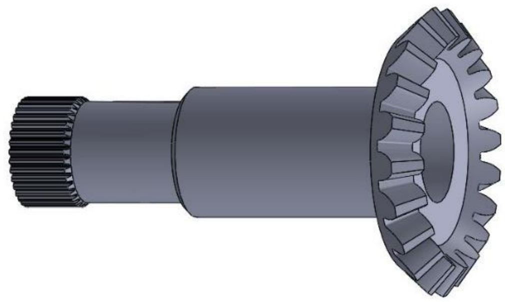
The first design alternative, shown in Fig. 3.2a, is the original generation for this bevel gear. It is a singular component design made of an AISI 4340 steel alloy. The second design alternative, shown in Fig. 3.2b, is a possible next generation for the bevel gear. Rather than a single component, it is an assembly of two components. The gear head is made of an AISI 4340 steel alloy and the shaft is made of a titanium alloy (Ti-6Al-4V), which are assembled by means of an inertial friction welding process. The third design alternative, shown in Fig. 3.2c, is another possible next generation for the bevel gear. Similar to Alternative 2, it is an assembly of two components. The gear head is made of an AISI 4340 steel alloy and the shaft is made of Ti-6Al-4V, which are assembled using of mechanical joining process by press fitting the splines.

3.5.1 Define Assessment Goal and Scope

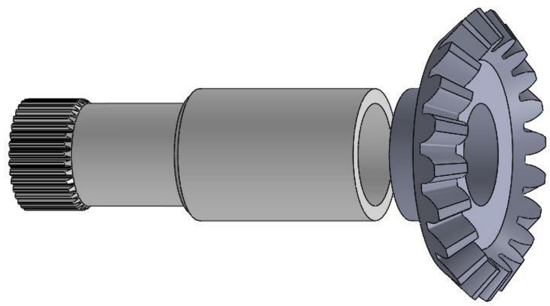
The primary goal of the bevel gear design study is to determine if the next generation of the bevel gears will be more sustainable than the current generation, and if so, which design alternative should be chosen based on sustainability considerations. This objective requires conducting a separate sustainability assessment for each alternative to determine their relative economic, environmental, and social performance. All three product designs are assumed to be functionally equivalent, so they can be compared on a one-to-one basis. The scope of the study comprises a gate-to-gate analysis. The study considers stock materials arriving to the manufacturing facility through to the final product manufacturing and assembly prior to shipping.

3.5.2 Select and Quantify Metrics

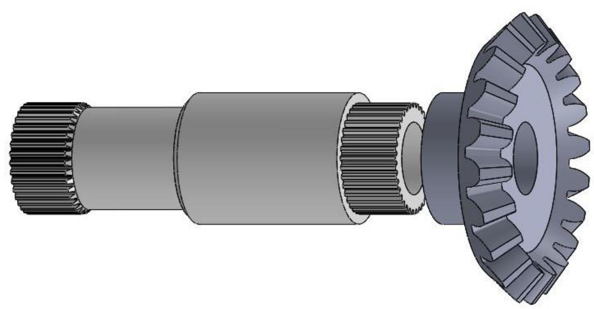
Sustainability metrics were selected for metal component manufacturing based on the considerations previously described and with input from an industry partner familiar with aircraft component design and manufacturing. Table 3.1 shows a subset of metrics applied to compare the three bevel gear design alternatives. This subset of sustainability metrics were found to best fit the goal and scope of the study.



a) Single component: AISI 4340 steel alloy



b) Friction welded assembly: AISI 4340 steel alloy
gear head and Ti-6Al-4V titanium alloy gear shaft



c) Mechanical joined assembly: AISI 4340 steel alloy
gear head and Ti-6Al-4V titanium alloy gear shaft

Figure 3.2: Selected Designs for Sustainability Assessment Include a) Alternative 1, b) Alternative 2, and c) Alternative 3

The selected metrics cover economic, environmental, and social aspects. They are commonly understood, can be applied to a variety of companies, and can be easily measured. Other metrics could be identified and applied towards the same presented design alternatives if desired. The following subsections discuss the selected sustainability metrics in general to define and demonstrate how they can be quantified.

Table 3.1: Selected Sustainability Metrics

Performance Area	Performance Indicator	Performance Measure	Abbreviation	Unit
Economic	Economic	Operating Cost	OP Cost	$
Environmental	Materials	Input Material Non-Flyaway Content	IMNF	%
	Energy	On-site Energy Consumption	ONS EC	kWh
	Water	Water Use	H2O	L
	Liquid Effluents	Water Discharge	H2O Dis	L
	Emissions	GHG Emissions	EM GHG	kg CO_2 eq.
		Pollutant Emissions	EM POL	kg
	Waste	Waste to Landfill	W2L	kg
		Waste to Recycle	W2R	kg
		Hazardous Waste	W Haz	kg
Social	Occupational Health & Safety	Acute Injuries	INJ	injuries
		Lost Work Days	LWD	days
		Chronic Illnesses	ILL	illnesses

3.5.2.1 Economic Metrics

The selected economic metric is operating cost. Operating cost (OP Cost) is an estimate of the production-related expenses. This includes materials and consumables used, on-site energy consumption, and labor. Each of these factors is multiplied by its respective unit cost and summed, as shown in Eq. 3.1. The mass of each consumable used is multiplied by its respective cost (summation used if multiple consumables for a single process) to obtain the consumable cost. Some examples of consumables include water and coolant consumption during a machining process, or abrasives used for a grinding process. The on-site energy consumption is multiplied by the average energy cost, which is dependent on the geographical location of where the energy is produced due to different electrical energy generation sources. The labor cost is the average wage of the operator for each process and multiplied by the process time.

$$\text{OP Cost} = \sum_{i=1}^{n} (m_{con} c_{con})_i + E_{on} c_e + t_p c_L \quad (3.1)$$

3.5.2.2 Environmental Metrics

The selected environmental metrics are input material non-flyaway content, on-site energy consumption, water use, water discharge, greenhouse gas emissions, pollutant emissions, waste to landfill, waste to recycle, and hazardous waste. Input material non-flyaway (IMNF) content relates to the use of material resources and waste production. It measures the proportion, by mass, of the initial input material that is not embodied by the final component. In Eq. 3.2, the IMNF content is calculated by the difference between the initial and final volume, during a single process, divided by the initial stock material volume.

$$\text{IMNF} = (V_i - V_f)/V_s \quad (3.2)$$

On-site energy consumption (ONS EC) measures the amount of energy used by in-house processes. It is determined by multiplying the power required of a machine by a run time. The equation for this metric is specific for each process and can vary greatly. The general formula for a mass reducing machine is shown in Eq. 3.3. A material removal machine typically has three power levels during machining, idling, and standby [62]. The power of the spindle motor during machining is multiplied by the machining time; the idle power is multiplied by the idle time; and the standby power is multiplied by the standby time. These levels are then summed to obtain the total process energy consumption. The standby power is the baseline power required for the machine to be on, and the standby time includes the total process time and setup time. The idle power is the power required while the machine is running but not removing material from the work piece, and the idle time includes the machining time and dwell time.

$$\text{ONS EC} = P_m t_m + P_i t_i + P_s t_s \tag{3.3}$$

Water use (H2O) measures the volume of water required for production. It is the total water that flows into a process or system during operation [96]. Process water use is determined by multiplying the water flow rate by the process time during which the water is used, as shown in Eq. 3.4.

$$\text{H2O} = r_w t_w \tag{3.4}$$

Water discharge (H2O Dis) measures the volume of water effluents that result from processing. It is the total water that exits a process or system and goes to a water treatment facility. This does not include water losses from evaporation or carry off by the work piece. The water discharge of a process is determined by multiplying the water discharge rate by the time the water is discharged by the process, as shown in Eq. 3.5.

$$\text{H2O Dis} = r_{wd} t_w \tag{3.5}$$

Greenhouse gas emissions (EM GHG) measures the mass of gases produced that are considered main contributors to global warming (carbon dioxide, methane, and nitrous oxide). The emissions are primarily produced by the generation of electrical energy required by a process. The rates are determined based on the geographical location of where the energy is produced. The emissions mass production rates are multiplied by their respective global warming potential factors in order to convert them to CO_2 mass equivalents [97]. The mass equivalent CO_2 production rates of the GHG emissions per unit energy generated are summed, and then multiplied by the on-site energy consumption to calculate the total GHG emissions in terms of CO_2 mass equivalent (Eq. 3.6).

$$\text{EM GHG} = E_{on}(r_{CO2}+r_{CH4}GWP_{CH4}+r_{NO2}GWP_{NO2}) \tag{3.6}$$

Pollutant emissions (EM POL) measures the mass of various substances produced that affect air quality, e.g., nitrous oxides (NO_x), sulfuric oxides (SO_x), particulate matter under 10 microns (PM10) in size, and volatile organic compounds (VOCs). Sources of these substances can come from electrical energy generation, combustion processes, and solvent evaporation [6]. The pollutant emissions rate that apply to the process are summed and multiplied by their respective process parameter. Equation 3.7, for example, shows the calculation of pollutant emissions due to the on-site electrical energy consumption.

$$\text{EM POL} = E_{on}(r_{NOx}+r_{SOx}) \tag{3.7}$$

Waste to landfill (W2L) measures the process waste that will be sent to landfill. This usually includes solid waste from consumables during production such as abrasives from a grinding process. The fraction of waste sent to the landfill is multiplied by its respective process parameter (summation used if there are multiple waste streams), such as material removed in the case of machining, as shown in Eq. 3.8.

$$\mathrm{W2L} = \sum_{i=1}^{n} (r_{land} m_r)_i \tag{3.8}$$

Waste to recycle (W2R) measures the process waste that will be sent to recycling. For most machining operations the metal chips are recycled. In this case, the fraction of waste sent to recycling is multiplied by the total material removed (summation used if there are multiple waste streams), as shown in Eq. 3.9.

$$\mathrm{W2R} = \sum_{i=1}^{n} (r_{rec} m_r)_i \tag{3.9}$$

Hazardous waste (W Haz) measures the total waste that must be disposed of according to hazardous waste regulations. An example of hazardous waste is the sludge produced from chemical bath processes. In the case of vapor degreasing, the metric for a given process is determined by multiplying the total volume of hazardous waste produced between tank refills by the density of the hazardous waste and the ratio of process time to time between tank refills (summation used if there are multiple waste streams), as shown in Eq. 3.10.

$$\mathrm{W\ Haz} = \sum_{i=1}^{n} \left(V_{haz} \rho_{haz} \left(\frac{t_p}{t_{ref}} \right) \right)_i \tag{3.10}$$

3.5.2.3 Social Metrics

The selected social metrics are acute injuries, lost work days, and chronic illnesses. Acute injuries (INJ) indicates the level of safety within the process work environment. Injury rates for specific job functions or process types can be determined from company data or the United States Bureau of Labor Statistics (BLS) [98]. The process injury incident rate is multiplied by the process time, as shown in Eq. 3.11.

$$INJ = r_{inj}t_p \tag{3.11}$$

Lost work days (LWD) indicates the average number of days an operator is unable to work due to various types of injuries such as contact with objects, repetitive motion, or exposure to harmful substances. The lost work days per injury rate for specific job function or process type can be determined from company data or the BLS [98]. The lost work day rate is multiplied by the number of acute injuries, as shown in Eq. 3.12.

$$LWD = r_{lwd}INJ \tag{3.12}$$

Chronic illnesses (ILL) indicates long term health effects, and are typically due to overexposure to harmful chemicals or environments. The illness rate for specific job function or process type can be determined from company data or the BLS [98]. The illness rate is multiplied by the process time, as shown in Eq. 3.13.

$$ILL = r_{ill}t_p \tag{3.13}$$

3.5.3 Define Key Unit Manufacturing Processes

Since the study scope is gate-to-gate analysis, the unit processes considered are the manufacturing processes to convert the stock materials into the final bevel gear product. Figure 3.3 shows the manufacturing process flow for Alternative 1. The stock AISI 4340 steel alloy arrives at the facility as a round bar with a 5.25 (133.35 mm) inch diameter, precut to 10 inches (254 mm) in length. It first is turned, drilled, and bored to create the outer and inner diameters of the gear blank. The teeth on the gear head and the splines on the shaft are then cut using a gear generator and gear hob, respectively. After the material removal processes are complete, the part is hand finished to deburr the edges. The gear is then vapor degreased to remove the oils from machining. The teeth on the gear head are then induction hardened, and afterwards placed in a natural gas oven for heat treatment to relieve the stress. Finally, the shaft is cadmium plated to inhibit corrosion.

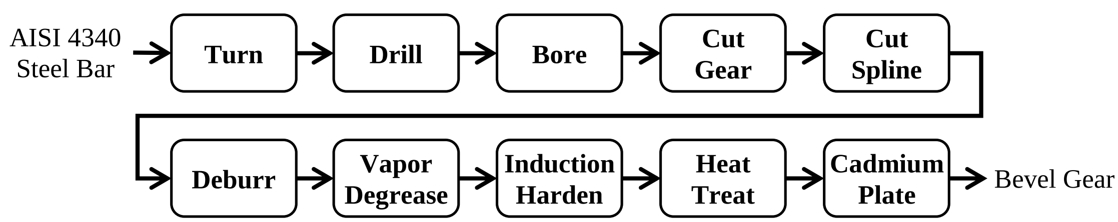


Figure 3.3: Alternative 1 Process Flow

Figure 3.4 shows the manufacturing process flow for Alternative 2. The stock AISI 4340 steel alloy material for the gear head arrives at the facility as a round bar with a 5.25 inch (133.35 mm) diameter, and precut to 5 inches (127 mm) in length. It first is turned, drilled, and bored to create the outer and inner diameters of the gear blank. The teeth of the gear are then cut using a gear generator. After the material removal processes are complete, the part is hand finished to deburr the edges. The gear head is then vapor degreased to remove the oils from machining. The teeth on the gear are then induction hardened, and afterwards placed in a natural gas oven for heat treatment to relieve the stress. The gear head does not require a cadmium plating process because corrosion does not occur in the teeth contact points.

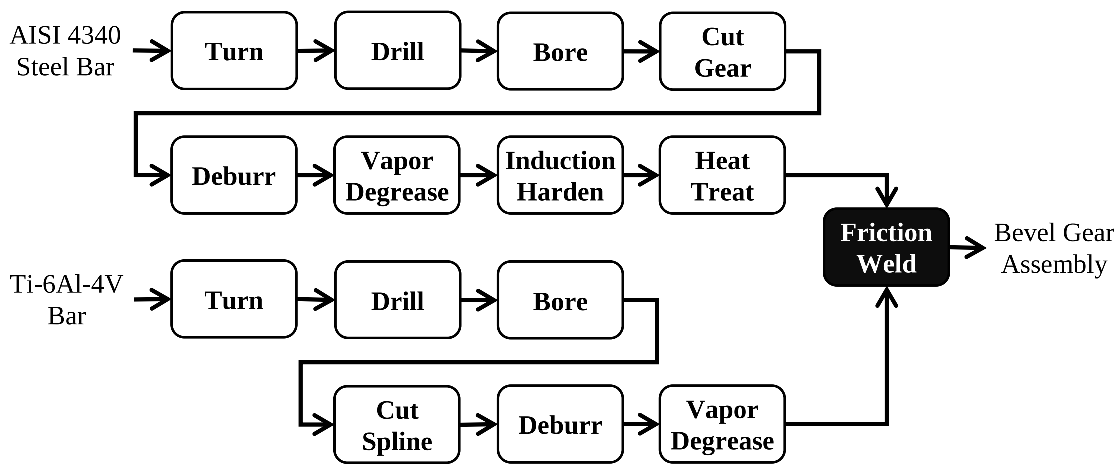


Figure 3.4: Alternative 2 Process Flow

The stock Ti-6Al-4V material for the Alternative 2 gear shaft arrives at the facility as a round bar with a 2.5 inch (63.5 mm) diameter, and precut to 8 inches (203.2 mm) in length. It first is turned, drilled, and bored to create the outer and inner diameters of the shaft. The spline is then cut using a gear hob. After the material removal processes are complete, the shaft is hand finished to deburr the edges. The gear shaft is then vapor degreased to remove the oils from machining. Titanium does not have a corrosion problem like its steel counterpart, so a cadmium plating process is not necessary. The gear head and shaft are assembled using an inertial friction welding process. Inertial friction welding uses a flywheel to generate the rotational force to weld the steel and titanium components together [99].

Figure 3.5 shows the manufacturing process flow for Alternative 3. The stock AISI 4340 steel alloy material for the gear head arrives at the facility as a round bar with a 5.25 inch (133.35 mm) diameter, and precut to 5 inches (127 mm) in length, similar to Alternative 2. It first is turned, drilled, and bored to create the outer and inner diameters of the gear blank. The teeth of the gear and internal spline are then cut using a gear generator and shaper respectively. After the material removal processes are complete, the gear head is hand finished to deburr the edges. The gear head is then vapor degreased to remove the oils from machining. The teeth on the gear are induction hardened, and afterwards placed in a natural gas oven for heat treatment to relieve the stress.

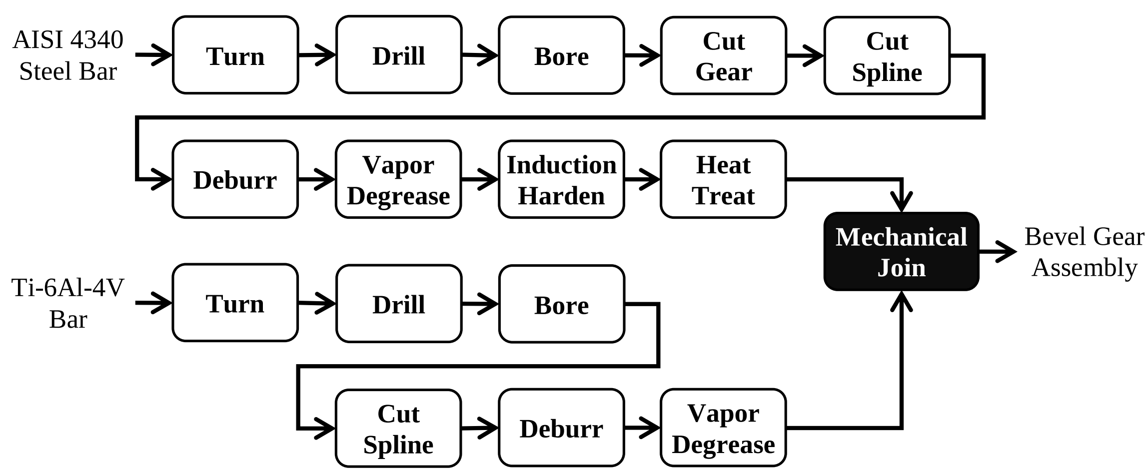


Figure 3.5. Alternative 3 Process Flow

The stock Ti-6Al-4V material for the Alternative 3 gear shaft arrives at the facility as a round bar with a 2.5 inch (63.5 mm) diameter, and precut to 8 inches (203.2 mm) in length, similar to Alternative 2. It first is turned, drilled, and bored to create the outer and inner diameters of the shaft. Both of the splines are then cut using a gear hob. After the material removal processes are complete, the shaft is hand finished to deburr the edges. The gear shaft is then vapor degreased to remove the oils from machining. The gear head and shaft are assembled using a mechanical joining process by press fitting the splines. The steel and titanium components have an interference fit.

All of the manufacturing processes selected for the three bevel gear design alternatives were identified as key contributors to the selected sustainability metrics. Typical processes in a manufacturing process flow such as material handling and dimension and hardness inspections were not included because they consume relatively few resources and make little contribution to the metrics.

3.5.4 Construct Mathematical Models

Most of the understanding for the manufacturing process practices and settings was aided through interactions with the industry sponsor and finalized through literature research. Unit process models were developed for each of the key manufacturing processes previously defined, and the mathematical relationships are detailed in the Appendix. All of the process-specific data collected were from literature sources. Emission production rates were found using eGRID data from the EPA [6]. The eGRID data defines the United States into sub-regions by transmission, distribution, and utility services territories of power plants. The WECC (Western Electricity Coordinating Council) Northwest sub-region was selected to generate the emission production rates. Data for the injury, illness, and lost work day rates came from the BLS [98]. The social metric rates vary based on labor function. Labor functions corresponding to the manufacturing processes were selected to quantify social metrics. A majority of the process parameter data for turning, drilling, boring, and gear and spline cutting are from the *Machinery's Handbook* [100]. Induction hardening data, such as frequencies, generator efficiencies, and power, were compiled by Haimbaugh [69].

3.5.5 Apply Models and Aggregate Metrics

The economic, environmental, and social metrics were quantified by applying the appropriate unit process models for each bevel gear design alternative. The process model results were aggregated to form the summary assessment results as seen in Table 3.2. All of the metrics were summed except for IMNF, which is a percentage. IMNF required a different aggregation method for Alternatives 2 and 3, since they are comprised of multiple components with varying IMNF percentages. To obtain the aggregated IMNF, the total volume of material removed for each process was summed and divided by the sum of the initial stock material volume for each component. The total IMNF could then be summed for all of the unit manufacturing processes.

Table 3.2: Assessment Results Summary

	Metric*	Total	Turn	Drill	Bore	Cut Gear	Cut Spline	Deburr	Induction Harden	Vapor Degrease	Heat Treat	Cd Plate	Friction Weld
Alternative 1	OP Cost	170.32	22.00	4.24	6.37	30.69	13.75	8.43	3.74	12.65	40.76	27.70	0
	IMNF	72.66	64.80	2.08	4.62	1.08	0.07	0	0	0	0	0	0
	ONS EC	249.15	4.75	0.30	0.48	0.10	0.57	2.31E-03	0.13	36.46	206.356	0.01	0
	H2O	24.47	0.09	3.86E-03	0.01	2.64E-03	0	0	6.67	0	0	17.70	0
	H2O Dis	3.02	0.01	4.11E-04	9.13E-04	2.81E-04	0	0	0	0	0	3.00	0
	EM GHG	15.98	1.77	0.11	0.18	0.04	0.21	8.63E-04	0.05	13.62	2.16E-05	2.19E-03	0
	EM POL	0.41	4.50E-03	2.81E-04	4.52E-04	9.58E-05	5.36E-04	2.19E-06	1.20E-04	0.40	1.93E-08	5.57E-06	0
	W2L	0.02	0	0	0	0	0	0.02	0	0	0	0	0
	W2R	20.27	18.04	0.58	1.29	0.02	8.42E-04	0	0	0.34	0	0	0
	W Haz	0.76	0	0	0	0	0	0	0	4.26E-03	0	0.76	0
	INJ	1.79E-04	2.82E-05	5.47E-06	8.20E-06	3.67E-05	1.64E-05	4.34E-06	5.87E-06	1.21E-05	5.87E-05	2.89E-06	0
	LWD	2.63E-03	6.91E-04	1.59E-04	2.38E-04	4.04E-04	1.80E-04	2.69E-04	5.28E-05	8.50E-05	5.28E-04	2.03E-05	0
	ILL	9.60E-06	1.90E-06	3.76E-07	5.63E-07	2.08E-06	9.29E-07	3.64E-07	1.42E-07	1.49E-06	1.42E-06	3.47E-07	0
Alternative 2	OP Cost	169.49	26.57	9.75	11.66	30.69	13.75	10.52	3.74	21.38	40.76	0	0.68
	IMNF	41.08	28.34	3.32	7.73	1.59	0.11	0	0	0	0	0	0
	ONS EC	293.29	2.45	0.55	0.65	0.10	0.57	3.43E-03	0.13	77.21	206.356	0	5.28
	H2O	6.72	0.03	0.01	0.01	2.64E-03	0	0	6.67	0	0	0	0
	H2O Dis	0.01	3.63E-03	6.85E-04	1.04E-03	2.81E-04	0	0	0	0	0	0	0
	EM GHG	32.47	0.92	0.20	0.24	0.04	0.21	1.28E-03	0.05	28.84	2.16E-05	0	1.97
	EM POL	0.67	2.32E-03	5.18E-04	6.13E-04	9.58E-05	5.36E-04	3.25E-06	1.20E-04	0.66	1.93E-08	0	0.01
	W2L	0.02	0	0	0	0	0	0.02	0	0	0	0	0
	W2R	6.65	4.69	0.64	0.75	0.02	5.90E-04	0	0	0.55	0	0	0
	W Haz	6.81E-03	0	0	0	0	0	0	0	6.81E-03	0	0	0
	INJ	2.06E-04	3.42E-05	1.26E-05	1.50E-05	3.67E-05	1.64E-05	6.45E-06	5.87E-06	1.94E-05	5.87E-05	0	7.09E-07
	LWD	3.35E-03	8.46E-04	3.65E-04	4.36E-04	4.04E-04	1.80E-04	4.00E-04	5.28E-05	1.36E-04	5.28E-04	0	4.96E-06
	ILL	1.17E-05	2.32E-06	8.64E-07	1.03E-06	2.08E-06	9.29E-07	5.41E-07	1.42E-07	2.38E-06	1.42E-06	0	3.35E-08
Alternative 3	OP Cost	181.29	26.57	8.48	11.65	30.69	27.51	10.52	3.74	21.38	40.76	0	0
	IMNF	39.02	28.75	3.46	5.02	1.59	0.21	0	0	0	0	0	0
	ONS EC	288.47	2.47	0.48	0.59	0.10	1.13	3.43E-03	0.13	77.21	206.36	0	0
	H2O	6.72	0.03	0.01	0.01	2.64E-03	0	0	6.67	0	0	0	0
	H2O Dis	0.01	3.69E-03	5.42E-04	7.56E-04	2.81E-04	0	0	0	0	0	0	0
	EM GHG	30.67	0.92	0.18	0.22	0.04	0.42	1.28E-03	0.05	28.84	2.16E-05	0	0
	EM POL	0.67	2.34E-03	4.56E-04	5.55E-04	9.58E-05	1.07E-03	3.25E-06	1.20E-04	0.66	1.93E-08	0	0
	W2L	0.02	0	0	0	0	0	0.02	0	0	0	0	0
	W2R	6.43	4.74	0.42	0.71	0.02	1.43E-03	0	0	0.55	0	0	0
	W Haz	6.81E-03	0	0	0	0	0	0	0	6.81E-03	0	0	0
	INJ	2.20E-04	3.42E-05	1.09E-05	1.50E-05	3.67E-05	3.27E-05	6.45E-06	5.87E-06	1.94E-05	5.87E-05	0	0
	LWD	3.48E-03	8.46E-04	3.17E-04	4.36E-04	4.04E-04	3.60E-04	4.00E-04	5.28E-05	1.36E-04	5.28E-04	0	0
	ILL	1.25E-05	2.32E-06	7.51E-07	1.03E-06	2.08E-06	1.86E-06	5.41E-07	1.42E-07	2.38E-06	1.42E-06	0	0

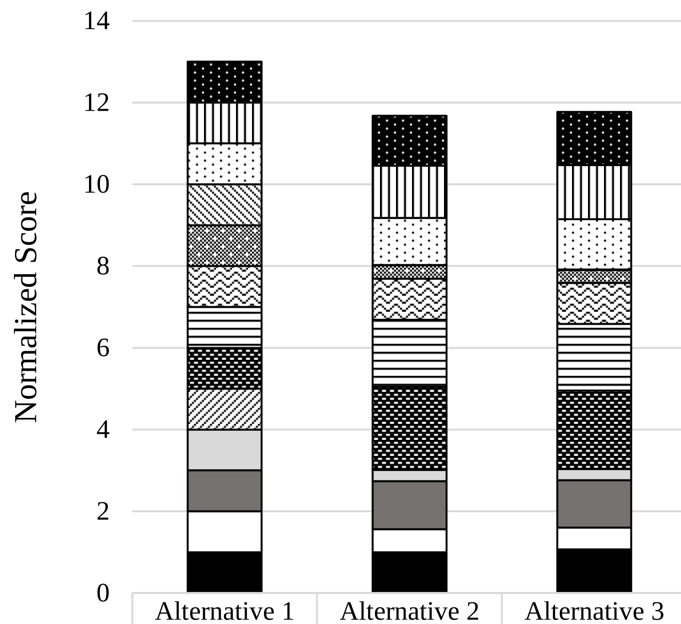
*OP Cost ($), IMNF (%), ONS EC (kWh), H2O (L), H2O Dis (L), EM GHG (kg CO_2 eq.), EM POL (kg), W2L (kg), W2R (kg), W Haz (kg), INJ (injuries), LWD (days), ILL (illnesses)

For each bevel gear alternative, the turning process is the greatest contributor to the input material non-flyaway content (>69%) and waste to recycling (>70%) metrics. The turning process is where most of the material is removed, resulting in the highest input material non-flyaway content and waste to recycle amount. The vapor degreasing process generates the highest GHG (>85%) and pollutant emissions (>98%). Due to the process continuously boiling the degreaser to create a vapor zone, it results in high electrical energy consumption and therefore the highest GHG emissions. The tank of the vapor degreasing process is open faced, resulting in the degreaser vapor escaping into the work environment generating the highest pollutant emissions. Another process to note is the cadmium plating process for Alternative 1. It has the greatest contribution to the water use (72%), water discharge (99%), and hazardous waste (99%) metrics. Cadmium plating uses a large tank and requires frequent chemical adjustments, resulting high water use and producing the most discharged water and hazardous waste.

3.5.6 Analyze and Compare Assessment Results

To compare the three alternative designs, the totals from Tab. 3.2 were normalized and displayed in a stacked bar graph (Fig. 3.6). The aggregated metric values for Alternative 1 were set to a value of one, and the corresponding normalized metric values for Alternatives 2 and 3 were obtained by dividing by the metric values for Alternative 1. From the figure, it appears the next generation of bevel gear designs have an improved sustainability performance over the current generation, the solid steel gear. For the most part this is true, because most of the environmental metrics decrease from the current to the next generation. The economic metric (operating cost) does not have much influence on the comparative sustainability performances because they are relatively the same between the three alternatives, with Alternative 1 and 2 being almost equal and

Alternative 3 increasing by 6%. All of the social metrics (i.e., acute injuries, lost work days, and chronic illnesses) increased however. Since Alternatives 2 and 3 have more manufacturing processes and a greater total processing time compared to Alternative 1, it increases the likelihood of occurrence of injuries and illnesses.



	Alternative 1	Alternative 2	Alternative 3
ILL	1	1.22	1.30
LWD	1	1.28	1.32
INJ	1	1.15	1.23
W Haz	1	0.01	0.01
W2R	1	0.33	0.32
W2L	1	1.00	1.00
EM POL	1	1.64	1.63
EM GHG	1	2.03	1.92
H2O Dis	1	0.00	0.00
H2O	1	0.27	0.27
ONS EC	1	1.18	1.16
IMNF	1	0.57	0.54
OP Cost	1	1.00	1.06

Figure 3.6: Comparison of Normalized Metric Values for the Design Alternatives

The decision of whether Alternative 2 (friction-welded assembly) or Alternative 3 (mechanically joined assembly) has a better sustainability performance is not clear. There are several metrics that are equal or are close to equal in value between the two designs. There are also several metrics for Alternative 2 that have a better performance than Alternative 3, and vice versa. Alternative 2 has a slightly greater amount of volume removed from the stock material compared to Alternative 3, resulting in the higher input material non-flyaway content and waste to recycling. The friction welding process consumes enough electrical energy to make the onsite energy consumption and GHG emissions slightly greater for Alternative 2. Operating cost for Alternative 3 is greater primarily because of the extra machining required to cut the internal spline of the gear head and the external spline of the gear shaft where the two components are joined. The extra machining also resulted in increasing the total processing time, raising the social metrics.

Without knowing the company or the decision maker's priorities, the selected design alternative cannot be conclusively determined. Comparing the bevel gear design alternatives in this fashion, however has brought to light the varying sustainability performance levels for each alternative to help guide the decision making process. If the alternatives were to be ranked according to the normalized metrics, then Alternative 2, the friction-welded bevel gear assembly design, would be selected.

3.6 Summary and Conclusions

Academic research and industrial practice in sustainable design and manufacturing are on the rise as policies and regulations continue to emerge, and as demand for sustainable products continues to grow. To assess product economic, environmental, and social sustainability performance there are several factors to consider, including manufacturing-related costs, energy and material use, and worker illnesses and injuries. Quantifying such factors to assist decision making requires obtaining a thorough understanding of unit manufacturing processes and the collection of process-specific data. These activities are key steps of the unit process-based sustainability assessment methodology presented above. To demonstrate the presented methodology, mathematical unit process models were constructed to accurately quantify a selected set of sustainability metrics for a representative manufactured metal product.

In this application, the unit process-based methodology was able to quantify and aggregate sustainability performance metrics for three alternative bevel gear designs from the manufacturing process level across economic, environmental, and social aspects of sustainability. This methodology has improved the accuracy of sustainability assessments compared to common, ad hoc assessment techniques through the use of unit process modeling to relate design and manufacturing parameter inputs to sustainability metric outputs. This approach can facilitate design for manufacturing and assembly analyses with sustainability performance considerations.

Utilizing this approach will allow design and manufacturing engineers to investigate tradeoffs between product design alternatives and to consider the sustainability performance of similar designs and processes. Since the scope of the research did not include developing a metric weighting scheme or multi criteria decision making, however, the methodology does not have the ability to objectively select between alternative product designs with similar process plans or metric tradeoffs, which must be addressed by future work. Future work must also aim to improve the accuracy of assessment results by constructing generalizable unit process models. By incorporating an understanding of the process physics, for example, assessment results can be accurately obtained for a variety of geometries, materials, processes, and process settings. In so doing, research will lead to design decision support frameworks and tools that can be utilized by engineers and managers to assist them in meeting corporate sustainability goals and complying with regulatory policies.

Acknowledgements

The authors would like to thank the Boeing Company and the Oregon Metals Initiative for their support of this research. The authors would also like to thank Ian Garretson for his assistance in this research.

Chapter 4: An Induction Hardening Process Model to Assist Sustainability Assessment of a Steel Bevel Gear

by
Michael D. Eastwood, Karl R. Haapala, Matthew D. Carter, and Ann E. Simmons

To be submitted to the International Journal of Advanced Manufacturing Technology
http://www.springer.com/engineering/production+engineering/journal/170

CHAPTER 4: AN INDUCTION HARDENING PROCESS MODEL TO ASSIST SUSTAINABILITY ASSESSMENT OF A STEEL BEVEL GEAR

4.1 Abstract

The manufacturing industry is beginning to make production and design decisions informed by principles of sustainability. This means balancing economics with environmental and social performance. In order for design and manufacturing engineers to make these types of decisions, they need to measure a product's sustainability performance at the process level. The purpose of this research is to develop an induction hardening unit manufacturing process model to assist in product sustainability assessments. Physics and engineering principles are used to construct the underpinning induction hardening mathematical models. The models are functions of process and design parameters to quantify the appropriate economic, environmental, and social metrics. The induction hardening model is demonstrated for hardening the teeth of a representative steel bevel gear. Bevel gear alternatives made from AISI 4340, 4140, and 4150 steel alloys were chosen to analyze the influence of material properties on the sustainability metrics. A tempering process model was incorporated into the sustainability assessment to obtain functional equivalence of the components. It was found that the electrical resistivity greatly impacts the electrical energy consumption of the induction hardening process, while the austenitizing temperatures of the three steel alloys have a lower effect. The differences in the steel alloys had a low impact on the operating cost, and did not affect the social metrics. Constructing unit process models

improves the accuracy of product sustainability assessments that are used to help decision makers investigating tradeoffs in process and design parameters.

4.2 Introduction

The incorporation of economic, environmental, and social considerations during the design and manufacturing decision making process is beginning to occur within the product manufacturing industry. The number of manufacturing companies making the fundamental changes toward sustainability goals is increasing worldwide [35]. This focus is in part due to the fact that the manufacturing industry is responsible for approximately 33% of global energy consumption [32]. Materials and energy intensive production patterns, as well as the concern of social responsibility, have led to the emergence of industry standards, government regulations, and sustainable development research. Balancing energy consumption, natural resource consumption, and human health with economic competitiveness can be difficult. Innovations in sustainable product design and production processes can, however, lead to substantial cost savings and allow a company to differentiate itself from its competitors, increasing its competitiveness [9], [34].

In the manufacturing industry, the measurement of economic performance is a familiar topic since manufacturing is a business function, but the measurement of environmental and social performance presents a more challenging task [36]. Life cycle assessment (LCA) methods and tools for measuring environmental performance often lack process-specific data used to provide accurate assessments to support design and manufacturing decisions at the process level [42]. Methods and tools for measuring social performance are currently quite limited [15]. To accurately measure sustainability performance associated with a manufacturing process, it is widely agreed that defining and quantifying the appropriate sustainability metrics is a necessary step [11], [101].

The current work modeling sustainable unit manufacturing processes has covered forming, material removal, and joining processes [62], [102]. Models of sustainability performance for surface hardening processes, such as induction hardening have yet to be developed [102]. Thus, the objective of this work is to develop a unit manufacturing process model for induction hardening. The purpose of the model is to quantify economic, environmental, and social performance to assist in the sustainability assessment, which is demonstrated for a steel bevel gear. In the discussion below, Section 4.3 provides background on unit process modeling and induction hardening. Section 4.4 describes the fundamentals of an induction hardening process. Section 4.5 details the construction and demonstration of the induction hardening process model. Finally, Section 4.6 discusses the conclusions discovered during the course of the research.

4.3 Background

An overview of the literature and work related to unit process modeling and sustainability characterization is presented below. A brief history of induction hardening is then presented, including a discussion of its increasing popularity over other common surface hardening techniques. Literature related to the research and modeling for induction hardening is also briefly reviewed. Lastly, the limitations of the prior research are discussed.

4.3.1 Unit Process Modeling and Sustainability Characterization

Sustainability assessments conducted for a product rarely link the sustainability performance results to unit manufacturing processes. Typically, the methods used to measure sustainability metrics and collect data are not well documented and proceed in an *ad hoc* manner. In recent years, however, evaluation of the sustainability of unit manufacturing processes has become more prevalent. Three groups with focused efforts in this area are the Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) Initiative [22], the Unit Process Life Cycle Inventory (UPLCI) project team [102], and the U.S. National Institute of Standards and Technology (NIST) [23]. These efforts have recently begun to converge [103].

The key objective of the CO2PE!-Initiative is to study the energy consumption and CO_2 emissions of discrete part manufacturing processes [22]. As part of the CO2PE!-Initiative, Kellens et al. [43] documented the UPLCI methodology to aid in the collection of data for unit manufacturing processes and the construction of unit process models. The methodology contains two approaches to generate reports with different levels of detail referred to as the screening approach and in-depth approach. The screening approach utilizes publicly available data and engineering calculations to estimate the energy use and material losses, which leads to an approximate life cycle inventory (LCI). The in-depth approach includes a study of process time, power, consumables, and emissions to provide more accurate LCI data that better characterizes the environmental impacts associated with manufacturing processes. Overcash and Twomey [62] have used the screening approach to generate and collect data for several unit manufacturing processes. They have produced narrative UPLCI reports for several common manufacturing processes, including material removal, mass conservation, joining, and heat treating processes.

Using the screening approach, Overcash et al. [60] developed a UPLCI for a drilling process. Estimates of process energy use and material and cutting fluid losses for drilling a set of holes were calculated using theoretical equations and data from a selected computer numerical controlled (CNC) machine. Similarly, Duflou et al. [61] developed a UPLCI for a laser cutting process using the in-depth approach, specifically for a CO_2 laser cutting machine and a selective laser melting machine. Several measurement studies were conducted in order to determine the energy use, process gas consumption, produced waste, and air emissions for the laser cutting machines.

In addition to the CO2PE!-Initiative and the UPLCI effort, one of the objectives of the Sustainable Manufacturing Program at NIST was to develop methods to evaluate and improve energy and materials efficiency for manufacturing processes and product assemblies [23]. A method developed by Feng et al. [63] calculates energy metrics for a general product assembly process. Specifically, the authors presented the metrics and equations for quantifying the energy consumption and energy efficiency for both the main equipment and auxiliary equipment that are necessary for an assembly process. A study for a hybrid laser welding process was conducted to estimate the energy consumption and efficiency for the individual sub-process as well as for the overall assembly process. Madan et al. [64] presented a guideline for characterizing the energy consumption for an injection molding process. The goal of the work was to stray away from high level analyses which do not accurately estimate the energy performance at the process level and to incorporate the pre- and post-operations. Similarly, Watkins et al. [65] described a method for characterizing the sustainability performance for a die casting process. The method developed is comprised of three parts: defining sustainability performance indicators, developing information models to quantify the indicators, and applying process-specific data sets to support and use in the information models. A die casting process was studied and theoretical energy consumption equations were compiled for each sub-process.

The work described previously provides methods, guidelines, and data for manufacturers to utilize to determine potential energy efficiency improvements and waste reduction opportunities. These are key factors for improving the sustainability performance of a final product. These concepts are demonstrated for induction hardening herein, since heat treatment processes have largely been neglected in sustainable manufacturing research, but represent a major source and manufacturing energy use [104].

4.3.2 Induction Hardening Background

Induction hardening is a form of heat treatment in which a conductive metal is heated by induction heating and then quenched [71]. The principle of electromagnetic induction was first discovered in 1831 by English physicist Michael Faraday [70]. Heating and melting of metals by means of electromagnetic fields was initially a challenging task due to the insufficient power sources that were only capable of producing low frequencies of 50-60 Hz. It was not until the early twentieth century that induction heating began being used in practice with the development of induction furnaces primarily used to melt steel. As induction heating technology advanced, it replaced several other heat treating processes such as flame furnaces and chemical-thermal treatments. Induction heating was more energy efficient, took less time, and reproduced results more reliably than other heat treating processes, therefore, making it a better process for mass production.

The use of induction heating to surface harden metal emerged in the late 1920s to the mid-1930s for hardening crankshafts used in piston engines [70]. The use of induction hardening has become widely used around the world for many applications, and is replacing conventional surface hardening processes due to its benefits of superior mechanical properties, lower manufacturing costs, and manufacturing compatibility [69]. Surface hardening processes such as carburizing and nitriding, for example, are being replaced by induction hardening because they require numerous preparatory and post-processing operations, along with greatly increased total processing time [71]. Figure 4.1 displays an example process flow comparison for carburizing and induction hardening a steel gear. As shown in the figure, carburizing requires additional processes, such as copper plating and removal of the plating, and the processing time for the carburizing process itself is longer than induction hardening, in addition to the processing time required for the other processes involved.

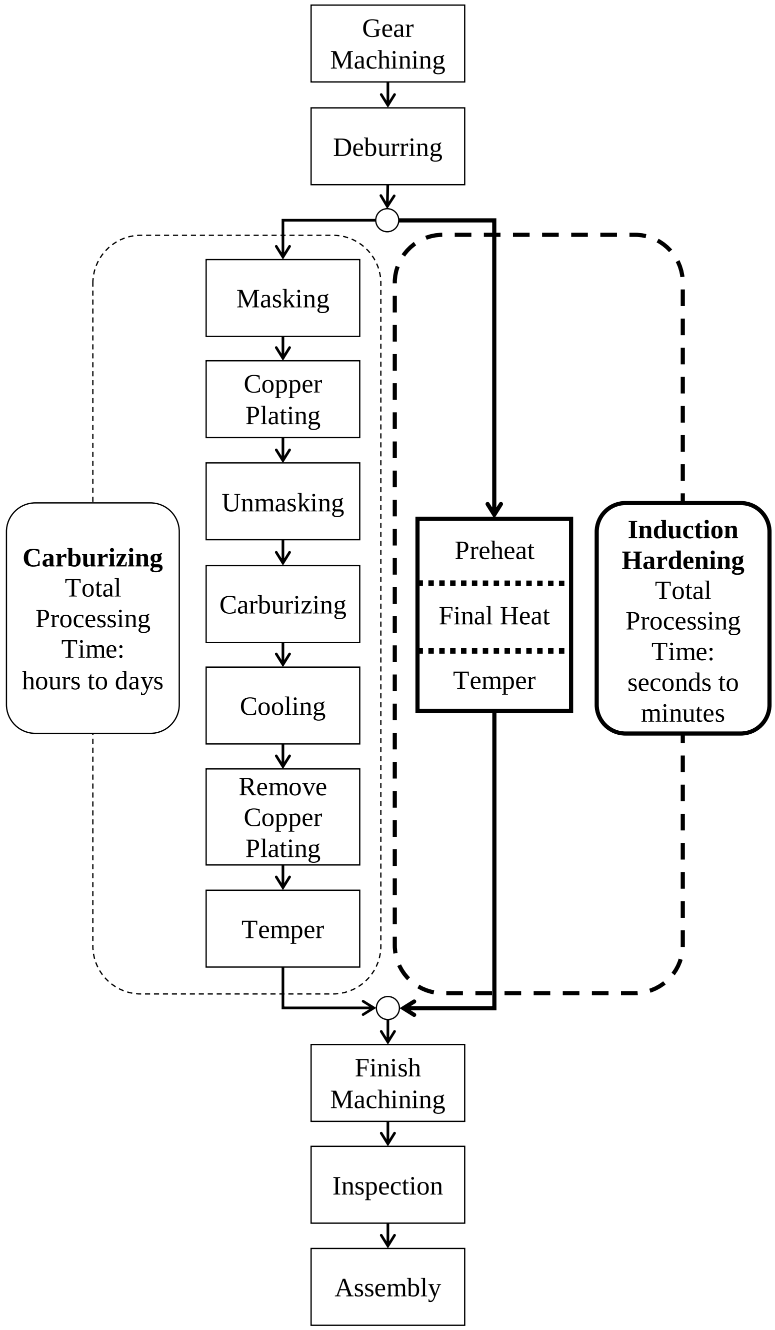


Figure 4.1. Manufacturing Process Flow Comparison between Carburizing and Induction Hardening for a Steel Gear

4.3.3 Induction Hardening Research and Models

The recent research and modeling for induction hardening studies the effects of process and design parameters on the workpiece properties such as hardness profile, hardness depth, and microstructure. A brief overview of the relevant work is presented next.

An experimental study conducted by Kurek et al. [72] observed the influence of process and design parameters on the temperature distribution in steel gears during an induction hardening process. The study investigated the effects of varying the alternating current (AC) frequency in the induction coil, gear radius, number of teeth, tooth length, tooth height, and inductor distance from the tooth. For each parameter, they were able to conclude the value that achieved the most desirable temperature distribution. Kristoffersen and Vomacka [73] conducted an experimental study to observe the influence of process parameters on the residual stresses after induction hardening for a cylindrical steel part. The process parameters examined included frequency, power, and heating time, as well as the microstructure prior to induction hardening. They concluded that for the same case depth, each process parameter and initial microstructure affected the residual stress state of the part due to their impacts on temperature distribution within the part during heating.

Model development for induction hardening incorporates the construction of mathematical models for analyzing the electromagnetic, thermodynamic, and microstructural transformations. Cajner et al. [24] developed a computer simulation to measure the surface hardness and hardening depths of cylindrical parts made of 42CrMo4 steel. The induction hardening model included input parameters from the power supply, quenchant, and heating time. Experimental results were able to validate their simulation. Detailed mathematical models were constructed by Melander [25] to calculate the temperature distribution, hardness profile, and residual stresses for the static and progressive induction hardening of an AISI 4142 cylindrical steel bar. A finite difference method (FDM) was used to solve for the magnetic field, temperatures, and phase transformations in the static case, where the workpiece does not move with respect to the induction coil. A finite element modeling (FEM) program was used to solve for the magnetic field, in the progressive case, where the workpiece moves through the coil. Only minor deviations were found between the calculations and the measured results.

A finite element analysis (FEA) model developed by Yuan et al. [26] measured the current and temperature distributions within an AISI 1070 steel part to determine the phase transformation and hardness profile. The model analyzed all of the key aspects of the process from the current in the coil to the quenching of the workpiece. The results of the model were found to be a close match to the experimental results. Barka et al. [27] developed an axisymmetric model for an FEA simulation to conduct a sensitivity study on the hardness profile for a AISI 4340 steel flat cylinder heated by induction. The sensitivity study related the effects of the frequency, power, and heating time on the resulting hardness profile. It was found that the heating time was the predominant factor in determining the hardened case depth, and there were no interactions found between these three parameters.

The prior work presented above provides an understanding of the induction hardening process, as well as the data and tools necessary for engineers to determine the appropriate parameters for achieving the desired workpiece properties. The simulation and FEA models contain key theoretical equations which serve as a baseline for the energy consumption equations detailed in Section 4.5.4.

4.3.4 Limitations of Prior Research

Despite the contributions of the reviewed research to unit process modeling for assessing sustainability performance and behavior of the induction hardening process, there are some limitations which are identified below:

i. Most of the reported research on unit process modeling only focuses on the environmental aspect rather than all three aspects of sustainability, i.e., economic, environmental, and social.
ii. Unit process models typically quantify one or two metrics such as energy consumption, emissions, or material losses. Sustainability assessment requires evaluation of a broader set of metrics.
iii. Metrics for the induction hardening process such as water use, energy consumption, emissions, injuries, and other sustainability metrics have yet to be developed.

This research attempts to address the identified gaps by developing a unit process model for induction hardening that covers the three aspects of sustainability to quantify a selected set of metrics. The goal is for the model to assist in conducting a product sustainability assessment for design and manufacturing engineers to utilize during decision making.

4.4 Fundamentals of Induction Hardening

The goal of induction hardening is to enhance the mechanical properties of a material such as its toughness, shear strength, and tensile strength by changing its microstructure. Induction hardening is used to harden specific areas of a workpiece without affecting the material properties of the part as a whole [71]. The process is used on numerous components such as gears, crankshafts, camshafts, valves, and drill bits [105]. The key features that make up an induction hardening system include a power supply, a heating station, and quench and cooling systems.

Figure 4.2 diagrams basic component of a modern high-frequency power supply for induction hardening. Essentially, the power supply can be seen as a frequency converter that changes 60 Hz (US), three-phase current into a higher frequency, single-phase current for induction heating [69], [106]. Solid-state or radio frequency (RF) power supplies convert the input line three-phase alternating current (AC) to single-phase direct current (DC). Inversion is used to produce DC sinusoidal pulses to form high frequency AC. This is accomplished through using thyristors, such as silicon controlled rectifiers (SCRs); transistors, such as isolated gate bipolar transistors (IGBTs) or metal-silicon-dioxide field-effect transistors (MOS FETs); or oscillator tubes. Load matching is done to match the load impedance with the output impedance of the power supply to transfer full power from the power supply to the induction coil. Solid-state power supplies typically have very high energy conversion efficiencies of greater than 90%, and RF power supplies have relatively low energy conversion efficiencies of roughly 50-60%. RF power supplies are used when high frequency and high voltage are desired.

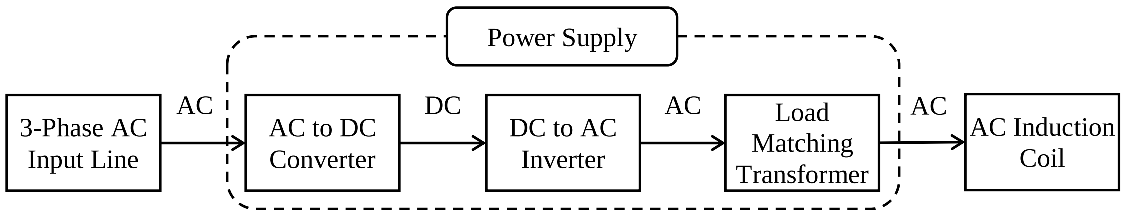


Figure 4.2. Basic Diagram of a Solid-State Power Supply for Induction Hardening

To heat a workpiece by induction, depending on the system, the workpiece is positioned within or next to an induction coil and energy is induced by an alternating current. The principles of hardening materials by induction heating are based on several laws of electromagnetism. When an alternating current is applied to an induction coil, it produces a time variable magnetic field of the same frequency [71]. This magnetic field induces an alternating current (also known as an eddy current) in a conductor or workpiece located within the coil, which produces heat by the Joule Effect. Hardening occurs on the surface because the current distribution in the workpiece is not uniform due to several electromagnetic phenomena such as the Skin Effect, which is the phenomenon of non-uniform current distribution within a conductor cross-section; the Proximity Effect, which is the phenomenon of current distribution distortion when multiple conductors with their own magnetic fields are in close proximity; and the Ring Effect, which is the phenomenon of current distribution distortion when the conductor is shaped into a ring.

The Skin Effect causes roughly 86% of the power supplied to the workpiece to be concentrated within the surface layer.

Material selection depends upon the working conditions and hardness required of the workpiece during its use-phase. Low-alloy, medium-carbon steels with 0.40-0.55% carbon content are the most commonly used steels in induction hardening [71]. The initial microstructure is a crucial factor affecting the resulting hardness profile. The most favorable initial microstructure is a homogenous fine-grained martensitic structure with a hardness of 30-34 HRC. This type of microstructure leads to a quicker and more consistent response to heat treating, as well as achieving higher hardness and deeper case depths. When induction hardening steel, it is heated to just above the upper critical temperature to the austenite phase, then rapidly quenched to prevent grain growth and to produce hardened martensite [71], [107]. The quenching system controls the cooling rate of the heated workpiece, making it an important aspect of the induction hardening process to achieve the desired hardness and microstructure [69]. Induction hardening is often followed by a tempering process to reduce brittleness and relieve residual stress, which also results in a slight reduction in hardness.

The sustainability assessment methodology developed in Chapter 3 is utilized to demonstrate sustainability assessment of the induction hardening unit manufacturing process. By combining life cycle inventory techniques with unit process modeling, the methodology provides a detailed quantification of sustainability metrics. The methodology is a six-step process of defining the assessment goal and scope, selecting and quantifying sustainability metrics, defining key unit manufacturing processes, constructing mathematical models, applying the models and aggregating the metrics, and analyzing and comparing the assessment results. The methodology is detailed in the sections below.

4.5 Application of the Sustainability Assessment Methodology

The demonstration study evaluates the sustainability performance of induction hardening the teeth of a bevel gear for several steel alloys (Fig. 4.3). Hardening will increase tooth hardness and fatigue strength in order to improve wear resistance. Common bevel gear steel alloys (i.e., AISI 4340, 4140, and 4150) were chosen based on their common use in induction hardening and capability of contour hardening profiles. Each bevel gear steel alloy will have a hardened case depth of 1.22 mm. These scenarios facilitate the effect of varying process and design parameters on sustainability performance.

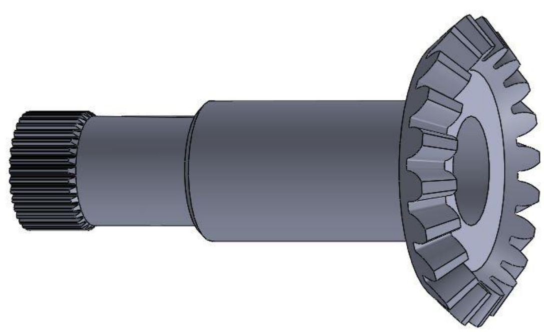


Figure 4.3. Bevel Gear Design Evaluated

AISI 4340, 4140, and 4150 are low-alloy, medium-carbon content steels with 0.38-0.43%, 0.38-0.43%, and 0.48-0.53% carbon content respectively [108]. The key differences between the steel alloys are the electrical resistivities and austenitizing temperatures. The gear made of AISI 4340 steel will be used as the baseline for comparison against the other alloys. Table 4.1 shows the carbon content, electrical resistivities, and recommended induction heating temperatures for the three steel alloys [106].

Table 4.1. Properties of Selected Steel Alloys

Steel Alloy	Carbon Content (%)	Electrical Resistivity (μΩm at 20°C)	Austenitizing Temperature (°C)
AISI 4340	0.38-0.43	24.8	870
AISI 4140	0.38-0.43	22.2	880
AISI 4150	0.48-0.53	24.5	850

The three steel alloys exhibit tradeoffs between the electrical resistivity and austenitizing temperature. Higher electrical resistivities result in reduced power transfer efficiency from the induction coil to the workpiece, while higher austenitizing temperatures require more power to reach the desired temperature. Process modeling can elucidate the effects of these tradeoffs on the sustainability metrics.

4.5.1 Define Assessment Goal and Scope

The first step of the methodology is defining the assessment goal and scope, which defines the study intent and establishes the system boundaries. The goal of this study is to determine which of three steel alloys for the bevel gear offers the best sustainability performance for the induction hardening process. This objective requires constructing an induction hardening unit process model, which will be applied to quantify the relative economic, environmental, and social performance of the three steel alloys (i.e., AISI

4350, 4140, and 4150). The scope of the study is the induction hardening process for the heat treatment of a single gear. This comprises the sub-process steps from the initial setup to removal of the gear from the machine.

4.5.2 Select and Quantify Metrics

The second step of the methodology is selecting and quantifying metrics. The metrics should be selected based on measurability, usefulness, and meaningfulness, and, if they are to be used for comparison purposes, the metrics should align with commonly used standard guidelines [38], [95]. The selected sustainability metrics are those from Chapter 3, with additional input from industry. Table 4.2 displays the sustainability metrics to be quantified for the sustainability assessment, as well as their respective general equations, which will be used to help guide the construction of the unit process model. The metrics were found to be the most applicable to measuring the sustainability performance of induction hardening the bevel gear. Other metrics could be identified and applied using this method if desired.

4.5.3 Define Key Unit Manufacturing Processes

The third step of the methodology is defining the key unit manufacturing processes in the product's manufacturing process flow which impact the economy, environment, and society. The induction hardening process was identified as one of the key unit manufacturing processes for producing the presented bevel gear and is a primary motivation for conducting this research. On average, up to 30% of the production costs for manufacturing a gear come from the heat treatment processes, with the remaining

70% coming from machining and finishing processes and consumables [109]. Induction hardening requires electrical energy, water, quenchant, and human interaction inputs which contribute to the selected sustainability metrics.

Table 4.2. Selected and Quantified Sustainability Metrics

Performance Area	**Performance Measure**	**General Equation**	**Unit**
Economic	Operating Cost	OP Cost $= \sum_{i=1}^{n} (m_{con} c_{con})_i + E_{on} c_e + t_p c_L$	\$
Environmental	On-site Energy Consumption	ONS EC $= P_m t_m + P_i t_i + P_s t_s$	kWh
	Water Use	H2O $= r_w t_w$	L
	GHG Emissions	EM GHG $= E_{on}(r_{CO2} + r_{CH4} GWP_{CH4} + r_{NO2} GWP_{NO2})$	kg CO_2 eq.
	Pollutant Emissions	EM POL $= E_{on}(r_{NOx} + r_{SOx})$	kg
Social	Acute Injuries	INJ $= r_{inj} t_p$	injuries
	Lost Work Days	LWD $= r_{lwd}$ INJ	days
	Chronic Illnesses	ILL $= r_{ill} t_p$	illnesses

4.5.4 Construct Mathematical Models

The fourth step of the methodology involves constructing the mathematical models, which requires gathering data and developing mathematical equations for each of the selected metrics. In order for the induction hardening unit process model to be used for decision making by design and manufacturing engineers, the mathematical equations to quantify the sustainability metrics should be functions of design and process parameter inputs. This allows for engineers with limited knowledge of sustainability principles or the process to perform the assessment. The induction hardening unit process model is comprised of economic, environmental, and social models, which are detailed below.

4.5.4.1 Economic Models for Induction Hardening

The selected economic metric is operating cost (OP Cost). OP Cost is an estimate of production-related expenditures. For the induction hardening process, this includes water and quenchant consumption, electrical energy consumption, and labor. Each of these factors is multiplied by its respective unit cost and then summed (Eq. 4.1).

$$\text{OP Cost} = V_{WL}c_w+V_qc_q+E_{on}c_e+t_pc_L \tag{4.1}$$

The volume of water and quenchant lost during the process can be obtained, for example, by knowing the percent concentration of quenchant in the quenchant mixture (p_q), the volume of the quenchant tank when full (V_T), the volume of the quenchant tank when low (V_{T_low}) prior to refilling, the duration of time the workpiece is quenched (t_q), and the duration of processing time between tank refills (t_{ref}). To calculate the volumes of water and quenchant lost, the respective percent concentrations are multiplied by the difference in tank volumes and the ratio of process time to refill time, as shown in Eqs. 4.2 and 4.3.

$$V_{WL} = \left(100-p_q\right)(V_T-V_{T\_low})\left(\frac{t_q}{t_{ref}}\right) \tag{4.2}$$

$$V_q = p_q(V_T-V_{T\_low})\left(\frac{t_q}{t_{ref}}\right) \tag{4.3}$$

For calculating the labor cost, the total process time is defined as the time from initial setup to removal of the gear from the machine. The amount of electrical energy is multiplied by the electricity unit cost. The calculation of the on-site electrical energy consumption is described in the next section.

4.5.4.2 Environmental Models for Induction Hardening

The quantified environmental metrics include on-site energy consumption, water use, greenhouse gas (GHG) emissions, and pollutant emissions. On-site energy consumption (ONS EC) is the total in-house energy required for production, and includes the electrical energy required by the induction hardening system generator to heat the workpiece and by the quenching system pumps to quench the workpiece and cool the induction coil. The total electrical energy to be supplied by the induction hardening system generator is the sum of the power required to heat the workpiece (workpiece power, P_w), radiation power losses (P_r), and the power lost in the induction coil (P_c) multiplied by the heating run time (t_{run}). The total electrical energy for the quenching system is the summation of the power from each pump motor (P_p) multiplied by the quenching time (t_q). The calculation for the ONS EC metric is shown in Eq. 4.4.

$$\text{ONS EC} = (P_w+P_r+P_c)t_{run}+\sum_{i=1}^{n}\left(P_p\right)_i t_q \tag{4.4}$$

The workpiece power (P_w) is calculated by multiplying the surface power density (P_o) by the surface area being heated (A_S), as shown in Eq. 4.5. The surface power density (Eq. 4.6) is a function of the magnetic field intensity at the surface (H_S), electrical resistivity of the workpiece (ρ), magnetic permeability of free space (μ_o), relative magnetic permeability of the workpiece (μ_r), and AC frequency (f) applied to the induction coil [71].

$$P_w = P_o A_S \tag{4.5}$$

$$P_o = H_S^2 \sqrt{\pi \rho \mu_o \mu_r f} \tag{4.6}$$

The Skin Effect equation (Eq. 4.7) describes the current penetration depth (δ) as a function of the electrical resistivity of the workpiece (ρ), relative magnetic permeability of the workpiece (μ_r), and the AC frequency (f) applied to the induction coil [71]. By knowing the desired hardened case depth, the skin effect equation can be rearranged to solve for the required induction coil frequency, as shown in Eq. 4.8. The current penetration depth can range from 1.2 to 2 times the hardened case depth depending on the induction coil frequency, thus the penetration depth is divided by a coefficient variable (C) [110]. For surface hardening at high frequencies to produce shallow case depths, the coefficient variable can be approximated as C=2 [106].

$$\delta = 503\sqrt{\rho/\mu_r f} \tag{4.7}$$

$$f = \rho/\left(\mu_r\left(\frac{\delta}{503C}\right)^2\right) \tag{4.8}$$

Electrical resistivity varies depending on material temperature, chemical composition, microstructure, and grain size [71], [111]. It is a measure of how strongly the material opposes the flow of electric current. Since the resistivity of metals tends to increase with increasing temperature, it is often approximated by the linear function shown in Eq. 4.9 [71].

$$\rho(T) = \rho_{\infty}[1+\alpha(T-T_{\infty})] \tag{4.9}$$

The magnetic field intensity at the workpiece surface can be calculated by first solving for the magnetic vector potential (A) expressed by the Biot-Savart Law (Eq. 4.10) [26]. The magnetic vector potential is a function of the AC applied to the induction coil (I) and the distance from the induction coil to the hardened workpiece surface (D). Figure 4.4 depicts a diagram to aid in solving the magnetic vector potential, A, at the field point, P, due to a magnetic field source point created by the instantaneous current in the induction coil, dl.

$$A = \frac{\mu_o I}{4\pi}\int \frac{dl}{|D|} \tag{4.10}$$

From the figure, the Biot-Savart Law takes the form shown in Eq. 4.11 in the spherical coordinate system. The equation can be simplified as shown in Eq. 4.12.

$$\vec{A}(\vec{D}) = \frac{\mu_o I}{4\pi}\int_0^{2\pi} \frac{(Rd\varphi)\cos\varphi}{|\vec{D}-\vec{R}|}\hat{\varphi} \tag{4.11}$$

$$\vec{A}(\vec{D}) = \frac{\mu_o I R^2}{4D^2}\sin\theta\hat{\varphi} \tag{4.12}$$

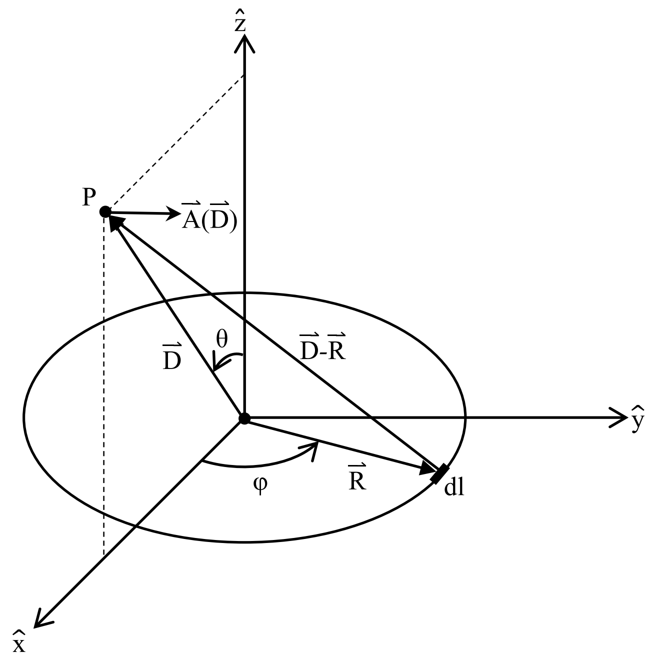


Figure 4.4. Diagram Depicting Relationships for Solving the Magnetic Vector Potential, A, at Field Point, P

From Gauss's Law (Eq. 4.13), the magnetic field density (B) can be related to the magnetic vector potential [26], [71], [112]. By taking the curl of the magnetic vector potential found in Eq. 4.12, the magnetic field density is of the form shown in Eq. 4.14.

$$B = \nabla \times A \tag{4.13}$$

$$\vec{B}\left(\vec{D}\right) = \left[\frac{\mu_o R^2 I}{2D^3}\cos\theta\right]\hat{r} + \left[\frac{\mu_o R^2 I}{4D^3}\sin\theta\right]\hat{\theta} + 0\hat{\varphi} \tag{4.14}$$

Faraday's Law (Eq. 4.15) describes the relationship between the magnetic field density (B) and the magnetic field intensity (H) [26], [71]. Applying Faraday's law to Eq. 4.14, changing from spherical to Cartesian coordinate system, and taking the magnitude of the magnetic field intensity vector, the equation for the magnetic field intensity at the surface of the workpiece (H_S) takes the form shown in Eq. 4.16.

$$H = \frac{B}{\mu_o \mu_r} \tag{4.15}$$

$$H_S = \left[\left(\frac{IR^2}{2D^3} \right)^2 \cos^2\theta \left(\frac{1}{4} \sin^2\theta + 1 \right) + \frac{1}{4} \sin^4\theta \right]^{1/2} \tag{4.16}$$

With the induction coil frequency, electrical resistivity, and magnetic field intensity at the workpiece surface now calculated, Eq. 4.6 can be used to calculate the surface power density. To obtain the radiation power losses (P_r) in Eq. 4.4, the radiation heat transfer equation can be used (Eq. 4.17) [106].

$$P_r = A_S \varepsilon \sigma (T_S^4 - T_\infty^4) \tag{4.17}$$

The calculation for the power lost in the induction coil (P_c) from Eq. 4.4, can be described by Eq. 4.18 [106]. The equation is a function of the coupling efficiency (η_c) between the coil and the workpiece, which depends on the coil design and size of the air gap between the induction coil and workpiece. For single turn coils that surround the workpiece with an air gap of roughly 3 mm, the coupling efficiency can be approximated as η_c=0.85.

$$P_c = (P_w + P_r) \left(\frac{1}{\eta_c} - 1 \right) \tag{4.18}$$

To obtain the total pump motor energy in Eq. 4.4, the power for each pump (P_p) needs to be calculated. Depending on the induction hardening system, there can be a various number of pumps to control the flow of quenchant and water to the workpiece and induction coil. For any particular pump, the power required by the pump can be approximated by taking the power of the motor (P_m) and dividing by the motor efficiency (η_m) as shown in Eq. 4.19.

$$P_p = P_m/\eta_m \tag{4.19}$$

The remaining environmental metrics can be calculated in a much more straightforward manner. Water use (H2O) measures the volume of water required for production, which is the total amount of water that flows into a system during operation [96]. H2O is quantified by multiplying the percent concentration of the water in the quenchant mixture ($100\text{-}p_q$) by the quenchant flow rate (r_q) and the quenching time (t_q), as shown in Eq. 4.20.

$$H2O = (100\text{-}p_q)r_q t_q \tag{4.20}$$

Greenhouse gas emissions (EM GHG) measures the mass of gases considered to be main contributors to global warming, which are produced by the generation of the electrical energy required for production. The GHG emissions mass generation rates are determined based on the geographical location of energy production using eGRID data from the United States Environmental Protection Agency (EPA) [6]. These rates are multiplied by their respective global warming potential factors to convert them to a CO_2

mass equivalent (kg CO_2 eq.) [97]. The total CO_2 mass equivalent generation rate is multiplied by the on-site energy consumption to obtain the EM GHG metric value, as shown in Eq. 4.21.

$$\text{EM GHG} = E_{on}(r_{CO2}+r_{CH4}GWP_{CH4}+r_{NO2}GWP_{NO2}) \tag{4.21}$$

Pollutant emissions (EM POL) measures the mass of substances that affect air quality, and result from the generation of the electrical energy required for production. The pollutant emissions mass generation rates are determined based the geographical location of where the energy is produced from the eGRID data provided by the EPA [6]. The rates are summed and multiplied by the on-site energy consumption, as shown in Eq. 4.22.

$$\text{EM POL} = E_{on}(r_{NOx}+r_{SOx}) \tag{4.22}$$

Equations 4.4-4.22 encompass the environmental models for quantifying the selected environmental metrics. The following section details the construction of the social models for induction hardening.

4.5.4.3 Social Models for Induction Hardening

The selected social metrics are acute injuries, lost work days, and chronic illnesses. Acute injuries (INJ) measures the average number of injuries that occur during the process. The injury incident rate (r_{inj}) is multiplied by the total process time (t_p), as shown in Eq. 4.23.

$$\text{INJ} = r_{inj}t_p \tag{4.23}$$

Lost work days (LWD) measures the average number of days an operator is unable to work due to various types of injuries. The lost work day rate (r_{lwd}) is multiplied by the average number of injuries, as shown in Eq. 4.24.

$$LWD = r_{lwd}INJ \tag{4.24}$$

Chronic illnesses (ILL) measures the average number of illnesses caused by the process. The illness incident rate (r_{ill}) is multiplied by the total process time (t_p), as shown in Eq. 4.25.

$$ILL = r_{ill}t_p \tag{4.25}$$

The process injury incident rate, lost work day rate, and illness incident rate can be determined from company data or data from the United States Bureau of Labor Statistics (BLS) [98]. With the economic, environmental, and social models complete, the induction hardening unit process model can be applied for assessing the sustainability performance for hardening the teeth of a bevel gear.

4.5.5 Apply Models and Aggregate Metrics

The fifth step of the methodology involves applying the models and aggregating the sustainability metrics to produce the assessment results. The models for quantifying economic, environmental, and social metrics described above were applied for the induction hardening of the bevel gear teeth. The appropriate process and design parameters were input into the mathematical models for all three steel alloys (AISI 4340, 4140, and 4150). The results were then aggregated to form the summary assessment results shown in Table 4.3. These induction hardening assessment results can be implemented into overall system-level sustainability assessment for producing the bevel gear if desired.

Table 4.3 shows the water use metric does not change among the three steel alloys, since the quenching rate was held constant for each steel alloy. Each of the social metrics also do not change among the three steel alloys, since the social metrics are functions of processing time, which was held constant. Since these metrics do not affect the decision for which bevel gear steel alloy has the best sustainability performance, they are excluded from the analysis in the next section.

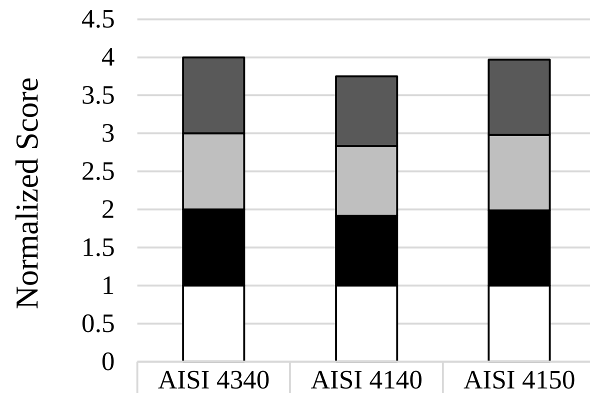
Table 4.3. Induction Hardening Assessment Results Summary

Metric	**AISI 4340**	**AISI 4140**	**AISI 4150**	**Unit**
OP Cost	1.934	1.933	1.934	$
ONS EC	0.172	0.158	0.170	kWh
H2O	6.000	6.000	6.000	L
EM GHG	0.064	0.059	0.064	kg CO_2 eq.
EM POL	1.630E-04	1.495E-04	1.614E-04	kg
INJ	2.935E-06	2.935E-06	2.935E-06	injuries
LWD	2.642E-05	2.642E-05	2.642E-05	days
ILL	7.085E-08	7.085E-08	7.085E-08	illnesses

4.5.6 Analyze and Compare Assessment Results

The sixth and final step of the methodology is to analyze and compare assessment results to identify the alternative with the best sustainability performance. To compare the induction hardening of the three bevel gear steel alloy alternatives, the sustainability metric totals from Table 4.3 were normalized and displayed in a stacked bar graph (Fig.

4.5). The normalized metric values for the three steel alloys were obtained by dividing each metric value by the corresponding value for the baseline AISI 4340 steel alloy.



	AISI 4340	AISI 4140	AISI 4150
EM POL	1	0.917	0.990
EM GHG	1	0.917	0.990
ONS EC	1	0.917	0.990
OP Cost	1	1.000	1.000

Figure 4.5. Comparison of Normalized Metric Values for Induction Hardening the Bevel Gear Steel Alloy Alternatives

From the figure, it appears that AISI 4140 and 4150 steel alloys have improved induction hardening sustainability performance for each metric over the AISI 4340 steel alloy, with 4140 having the best sustainability performance. On-site energy consumption decreased for the AISI 4140 and 4150 steels by roughly 8.3% and 1%, respectively, resulting in an equivalent decrease in the GHG and pollutant emissions, since they are directly proportional to on-site energy consumption. The operating cost remained essentially unchanged for the alternative steel alloys. The slight change in cost is due to the on-site energy consumption, which has little influence on the overall cost compared to water, quenchant, and labor costs.

Analyzing the changes in electrical resistivity and austenitizing temperature among the three steel alloys can illustrate how they influence the differences in on-site energy consumption. Pairwise comparisons between the three steel alloys were conducted to evaluate the sensitivity of energy end use to material properties. Table 4.4 shows the relative change in electrical resistivity and austenitizing temperature for the different alloys, as well as the relative change in the various sources energy consumption to illustrate how these parameters affect the on-site energy consumption metric. The sources of energy consumption include the energy to heat the workpiece, energy lost due to radiation, and energy lost from the induction coil. The energy consumption from the quenching system was not included, since it remains the same for each steel alloy. It is important to note that the workpiece energy consumption and coil energy loss are functions of both parameters, whereas radiation energy loss is solely a function of the austenitizing temperature. The relative change values were calculated by taking the corresponding difference between the values for the two steel alloys and then dividing by the associated value for the first alloy in the pairwise comparison.

It can be seen that the relative change of the workpiece energy consumption, coil energy loss, and total energy consumption correlate well with relative change in electrical resistivity. The relative change of radiation energy loss exponentially corresponds to the relative change in austenitizing temperature, as expected because the temperature is raised to the fourth power in the radiation heat transfer equation. Since radiation energy loss was low compared to the other sources of energy consumption, it had a lower impact on the total energy consumption. These findings reveal that the change in electrical resistivity has a much greater influence on energy consumption than the change in austenitizing temperature for induction hardening. In practice, steel alloys with lower electrical resistivities should be selected to reduce electrical energy consumption.

Table 4.4. Pairwise Comparison of the Steel Alloys Considered

	Sensitivity (% Relative Change)					
Pair Compared	Electrical Resistivity	Austenitizing Temperature	Workpiece Energy	Radiation Energy Loss	Coil Energy Loss	Total Energy Consumption
4340 vs. 4140	-10.484	+1.149	-10.481	+3.562	-10.467	-10.467
4340 vs. 4150	-1.210	-2.299	-1.258	-6.849	-1.264	-1.264
4140 vs. 4150	+10.360	-3.409	+10.302	-10.053	+10.279	+10.279

Due to the uncertainty of the models and supporting data, however, a clear choice for which alloy to select is not evident based on the induction hardening process alone. Thus, the effect of the specified alloy on other production processes and overall performance during use must be examined, as demonstrated below.

4.5.7 Tempering of the Steel Bevel Gears

A tempering process follows induction hardening to reduce brittleness, relieve stress, and increase toughness [108]. Tempering also reduces the case hardness, which is a key indicator of component functional equivalence. Therefore, the tempering process needs to be incorporated into the sustainability assessment to ensure a fair comparison of the three steel bevel gear alternatives.

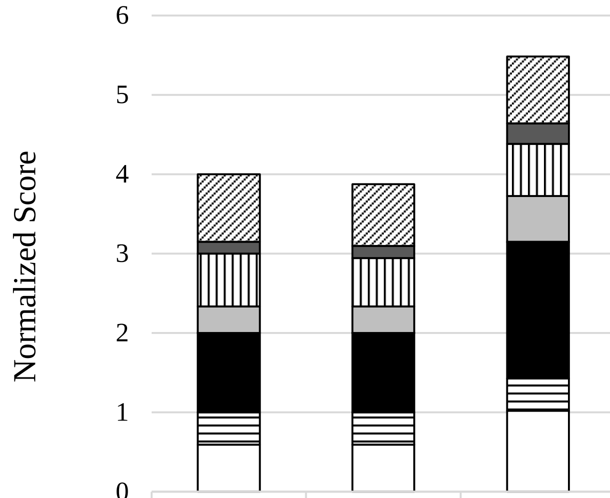
The hardened profile and case depth are controlled by the induction hardening process, which is assumed to produce contour hardened profiles with case depths of 1.22 mm for each bevel gear. Assuming 100% martensite transformation, the post-quench case hardnesses are 56, 56, and 60 HRC for the AISI 4340, 4140, and 4150 steel alloys, respectively [113]. For achieving functional equivalence, the gears are tempered to reach a final case hardness of 55 HRC. Thus, a tempering process model (Appendix A.3) for a natural gas heat treatment was developed to assist sustainability assessment. The post-temper hardness for each alloy is primarily controlled by the tempering temperature [108]. To achieve 55 HRC in a two-hour tempering process, tempering temperatures of 165, 165, and 320°C are required for AISI 4340, 4140, and 4150 steel alloys, respectively. The sustainability metrics obtained using the tempering process model are aggregated with those reported in Table 4.3 to form the summary assessment results for the process flow as shown in Table 4.5.

Table 4.5. Induction Hardening and Tempering Assessment Results Summary

Metric	**AISI 4340**	**AISI 4140**	**AISI 4150**	**Unit**
OP Cost	4.764	4.763	6.804	$
ONS EC	165.942	165.928	285.380	kWh
H2O	6.000	6.000	6.000	L
EM GHG	0.097	0.091	0.119	kg CO_2 eq.
EM POL	1.920E-04	1.785E-04	2.113E-04	kg
INJ	6.164E-05	6.164E-05	6.164E-05	injuries
LWD	5.544E-04	5.544E-04	5.544E-04	days
ILL	1.491E-06	1.491E-06	1.491E-06	illnesses

To compare the induction hardening and tempering of the three bevel gear steel alloy alternatives to achieve functional equivalence, the sustainability metrics totals were normalized and displayed in a stacked bar graph (Fig. 4.6). Once again, since the water use and social metrics were equivalent for each alloy, they were excluded from this analysis. The normalized metric values for the three steel alloys were obtained by dividing the values for each alternative by the corresponding metric values for the baseline AISI 4340 steel alloy. The figure differentiates the relative sustainability metrics impacts from the tempering (T) and induction hardening (IH) process, which are denoted by solid fills and pattern fills, respectively.

It can be seen that the AISI 4150 steel alloy has the worst sustainability performance and the AISI 4140 steel alloy has the best sustainability performance. The normalized metric variations between the AISI 4340 and 4140 steel alloys remain relatively unchanged from those for induction hardening of the bevel gears, since the same tempering process is used for the two steel alloys. The 95% increase in tempering temperature for the AISI 4150 steel alloy increases the operating cost (42.3%), on-site energy consumption (71.8%), GHG emissions (23.5%), and pollutant emissions (10%). Although the sustainability metrics for the three alternatives were similar for the induction hardening unit process, obtaining functionally equivalent products using tempering significantly altered the comparative sustainability performance.



	AISI 4340	AISI 4140	AISI 4150
EM POL (IH)	0.849	0.779	0.840
EM POL (T)	0.151	0.151	0.260
EM GHG (IH)	0.665	0.610	0.658
EM GHG (T)	0.335	0.335	0.576
ONS EC (IH)	0.001	0.001	0.001
ONS EC (T)	0.999	0.999	1.719
OP Cost (IH)	0.406	0.406	0.406
OP Cost (T)	0.594	0.594	1.022

Figure 4.6. Comparison of Normalized Metric Values for Induction Hardening and Tempering for the Bevel Gear Steel Alloy Alternatives

This reinforces the conclusion that unit manufacturing process models must ultimately be considered as a portion of the overall manufacturing process flow, as they can impact upstream processes. In this case, the construction of the induction hardening unit process model is only one aspect of characterizing the sustainability performance of the bevel gear. The other processes in the manufacturing process flow are affected by the bevel gear material properties and induction hardening process parameter choices, which can impact the overall sustainability performance results.

4.6 Summary and Conclusions

The manufacturing industry is beginning to make sustainability-conscious decisions with regard to the production of their products. To make proper design and manufacturing decisions, engineers need to conduct coordinate process- and system-level sustainability assessments of their products. When assessing the economic, environmental, and social performance of manufacturing, there are several factors to consider, including operation costs, energy and material consumption, and worker health and safety. Quantifying such factors to assist in decision making requires a thorough understanding of manufacturing processes and collecting the necessary process-specific data. This is important for constructing unit process models for each of the manufacturing processes involved in the production of a product. In the research reported, an induction hardening process was studied to construct a unit process model to quantify a selected set of sustainability metrics. This model was used to assist in the process-level sustainability assessment of a steel bevel gear. It was also paired with a tempering process model to demonstrate the sustainability assessment of a process flow.

Mathematical unit process models were able to quantify the economic, environmental, and social metrics associated with induction hardening and tempering the teeth of the bevel gear for three different steel alloys. The induction hardening unit process model can be utilized by design and manufacturing engineers to conduct sustainability assessments of a bevel gear, and aid in the investigation of tradeoffs between materials and process and design parameters. This work enables engineers with limited domain knowledge to conduct assessments, allowing the design and manufacture of more sustainable products and processes.

The induction hardening process model illustrates a step toward improving the accuracy of sustainability assessments by implementing physics and engineering principles into unit process models. Future work aims to verify the presented model by comparing the assessment results against experimental data on electrical energy consumption, process times, and liquid flows. The model calculates sustainability metrics based on process and design parameter inputs. By incorporating optimization techniques in the future, design and manufacturing engineers could determine the process and design parameters to maximize sustainability performance for induction hardening and associated process flows to help meet corporate goals.

Acknowledgements

The authors would like to thank the Boeing Company and the Oregon Metals Initiative for their support of this research. The authors would also like to thank Alex Cimino-Hurt for his review of this manuscript, and Ian Garretson for his assistance in this research.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Summary

Academic research and industrial practice in sustainable design and manufacturing are on the rise as policies and regulations continue to emerge, and as demand for sustainable products continues to grow. Thus, the manufacturing industry is beginning to make production and design decisions informed by principles of sustainability. To make the proper design and manufacturing decisions in this regard, engineers will benefit from conducting process level sustainability assessments of their products. Assessing a product's sustainability performance from economic, environmental, and social sustainability perspectives requires several factors to be considered, including manufacturing-related costs, energy and material use, and worker illnesses and injuries. Quantifying such factors to assist decision making requires obtaining a thorough understanding of unit manufacturing processes and the collection of process-specific data. This is important for constructing unit manufacturing process models for each of the processes involved in the production of a product. These activities are key steps of the unit manufacturing process-based sustainability assessment methodology presented.

To demonstrate the methodology, mathematical unit process models were constructed to accurately quantify a selected set of sustainability metrics for a bevel gear. In Chapter 3, three bevel gear design alternatives were assessed and compared to determine which had the best overall sustainability performance. In Chapter 4, the methodology was applied to an induction hardening process to detail the construction of a unit manufacturing process model. The induction hardening process model was used to assist in the sustainability assessment of bevel gear. It was demonstrated for identifying the sustainability impacts of hardening the teeth of a bevel gear made from three different steel alloys at a process level, and when considering the subsequent tempering process.

5.2 Conclusions

The unit manufacturing process-based methodology developed and demonstrated in this research was able to quantify and aggregate sustainability performance metrics for three alternative bevel gear designs from the process level across economic, environmental, and social aspects. For each bevel gear alternative, it was found that the turning process had the greatest contribution to the input material non-flyaway content and waste to recycling metrics; the vapor degreasing process had the greatest contribution to the GHG (greenhouse gas) and pollutant emissions metrics; and cadmium plating had the greatest contribution to the water use, water discharge, and hazardous waste metrics. Normalizing the sustainability metrics to the baseline design levels allowed for comparing the three bevel gear design alternatives. If the alternatives were to be ranked according to the normalized metrics, then Alternative 2, the friction-welded assembly, would be selected to have the best sustainability performance.

This methodology improves the accuracy of sustainability assessments compared to common, *ad hoc* assessment techniques through the use of unit process modeling to relate design and manufacturing parameter inputs to sustainability metric outputs. This approach can facilitate design for manufacturing and assembly analyses with sustainability performance considerations.

In addition, the application of mathematical unit process models were able to quantify the economic, environmental, and social metrics associated with induction hardening and tempering the teeth of the bevel gear for three different steel alloys. It was found that the on-site energy consumption for induction hardening was greatly impacted by the electrical resistivity of the steel alloy compared to the austenitizing temperature. The electrical resistivity and austenitizing temperature had a small impact on the operating cost metric, and did not affect the social metrics. A tempering process was included for obtaining functionally equivalent products. This demonstrated that different materials can have varying sustainability performances for different processes. The induction hardening process model illustrates a step toward improving the accuracy of sustainability assessments by implementing physics and engineering principles into unit manufacturing process models, and can relate process and design parameter inputs to sustainability metric outputs.

Utilizing this unit process-based sustainability assessment methodology and induction hardening unit process model will allow design and manufacturing engineers to investigate the sustainability performance tradeoffs between product design alternatives with varying geometries, materials, process plans, and process and design parameters.

5.3 Contributions

The presented work focused on unifying product sustainability assessments and unit manufacturing process modeling, and provides several contributions to the research community. A unit process-based product sustainability assessment methodology was developed to measure the sustainability performance for the production of a product at the process level. Based on prior research, this work is the first reported unit process modeling approach for quantifying economic, environmental, and social metrics, simultaneously. This approach is needed to understand the interactions and achieve a balance between the three sustainability aspects. This work also presents the first known induction hardening unit process model for quantifying sustainability metrics. As the induction hardening process is becoming a widely used technique for surface hardening, an understanding of the process is needed to determine its influence on the sustainability performance of a product.

5.4 Research Limitations

Several manufacturing processes were studied and modeled as part of this research, however, the lack of access to the manufacturing processes prevented validation of the unit manufacturing process models. Experimental studies would be helpful in determining the accuracy of the unit manufacturing process models in quantifying the sustainability metrics. The presented methodology is capable of measuring and comparing product sustainability performance. Without a decision support framework or knowledge of a company or decision maker's priorities, however, the selection of a product design alternative cannot be conclusively determined.

5.5 Opportunities for Future Research

Due to the limitations above, some opportunities for future research have been identified, and include improving the accuracy of the sustainability assessment methodology, incorporating a framework for decision making, and optimizing the input parameters to achieve greater sustainability performance. These opportunities are discussed below.

5.5.1 Improving the Accuracy of the Sustainability Assessment Methodology

To provide greater accuracy for design and manufacturing engineers to make more informed decisions, the sustainability assessment methodology needs to be improved. Selecting and quantifying a broad set of metrics allows for more in-depth investigation of design and manufacturing tradeoffs. Broadening the scope to incorporate auxiliary equipment that is involved with a manufacturing process, such as a material handling system, into the unit manufacturing process models can further identify the sustainability impacts from manufacturing processes. The in-depth approach described by Kellens et al. [43] can be adopted to conduct experimental studies to determine process inputs and outputs, e.g., time, power, consumables, and emissions. This approach is needed to validate and provide more accurate data for the unit manufacturing process models. The implementation of a finite element analysis for the induction hardening unit process model can help to more accurately identify the affects the input parameters have on the sustainability metrics.

5.5.2 Design Decision Support Framework

To assist design and manufacturing engineers in decision making when comparing the sustainability performance of product alternatives, a design decision support framework needs to be implemented. Previous weighting approaches such as decision tree analysis and AHP (analytic hierarchy process) could be used to weight and aggregate the sustainability metrics together to provide an overall product score. This will aid decision makers to select a product alternative based on their sustainability priorities. A new decision support framework could be developed if previous approaches are found to be insufficient.

5.5.3 Optimization of Process and Design Parameters

To determine the process and component design parameters that result in the best sustainability performance, an optimization method is needed. For example, a genetic algorithm could be used to find the optimal set of process and product design parameters to solve the multi-objective problem of optimizing sustainability metrics values, while remaining within the manufacturing process and product design constraints. This entails the construction of the objective functions and constraints, and writing the genetic algorithm code in a software program such as Matlab.

BIBLIOGRAPHY

[1] R. Hansmann, H. Mieg, and P. Frischknecht, “Principle sustainability components: empirical analysis of synergies between the three pillars of sustainability,” *International Journal of Sustainable Development & World Ecology*, vol. 19, no. 5, pp. 451–459, 2012.

[2] B. Giddings, B. Hopwood, and G. O’Brien, “Environment, Economy, and Society: Fitting them together into Sustainable Development,” *Sustainable Development*, vol. 10, pp. 187–196, 2002.

[3] R. Lozano, “Envisioning sustainability three-dimensionally,” *Journal of Cleaner Production*, vol. 16, no. 17, pp. 1838–1846, Nov. 2008.

[4] “United Nations Conference on Environment and Development,” United Nations Sustainable Development, Rio de Janeiro, Brazil, 1992.

[5] “Code of Federal Regulations,” *U.S. Government Printing Office*. [Online]. Available: http://www.gpo.gov/fdsys/browse/collectionCfr.action?collectionCode=CFR. [Accessed: 14-Jan-2014].

[6] “United States Environmental Protection Agency,” *EPA*. [Online]. Available: www.epa.gov. [Accessed: 14-Jan-2014].

[7] P. Sweeney, “Manufacturers Embrace Sustainability in a Competitive World Market,” U.S. Department of Commerce, Washington D.C, USA, Oct. 2010.

[8] K. R. Haapala, K. Poppa, R. B. Stone, and I. Y. Tumer, “Automating Environmental Impact Assessment during the Conceptual Phase of Product Design,” presented at the AAAI Spring Symposium: Artificial Intelligence and Sustainable Design, 2011.

[9] F. Le Bourhis, O. Kerbrat, J.-Y. Hascoet, and P. Mognol, “Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing,” *The International Journal of Advanced Manufacturing Technology*, vol. 69, no. 9–12, pp. 1927–1939, 2013.

[10] N. Borland, D. Wallace, and H. P. Kaufmann, “Integrating Environmental Impact Assessment into Product Design,” in *DETC98/DFM-5730*, Atlanta, Georgia, 1998.

[11] Z. Jiang, H. Zhang, and J. W. Sutherland, “Development of an Environmental Performance Assessment Method for Manufacturing Process Plans,” *The International Journal of Advanced Manufacturing Technology*, Jun. 2011.

[12] C. Hendrickson, A. Horvath, S. Joshi, and L. Lave, "Economic Input–Output Models for Environmental Life-Cycle Assessment," *Environmental Science & Technology*, vol. 32, no. 7, pp. 184–191, Apr. 1998.

[13] H.-J. Kim, G. A. Keoleian, and S. J. Skerlos, "Economic Assessment of Greenhouse Gas Emissions Reduction by Vehicle Lightweighting Using Aluminum and High-Strength Steel," *Journal of Industrial Ecology*, vol. 15, no. 1, pp. 64–80, 2011.

[14] E. Beaver, "LCA and Total Cost Assessment," *Environmental Progress*, vol. 19, no. 2, pp. 130–139, 2000.

[15] A. Jørgensen, A. Bocq, L. Nazarkina, and M. Hauschild, "Methodologies for Social Life Cycle Assessment," *The International Journal of Life Cycle Assessment*, vol. 13, no. 2, pp. 96–103, Dec. 2007.

[16] I. Schmidt, M. Meurer, P. Saling, A. Kicherer, W. Reuter, and C.-O. Gensch, "SEEbalance - Managing Sustainability of Products and Processes with the Socio-Eco-Efficiency Analysis by BASF," *Greener Management International*, vol. 45, pp. 79–94, Mar. 2004.

[17] L. C. Dreyer, M. Z. Hauschild, and J. Schierbeck, "A framework for social life cycle impact assessment," *International Journal of Life Cycle Assessment*, vol. 11, no. 2, pp. 88–97, 2006.

[18] X. Lin and K. R. Polenske, "Input—output modeling of production processes for business management," *Structural Change and Economic Dynamics*, vol. 9, no. 2, pp. 205–226, Jun. 1998.

[19] K. Tornberg, M. Jämsen, and J. Paranko, "Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company," *International Journal of Production Economics*, vol. 79, no. 1, pp. 75–82, 2002.

[20] A. C. K. Choi, H. Kaebernick, and W. H. Lai, "Manufacturing Processes Modelling for Environmental Impact Assessment," *Journal of Materials Processing Technology*, vol. 70, no. 1–3, pp. 231–238, Oct. 1997.

[21] T. Li and C. Yuan, "Numerical Modeling of Specific Energy Consumption in Machining Process," in *Proceedings of the ASME 2013 International Manufacturing Science and Engineering Conference*, Madison, Wisconsin, USA, 2013, p. V002T04A009 (6 pages).

[22] "Cooperative Effort on Process Emissions in Manufacturing," *CO2PE!* [Online]. Available: www.co2pe.org. [Accessed: 20-Apr-2014].

[23] "Sustainable Manufacturing Program," *National Institute of Standards and Technology*, 01-Oct-2011. [Online]. Available: www.nist.gov/el/msid/lifecycle/sustainable_mfg.cfm. [Accessed: 20-Apr-2014].

[24] F. Cajner, B. Smoljan, and D. Landek, "Computer Simulation of Induction Hardening," *Journal of Materials Processing Technology*, vol. 157–158, pp. 55–60, 2004.

[25] M. Melander, "Theoretical and Experimental Study of Stationary and Progressive Induction Hardening," *Journal of Heat Treating*, vol. 4, no. 2, pp. 145–166, 1985.

[26] J. Yuan, J. Kang, Y. Rong, and R. D. Sisson, Jr., "FEM Modeling of Induction Hardening Processes in Steel," *Journal of Materials Engineering and Performance*, vol. 12, no. 5, pp. 589–596, 2003.

[27] N. Barka, P. Bocher, and J. Brousseau, "Sensitivity study of hardness profile of 4340 specimen heated by induction process using axisymmetric modeling," *International Journal of Advanced Manufacturing Technology*, vol. 69, no. 9–12, pp. 2747–2756, 2013.

[28] WCED, "Report of the World Commission on Environment and Development, Our Common Future," United Nations, Oxford, 1987.

[29] USDOC, "How does Commerce define Sustainable Manufacturing?," *International Trade Administration, U.S. Department of Commerce*, 2011. [Online]. Available: http://trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp. [Accessed: 30-Dec-2012].

[30] H. Zhang, J. Calvo-Amodio, and K. R. Haapala, "Establishing Foundational Concepts for Sustainable Manufacturing Systems Assessment through Systems Thinking," *International Journal of Strategic Engineering Asset Management*, 2014.

[31] T. G. Gutowski, J. M. Allwood, C. Herrmann, and S. Sahni, "A Global Assessment of Manufacturing: Economic Development, Energy Use, Carbon Emissions, and the Potential for Energy Efficiency and Material Recycling," *The Annual Review of Environment and Resources*, vol. 38, pp. 12.1–12.26, 2013.

[32] IEA, "Worldwide Trends in Energy Use and Efficiency: Key Insights from IEA Indicator Analysis," International Energy Agency, 2008.

[33] B. Fisher and N. Nakicenovic, *Issues related to mitigation in the long-term context*. Cambridge, UK: Cambridge University Press, 2007.

[34] P. Young, G. Byrne, and M. Cotterell, “Manufacturing and the Environment,” *The International Journal of Advanced Manufacturing Technology*, vol. 13, no. 7, pp. 488–493, 1997.

[35] F. Jovane, H. Yoshikawa, L. Alting, C. R. Boër, E. Westkamper, D. Williams, M. Tseng, G. Seliger, and A. M. Paci, “The incoming global technological and industrial revolution towards competitive sustainable manufacturing,” *CIRP Annals - Manufacturing Technology*, vol. 57, no. 2, pp. 641–659, 2008.

[36] K. R. Haapala, F. Zhao, J. Camelio, J. W. Sutherland, S. J. Skerlos, D. A. Dornfeld, I. S. Jawahir, A. F. Clarens, and J. L. Rickli, “A Review of Engineering Research in Sustainable Manufacturing,” *Journal of Manufacturing Science and Engineering*, vol. 135, no. 4, pp. 041013–1 – 041013–16, Aug. 2013.

[37] I. S. Jawahir, O. W. Dillon, K. E. Rouch, K. J. Joshi, A. Venkatachalam, and I. H. Jaafar, “Total Life-cycle Considerations in Product Design for Sustainability: A Framework for Comprehensive Evaluation,” in *Proceedings of the 10th International Research/Expert Conference*, Barcelona, Spain, 2006, pp. 1–10.

[38] S. C. Feng, C. Joung, and G. Li, “Development Overview of Sustainable Manufacturing Metrics,” in *Proceedings of the 17th CIRP International Conference on Life Cycle Engineering*, Hefei, China, 2010.

[39] T. Lu, A. Gupta, A. D. Jayal, F. Badurdeen, S. C. Feng, O. W. Dillon, and I. S. Jawahir, “A Framework of Product and Process Metrics for Sustainable Manufacturing,” in *Proceedings of the Eighth International Conference on Sustainable Manufacturing*, Abu Dhabi, UAE, November 22-24, 2010.

[40] B. Ness, E. Urbel-Piirsalu, L. Olsson, and S. Anderberg, “Categorising tools for sustainability assessment,” *Ecological Economics*, vol. 60, pp. 498–508, 2007.

[41] W. Kloepffer, “Life Cycle Sustainability Assessment of Products,” *The International Journal of Life Cycle Assessment*, vol. 13, no. 2, pp. 89–95, Feb. 2008.

[42] M. Mani, J. Madan, J. H. Lee, K. Lyons, and S. K. Gupta, “Characterizing Sustainability for Manufacturing Performance Assessment,” in *Computers and Information in Engineering Conference*, Chicago, IL, USA, 2012.

[43] K. Kellens, W. Dewulf, M. Overcash, M. Z. Hauschild, and J. R. Duflou, “Methodology for Systematic Analysis and Improvement of Manufacturing Unit Process Life Cycle Inventory (UPLCI) CO2PE! Initiative (Cooperative Effort on Process Emissions in Manufacturing), part 1: methodology description,” *The International Journal of Life Cycle Assessment*, vol. 17, no. 1, pp. 69–78, 2012.

[44] J. Reap, F. Roman, S. Duncan, and B. Bras, “A Survey of Unresolved Problems in Life Cycle Assessment: Part 1: Goal and Scope and Inventory Analysis,” *The International Journal of Life Cycle Assessment*, vol. 13, no. 4, pp. 290–300, 2008.

[45] T. P. Seager, “Chapter 1: Understanding Industrial Ecology and the Multiple Dimensions of Sustainability,” in *Strategic Environmental Management*, R. Bellandi, Ed. John Wiley & Sons, 2004, pp. 17–70.

[46] ISO, “ISO 14040:2006, Environmental Management - Life Cycle Assessment - Principles and Framework,” International Organization for Standardization, Jul. 2006.

[47] M. Hauschild, J. Jeswiet, and L. Alting, “From Life Cycle Assessment to Sustainable Production: Status and Perspectives,” *CIRP Annals - Manufacturing Technology*, vol. 54, no. 2, pp. 1–21, 2005.

[48] M. A. Curran, “Life Cycle Assessment: Principles and Practice,” EPA/600/R-06/060, U.S. Environmental Protection Agency, Cincinnati, OH, EPA/600/R-06/060, May 2006.

[49] K. R. Haapala, F. Zhao, J. Camelio, J. W. Sutherland, S. J. Skerlos, D. A. Dornfeld, I. S. Jawahir, H. C. Zhang, and A. F. Clarens, “A review of engineering research in sustainable manufacturing,” in *Proceedings of the ASME 2011 International Manufacturing Science and Engineering Conference*, 2011, pp. 599–619.

[50] W. Leontief, *Input-Output Economics*. New York: Oxford University Press, 1986.

[51] V. Kumar and J. W. Sutherland, “Development and Assessment of Strategies to Ensure Economic Sustainability of the U.S. Automotive Recovery Infrastructure,” *Resources, Conservation and Recycling*, vol. 53, no. 8, pp. 470–477, Jun. 2009.

[52] M. J. Hutchins, J. S. Gierke, and J. W. Sutherland, “Decision Making for Social Sustainability: A Life-Cycle Assessment Approach,” in *Technology and Society, 2009. ISTAS ’09. IEEE International Symposium on*, 2009, pp. 1 –5.

[53] G. Munda, “‘Measuring Sustainability’: A Multi-Criterion Framework,” *Environment, Development and Sustainability*, vol. 7, no. 1, pp. 117–134, Jan. 2005.

[54] D. D. Eastlick and K. R. Haapala, “Increasing the utility of sustainability assessment in product design,” in *ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, 2012, pp. 713–722.

[55] H. Zhang and K. R. Haapala, “Integrating Sustainability Assessment into Manufacturing Decision Making,” in *Leveraging Technology for a Sustainable*

World, D. A. Dornfeld and B. S. Linke, Eds. Springer Berlin Heidelberg, 2012, pp. 551–556.

[56] I. S. Jawahir and A. D. Jayal, "Product and Process Innovation for Modeling of Sustainable Machining Processes," in *Advances in Sustainable Manufacturing*, G. Seliger, M. M. K. Khraisheh, and I. S. Jawahir, Eds. Springer Berlin Heidelberg, 2011, pp. 301–307.

[57] National Research Council (U.S.), *Unit Manufacturing Processes: Issues and Opportunities in Research*. Washington, D.C.: National Academy of Sciences, 1995.

[58] A. Zakarian and A. Kusiak, "Analysis of Process Models," *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 23, no. 2, pp. 137–147, 2000.

[59] ASTM, "WK35705 New Guide for Sustainability Characterization of Manufacturing Processes," 21-May-2014. [Online]. Available: http://www.astm.org/DATABASE.CART/WORKITEMS/WK35705.htm. [Accessed: 22-May-2014].

[60] M. Overcash, J. Twomey, and D. Kalla, "Unit Process Life Cycle Inventory for Product Manufacturing Operations," presented at the ASME 2009 International Manufacturing Science and Engineering Conference, West Lafayette, Indiana, USA, 2009, vol. 1, pp. 49–55.

[61] J. R. Duflou, K. Kellens, and W. Dewulf, "Unit Process Impact Assessment for Discrete Part Manufacturing: A State of the Art," *CIRP Journal of Manufacturing Science and Technology*, vol. 4, no. 2, pp. 129–135, 2011.

[62] M. Overcash and J. Twomey, "Unit Process Life Cycle Inventory (UPLCI) – A Structured Framework to Complete Product Life Cycle Studies," in *Leveraging Technology for a Sustainable World*, D. A. Dornfeld and B. S. Linke, Eds. Springer Berlin Heidelberg, 2012, pp. 1–4.

[63] S. C. Feng, S. Kumaraguru, C. U. Brown, and B. Kulvatunyou, "Energy Metrics for Product Assembly Equipment and Processes," *Journal of Cleaner Production*, vol. 65, pp. 142–151, 2014.

[64] J. Madan, M. Mani, and K. Lyons, "Characterizing Energy Consumption of the Injection Molding Process," in *ASME 2013 Manufacturing Science and Engineering Conference*, Madison, WI, 2013.

[65] M. Watkins, M. Mani, K. Lyons, and S. Gupta, "Sustainability Characterization for Die Casting Process," in *ASME 2013 International Design Engineering Technical Conferences*, Portland, OR, 2013.

[66] J. Gediga, H. Beddies, H. Florin, R. Loser, M. Schuckert, H. G. Haldenwanger, and W. Schneider, “Process Modeling in the Life Cycle Design - Environmental Modeling of Joining Technologies within the Automotive Industry,” in *Proceedings of Total Life Cycle Conference & Exposition*, Graz, Austria, 1998, pp. 2081–2084.

[67] K. R. Haapala, A. V. Catalina, M. L. Johnson, and J. W. Sutherland, “Development and Application of Models for Steelmaking and Casting Environmental Performance,” *Journal of Manufacturing Science and Engineering*, vol. 134, no. 5, pp. 051013–1 – 051013–13, 2012.

[68] D. Fratila, “Evaluation of near-dry machining effects on gear milling process efficiency,” *Journal of Cleaner Production*, vol. 17, no. 9, pp. 839–845, 2009.

[69] R. E. Haimbaugh, *Practical Induction Heat Treating*. Materials Park, OH: ASM International, 2001.

[70] A. Mühlbauer, *History of Induction Heating & Melting*. Essen, Germany: Deutsche Nationalbibliothek, 2008.

[71] V. Rudnev, D. Loveless, R. Cook, and M. Black, *Handbook of Induction Heating*. New York, NY: Marcel Dekker, Inc., 2003.

[72] K. Kurek, M. Niklewicz, and A. Smalcerz, “Estimation of chosen parameters influence on induction hardening process of gears,” Silesian University of Technology, Gliwice, Silesia, Poland.

[73] H. Kristoffersen and P. Vomacka, “Influence of process parameters for induction hardening on residual stresses,” *Materials & Design*, vol. 22, pp. 637–644, 2001.

[74] D. Hömberg, “A mathematical model for induction hardening including mechanical effects,” *Nonlinear Analysis Real World Applications*, vol. 5, no. 1, pp. 55–90, 2004.

[75] A. Bokota and S. Iskierka, “Numerical analysis of phase transformations and residual stresses in steel cone-shaped elements hardened by induction and flame methods,” *International Journal of Mechanical Sciences*, vol. 40, no. 6, pp. 617–629, 1998.

[76] C. Chaboudez, S. Clain, R. Glardon, J. Rappaz, M. Swierkosz, and R. Touzani, “Numerical Modelling of Induction Heating of Long Workpieces,” *IEEE Transactions on Magnetics*, vol. 30, no. 6, pp. 5028–5037.

[77] R. K. Singh, H. R. Murty, S. K. Gupta, and A. K. Dikshit, “An overview of sustainability assessment methodologies,” *Ecological Indicators*, vol. 15, no. 1, pp. 281–299, 2012.

[78] D. Hunkeler and G. Rebitzer, "The Future of Life Cycle Assessment," *International Journal of Life Cycle Assessment*, vol. 10, no. 5, 2005.

[79] J. Elkington, *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Capstone Publishing Ltd, Oxford, 1997.

[80] M. C. Chiu and G. E. O. Kremer, "Investigation of the Applicability of Design for X Tools during Design Concept Evolution: a Literature Review," *International Journal of Product Development*, vol. 13, no. 2, pp. 132–167, 2011.

[81] J. Ranganathan, "Sustainability Rulers: Measuring Corporate Environmental and Social Performance," Sustainability Enterprise Perspectives, Washington D.C., May 1998.

[82] S. Rachuri, R. D. Sriram, and P. Sarkar, "Metrics, Standards and Industry Best Practices for Sustainable Manufacturing Systems," in *5th Annual IEEE Conference on Automation Science and Engineering*, Bangalore, India, 2009, pp. 472 –477.

[83] "Sustainability Reporting Guidelines," Global Reporting Initiative, Version 3.1, 2011.

[84] "DJSI Family Overview," *Dow Jones Sustainability Indices*. [Online]. Available: http://www.sustainability-indices.com/index-family-overview/djsi-family.jsp. [Accessed: 29-Dec-2012].

[85] "ISO 14031:1999 Environmental Management - Environmental Performance Evaluation - Guidelines," *ISO 14301:1999*. [Online]. Available: http://www.iso.org/iso/catalogue_detail?csnumber=23149. [Accessed: 29-Dec-2012].

[86] A. Wyckoff, "OECD Sustainable Manufacturing Toolkit: Seven Steps to Environmental Excellence," OECD.

[87] W.-P. Schmidt, "Product Sustainability Index," *Ford of Europe, Germany*, 2007. [Online]. Available: http://corporate.ford.com/doc/sr11-ford-psi.pdf. [Accessed: 29-Dec-2012].

[88] S. Suh and G. Huppes, "Methods for Life Cycle Inventory of a Product," *Journal of Cleaner Production*, vol. 13, pp. 687–697, 2005.

[89] M. Campanelli, J. Berglund, and S. Rachuri, "Integration of Life Cycle Inventories Incorporating Manufacturing Unit Processes," in *ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Washington D.C., USA, 2011.

[90] C. Jiménez-Gonzalez, S. Kim, and M. Overcash, “Methodology for developing gate-to-gate Life cycle inventory information,” vol. 5, no. 3, pp. 153–159, May 2000.

[91] W. Zhenwei and H. Li, “Manufacturing-Oriented Discrete Process Modeling Approach Using the Predicate Logic,” *IEEE Transactions on Knowledge and Data Engineering*, vol. 21, no. 12, pp. 1803–1806, 2009.

[92] A. Culaba and M. Purvis, “A Methodology for the Life Cycle and Sustainability Analysis of Manufacturing Processes,” *Journal of Cleaner Production*, vol. 7, no. 6, pp. 435–445, Dec. 1999.

[93] D. D. Eastlick, M. V. Sahakian, and K. R. Haapala, “Sustainable Manufacturing Analysis for Titanium Components,” in *Design for Manufacturing and the Lifecycle Conference (DFMLC)*, Washington, D.C., 2011.

[94] M. D. Eastwood, K. R. Haapala, M. D. Carter, and P. W. Liner, “Product and Process Design for Sustainable Assembly,” in *ASME 2013 International Mechanical Engineering Congress & Exposition*, San Diego, CA, 2013.

[95] V. Veleva and M. Ellenbecker, “Indicators of Sustainable Production: Framework and Methodology,” *Journal of Cleaner Production*, vol. 9, no. 6, pp. 519–549, Dec. 2001.

[96] B. Bras, F. Tejada, J. Yen, J. Zullo, and T. Guldberg, “Quantifying the Life Cycle Water Consumption of a Passenger Vehicle,” SAE International, Warrendale, PA, 2012-01-0646, Apr. 2012.

[97] “Fourth Assessment Report of the Intergovernmental Panel on Climate Change,” *IPCC - Intergovernmental Panel on Climate Change*. [Online]. Available: http://www.ipcc.ch/publications_and_data/publications_ ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm. [Accessed: 29-May-2011].

[98] “Bureau of Labor Statistics,” *United States Department of Labor*. [Online]. Available: http://www.bls.gov/. [Accessed: 12-Apr-2013].

[99] M. Uzkut, B. S. Unlu, S. S. Yilmaz, and M. Akdag, “Friction Welding and its Applications in Today’s World,” presented at the 2nd International Symposium on Sustainable Development, Sarajevo, Bosnia-Herzegovina, 2010, pp. 710–724.

[100] E. Oberg and C. J. McCauley, *Machinery’s Handbook*. New York, N.Y: Industrial Press, 2012.

[101] E. O’Driscoll, D. Óg Cusack, and G. E. O’Donnell, “The development of energy performance indicators within a complex manufacturing facility,” *The International*

Journal of Advanced Manufacturing Technology, vol. 68, no. 9–12, pp. 2205–2214, 2013.

[102] D. Kalla, M. Overcash, J. Twomey, and E. Griffing, "Manufacturing Unit Process Life-Cycle Heuristics." [Online]. Available: http://cratel.wichita.edu/uplci/. [Accessed: 06-Jun-2014].

[103] "Leveraging Technology for a Sustainable World," *19th CIRP Conference on Life Cycle Engineering*, 23-May-2012. [Online]. Available: http://lce2012.berkeley.edu/home.html. [Accessed: 06-Jun-2014].

[104] K. R. Haapala, J. L. Rivera, and J. W. Sutherland, "Reducing Environmental Impacts of Steel Product Manufacturing," *Trans. NAMRI/SME*, vol. 37, pp. 419–426, 2009.

[105] "Induction heating applications: The processes, the equipment, the benefits," EFD Induction, 2010.

[106] S. L. Semiatin and D. E. Stutz, *Induction Heat Treatment of Steel*. Metals Park, Ohio: American Society for Metals, 1986.

[107] T. G. Digges, S. J. Rosenberg, and G. W. Geil, "Heat Treatment and Properties of Iron and Steel," United States Department of Commerce, Nov. 1966.

[108] P. M. Unterweiser, H. E. Boyer, and J. J. Kubbs, *Heat Treater's Guide: Standard Practices and Procedures for Steel*. Metals Park, Ohio: American Society for Metals, 1982.

[109] J. R. Davis, *Gear Materials, Properties, and Manufacture*. Materials Park, OH: ASM International, 2005.

[110] V. Rudnev, "A common misassumption in induction hardening," Inductoheat, 2004.

[111] P. L. Rossiter, *The Electrical Resistivity of Metals and Alloys*. New York, NY: Cambridge University Press, 1987.

[112] O. Biro and K. Preis, "On the Magnetic Vector Potential in the Finite Element Analysis of Three-Dimensional Eddy Currents," *IEEE Transactions on Magnetics*, vol. 25, no. 4, pp. 3145–3159, 1989.

[113] K.-E. Thelning, *Steel and Its Heat Treatment*, Second Edition. London, England: Butterworths, 1984.

[114] R. H. Todd, *Manufacturing processes reference guide*, 1st ed. New York: Industrial Press, 1994.

[115] Code of Federal Regulations, “Part 63 - National Emission Standards for Hazardous Air Pollutants for Source Categories.” U.S. Government Printing Office, 2011.

[116] Michigan Department of Environmental Quality, “Emission Calculation Fact Sheet: Electroplating Operations.” Environmental Science and Services Division, 2005.

[117] BEE, “Energy Performance Assessment of Furnaces.” Bureau of Energy Efficiency.

[118] EPA, “Natural Gas Combustion.” Environmental Protection Agency.

APPENDICES

A. Unit Manufacturing Process Models

Unit manufacturing process models are often categorized according to the Allen and Todd hierarchy [114]. The hierarchy categorizes manufacturing processes by their technological similarities and include mass reducing, surface finishing, heat treatment, and joining processes. Examples of the several unit manufacturing process models developed as part of this research are presented below for each process category.

A.1 Mass Reducing

Mass reducing processes shape a workpiece by removing material. These processes include single-point cutting, multi-point cutting, and abrasive machining. Turning is a single-point mass reducing process. It is a machining process in which a non-rotary single-point cutting tool moves parallel to the axis of a rotating workpiece to remove material to form external geometries. Sustainability metrics that apply to turning include operating cost, input material non-flyaway content, on-site energy consumption, water use, water discharge, GHG emissions, pollutant emissions, waste to recycling, injuries, lost work days, and illnesses. Table A.1 presents the general sustainability metric equations for assessing the turning process.

Table A.1 Turning Unit Process Model Equations

Metric (unit)	**Equation**	**Reference**
Operating Cost ($)	OP Cost = $V_c c_c + V_{WL} c_w + E_{on} c_e + t_p c_L$	
Input Material Non-Flyaway Content (%)	IMNF = $(V_i+V_f)/V_s$	
On-site Energy Consumption (kWh)	ONS EC = $P_m t_m + P_i t_i + P_s t_s$; $P_m = K_p C_f Q W/\eta_m$; $Q = 0.25\pi(D_i^2 - D_f^2) f_r$	[60], [100]
Water Use (L)	H2O = $V_{WT}(t_m/t_{ref})$	[96]
Water Discharge (L)	H2O Dis = $(100-p_c)V_{dis}t_m$	
GHG Emissions (kg CO_2 eq.)	EM GHG = $E_{on}(r_{CO2}+r_{CH4}GWP_{CH4}+r_{NO2}GWP_{NO2})$	[6], [97]
Pollutant Emissions (kg)	EM POL = $E_{on}(r_{NOx}+r_{SOx})$	[6]
Waste to Recycling (kg)	W2R = $V_r\rho_r+V_c\rho_c$	
Acute Injuries (injuries)	INJ = $r_{inj}t_p$	[98]
Lost Work Days (days)	LWD = r_{lwd}INJ	[98]
Chronic Illnesses (illnesses)	ILL = $r_{ill}t_p$	[98]

Gear cutting is categorized as a multi-point mass reducing process. It is a machining process in which one (or sometimes two) multi-point cutting tool removes material to shape the teeth of a gear. Sustainability metrics that apply to gear cutting include operating cost, input material non-flyaway content, on-site energy consumption, water use, water discharge, GHG emissions, pollutant emissions, waste to recycling, injuries, lost work days, and illnesses. Table A.2 presents the general sustainability metric equations for assessing the gear cutting process.

Table A.2 Gear Cutting Unit Process Model Equations

Metric (unit)	**Equation**	**Reference**
Operating Cost ($)	OP Cost = $V_c c_c + V_{WL} c_w + E_{on} c_e + t_p c_L$	
Input Material Non-Flyaway Content (%)	IMNF = $(V_i + V_f)/V_s$	
On-site Energy Consumption (kWh)	ONS EC = $P_m t_m + P_i t_i + P_s t_s$; $P_m = K_p C_f QW/\eta_m$; $Q = A_r f_c \omega_b$	[60], [100]
Water Use (L)	H2O = $V_{WT}(t_m/t_{ref})$	[96]
Water Discharge (L)	H2O Dis = $(100-p_c)V_{dis} t_m$	
GHG Emissions (kg CO_2 eq.)	EM GHG = $E_{on}(r_{CO2} + r_{CH4} GWP_{CH4} + r_{NO2} GWP_{NO2})$	[6], [97]
Pollutant Emissions (kg)	EM POL = $E_{on}(r_{NOx} + r_{SOx})$	[6]
Waste to Recycling (kg)	W2R = $V_r \rho_r + V_c \rho_c$	
Acute Injuries (injuries)	INJ = $r_{inj} t_p$	[98]
Lost Work Days (days)	LWD = r_{lwd}INJ	[98]
Chronic Illnesses (illnesses)	ILL = $r_{ill} t_p$	[98]

A.2 Surface Finishing

Surface finishing processes are performed to alter the surface of a workpiece to achieve a certain property. These include surface preparation and chemical coating processes. Vapor degreasing is categorized as a surface preparation process within surface finishing. A workpiece is loaded into a chamber of vaporized solvent to dissolve oils and greases, which leaves a clean surface. Sustainability metrics that apply to vapor degreasing include operating cost, on-site energy consumption, GHG emissions, pollutant emissions, waste to recycling, hazardous waste, injuries, lost work days, and illnesses. Table A.3 presents the general sustainability metric equations for assessing the vapor degreasing process.

Table A.3 Vapor Degreasing Unit Process Model Equations

Metric (unit)	**Equation**	**Reference**
Operating Cost ($)	$OP\ Cost = V_d c_d + E_{on} c_e + t_p c_L$	
On-site Energy Consumption (kWh)	$ONS\ EC = (100/\eta_{vd}) m_d r_{HE}$; $r_{HE} = c_p(T_i - T_f)$	
GHG Emissions (kg CO_2 eq.)	$EM\ GHG = E_{on}(r_{CO2} + r_{CH4} GWP_{CH4} + r_{NO2} GWP_{NO2})$	[6], [97]
Pollutant Emissions (kg)	$EM\ POL = E_{on}(r_{NOx} + r_{SOx}) + m_{de}$; $m_{de} = t_p W_e A_{ST}(100 - p_{red})$	[6], [115]
Waste to Recycling (kg)	$W2R = V_d \rho_d t_p$	
Hazardous Waste (kg)	$W\ Haz = V_{sd} \rho_s t_p$	
Acute Injuries (injuries)	$INJ = r_{inj} t_p$	[98]
Lost Work Days (days)	$LWD = r_{lwd} INJ$	[98]
Chronic Illnesses (illnesses)	$ILL = r_{ill} t_p$	[98]

Cadmium plating is categorized as a chemical coating process within surface finishing. It is a type of electroplating process in which a workpiece is negatively charged and immersed in a bath of aqueous positively charged metal salts to deposit a cadmium coating on the surface. Sustainability metrics that apply to cadmium plating include operating cost, on-site energy consumption, water use, water discharge, GHG emissions, pollutant emissions, hazardous waste, injuries, lost work days, and illnesses. Table A.4 presents the general sustainability metric equations for assessing the cadmium plating process.

Table A.4 Cadmium Plating Unit Process Model Equations

Metric (unit)	**Equation**	**Reference**
Operating Cost ($)	OP Cost = $\Sigma(V_{cp}c_{cp})+V_{WL}c_w+E_{on}c_e+t_pc_L$	
On-site Energy Consumption (kWh)	ONS EC = $P_{stk}t_{stk}+P_{r1}t_{r1}+P_{r2}t_{r2}$; $P_{stk} = I_{stk}A_SV_{pv}$	
Water Use (L)	H2O = $V_{WT}(t_p/t_{ref})$	[96]
Water Discharge (L)	H2O Dis = $(100-p_{cp})V_{dis}t_p$	
GHG Emissions (kg CO_2 eq.)	EM GHG = $E_{on}(r_{CO2}+r_{CH4}GWP_{CH4}+r_{NO2}GWP_{NO2})$	[6], [97]
Pollutant Emissions (kg)	EM POL = $E_{on}(r_{NOx}+r_{SOx})+(r_{Cd}+r_{CN})t_p$; $r_{Cd} = 3600M_{Cd}A_{ST}P_{Cd}K_{Cd}/(R_gT_T)$	[6], [116]
Hazardous Waste (kg)	W Haz = $V_s\rho_st_p$	
Acute Injuries (injuries)	INJ = $r_{inj}t_p$	[98]
Lost Work Days (days)	LWD = r_{lwd}INJ	[98]
Chronic Illnesses (illnesses)	ILL = $r_{ill}t_p$	[98]

A.3 Heat Treatment

Heat treatment processes are those that cause physical and chemical changes within a workpiece, such as its mechanical properties, by controlled heating to a certain temperature. These include recovery and surface hardening processes. Natural gas oven heat treatment is categorized, as used in this research, as a recovery process within heat treatment. The recovery process is a type of tempering process to reduce brittleness and stress, and increase toughness. Sustainability metrics that apply to natural gas oven heat treatment include operating cost, on-site energy consumption, GHG emissions, pollutant emissions, injuries, lost work days, and illnesses. Table A.5 presents the general sustainability metric equations for assessing the natural gas oven heat treatment process.

Table A.5 Natural Gas Oven Heat Treatment Unit Process Model Equations

Metric (unit)	**Equation**	**Reference**
Operating Cost ($)	OP Cost = $E_{CH4}c_{CH4}$	
On-site Energy Consumption (kWh)	ONS EC = $(q_{f\_loss}+q_{c\_loss})t_p+E_p$	[117]
GHG Emissions (kg CO_2 eq.)	EM GHG = $(m_{CH4}/\rho_{CH4})*(r_{CO2}+r_{CH4}GWP_{CH4}+r_{NO2}GWP_{NO2})$	[97], [118]
Pollutant Emissions (kg)	EM POL = $(m_{CH4}/\rho_{CH4})*(r_{NOx}+r_{SOx}+r_{PM}+r_{AH}+r_{Pb}+r_{Hg})$	[118]
Acute Injuries (injuries)	INJ = $r_{inj}t_p$	[98]
Lost Work Days (days)	LWD = r_{lwd}INJ	[98]
Chronic Illnesses (illnesses)	ILL = $r_{ill}t_p$	[98]

A.4 Joining

Joining processes are those that combine two or more workpieces into a single unified workpiece. These include mechanical joining processes. Friction welding is categorized as a mechanical joining process within joining. In inertial friction welding, one workpiece is fixed and another is spun at a high speed. The two workpieces are then forced together at high pressure, and the heat formed from the friction softens the weld zone to enable solid state joining of the two workpieces. Sustainability metrics that apply to friction welding include operating cost, on-site energy consumption, GHG emissions, pollutant emissions, injuries, lost work days, and illnesses. Table A.6 presents the general sustainability metric equations for assessing the friction welding process.

Table A.6 Friction Welding Unit Process Model Equations

Metric (unit)	**Equation**	**Reference**
Operating Cost ($)	OP Cost = $E_{on}c_e+t_pc_L$	
On-site Energy Consumption (kWh)	ONS EC = $0.5I_M\omega_r^2$; $I_M = 0.5m_p(ID^2+OD^2)$	
GHG Emissions (kg CO_2 eq.)	EM GHG = $E_{on}(r_{CO2}+r_{CH4}GWP_{CH4}+r_{NO2}GWP_{NO2})$	[6], [97]
Pollutant Emissions (kg)	EM POL = $E_{on}(r_{NOx}+r_{SOx})$	[6]
Acute Injuries (injuries)	INJ = $r_{inj}t_p$	[98]
Lost Work Days (days)	LWD = r_{lwd}INJ	[98]
Chronic Illnesses (illnesses)	ILL = $r_{ill}t_p$	[98]