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Title: Process-Based Modeling for Cradle-to-Gate Energy and Carbon Footprint Reduction in Product Design

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Interest in accounting for environmental impacts of products, processes, and systems during the design phase is increasing. Numerous studies have undertaken investigations for reducing environmental impacts across the product life cycle. Efforts have also been launched to quantify such impacts more accurately. Life cycle energy consumption and carbon footprint are among the most frequently adopted and investigated environmental performance metrics. As efforts continue to incorporate environmental sustainability into product design, struggles persist in concurrent consideration of environmental impacts resulting from the manufacturing processes and supply chain network design. Thus, the objective of this research is to present a framework for reducing product cradle-to-gate energy consumption and carbon footprint through simultaneous consideration of manufacturing processes and supply chain activities. The framework developed in this thesis relies on unit process modeling, and is demonstrated for production of a bicycle pedal. It is shown that simultaneous consideration of manufacturing and supply chain processes can impact decision-making and improve product environmental sustainability at the design stage. The work presented contributes to the state of the science in sustainable design and manufacturing research. In addition, a point of departure is established for the research community to move current efforts forward for concurrent consideration of multiple stages of the product life cycle in pursuit of environmental, economic, and social sustainability.

Process-Based Modeling for Cradle-to-Gate Energy and Carbon Footprint Reduction in Product Design

by

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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.

Ahmed J. Alsaffar, Author

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LIST OF ACRONYMS

B100	100% Biodiesel from Soybeans
BOF	Basic Oxygen Furnace
CAFE	Corporate Average Fuel Economy
CED	Cumulative Energy Demand
CES	Carbon Emission Signature
CFC	Chlorofluorocarbon
CH_4	Methane
CO_2	Carbon Dioxide
CO2PE!	Cooperative Effort on Process Emissions in Manufacturing
DfE	Design for Environment
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EBM	Environmentally Benign Manufacturing
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ETAP	Environmental Technologies Action Plan
FWS	Fish and Wildlife Service
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
IPCC	Intergovernmental Panel on Climate Change

LIST OF ACRONYMS (Continued)

ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
N_2O	Nitrous Oxide
NAE	National Academy of Engineering
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NPS	National Park Service
NRC	National Research Council
OHF	Open Hearth Furnace
PFC	Perfluorocarbon
SC	Supply Chain
SF_6	Sulfur Hexafluoride
UNEP	United Nations Environment Programme
UNFCCC	United Nations Environment Programme
UPLCI	Unit Process Life Cycle Inventory
WTEC	World Technology Evaluation Center

CHAPTER I – INTRODUCTION

1.1. Chapter Overview

This chapter addresses the motivating drivers in pursuit of conducting the research outlined in this thesis. It describes the research problem and thesis objectives and provides an outline of the thesis.

1.2. Motivation for the Research

High energy demands are leading causes to consuming great amounts of non-renewable resources, commonly referred to as fossil fuels. The combustion of fossil fuel to generate energy is accompanied with the emission of various kinds of greenhouse gases (GHG), often measured in terms of carbon dioxide (CO_2) equivalent and referred to as carbon footprint. Climate change is, as a result, one major concern of GHG emission and is one of the most challenging environmental problems faced by decision-makers of leading countries in the recent era. Both the environment and people are being endangered by the potential risks of GHGs, e.g. coastal flooding due to increased levels of sea-water and eco-system damage due to continuous increase in atmosphere temperature (Hunter, 2010). Because GHGs are mostly due to human activities resulting from industrial and transportation operations, as will be seen in Chapter 2, assessment methods and frameworks are needed to minimize the emission of GHGs to sustain the current resources of the environment and foster its future uses from the risks of GHGs mentioned above.

1.3. Problem Description

Global climate change, high consumption of energy, and health concerns are continuously raising apprehensions among legislators, other government decision makers, and the public. While some manufacturers, service firms, and logistics companies are taking serious steps toward integrating sustainability principles in their practices, environmental performance measures are often not accounted for in the product development stage.

To improve decisions related to energy consumption and associated carbon footprint of manufacturing processes and supply chain networks, simultaneous consideration of manufacturing and supply chain activities needs to be investigated from a cradle-to-gate life cycle perspective. Different supply chain schemes can introduce a variety of manufacturing capabilities in terms of adopted unit manufacturing processes and related machines capabilities, as well as different power profiles yielding to different energy utilization and, in turn, different carbon footprint.

1.4. Thesis Objectives

The research presented herein serves several objectives to address the problem described above. First, it will provide a comprehensive review of recent literature reported between the years 1990 and 2011 to summarize past and current findings and methods relating to the environmental sustainability of products, processes, and systems. The review will help identify current research gaps to support the novelty of the work presented in this thesis. The second main objective is to support decision-making related to energy consumption of manufacturing activities and supply chain network designs by developing parametric models to compute the energy consumption involved in manufacturing processes and supply chain networks and, in turn, recognize the corresponding carbon footprint using reported emission conversion factors. Thus, at the design stage, engineers and managers will be able to recognize the effect of choosing different suppliers on the adopted manufacturing processes, transportations modes, energy profiles, and related carbon footprint. Finally, an application of the method will be undertaken to verify the mechanics and potential of the approach in enhancing the decision-making process in product design for cradle-to-gate energy use and carbon footprint reduction.

1.5. Thesis Outline

This thesis is composed of five chapters. The current chapter (Chapter 1) provides the motivation behind the research conducted in this thesis, gives a description of the research problem under investigation, and outlines the thesis objectives and chapters flow. Chapter 2 provides a literature review of prior work related to sustainable manufacturing and supply chains. The literature covered in the chapter focuses on recent literature, i.e., 2000-2011, but traces back to the early 1990s for a more complete review. Chapter 3 describes the overall framework of the method developed under this research. It also describes the analytical models developed (in Section 3.2) in support of the computation of the energy consumption of various forming and machining unit processes. Section 3.3 describes the approach adopted in establishing the supply chain networks, or, more specifically, the basis of the selection of supplier location, transportation routes, and modes. Section 3.4 elucidates the process of converting energy use to carbon footprint and provides a description of emission conversion factors. Chapter 4 demonstrates the method described in Chapter 3 using a bicycle pedal. Geometric, material, and assembly details of the product were recorded at Wayne State University as a part of a collaborative National Science Foundation project and subsequently underwent manufacturing process analysis at Oregon State University. Furthermore, data and process models were organized and managed using Microsoft Excel. Chapter 5 summarizes and concludes the research discussed in previous chapters. Recommendations for future work are also discussed to improve on the findings and carry the research forward.

CHAPTER II – LITERATURE REVIEW

2.1. Chapter Overview

In this chapter, a brief background of sustainability is given. Different definitions and metrics are discussed. Energy utilization and carbon footprint are described in more detail, in addition to a general overview of societal implications of environmental impacts. Next, a comprehensive review of the recent literature on sustainable manufacturing and supply chain research is presented. Additionally, a review of current methods and tools used in assessing the environmental sustainability of products, processes, and system is included. Finally, limitations and research gaps of prior work are identified to support the novelty of this research. The chapter closes with a summary and conclusions based on the work reviewed.

2.2. Background

The concept of sustainability emerged as a critical aspect of production, particularly in developed countries as early as the 1960s (U.S. EPA, 2011), due to industrial growth and expansion. It is widely agreed that the journey of sustainability began when marine biologist Rachel Carson reported on the environmental impacts of chemical pesticides in her book *Silent Spring* (Carson, 1962). Her immediate attention and long-term vision sparked controversy in the U.S. and led others to convey their concerns about the environmental dangers of human activities, such as Murray Bookchin in 1962 (Bookchin, 1974) and Barry Commoner in 1971 (Commoner, 1971). These pioneers and their initiatives inspired scientists and researchers around the globe and led to advances toward environmental protection. One result was the establishment of the U.S. Environmental Protection Agency (EPA) in 1970, which addresses the environmental damage caused by humans and to set regulations and policies in pursuit to restrict current and prospective threats to the environment. Today, more than ever, researchers across many disciplines in academia and industry are vigorously pursuing the integration of sustainability principles into the design of processes, products, and systems to meet market and governmental expectations in sustaining human quality of life (Sutherland and Gunter, 2001; Jeswiet and Hauschild, 2005; Rajemi et al. 2010; Zhnag, 2010).

2.2.1. Sustainability Definition

Sustainability is broad, multifaceted, and complex in terms of practical objectives and goals (Fullan, 2005). Fullan defined sustainability as the ability to consider, involve, and coordinate the challenges and obstacles presented in a system due to continuous improvements and human values for quality development. Indeed, this definition encompasses many interpretations and warrants further discussion. Linguistically, sustainability derives its meaning from the act of enduring or nourishing. Hargreaves and Fink (2006) argued that sustainability is not necessarily the act of sustaining a particular resource; rather, it is the development of human made processes and systems in a way that guards against sacrificing natural resources, in the present and the future. The U.S. EPA states that sustainability means guarding the environment and human health against the exhaustive consumption of the ecological resources (U.S. EPA, 2011). While there is disagreement on how sustainability is attained or retained, all definitions confirm the need for practices that will responsibly utilize current resources and be cognizant of future generations.

2.2.2. Sustainability Metrics

The need to understand the characteristics, inputs, and outputs of processes, products, and systems is imperative in defining, assessing, and measuring the related environmental impacts (Ramani et al., 2010). A metric can be defined as a quantifiable measure used to assess the performance of an entity. Figure 1.1 shows various types of environmental metrics that could be used in assessing manufactured products and manufacturing processes and systems. The metrics are characterized in terms of being related to inputs, outputs, downstream, and other measures.

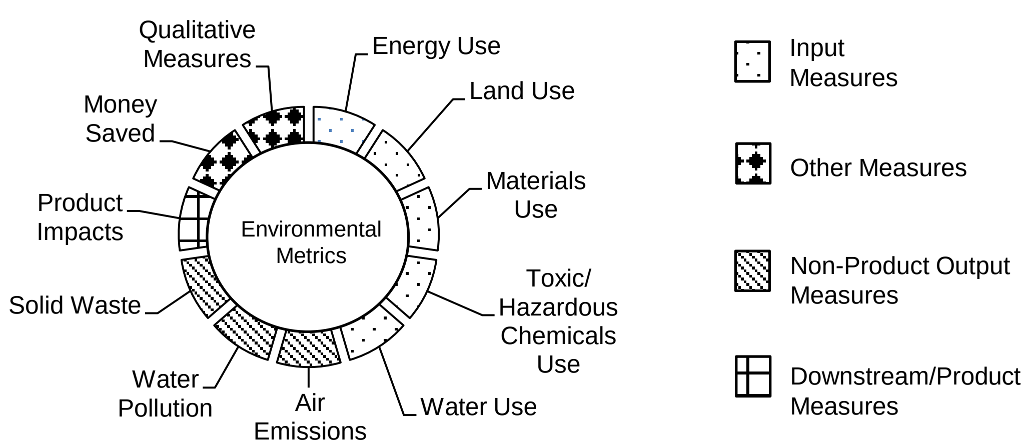


Figure 1.1: Environmental Metrics (Frosch et al., 1999, U.S. EPA, 2011)

The U.S. National Academy of Engineering (NAE) has indicated that carbon, energy, and climate are among the research areas considered by the fourteen grand challenges (U.S. NAE, 2008). Energy consumption, for instance, results in carbon dioxide and other greenhouse gas (GHG) emissions, which, in turn, can be interpreted on an environmental basis. Figure 1.2 shows the generation of GHG emissions in the units of mass of carbon dioxide equivalent (kg CO_2 eq.) resulting from U.S. economic sectors in 1990 and 2009. It can be seen that reduction of industrial energy use, which includes product manufacturing industry, and the reduction of transportation energy, which results from the shipping of goods, are critical to the reduction of national level GHG emissions. It has been estimated that around one-third and one-fourth of the total energy was consumed by transportation sector and manufacturing industries, respectively (U.S. EIA, 2004).

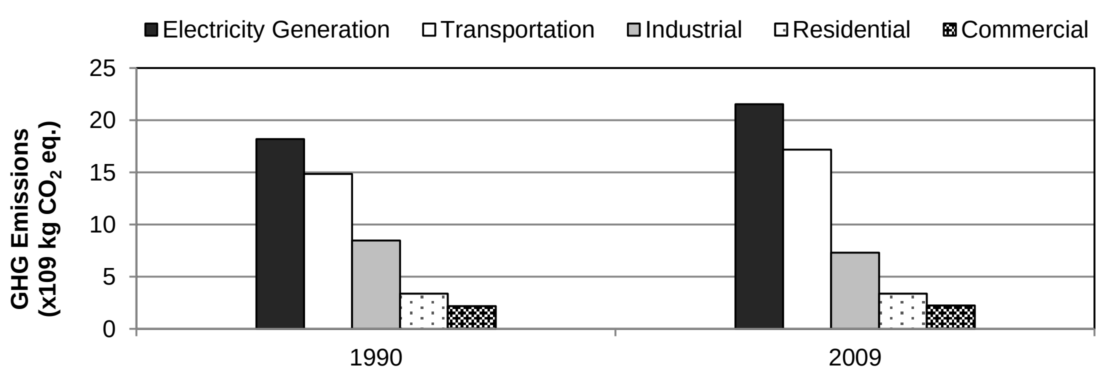


Figure 1.2: GHG Emissions Resulting from Fossil Fuel Combustion in the United States within Various Sectors, 1999 and 2009 (U.S. EIA, 2004)

This thesis reports on the recent design and manufacturing literature that has adopted energy consumption and carbon footprint as environmental metrics. An approach is presented (Chapter 3) and demonstrated (Chapter 4) to simultaneously reduce manufacturing and supply chain energy and carbon footprint using manufacturing process-based models coupled with supply chain processing information. Two metric categories, i.e., energy and carbon footprint, are explored in the sections; below, which support the method developed.

2.2.3. Energy Use and Carbon Footprint

Energy consumption remains largely dependent on fossil fuels in the U.S. (Figure 1.3). Electrical energy is primarily generated using fossil fuels (coal and natural gas), while industrial and transportation energy are primarily liquid petroleum based (U.S. EIA, 2011). Thus, industrial and transportation energy consumption strongly influences sector-related carbon dioxide emissions.

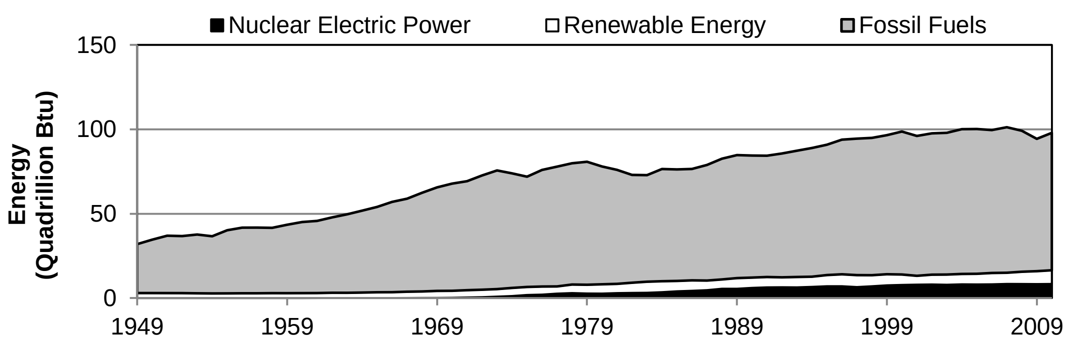


Figure 1.3: U.S. Primary Energy Consumption by Major Source, 1949-2010 (U.S. EIA, 2011)

Carbon dioxide emissions are a constituent of GHGs, which are gases that have the potential to absorb infrared radiation that is redirected back to the atmosphere after sunlight strikes the Earth's surface (U.S. EIA, 2004). As a result, heat can be trapped in the lowest layers of the atmosphere over time (U.S. EIA, 2004; U.S. NASA, 2011), which raises concerns about their influence on the global environment. While some GHGs are naturally synthesized, e.g., water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), others are strictly anthropogenic, e.g., chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (U.S. EIA, 2011). Figure 1.4 shows the contribution of GHG emissions in the U.S. by gas in 2007 (U.S. EIA, 2008). Direct carbon dioxide accounts for more than three quarters of the total GHG emissions. Other GHGs can also be interpreted on the basis of carbon dioxide. The following section describes the concept of carbon footprint and summarizes the equivalence measure of GHG on the basis of carbon dioxide.

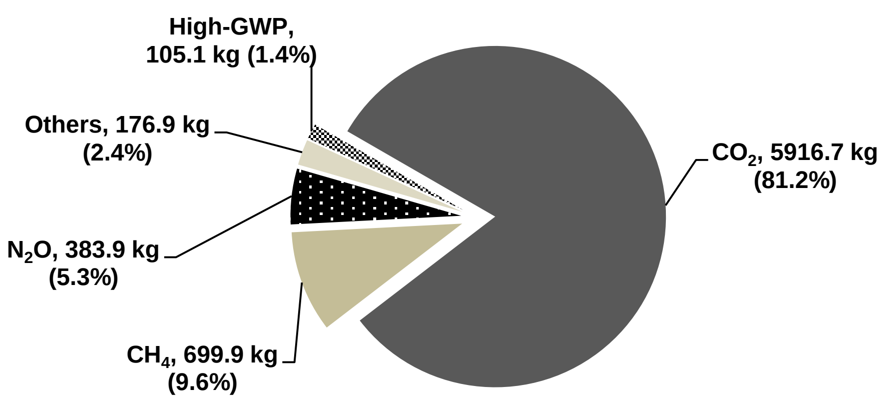


Figure 1.4: U.S. Greenhouse Gas Emissions by Gas during 2007 (U.S. EIA, 2008)

The concept of carbon footprint has been introduced to provide a common measure of overall GHG emissions, as well as provide a metric for improvement tracking (Wiedmann and Minx, 2007; ETAP, 2007). Carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann and Minx, 2007). Table 2.1 summarizes the measures of the main GHGs on the basis of CO_2 eq. during the years 2001 and 2007 as reported by IPCC third and fourth reports (IPCC, 2007a).

Table 2.1: Greenhouse Gases Equivalency to Carbon Dioxide (IPCC, 2007a).

Greenhouse Gas Name	**Greenhouse Gas Code**	**Formula**	**Global Warming Potential**	
			2001	**2007**
Carbon Dioxide	CO_2	CO_2	1	1
Methane	CH_4	CH_4	23	25
Nitrous Oxide	N_2O	N_2O	296	298
Hydrofluorocarbons	HFCs	CHF_3, CH_2F_2, CH_3F, CHF_2CF_3, CHF_2CHF_2, CH_2FCF_3, CHF_2CH2F, CF_3CH_3, CH_2FCH_2F, CH_3CHF_2, CH_3CH_2F, CF_3CHFCF_3, $CH_2FCF_2CF_3$, CHF_2CHFCF_3, $CF_3CH_2CF_3$, $CH_2FCF_2CHF_2$, $CHF_2CH_2CF_3$, $CF_3CH_2CF_2CH_3$, $CF_3CHFCHFCF_2CF_3$	(12-12000)	(-3-14800)

Table 2.1: Greenhouse Gases Equivalency to Carbon Dioxide (IPCC, 2007a).

Greenhouse Gas Name	**Greenhouse Gas Code**	**Formula**	**Global Warming Potential**	
Perfluorocarbons	PFCs	CF_4, C_2F_6, C_3F_8, C_4F_{10}, c-C_4F_8, C_5F_{12}, C_6F_{14}	(5700-11900)	(7390-12200)
Chlorofluorocarbons[3]	CFCs	$CC_{l3}F$, $CC_{l2}F_2$, $CC_{l}F_3$, $CC_{l2}FCC_{l}F_2$, $CC_{l}F_2CC_{l}F_2$, $CF_3CC_{l}F_2$	N/A	N/A
Other Gases, e.g., Nitrogen Trifluoride	NF_3	NF_3	10800	17200

The importance of using carbon footprint as an environmental measure of manufacturing activities has been reported widely in the literature (e.g., Laurent et al., 2010; Boguski, 2010; Jeswiet and Nava, 2009; and Joyce et al., 2010), and therefore, is adopted by this thesis as well. Next, several global environmental policy efforts that impact manufacturing industry are described.

2.2.4. Societal Implications of Manufacturing

The United Nations Environment Program (UNEP) is an international program with a mission to assist countries with their environmental activities and help developing countries to be environmentally sustainable through practices and policies (UNEP, 2011). The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (UNFCCC, 2011), are examples of agreements that seek to monitor and insure regulations set for climate change laws. Similarly, the

Intergovernmental Panel on Climate Change (IPCC) is focusing efforts on global climate change issues related to carbon and other GHG emissions (IPCC, 2007a).

The U.S. is a key contributor to the formulation of environmental policy through several agencies, e.g., the Environmental Protection Agency (EPA), the Fish and Wildlife Service (FWS), and the National Park Service (NPS). United States policy initiatives that focus on energy use and GHG emissions reduction include the Energy Policy Act of 2005, Corporate Average Fuel Economy (CAFE) regulations, first enacted in 1975, and National Environmental Policy Act (NEPA) of 1969.

Table 2.2: Summary of Environmental Policies

Policy	**Place**	**Year**	**Participants**
California Air Resources Board (CARB)	United States	1967	California
National Environmental Policy Act (NEPA)	United States	1969	United States
Corporate Average Fuel Economy (CAFÉ)	United States	1975	United States
Kyoto Protocol	Kyoto, Japan	1997	37 industrialized countries and the European Union
The Road to Copenhagen	Copenhagen, Denmark	2000	Worldwide
The Regional Greenhouse Gas Initiative (RGGI)	United States	2003	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, New Jersey, Rhode Island, Vermont

Table 2.2: Summary of Environmental Policies

Policy	Place	Year	Participants
The Western Climate Initiative (WCI)	United States	2007	Arizona, California, Montana, New Mexico, Oregon, Utah, Washington, British Columbia, Manitoba, Ontario, and Quebec
Midwestern Greenhouse Gas Reduction Accord (MGGRA)	United States	2007	Minnesota, Wisconsin, Illinois, Iowa, Michigan, Kansas, and the Canadian Province of Manitoba.

Legislation and regulations focused on environmental management systems within the manufacturing industry pose great challenges to engineers, managers, and other decision makers in developing and implementing greener and cleaner technologies and to practices. Manufacturing impacts such as high energy consumption and GHG emissions initiated research on unit manufacturing process modeling. Such research has been reported for various manufacturing processes to understand and alleviate the environmental impacts at the process level, e.g., sand casting (Dalquist and Gutowski, 2004), steelmaking processes (Haapala et al., 2004 and 2009), machining (Gutowski et al., 2006), forming (Nava, 2009), and assembly (Jeswiet and Nava, 2009). Thus, such process models can be applied to reduce manufacturing energy consumption, GHG emissions, waste generation, and material utilization (Ilgin and Gupta, 2010). Recent research progress and findings (1990-2011) are summarized below. Based on this prior work, a framework is then presented toward improved engineering practices for environmentally sustainable product design and manufacturing (Chapter 3). The focus of the following discussion is on energy use and GHG emissions reduction in manufacturing and supply chains.

2.3. Sustainable Manufacturing Process Research

Research on manufacturing processes has been stressed by the U.S. National Research Council (NRC) (U.S. NRC, 1995). In light of the competition in manufacturing sectors between the leading industrial countries, the NRC showed that the United States continues to struggle in maintaining and improving the technology of manufacturing processes and related equipment compared to Japan and European countries. Research at the process level which includes understanding of the workpiece material behavior, development of process simulation schemes and modeling techniques, sensors, control, and precision and metrology, and finally machine and instrument design is required and imperative to enhance competitiveness. Similar study conducted globally by a group of scientists in manufacturing research and technology concluded that product and process design models are needed to understand the economic value and environmental performance of products and systems (Gutowski et al., 2001).

Giachetti (1998) developed an analytical tool that supports the design for manufacturing (DfM) objectives through the development of a database that stores material characteristics. Lin and Polenske (1998) used an input-output process model to investigate the influence of different steelmaking processes on the cost of disposed wastes. Similarly, Sutherland and Gunter (2001) proposed a general input-output process based methodology that looked at the effect of process planning on waste generation. Hernandez-Matias (2006) concluded that most prior work in manufacturing process modeling was either theoretically driven or centered on a particular process. The study revealed that the most widely investigated metrics include economic value of production, cycle time or throughput of processes, and optimization of manpower.

Rajemi et al. (2010) developed a methodology to model the energy consumption for machining processes. Their model was illustrated for a turning process to identify the effect of process parameters on energy use. Nava (2009) investigated a method to minimize the energy consumption and related carbon footprint in metal forming processes by estimating the energy of the mechanical work, converting energy to CO_2, and providing an optimization approach to minimize the resultant CO_2. Gutowski et al. (2006) investigated the energy requirements for various manufacturing processes. They concluded that the specific energy requirement is variable with respect to the unit processes, which is in opposition to how process energy is treated in most LCA studies. Haapala et al. (2004) studied a set of manufacturing processes, e.g., sand casting, bending, welding, and laser cutting, for the production of large steel products. Their objective was to estimate the materials and energy use and correlated wastes using a spreadsheet tool. A global collaborative of researchers have established a method for manufacturing process analysis to support LCA, identified in the US as unit process life cycle inventory, *uplci*, and in Europe as CO2PE! (Kellens et al., 2011a and 2011b). The method quantifies energy use for manufacturing processes by using data found in the literature or from experimentation. The method has been demonstrated for a drilling operation (Overcash et al., 2009) and reported for several of the more than 100 unit processes available online on the *uplci* website (Overcash and Twomey, 2010).

The manufacturing research community continues to invest in projects related to the design and modeling of manufacturing processes and systems to enhance their environmental performance. This is often approached by focusing on reducing the energy consumption, and hence the carbon footprint, of manufacturing activities. A recent study by Branker et al. (2011) linked the reduction of energy consumption and the associated carbon footprint to the reduction of manufactured product total cost. The model is based on a microeconomic model that considers parameters like energy, power, and selected environmental impacts, e.g., carbon footprint. Fang et al. (2011) investigated applying linear programming to optimize the peak power load and energy use of manufacturing systems. Jeswiet and Nava (2009) proposed a calculated carbon emission signature (CES) for correlating electrical energy use to the GHG emissions for a number of traditional manufacturing processes which has also been discussed by (Laurent et al., 2010). Dietmair and Verl (2008) presented a model for forecasting machine energy consumption, which was then illustrated for milling machines. Diaz et al. (2011) investigated the impact of different material removal rates on the specific energy requirement for a milling machine. The study revealed that machining time is a principle cause for higher energy consumption. Eastlick et al. (2011) developed a method to compare product design alternatives on the basis of environmental, economic, and social measures. The method was based on manufacturing unit process models and is illustrated for the production of a titanium component. Although their study concluded that the method can enhance the decision making by considering additional criteria such as economic and social aspects of the design, it had limited capabilities in assessing the overall sustainability performance of design variants. Alsaffar et al. (2011) looked at how changes in the design of three-ring binder affect manufacturing and supply chain designs. The study was conducted use an LCA tool, i.e., SimaPro software and compared eight three-ring binder design alternatives. They concluded that transportation impact was always minor compared to material and manufacturing impacts. Haapala et al. (2011) conducted a comprehensive review of sustainable manufacturing developments at the process and system levels. In addition, the study identified current challenges as well as future opportunities in improving sustainable manufacturing research and practice. Efforts have also focused on reduction of energy use and carbon footprint from a supply chain perspective, as discussed below.

2.4. Sustainable Supply Chain Research

Ilgin and Gupta (2010) presented a comprehensive literature review on current advances and activities in environmentally conscious manufacturing and product recovery (ECMPRO) from 540 peer-reviewed publications. The review focused on research trends related to four phases of the product life cycle which were, environmentally sustainable product design, supply chain design, remanufacturing, and disassembly activities. Seuring and Müller (2008) synthesized an extensive literature review of 191 scholarly articles on sustainable supply chain management published from 1994-2004. Although their review was broad and conceptual in nature and business-oriented, it offered evidence that studies were deficient in connecting energy use and GHG emissions impacts during supply chain operations, which was reiterated by Cholette and Venkat (2009). The environmental sustainability of a supply chain network is subject to many factors, e.g., technology use, energy use, network density and route, inventory policy, trade policy, and shipment policy (Sundarakani et al., 2010). A study by Saunders and Barber (2007) found that transportation methods, loads, and routes result in various levels of carbon dioxide equivalent emissions. Their study reported a case study for shipment of lamb via sea (Cholette and Venkat, 2009; Sundarakani et al., 2010, Saunders and Barber, 2007). The results concluded that raising lambs within the UK accounts for 34 % emission increase compared to shipping the same product from New Zealand to the UK which also considers shipping emissions.

Ibbotson et al. (2011) examined a dozen different supply chain network designs subject to various transportation modes and routes, loads to be transported, and energy profile per location. Their study concluded that rail transport exhibited a 3-9% lower carbon footprint than other transportation modes. Furthermore, it has been reported that using local suppliers can cut the carbon footprint of rail transport by 10% (Herman et al., 2010).

Chiu et al. (2010) investigated a methodology that combines a graph theory approach for generating product design concepts with LCA to simultaneously account for cost and carbon footprint at the product development phase. Their approach was applied to study a global bicycle supply chain. The results showed promising potential in informing decision makers of the impacts investigated at the design stage.

A study by Sundarankani et al. (2010) considered heat transfer across various nodes of the supply chain. Their methodology examined the direct GHG emissions from links within a closed loop. The objective of the study was to better understand the heat flux concentrated at each node and the resultant carbon footprint. Bevilacqua et al. (2011) performed a study on the effect of different supply chain networks for a textile company. Variations on transportation type, combinations of transportation type and route, and selection of suppliers to minimize environmental impacts were explored. To validate results, the study was supported by analytical methods including Monte Carlo simulation and sensitivity analysis.

Ramudhin et al. (2010) proposed a novel model in the design of sustainable supply chain networks. The model considers carbon market sensitive strategic planning in the design of supply chains. Their study showed that decision-making is greatly influenced by internal and external factors related to the design of the supply chain. The methodology was later extended to a mixed-integer linear programming problem to evaluate the trade-offs between costs and carbon emission in logistics operations using goal programming (Chaabane et al., 2011). The study considered supplier, sub-supplier, and transportation type selection in the design phase. A case study for steelmaking was carried out to demonstrate the methodology. Nagurney et al. (2006) discussed the applicability of enforcing carbon taxes within the electricity supply chain and presented a model for determining the optimal carbon tax values. In addition to the research conducted on sustainable manufacturing and supply chain designs, environmental assessment tools and method have been developed and are introduced next.

2.5. Current Methods and Tools for Environmental Sustainability

Systematic approaches for the development of environmentally friendly products have been developed throughout the years to meet customer expectations and address industrial commitment to environmental policies and legislations. Several such approaches that have been previously described are introduced below.

2.5.1. Environmentally Benign Manufacturing (EBM)

The importance of improving business environmental performance has been widely addressed through the concept of Environmentally Benign Manufacturing (EBM). This system-level approach adopts green manufacturing processes, which are those that are material and energy efficient, among other aspects (Sutherland et al., 2003). A review of analytical tools and frameworks aiding environmental competitiveness was conducted by a World Technology (WTEC) Division panel (Gutowski, 2001). Several major approaches were discussed for evaluating impacts and possible improvements from an environmental perspective. These included metrics and data-based approaches, in addition to design for environment (DFE) and life cycle assessment (LCA).

2.5.2. Design for Environment (DfE)

Design for Environment (DfE), also known as Ecodesign, is a design method that focuses on environmental, health, and safety matters correlated with the development of product throughout its complete life cycle beginning with material extraction and ending with and disposal or end-of-life (Fiksel, 1993). It has been hypothesized that product environmental concerns can be designed-in during the early design phase to alleviate impacts (Chiu et al., 2010). Hence, DfE provides a basis for understanding the environmental attributes at each stage of the product life cycle and consequently supplies a foundation to decision-making before manufacturing takes place (Jeswiet and Hauschild, 2005).

2.5.3. Life Cycle Assessment (LCA)

In addition to design methodologies that target developing products with respect to the environment (e.g., DfE), methods and tools that can assist with predicting environmental impacts across product life cycle stages were desired, and in turn, developed. LCA is the most popular and widely used method in assessing comprehensively various environmental impacts, e.g., CO_2 equivalent and global warming potential from cradle-to-grave, i.e., from material extraction through end of life as shown in Figure 2.1 (Hertwich et al., 2000).

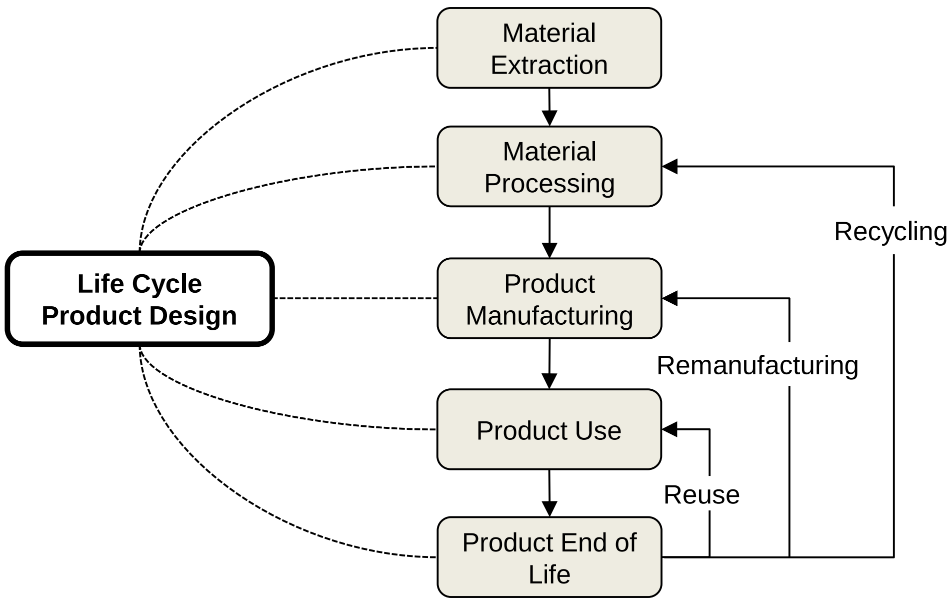


Figure 2.1: Product Life Cycle from Cradle-to-Grave

LCA is often supported by a set of standards enforced on manufacturers by governments as part of initiatives led by the United Nations (UN). The standards formulated in the ISO 14000 series, are a part of environmental management system (EMS) systems introduced in the 1990s (Corbett and Kirsch, 2001). Figure 2.2 shows the principles and framework for conducting an LCA as described by ISO 14040:2006 (ISO, 2012). These principles are briefly discussed below.

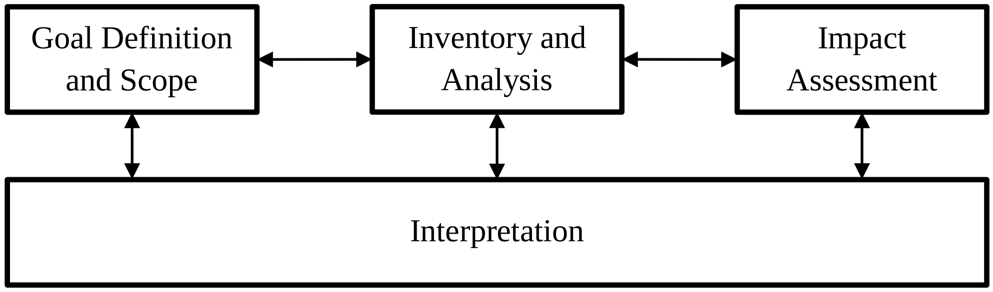


Figure 2.2: LCA Principles and Framework According to ISO 14040 (ISO, 2012)

LCA is a system-level approach that is composed of four major phases, 1) Goal and scope definition, 2) Life cycle inventory (LCI), 3) Life cycle impact assessment (LCIA), and 4) Life cycle improvement analysis (Svoboda, S., 1995 and ISO, 2012). The goal definition and scope identification phase elucidates the boundaries of the system and any relevant appropriate functional unit for comparison and analysis purposes (Rebitzer et al., 2004). Data collection phase is considered the most challenging and time consuming aspect in performing an LCA study. Thus, several databases (e.g., *ecoinvent* database (http://www.ecoinvent.org/database/) and U.S. LCI database (http://www.nrel.gov/lci/)) have been developed to alleviate the burden of data collection in compiling life cycle inventories (LCI). The data are usually represented in terms of raw material and energy inputs to a particular system or activity (PRé Consultants, 2010).

The life cycle impact assessment (LCIA) phase is concerned with determining the environmental impacts resulting from every life cycle stage for the product, process, or system under consideration (Jolliet et al., 2003). Several impact methods exist to support decision makers with predicting potential environmental impacts to their business. For example, ReCiPe 2008 is an impact method relatively new to practice (Goedkoop et al., 2009). It is based on midpoint and endpoint indicators and has the potential to show impact results for eighteen categories at the midpoint level e.g., water use, energy content, and ozone concentration (ReCiPe, 2012), which are combined into three endpoint damage types, i.e., damage to human health, damage to the ecosystem, and resources surplus costs. In addition, there are different weighting sets that can be applied to assess the sensitivity of results, e.g., individualist, hierarchist, and egalitarian, (Hofstetter, 1998, Bare et al., 2000, Thompson et al. 1990) available through LCA tools such as SimaPro (PRé Consultants, 2011). Cumulative Energy Demand (CED) is another environmental indicator methodology that quantifies the direct and indirect energy usage during the total life cycle from different primary sources, i.e., renewable and nonrenewable resources (Frischknecht et al., 2003).

Finally, the Intergovernmental Panel on Climate Change (IPCC) developed a method for assessing the environmental impacts of human-kind activities (IPCC, 2007). This method looks at the global warming potential (GWP) as a result of GHG emissions using characterization factors with timeframes ranging from 20-500 years (Joos et al., 2001). The method excludes indirect formation of certain gases (e.g., nitric oxide), ignores radiative forcing resulting from gas emissions, and finally excludes any indirect effect from carbon oxide emissions. IPCC lacks normalization and weighting representation, but is a good method in quantifying the carbon footprint resulting from activities involving the combustion of fossil fuels. Table 2.2 summarizes several tools and databases used in academic research and industrial practices for environmental impact analysis. These and others methods and tools are summarized elsewhere (http://lct.jrc.ec.europa.eu/)

Table 2.3: Tools and Databases for Life Cycle Environmental Analysis

Tools and Databases	**Developer**	**Description**
GaBi	PE International GmbH	Assist product environmental life cycle assessment (LCA)
SimaPro	PRé Consultants B.V.	
openLCA	GreenDeltaTC GmbH	
TEAM	Ecobilan - PricewaterhouseCoopers	
EIO-LCA	Green Design Institute, Carnegie Mellon University	
Umberto	Ifu Hamburg GmbH	Assist substance and material flow analysis (SFA/MFA)
Sankey Editor	STENUM GmbH	
STAN	Vienna University of Technology	
DEAM	Ecobilan - PricewaterhouseCoopers	

Table 2.3: Tools and Databases for Life Cycle Environmental Analysis

Tools and Databases	Developer	Description
ecoinvent	Swiss Centre for Life Cycle Inventories	Compile process input/output data of materials and energy
US LCI	U.S. National Renewable Energy Laboratory	
DEAM	Ecobilan - PricewaterhouseCoopers	

2.6. Limitations of Prior Work

Frameworks and tools mentioned in Section 2.5 are among the most popular and widely used methodologies in assessing the environmental impacts of products, processes, and systems, yet several limitations have been identified in providing accurate results (Sheng and Worhach, 1998; Reap et al., 2006; De Benedetto & Klemeš, 2009; Bright, Cherubini, & Strømman, 2012). These limitations are summarized below:

- Time intensity in data collection
- Errors involved in data collected
- Inaccuracy in defining the scope and boundaries of systems
- Variability of the process model parameters
- Uncertainty of chemicals and materials properties
- Lack of accommodating pre-defined processes and systems

From the foregoing literature review, two additional primary limitations have been identified in supporting and assessing the environmental impacts of manufacturing processes. First, dependence on LCA tools can provide an overall assessment of the environmental performance of products, processes, and systems, yet the presence of the above identified deficiencies can yield inaccurate and uncertain conclusions. The development of parametric-process models can overcome several of these deficiencies and yield more accurate results. In particular, identification and manipulation of impactful parameters is easily accessible through process planning. Second, in addition to development of parametric-models, simultaneous consideration of manufacturing processes and supply chain design alternatives are being developed for the purpose of minimizing of overall carbon footprint of the product's cradle-to-gate life cycle.

2.7. Summary and Conclusions

An overview of sustainability definitions and metrics has been given in the beginning of this chapter. Despite differences in defining sustainability, all definitions call for practices that will responsibly utilize current resources and be cognizant of future generations. Energy consumption and carbon footprint metrics have been discussed in more detail. Societal implication from manufacturing and supply chain activities were mentioned. International and U.S. non-governmental initiatives, acts, and agreements in addition to government policy efforts continue to impose restrictions on human activities deleteriously impacting the environment and people. Prior work on sustainable manufacturing and supply chain research has been introduced, focusing on research from the past ten years. Furthermore, brief coverage of frameworks used in assessing the environmental impacts of products, processes, and systems has been reported in Section 2.5. Tools and databases are summarized in Table 2.2. It was shown and concluded that current methodologies and tools suffer from several deficiencies and can lead to inaccurate and uncertain assessments. The major deficiencies include incomprehensive current databases, in addition to difficulties with data aggregation in terms of source quality or time intensity. Other deficiencies include variability and uncertainties found with material and chemical compositions, process parameters, or machine capabilities. The second limitation identified was the lack of simultaneous consideration of multiple stages of the product life cycle, e.g. manufacturing processes and supply chains. The remainder of this thesis is, therefore, devoted to addressing the research gaps identified herein through the development of the method (Chapter 3), followed by a demonstration of the method (Chapter 4), and finally assessing, interpreting, and concluding the applicability and potential contribution of this work to the body of knowledge, as well as providing recommendations for future research (Chapter 5).

CHAPTER III – DEVELOPMENT OF AN INTEGRATED FRAMEWORK

3.1. Chapter Overview

This chapter describes the methodology developed as a part of this thesis work (Section 3.2.). Quantitative models for estimating the energy consumption of various manufacturing unit processes are given in Section 3.3. Supply chain design considerations are presented in Section 3.4 based on location and transportation routes and modes. Section 3.5 describes the approach of converting energy to carbon footprint. Finally, a summary and conclusions are given in Section 3.6.

3.2. Methodology Overview

From the foregoing chapters, it is clear that sustainable product manufacturing requires the integrated analysis of manufacturing processes and supply chains on the basis of associated economic, environmental, and social issues at the design stage. An approach addressing the limitations highlighted in Chapter 2 is presented herein. The approach accounts for energy use and related carbon footprint to support simultaneous design of manufacturing process flows and the supply chain network within a cradle-to-gate scope (Figure 3.1). The figure shows the product complete life cycle, i.e., cradle-to-grave enclosed by the upper gray top box, and covers stages beginning with material extraction and ending with disposal. Product design is shown to be fed to the product life cycle to determine the required activities across all phases of the product. The impacts of the different phases remain unknown until all activities are complete.

The stages highlighted in the darker gray box, i.e., raw material extraction, material processing, and manufacturing, are known as the product cradle-to-gate life cycle.

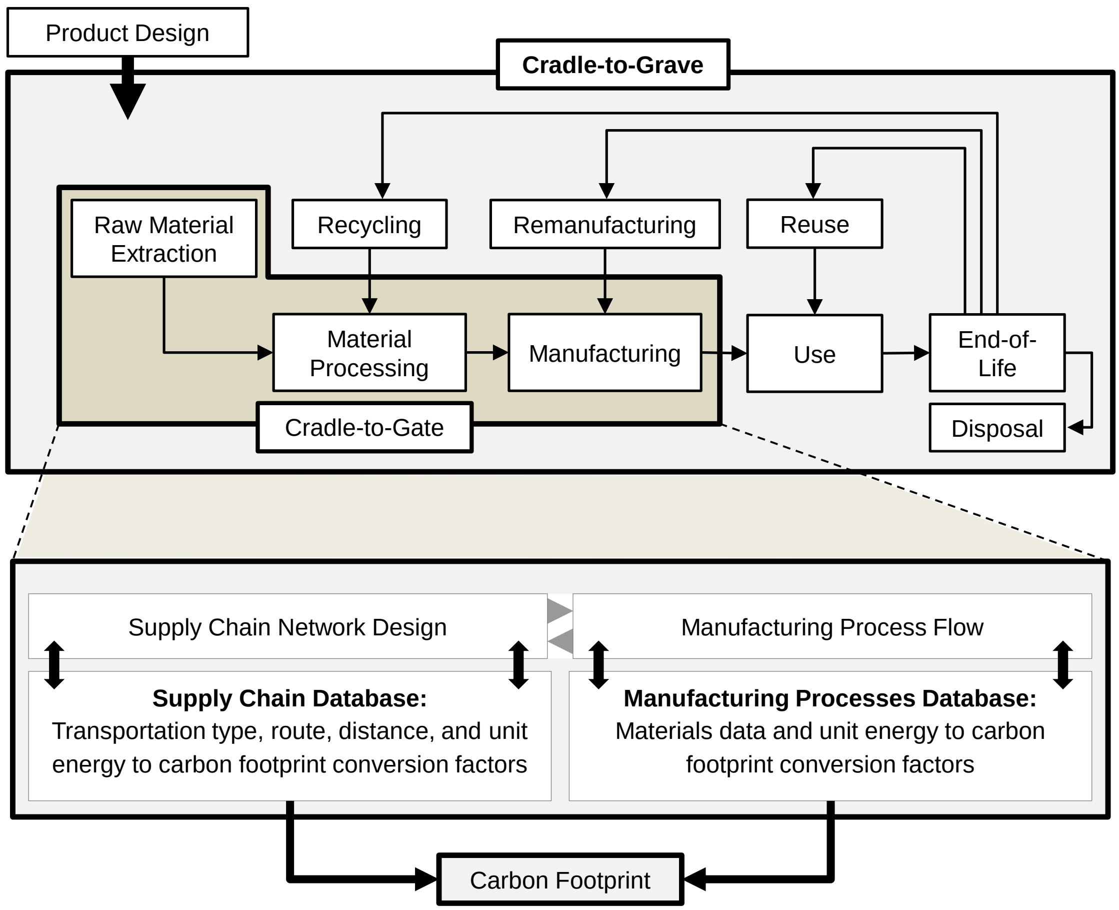


Figure 3.1: A Framework to Integrate Energy and Carbon Footprint Reduction into Manufacturing Process Flow and Supply Chain Network Design

Figure 3.1 shows how cradle-to-gate stages can be considered in a process-based and in a simultaneous manner to predict the overall carbon footprint. Data and information must be collected for each process from cradle to gate, i.e., material extraction through component manufacturing and assembly. With this knowledge, the energy and carbon footprint can be calculated for various supply chain configurations to determine the optimal route to product manufacture. Figure 3.2 shows various supply chain configurations for production of *n* components of a given product. Each supply chain configuration is subject to a combination of different transportation modes and routes, supplier locations, and distances. If a supply chain configuration is selected, such as that highlighted in Figure 3.2, the total carbon footprint can be calculated by summing the resultant footprints for each link, i.e., represent distance and transportation mode and each node i.e., represent different location of the supply chain.

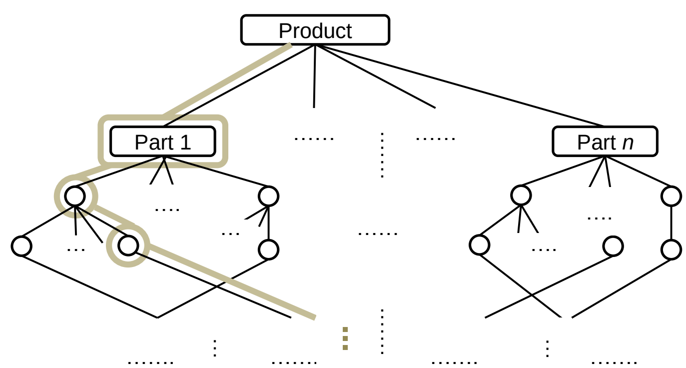


Figure 3.2: Alternative Supply Chain Network Configurations for a Product Design

Figure 3.3 displays the general approach for determining materials and energy use and the wastes and emissions associated with each unit process and/or supply chain entity. Each input and output represents a vector of flows for each type, which must be normalized to a common reference flow. While this procedure is well-established for life cycle assessment studies, it is data, time, and resource intensive. Thus, to facilitate the approach, process-based models, which are indicative of each process, can be devised that elucidate the mathematical relationships of process inputs and outputs (Sutherland and Gunter, 2001). Similarly, relationships can be established for supply chain entities, describing transportation modes, distances, and associated energy use and carbon footprint on a per-mass or per-volume basis. Product types can be mass or volume limited for transport using common modes.

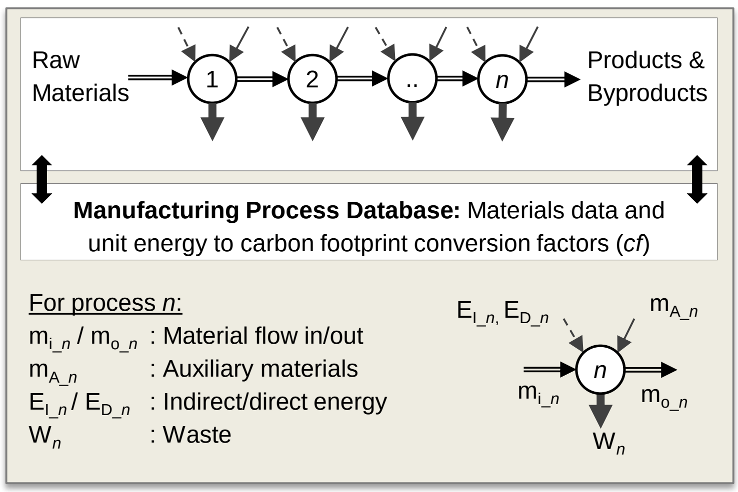


Figure 3.3: Input and Output Modeling for Unit Manufacturing Processes and Linking of Models for Manufacturing Process Flow

In addition to identifying the best supply chain configuration, the analysis would contribute to targeting the most impactful entities and facilitate reconfiguration of the supply chain. If existing supply chains are evaluated and found to perform poorly from a sustainability perspective, alternative manufacturing and supply chain solutions could be developed that lead to process innovations or identification of new supply chain partners.

3.3. Manufacturing Energy Consumption Models

Unit manufacturing processes undergo mechanical work and chemical reactions in an effort to amend one or several characteristics of its original stage (U.S. NRC, 1995). Materials, chemicals, electricity, fuel are primary inputs considered at the process level. In this section, development for energy consumption models for various processes is provided.

3.3.1. Metal – Casting Processes

Metal-casting, one of the most ancient processes is a forming process in which liquefied metal, e.g., iron, or aluminum is poured into a shaped mold according to the geometric details of the part or product design (Kalpakjian, 2010).

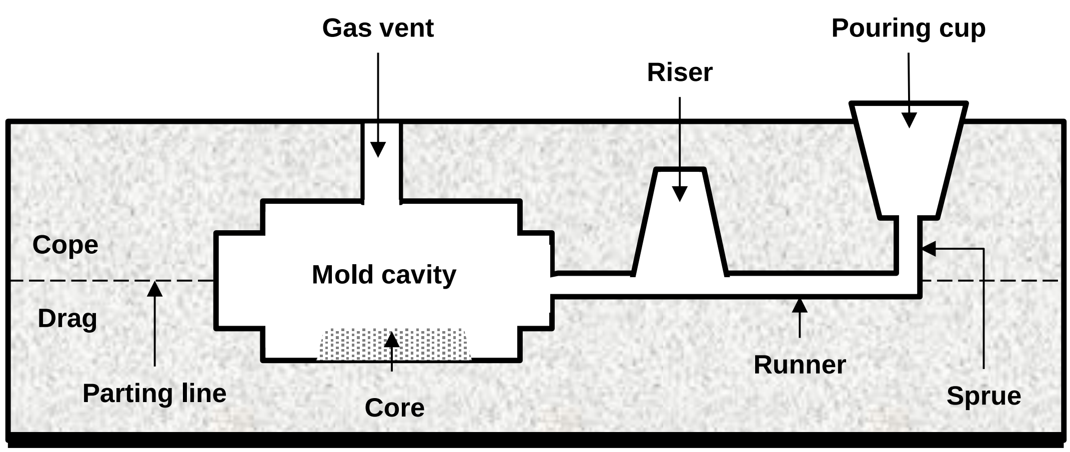


Figure 3.4: Mold for Sand Casting (adapted from www.substech.com/)

The energy consumption ($E_{casting}$) used in casting can be determined based on the specific energy applied to the total mass of the molten part as shown in Equation 3.1 (Boustead and Hancock, 1979)

$$E_{casting} = m \cdot C_E$$

Equation 3.1: Metal-Casting – Energy Consumption

The specific energy for various materials and processes are reported in the literature for various material processing technologies (Boustead and Hancock, 1979; Stubbles, 2000). Table 3.1 defines the casting parameters and the units used in Equation 3.1.

Table 3.1: Energy Consumption Parameters for Metal-casting

Parameter	**Name**	**Units**
m	Mass of metal poured	kg
C_E	Specific energy	MJ/kg

Steelmaking requires high melting points of carbon-rich pig iron, chemicals, and oxygen and is made using various kinds of furnaces. Primary steel, for instance, can be made using either an open hearth furnace (OHF) or basic oxygen furnace (BOF), which are more common in steelmaking compared to other kinds of furnaces, e.g., cupola, induction, and reverberatory (Kwon, 2005), while secondary steel is made primarily using electric arc furnaces (EAF) (Price et al., 2002; Stubbles, 2000).

The OHF is the oldest process for making steels in the world and traces back to as early as the 8th century in Spain. By the dawn of the 19th century, the OHF became the main process for steelmaking in Europe and North America. The OHF is known for its high energy intensity (3.9–5.0 GJ/t), low productivity rate, and high capital cost (Price et al., 2002). Therefore, the OHF was replaced by the BOF in most countries, including the U.S., by the 1960s (Price et al., 2002). In the BOF, a combination of chemicals and scrap metals are used in the process of steelmaking. Typically, around 70-80% is molten iron plus other chemicals, while the remaining 20-30% is scrap metals (Turkdogan, 1996). The BOF utilizes an estimated total of about 20 MJ of energy and produces an equivalent of 0.47 kg of CO_2 for 1 kg of steel (Stubbles, 2000).

The EAF was introduced to developed countries during the 1960s to reduce the use of energy and capital spending (IISI, 2007a). The EAF is used to produce carbon and alloy steels from either a 100% scrap metals or a mixture of scrap metals and direct reduced iron (DRI) (WCA, 2012). The process of melting scrap metals using an EAF involves a combination of electrical energy and chemicals. The energy consumption for the production of 1 kg of steel is estimated to be about 11.5 MJ resulting in 0.29 kg of equivalent CO_2.

3.3.2. Injection Molding

The injection molding process is applied specifically to polymer materials to transform a solid polymer into its liquefied form which, in turn, is fed into shaped mold cavities. Specifically, the process starts with liquefying the polymer material, feeding it to a heated barrel, and applying high pressure rates to the material, typically ranging from 70 to 200 MPa, to inject it into the mold cavity (Kalpakjian, 2010). Figure 3.5 shows the stages in which injection molding process go through, i.e., clamping, molding, and injection.

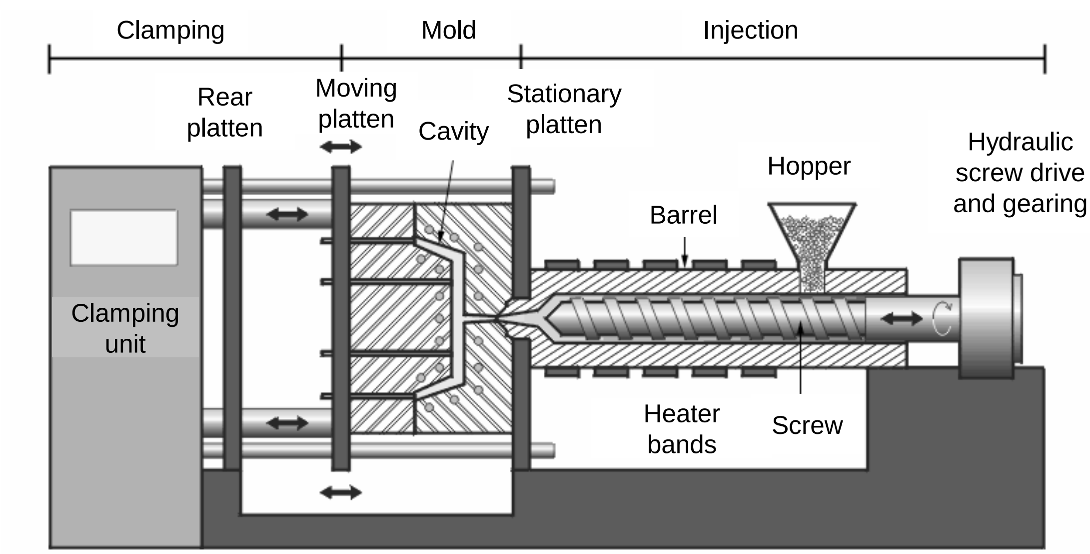


Figure 3.5: Illustration of Injection Molding Process (Plastic Injection Molding, 2002)

The energy consumption is calculated based on four different phases of the process, i.e., setup, filling, cooling, and resetting (Weissman et al., 2010). Due to the complexity of modeling and estimating the parameters of the energy consumption in injection molding, the model presented in this thesis is based on an experiment conducted by Weissman et al., (2010). Their approach includes determination of the mold volume and approximation of the machine's parameters as shown below in Equations (3.2 – 3.11). Injection molding model parameters are defined in Table 3.3.

In estimating the machine energy use, several processes parameters need to be obtained such as the clamping force, shot size, and stroke length as shown in Equation 3.2, 3.3, and 3.4, in addition to other information, such as maximum flow rate, Q_{max}, and power profile, which will be discussed in Section 3.4. Clamping force, F_{clamp}, is the amount of machine exertion during the injection process to keep the mold closed (Equation 3.2):

$$F_{clamp} = P_{max}A_{activity}$$

Equation 3.2: Injection Molding – Clamping Force

It can be seen that the clamping force is the product of the maximum cavity pressure, P_{max}, and projected area of mold cavity parallel to parting line, $A_{activity}$. The stroke lengh, L_{stroke}, is determined based on twice the maximum part depth, *D*, plus a constant ($C = 5$) as shown in Equation 3.3.

$$L_{stroke} = 2D + C$$

Equation 3.3: Injection Molding – Stroke Length

The volume of the cavity is equivalent to the sum of the part volume and the runner system in which the molten polymer is kept within the injection nozzle as described in Equation 3.4 assuming, n_{cavity}, is one for per unit production

$$V_{cavity} = n_{cavity}V_{part} + V_{runners}$$

Equation 3.4: Injection Molding – Volume of Cavity (Shot Size)

The filling, cooling, and resetting time is shown in Equations 3.5-3.7 as shown below:

$$t_{fill} = \frac{2V_{cavity}}{Q_{max}}$$

Equation 3.5: Injection Molding – Filling Time

$$t_{cool} = \frac{h_{max}^2}{\pi^2\alpha}\ln\left[\frac{4(T_i - T_m)}{\pi(T_x - T_m)}\right]$$

Equation 3.6: Injection Molding – Cooling Time

$$t_{reset} = 1 + \left(1.75 + \sqrt{\frac{L_{stroke}}{L_{stroke}^{max}}}\right)t_d$$

Equation 3.7: Injection Molding – Reset Time

The energy consumption during filling, cooling, and resetting is described in Equation 3.8, 3.10, and 3.11 respectively.

$$E_{fill} = \frac{P_{fill} \cdot t_{fill}}{n_{cavities}}$$

Equation 3.8: Injection Molding – Filling Energy

$$E_{cool} = \frac{P_{cool} \cdot t_{cool}}{n_{cavities}}$$

Equation 3.9: Injection Molding – Cooling Energy

$$E_{reset} = \frac{P_{reset} \cdot t_{reset}}{n_{cavities}}$$

Equation 3.10: Injection Molding – Resetting Energy

The power in the above equations can be based on a 5.5 kW machine (Weissman et al., 2010) as shown in Table 3.2:

Table 3.2: Power Values for a 5.5 kW Injection Molding Machine (Weissman et al., 2010)

Parameter	**Power (kW)**
P_{fill}	3.034
P_{cool}	1.411
P_{reset}	2.399

Table 3.3 summarizes the energy consumption parameters for injection molding process.

Table 3.3: Energy Consumption Parameters for Injection Molding

Parameter	**Name**	**Units**
V_{clamp}	Volume of cavity (shot size)	mm^3
P_{max}	Maximum cavity pressure	kN/mm^3
A_{cavity}	Projected area of mold cavity parallel to parting line	mm^2
L_{stroke}	Maximum required stroke length for machine	mm
D	Maximum part depth	mm
$n_{cavities}$	Number of mold cavities	
F_{clamp}	Clamping force	kN
h_{max}	Maximum wall thickness of part	mm
T_i	Polymer injection temperature	^0C
T_x	Recommended part ejection temperature	^0C
T_m	Recommended mold temperature	^0C
k	Thermal conductivity	
ρ_{resin}	Density of material	kg/mm^3
c_{resin}	Specific heat	J/g^0C
α	Thermal diffusivity of material	
V_{cavity}	cavity volume	mm^3
Q_{max}	Maximum flow rate of polymer from the nozzle	mm^3/s
$t_{(setup,\ fill,\ cool,\ reset)}$	Time during (Setup, fill, cool, and reset)	s
$P_{(setup,\ fill,\ cool,\ reset)}$	Power from (Setup, fill, cool, and reset)	kW
$E_{(setup,\ fill,\ cool,\ reset)}$	Energy from (Setup, fill, cool, and reset)	kJ

3.3.3. Metal – Forming Processes

Metal-forming is the process of changing the workpiece from one shape to another by using various kinds of processes, e.g., rolling, forging, extrusion, drawing, and sheet-metal forming. Forming is done once the part has gone through the casting process in which the stock material, e.g., plate, sheet, rod, or wire, is made. Below, a brief description of forging and bending processes is given. In addition, the energy models of forging and bending processes are also given.

3.3.3.1. Forging

Forging is a forming process that uses compressive forces on a heated workpiece using different types of dies, e.g., open-die and closed-die, to deform its geometric features. The major application of forging is the manufacturing of discrete parts, such as bolts, nuts, rivets, and steel balls (Kalpakjian, 2001). Figure 3.6 shows the process for an open-die forging. Applying compressive forces, the dimensional features changes from the initial work piece (left in figure) to the final desire shape (right in figure).

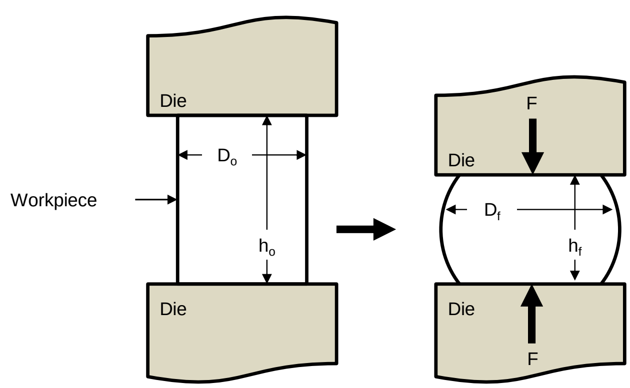


Figure 3.6: Basics of Open-die Forging (Kalpakjian, 2001)

The compressive force used in an open-die forging process is shown in Equation 3.11 (Kalpakjian, 2001).

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right)$$

Equation 3.11: Forging – Force

Flow stress, Y_f, can be obtained for various materials based on given curves of true strain, ε, versus true stress, σ_T, (Kalpakjian, 2001). The actual power can then be calculated for a given efficiency factor, f_{eff}, between 0 and 1 and a die speed, v_{die}, capable of achieving the required force as given in Equation 3.12.

$$P_{actual} = F v_{die}(1 + f_{eff})$$

Equation 3.12: Forging – Actual Power

The energy consumption can therefore be computed according to Equation 3.13 in which the die speed operates at, v_{die}, and the final workpiece height, h_f, are available.

$$E_c = \frac{P_{actual} h_f}{v_{die}}$$

Equation 3.13: Forging – Energy Consumption

Table 3.4 defines the open-die forging parameters and the units used in obtaining the energy consumption.

Table 3.4: Energy Consumption Parameters for Forging

Parameter	**Name**	**Units**
K	coefficient of friction	*MPa*
h_o and h_f	Initial and final rod height	*mm*
d_o	Initial rod diameter	*mm*
μ	Coefficient of friction	
r_o and r_f	Initial and final rod radius	*mm*
ε	True strain	
n	Strain-hardening exponent	
Y_f	Flow stress of the material	*MPa*
F	Forging Force	*MN*
v	Velocity	*mm/s*
f_{eff}	Efficiency factor	
P_{ideal}	**Ideal power**	***KW***
P_{actual}	**Actual power**	***KW***

3.3.3.2. Bending

Bending is a deformation process in which the workpiece is manipulated on the basis of a neutral axis at different bending angles according to the part's design specifications. Figure 3.7 illustrates the bending process for a sheet metal.

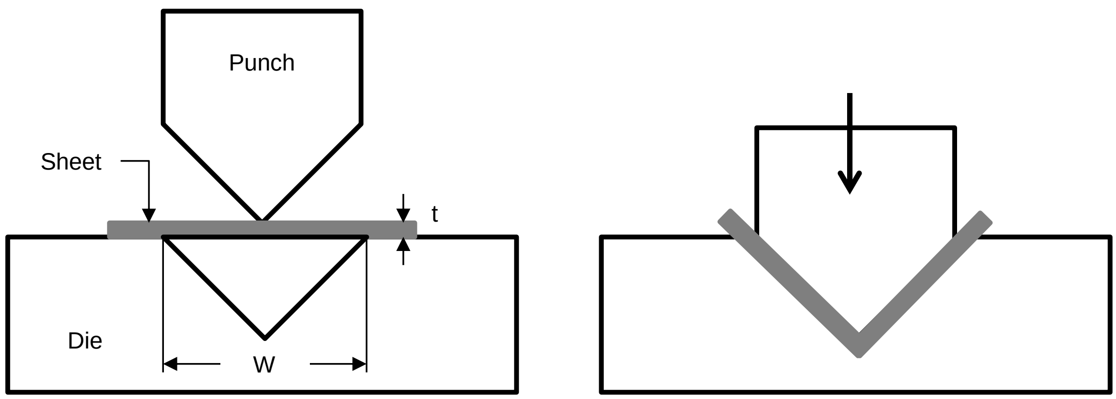


Figure 3.7: Illustration of Bending Process in a Sheet Metal (adapted from Lange, 1985)

Sheet metals are the most common materials that undergo bending. Forces are compressive to the inside of the metal's neutral plane, while tensile forces act outside of the neutral plane of the material as limited as their bend allowance. The bending force can be described in Equation 3.14 as follows (Lange, 1985):

$$F = \frac{Y \cdot t^2 \cdot L \cdot cos\left(\frac{a}{2}\right) \cdot \left(cos\left(\frac{a}{2}\right) + \mu \cdot sin\left(\frac{a}{2}\right)\right)}{W_d - \left(2 \cdot \sin\left(\frac{a}{2}\right) \cdot \left(\frac{R}{\sin\ (a)} + t\right)\right) + \mu \cdot t \cdot \cos\left(\frac{a}{2}\right)}$$

Equation 3.14: Bending – Force

The flow stress, Y, is a function of the punch radius, R, the workpiece thickness, t, and bend angle, a, as represented in Equation 3.15 (Lange, 1985).

$$Y = \frac{2 \cdot S}{\sqrt{3}\,(e+1)} \cdot \left(log \sqrt{1 + \frac{t.\sin\ (a)}{R}} \right)^{e}$$

Equation 3.15: Bending – Flow Stress

The energy consumption can be calculated by means of Simpson's 3/8 rule for numerical integration once the bending force and punch displacement are calculated for various bending angles. This can be performed using a spreadsheet program to obtain the area under the curve for corresponding bending forces at various punch displacements (See Appendix A). Table 3.4 summarizes the parameters typically used in computing the energy consumption of the bending process.

Table 3.5: Energy Consumption Parameters for Bending

Parameter	Name	Units
F	Force required to bend	*N*
t	Plate thickness	*mm*
L	Length of the plate	*mm*
a	Bend angle	*deg*
W_d	Die width	*mm*
R	Radius of punch	*mm*
µ	Coefficient of friction	
Y	Flow stress	*MPa*
S	Material strength coefficient	N/mm^2
ε	Strain hardening exponent	

3.3.4. Machining Processes

Material removal processes are categorized as machining processes. Such processes use a cutting technique to remove material from the workpiece to arrive at a desired shape. Examples of machining processes include turning, drilling, and milling. Various machining processes are often applied to the workpiece once it is cast and formed. These processes and the associated energy consumption will be discussed in further detail in the next subsections.

3.3.4.1. Turning

One of the most common and basic machining operations is turning. Turning involves rotating the workpiece to be cut against a single cutting edge moving parallel to the workpiece rotational axis. Turning processes can take on various forms, e.g., grooving, boring, drilling, knurling, reaming, and threading.

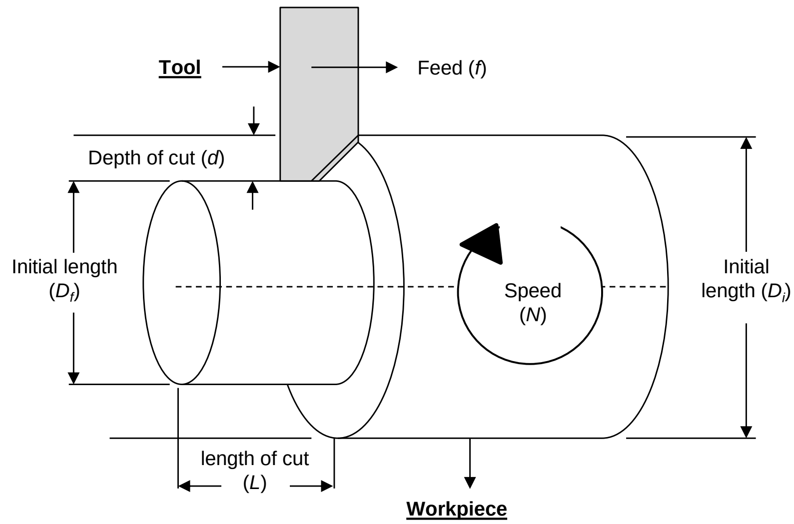


Figure 3.8: Schematics of Turning Operation Showing the Process Parameters (DeGarmo et al., 1988)

Equations 3.17 and 3.18 (Kalpakjian, 2001) gives the energy consumption for turning and drilling processes. Turning model parameters are defined in Table 3.7

$$E_c = 0.06 \cdot \pi \left(\frac{D_i^2 - D_f^2}{4} \right) L \cdot U$$

Equation 3.16: Turning – Energy Consumption

$$E_c = 0.06 \cdot \pi \frac{D_d^2}{4} . d. U$$

Equation 3.17: Drilling – Energy Consumption

Various materials require different tool types depending on hardness level. Table 3.6 reports the average unit power requirements at selected hardness levels for steels

Table 3.6: Average Unit Power Requirement[1,2] (Kalpakjian, 2001)

Rockwell scale	Hardness	Average Unit Power (kW/cm^3 per min.)	
		Sharp	**Dull**
HB	85-200	0.050	0.064
HRC	35-40	0.064	0.077
HRC	40-50	0.068	0.086
HRC	50-55	0.091	0.114
HRC	55-58	0.155	0.191

Table 3.5 gives a summary of the parameters for turning process energy modeling.

Table 3.7: Energy Consumption Model Parameters for Turning

Parameters	Name	Units
$E_{turning}$	Energy consumption	*kJ*
D_i	Initial diameter	*mm*
D_f	Final diameter	*mm*
d	Depth of cut	*mm*
L	Length of cut	*mm*
U	Unit power	*kW/cm^3 per min*

[1] For Steels, wrought and cast (plain carbon, alloy, and tool steels) in kw/cm^3 per min
[2] Power requirements at spindle drive motor, corrected for 80% spindle drive efficiency

3.3.4.2. Milling

Unlike turning processes, milling performs operations on a stationary workpiece while the cutting tool rotates to remove material. When the cutter is fed into the workpiece, the number of passes, p, needs to be computed for the cutting width, W, and cutter diameter, D_c, as shown in Equation 3.18.

$$p = \frac{W}{D_c}$$

Equation 3.18: Milling – Number of Tool Passes

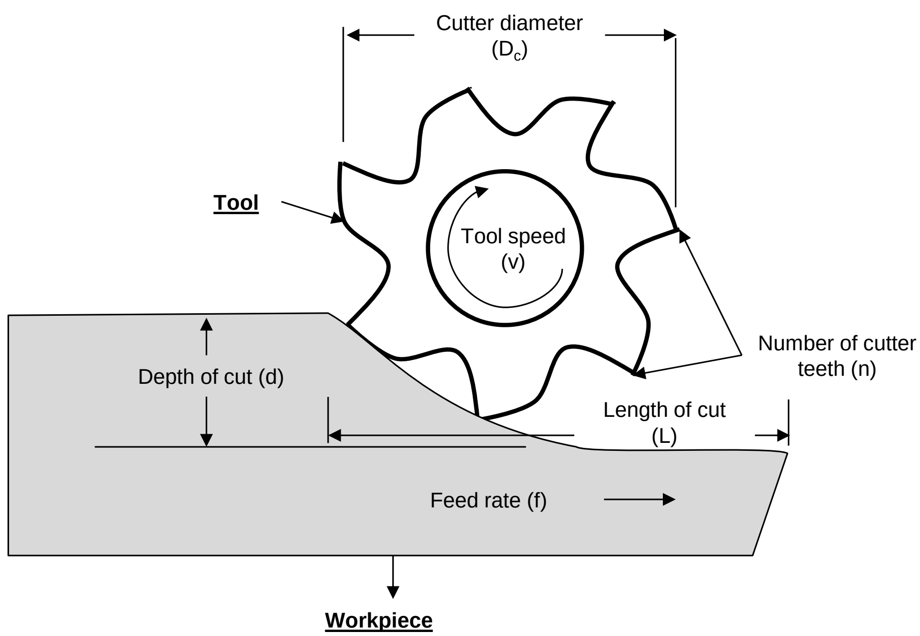


Figure 3.9: Milling Process Terminology Using a Slab Mill (DeGarmo et al., 1988)

The energy consumption model for milling is similar to the models of turning and drilling, but also considers the cutting depth, d, and the number of tool passes, p,

$$E_c = 0.06 \cdot D_c \cdot d \cdot p \cdot L \cdot U$$

Equation 3.19: Milling – Energy Consumption

A summary of the milling energy consumption model parameters are given in Table 3.8.

Table 3.8: Energy Consumption Parameters for Milling

Parameters	Name	Units
p	Number of tool passes	
W	Width of desired cut	*mm*
D_c	Cutter diameter	*mm*
$E_{milling}$	Energy consumption	*kJ*
d	Depth of cut	*mm*
L	Length of cut	*mm*
U	Unit power	

3.3.4.3. Laser Cutting

One of the most commonly used methods in plate cutting is laser cutting process. It provides narrow kerf width and high finish precision due to computerized control. one advantage of using laser cutting is the ability to process a variety of thickness and shapes. Another advantage is the ability to combine laser cutting with other processes like punching and shearing.

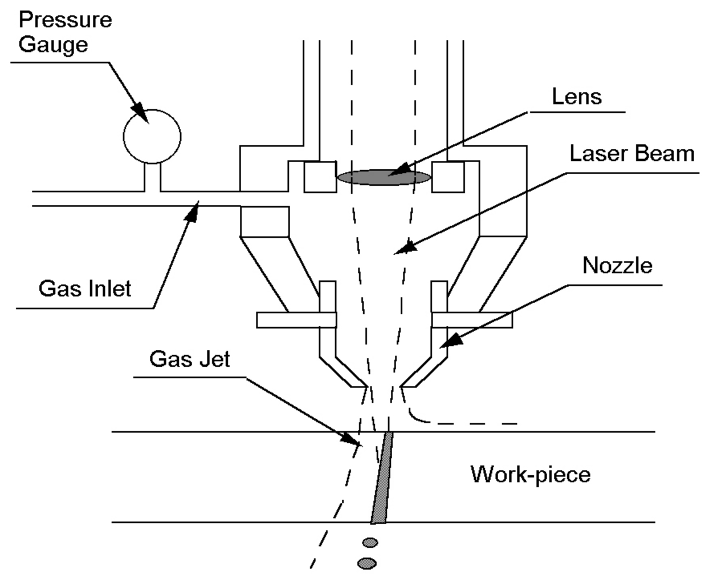


Figure 3.10: Gas Jet Laser Cutting (Chen et al., 2000)

$$z = \frac{2 \cdot \alpha \cdot P}{\rho \cdot v \cdot b \cdot \sqrt{\pi} \cdot (C_p \cdot (T_v - T) + L_f)}$$

Equation 3.20: Laser Cutting – Kerf Depth

$$E_c = \frac{P.X}{v}$$

Equation 3.21: Laser Cutting – Energy Consumption

Table 3.9: Energy Consumption Parameters for Laser Cutting

Parameters	**Name**	**Units**
z	Kerf depth	mm
α	Material absorptivity	
P	Laser power	W
ρ	Material density	kg/mm^3
v	Scanning velocity	mm/s
b	Laser beam diameter	mm
C_p	Specific heat capacity	J/kg-K
T_v	Material melting point	K
T	Ambient temperature	K
L_f	Material latent heat of fusion	kJ/kg^4
E_{laser}	Energy consumption	kJ
X	Length of cut	mm

3.3.4.4. Flame Cutting

Flame cutting is cutting operation especially suited for steel plate with large thickness and is used for heavy materials. To perform this kind of cutting, Oxygen and Acetylene are used to produce flame. Flame cutting is commonly used on low carbon steel.

$$E_c = \frac{G_c \cdot X \cdot C_v}{C_s} \cdot \frac{1000}{60}$$

Equation 3.22: Flame Cutting – Energy Consumption

Table 3.9 gives a summary of the parameters used in flame cutting energy consumption.

Table 3.10: Energy Consumption Parameters for Flame Cutting

Parameters	**Name**	**Units**
G_c	Gas consumption of acetylene	m^3/h
C_v	Calorific value of acetylene	kJ/m^3
C_s	Cutting Speed	mm/min
X	Length of cut	m
t	Plates Thickness	mm

3.4. Supply Chain Energy Models

Supply chains are becoming more complex and challenging to manage due to globalization. One pressing issue is the management of direct carbon dioxide emitted due to the combustion of transportation fuels. In this section, an approach to designing different supply chains is presented. The justification of selecting and locating suppliers, selecting transportation routes and modes is also described. The final destination of all the designed supply chains was chosen to be Irvine, CA, USA based on the location of the actual manufacturer of the representative product.

The environmental performance of the supply chain transportation is affected by several factors such as vehicle technology, e.g., conventional vehicles with internal combustion engines, fuel cell-powered vehicles, fully electric and hybrid electric vehicles, and compressed air cars; transportation network efficiency; and types of fuel.

For instance, diesel can result in greater carbon dioxide emissions than a 100% biodiesel from soy beans (Kutz, 2008), as shown in Table 3.11 for a bus.

Table 3.11: Life Cycle CO_2 Emissions by Fuel Type for a Bus (Kutz, 2008)

Fuel Type Bus Emission	**(kg CO_2/km)**
Gasoline	4.54
Petroleum Diesel	13.3
Compressed Natural Gas	11.7
B20 (20% Biodiesel/80% Diesel)	11.5
Ethanol from Corn	11.0
Hydrogen from Natural Gas	7.3
B100 (100% Biodiesel from Soy Beans)	3.7
Hydrogen from Electrolysis	1.3

The basis of locating suppliers is assumed to be dependent on the supplier's production volume of the required raw material. For instance, steel suppliers can be either from China, India, USA, or Luxembourg since these countries represent the highest production volumes of global steel production. Similarly, the selection of the links and routes are based on geographical location related to the final destinations. Therefore, the nodes, i.e., suppliers-suppliers, warehouses, and retailers, were chosen carefully and logically based on distance calculators developed by Google and NASA (Google, 2012; NASA, 2012) websites. Table 3.12 shows alternative supply chains scenarios for steel and aluminum components. Each supply chain in the table is assumed to cover the product cradle-to-gate life span. Thus, locations for material processing and manufacturing processing are shown along with the transportation modes utilized and relevant distances.

Table 3.12: Supply Chain Scenarios

Material	**SC**	**From**	**To**	**Route**	**Mode**	**Distance (km)**
Steel Alloys	1	Luxemburg, Luxemburg	Cardiff, Wales, UK	Land	Rail	691
		Cardiff, Wales, UK	Bridgeport, CT, USA	Sea	Deep-sea container	5297
		Bridgeport, CT, USA	Columbus, OH, USA	Land	Road	842
		Columbus, OH, USA	Irvine, CA, USA	Land	Road	3161
	2	New Delhi, India	London, UK	Sea	Deep-sea container	6724
		London, UK	New York, NY, USA	Sea	Barge	5587
		New York, NY, USA	Austin, TX, USA	Land	Road	2432
		Austin, TX, USA	Irvine, CA, USA	Land	Road	1928
	3	Pittsburg, PA, USA	Irvine, CA, USA	Land	Intermodal road/rail	3417
	4	Beijing, China	Shanghai, China	Land	Intermodal road/rail	1066
		Shanghai, China	Honolulu, HI, USA	Sea	Deep-sea container	7964
		Honolulu, HI, USA	San Francisco, CA, USA	Sea	Deep-sea container	3855
		San Francisco, CA, USA	Anaheim, CA, USA	Land	Road	651.2
		Anaheim, CA, USA	Irvine, CA, USA	Land	Road	27.2
Aluminum Alloys	1	New York, NY, USA	Pittsburg, PA, USA	Land	Road	508
		Pittsburg, PA, USA	Irvine, CA, USA	Land	Road	3417
	2	Montreal, Canada	Boston, MA, USA	Air	Airfreight	404
		Boston, MA, USA	Salt Lake City, UT, USA	Air	Airfreight	3376
		Salt Lake City, UT, USA	Riverside, CA, USA	Land	Rail	902
		Riverside, CA, USA	Irvine, CA, USA	Land	Road	49

The supply chain design will shape the manufacturing process flow based on suppliers' manufacturing process capabilities. For example, the production of a steel part may follow SC3a and undergo three related processes, e.g., casting, stamping, and milling. On the other hand, the same part can be manufactured through SC3B but, undergo a different set of processes, e.g., casting, laser cutting, and milling. It is assumed that the first node, i.e., the starting location of each supply chain, represents the location at which all material upstream processing occurs. By the same token, it is assumed that the *n-1* location represents the location for all remaining manufacturing processes for the part. Assembly of components will occur at location n. Thus, simultaneous consideration of supply chain design and manufacturing processes are accounted for the production of a product.

3.5. Carbon Footprint Estimation

The carbon equivalent emissions due to transportation from location j-1 to location j, $e_{t(j)}$, can be expressed as the product of the mass to be transported, m, the distance of the travel link, d_j, and the average emission factor of the utilized transportation mode, β_m, as expressed in Equation 3.23. Travel links are based on a starting point, j-1, and ending point, j, where $j=1, 2, \ldots, l$

$$e_{t(j)} = m \cdot d_j \cdot \beta_m$$

Equation 3.23: Emissions due to a Unit Transportation Process

Below is a table of the average emission factors, β_m, for various means of transportation.

Table 3.13: Recommend Average Emission Factors (McKinnon, 2003)

Transport mode	**Emission Factor gCO_2/tonne-km**
Road transport	62
Rail transport	22
Barge transport	31
Short sea	16
Intermodal road/rail	26
Intermodal road/barge	34
Intermodal road/short sea	21
Deep-sea container	8
Deep-sea tanker	5
Airfreight	602

Similarly, the carbon equivalent emissions due to manufacturing process i at location j, $e_{m(i,j)}$, is the product of the energy consumption, $E_{(i,j)}$, of the process and the energy to carbon footprint conversion factor, α, depending on the power profile of location j, as shown in Equation 3.24.

$$e_{m(i,j)} = E_{(i,j)}.\alpha$$

Equation 3.24: GHG Emissions due to a Manufacturing Process

The energy to carbon footprint conversion factor α can be obtained from, for example, the eGrid database developed by the U.S. EPA (US EPA, 2010) or the data reported by the U.S. EIA, which also include data from foreign countries (US EIA, 2010).

$$e_{total} = \sum_{j}^{m-1} e_{t(j)} + \sum_{i=1}^{n} e_{m(i,j)}$$

Equation 3.25: Total Emissions from Manufacturing and Transportation

3.6. Summary and Conclusions

This chapter presented an integrated approach to consider manufacturing processes and supply chain energy use and carbon footprint within a cradle-to-gate scope of the product life cycle. In particular, analytical models for various manufacturing unit processes were described. Similarly, supply chain models were developed to evaluate alternative designs. An approach for estimating carbon footprint on the basis of energy consumption was also described. In chapter 4, a case study for a bicycle pedal will demonstrate the use of the models developed in this chapter. The next chapter (Chapter 4) will present an application of the method developed in the current chapter.

CHAPTER IV – DEMONSTRATION OF THE FRAMEWORK

4.1. Chapter Overview

This chapter presents an application of the method developed in Chapter 3 using a bicycle pedal. Manufacturing process flows required for the manufacture of each sub-component of the pedal were identified and analyzed for energy use (Appendix A). Similarly, supply chain network designs alternatives were assessed (Appendix B). Results are discussed on the basis of environmental performance of process and supply chain planning in the design phase. In closing, summary and conclusions are provided.

4.2. Representative Product

The representative product demonstrated in this chapter is a bicycle pedal manufactured by Shimano Inc. (shown in Figure 4.1). The pedal is assembled from ten primary sub-components in which nine parts are assumed to be made of 1045 steel and one is made of aluminum. Figure 4.2 shows the disassembled product components with the corresponding identification numbers and names. The identification numbers of the components will be used throughout this section to indicate and refer to the different parts.

Supply chain scenarios for each of the ten components were constructed and analyzed using the procedure described in Chapter 3. Individual components analysis results are reported in Appendix A and Appendix B. The process is demonstrated in details for the body plate (components) in Section 3.4. Results for the overall pedal assembly are also reported and discussed.

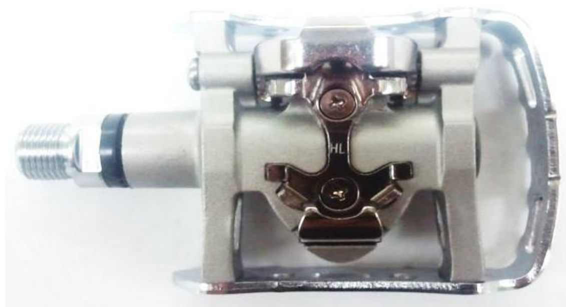


Figure 4.1: Bicycle Pedal

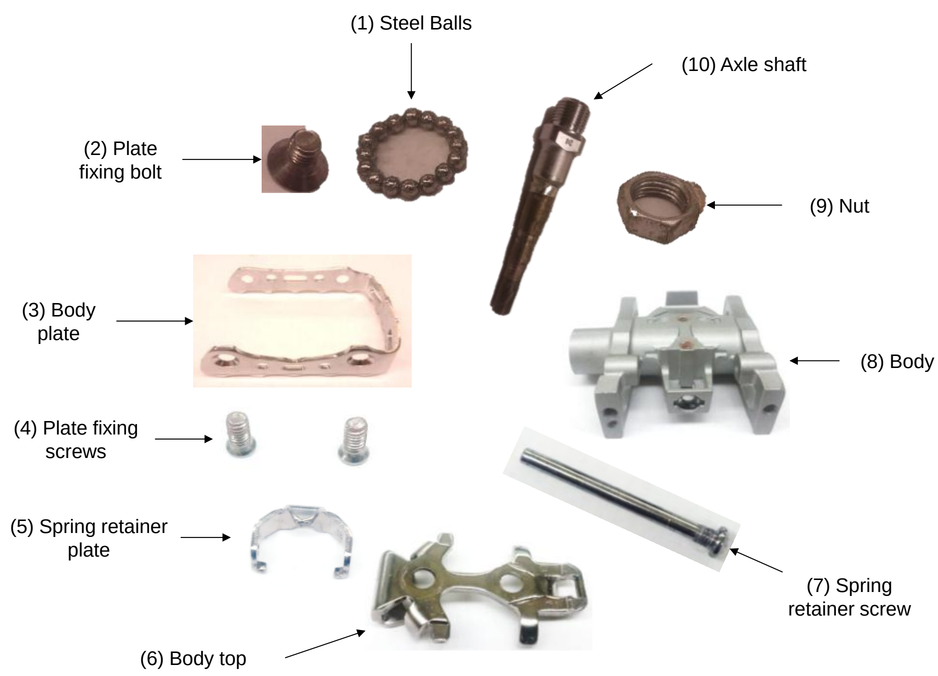


Figure 4.2: Disassembled Bicycle Pedal

The framework is composed of five steps. First, all possible supply chain networks are constructed based on potential suppliers. Information such as transportation mode to be used, distance to be traveled, mass to be transported, and related emission factors must be aggregated and made available in the design of the supply chain network. Second, manufacturing facility locations are identified within the supply chain. Third, manufacturing unit process analysis is conducted for a given product design to identify energy use. Fourth, compute the transport mass and distance for each mode. Fifth, the carbon footprint is computed from manufacturing activities and transportation operations. The method is next illustrated for the body plate (part 3) and results are then summarized for the pedal assembly.

4.3. Demonstration of the Framework

The choice of suppliers is assumed to be based on production capacity. For instance, steel suppliers may be chosen from Luxembourg, China, or the USA, since these countries account for the highest percentage of steel production in the world. While the supply chains were constructed fictitiously, (e.g., suppliers, transfer points, and facility locations) the reported data (e.g., travelling routes and distances) were synthesized from credible sources such as Google maps and the NASA distance calculator. The supply chains associated with the cradle-to-gate life cycle of the two pedal plate supply chain scenarios, SC3a and SC3b, are shown in Figure 4.3.

The body plate (Figure 4.3) is assumed to be constructed from 11 gauge (3mm) stainless steel sheet, and has a mass of 59.9 grams. The blank from which the part is formed is assumed to have a mass of 135 grams.

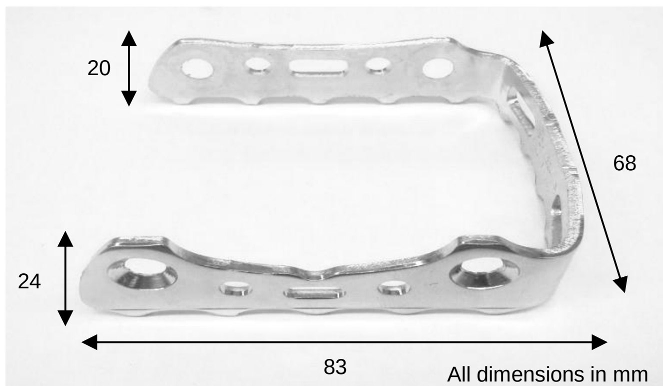


Figure 4.3: Bicycle Pedal Body Plate

The pedal body plate can be manufactured in a number of ways. Typically, it would undergo steelmaking, continuous casting, rolling, punching, bending, and machining processes. For convenience, two alternative manufacturing flows are presented in Table 4.1 that are associated with two supply chain network designs (SC3a and SC3b). SC3a is capable of producing the part in the following sequence: stock sheet production, laser cutting, bending, and chamfering, as shown in Figure 4.3(A), with Luxemburg being the steel sheet production location, assumed to utilize an electric arc furnace mini-mill, and Columbus, OH being the component manufacturing facility. On the other hand, SC3b imposes a different manufacturing process flow (stock sheet production, stamping, bending, and chamfering) due to supply chain capabilities, as shown in Figure 4.3(B). Bejing, China is the production location for the steel plate, assumed to use a basic oxygen furnace integrated mill. Component production will occur in Anaheim, CA. Other locations indicate material/part transfer points in the supply chain. Final destination is identified to be Irvine, CA, where the assembly of the product occurs.

Table 4.1 provides data and information about the supply chain locations, transportation modes utilized, and corresponding distances used in the analysis. The basis of the analysis is one pedal body plate. The carbon footprint due to transportation can be calculated using Equation 3.23, where the volume to be reported from Luxembourg, Luxembourg to Columbus, Ohio is the blank mass from which the actual product is made (135 grams). The transportation mass from Columbus, Ohio to Irvine, California then changes to the final mass of the product (59.9 grams), since it has undergone all forming/machining processes. The distances between all locations and related transportation modes are reported in Table 4.1. The GHG emission factors are obtained from Table 3.12 based on transportation mode utilized. The carbon footprint due to manufacturing processes was calculated using Equation 3.24 once the energy consumption was computed for each manufacturing unit process adopted in the product manufacturing sequence. The energy use in the upstream process captures the total energy from material extraction, transportation, and associated services in the making of the material.

Table 4.1: Supply Chain Scenarios for Production of the Pedal Body Plate (Part 3)

SC	Transportation					Manufacturing		
	From	**To**	**Mode**	**Distance (km)**	**CO_2 eq. (g)**	**Multiplier**	**Emission Factor**	**CO_2 eq. (g)**
3a	Luxemburg, Luxemburg	Cardiff, Wales, UK	Rail	691	2.05	134.8 g	0.29 g/g	39.09
	Cardiff, Wales, UK	Bridgeport, CT, USA	Deep-sea container	5297	5.71	-	-	-
	Bridgeport, CT, USA	Columbus, OH, USA	Road	842	7.04	-	-	-
	Columbus, OH, USA	Irvine, CA, USA	Road	3161	11.74	43.835 kJ	0.400 g/kJ	18.89
3b	Beijing, China	Shanghai, China	Intermodal road/rail	1066	3.74	134.8 kg	0.47 g/g	63.36
	Shanghai, China	Honolulu, HI, USA	Deep-sea container	7964	8.59	-	-	-
	Honolulu, HI, USA	San Francisco, CA, USA	Deep-sea container	3855	4.16	-	-	-
	San Francisco, CA, USA	Anaheim, CA,USA	Road	651.2	5.44	-	-	-
	Anaheim, CA,USA	Irvine, CA, USA	Road	27.2	0.10	14.671 kJ	0.238 g/kJ	3.50

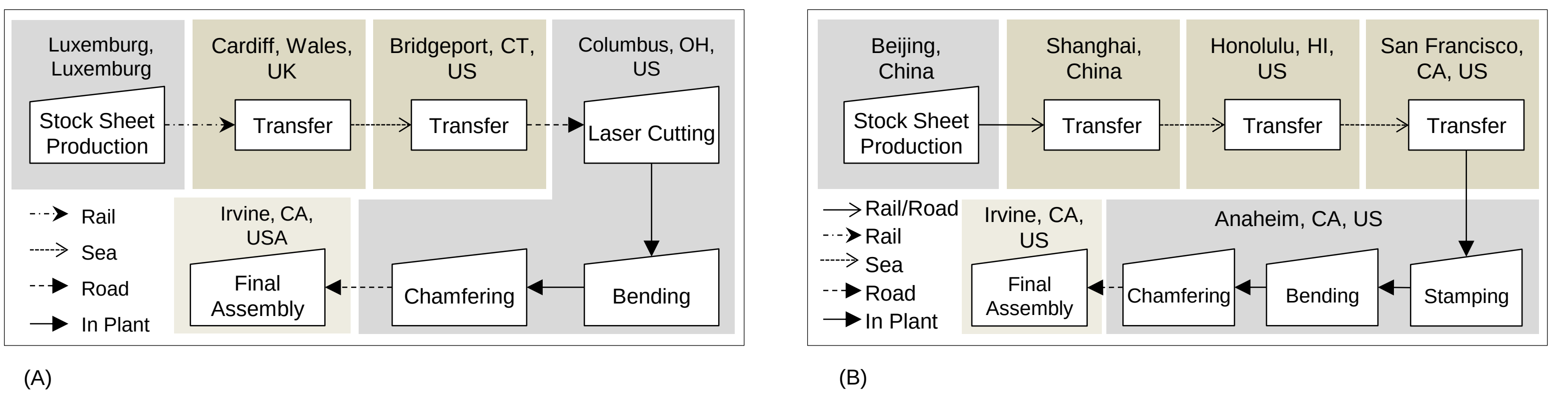


Figure 4.4: Supply Chain Alternatives (A) SC3a and (B) SC3b for Pedal Body Plate Production

All unit processes require knowledge about the part's details, e.g., dimensional characteristics and material type as well as machine details that compatible to operate based on the given part's demands. All these information are reported in Appendix A (refer to Table A.3a and Table A.3b). The energy use is then converted to carbon dioxide equivalent based on emissions factors reported in (Table B.1) (U.S. EPA 2007). The results are summarized in Figures 4.5 and 4.6 for pedal body plate production supply chain alternatives SC3a and SC3b, respectively.

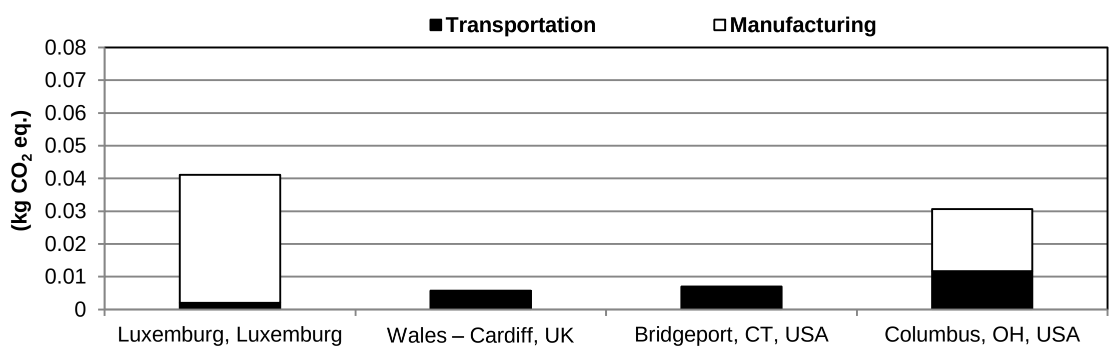


Figure 4.5: Carbon Footprint of Supply Chain Alternative 1 (SC3a)

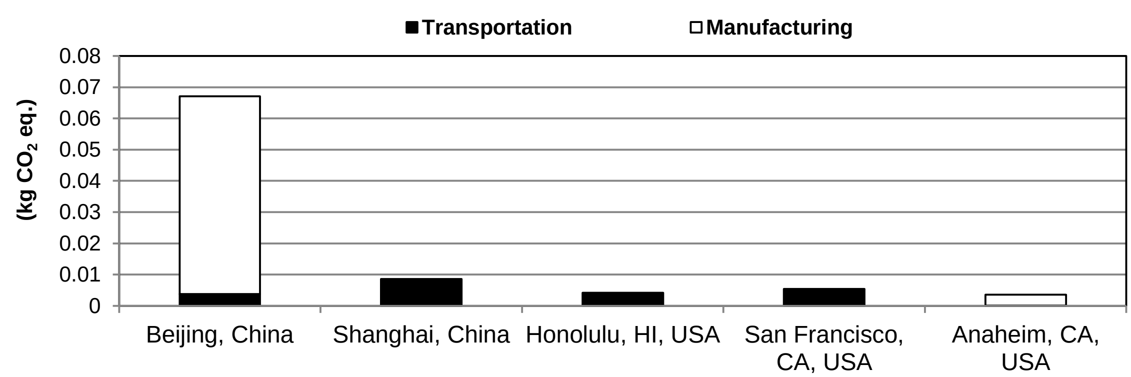


Figure 4.6: Carbon Footprint of Supply Chain Alternative 2 (SC3b)

It is clear from the figures above that the manufacturing processes are dominating the majority of carbon dioxide equivalent emission especially at the steel production location for the peal body plate. Further investigation of the results shown in the above figures is conducted next.

4.3.1. Supply Chain Network Design Analyses

Analyses pertaining to supply chain network design are performed in this section. Figures 4.7 and 4.8 show the cumulative distances, transportation modes, and carbon footprint for alternatives SC3a and SC3b. In SC3a, the total distance is 9991 km in which around 53% is via sea using a deep-sea container. It is apparent from the chart that the resultant CO_2 in the mentioned travel link, i.e., from Cardiff, Wales, UK to Bridgeport, CT, USA, is lower than other transportation modes relevant to the traveled distance. In fact, the total CO_2 generated using the deep-sea container accounts for one fifth of the total CO_2.

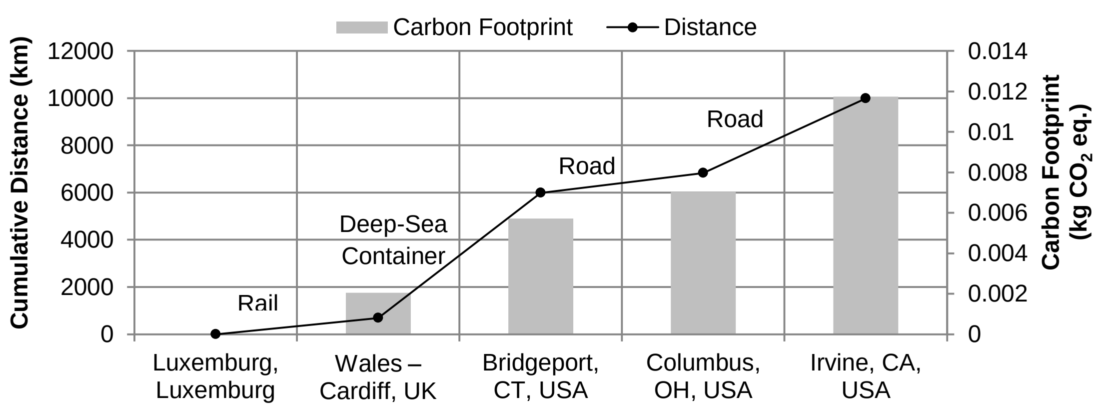


Figure 4.7: Transportation Distance and Resultant Carbon Footprint for alternative SC3a

In comparison, SC3b requires a total distance of 13563 km traveled, yet its total CO_2 is lower than that for SC3a due to a dependence on sea transportation, in particular, the utilization of deep-sea container, which generates 8 g CO_2/tonne-km as indicated by Table 3.12.

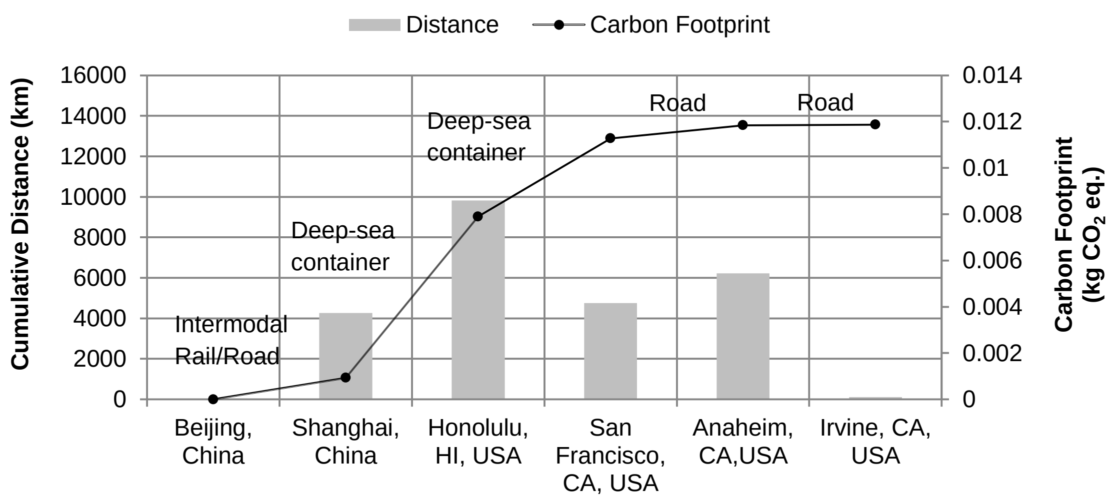


Figure 4.8: Transport Distance and Resultant Carbon Footprint for alternative SC3b

A breakdown of the distances and CO_2 contributions to the total distance and carbon footprint, respectively, are presented in Table 4.2.

Table 4.2: Distance and Carbon Footprint Contributions by Transportation Mode for Supply Chain Alternatives SC3a and SC3b

Transportation Mode	**SC3a**		**SC3b**	
	Distance (%)	**CO_2 (%)**	**Distance (%)**	**CO_2 (%)**
Rail	6.92	7.72	-	-
Deep-Sea Container	53.02	21.52	87.14	57.87
Road	40.07	70.75	5.00	25.17
Rail/Road	-	-	7.86	16.96

Figure 4.6 shows that road transportation is dominating the amount of carbon dioxide equivalent emissions with about 71% of the total emissions. Thus, these transportation routes could be identified as impactful to the supply chain carbon footprint outcome. Prior knowledge of the nature of the routes would be necessary in identifying alternative transportation modes such as rail or intermodal rail/road transportation, which can alleviate the production of carbon dioxide equivalent emissions.

Although SC3b involves about 36% more travel distance compared to SC3a, it is interesting to note that it emits less carbon dioxide equivalent emissions than SC3a due to dependence on sea transport by deep-sea container, which accounts for about 87% of the total distance traveled.

Similar to SC3a, road travel is again identified as the most impactful transportation mode in SC3b with around 25% of the carbon dioxide equivalent emissions resulting from traveling 5% of the total distance. Hence, transportation planning could be exploited to replace impactful transportation modes and subsequently, enhance the environmental performance of the supply chain. The observations noted in this section will become particularly useful when considered in conjunction with the manufacturing process environmental performance as will be seen in the upcoming sections.

4.3.2. Manufacturing Processes Analyses

Figure 4.9 shows the resultant carbon footprint from manufacturing activities associated with SC3a and SC3b. Black bars shows the carbon footprint from upstream processes, while grey bars show the total carbon footprint from forming and machining processes. As discussed before, upstream processes are affected directly by the type of furnace used and the location power profile. It is not a surprise that the upstream processes in SC3a perform better in terms of CO_2 emission than that in SC3b. The reason is due to the employment of EAF in Luxembourg which as discussed in Chapter 3 has lower carbon footprint as compared to BOF which is assumed to be utilized in SC3b. While the upstream carbon footprint in SC3a is one third lower than that in SC3b, forming and machining process carbon footprint in SC3a is five times greater than that for SC3b. Further investigation of individual process is imperative in identifying and eliminating impactful processes.

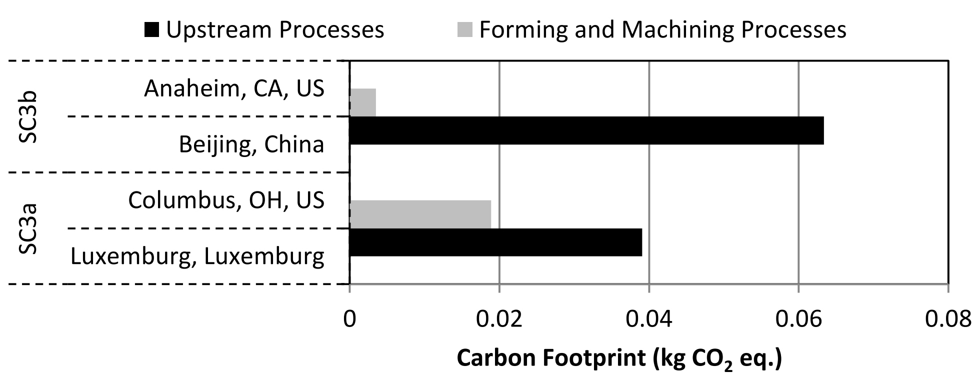


Figure 4.9: Resultant Carbon Footprint from Manufacturing Processes for Supply Chain Alternatives SC3a and SC3b

Figures 4.10 and 4.11 show the energy consumption and related carbon footprint for each manufacturing unit process within the forming and machining categories for alternatives SC3a and SC3b, respectively. From the figures, there are two main observations regarding the amount of carbon dioxide equivalent emissions released from each process flow. First, while chamfering and bending are common processes between the two process flows and they consume the same energy in each scenario, their carbon footprints differ due to the power profile of each location. The second observation is regarding the alternative cutting processes used in each sequence, i.e., laser cutting and stamping, as shown in Figure 4.10 and 4.11. Laser cutting consumes around 70 kJ in contrast to stamping which consumes around 40 kJ. Thus, laser cutting accounts for about 1.75 times the energy required using stamping. Hence, it is identified as an impactful process prior to the conversion to carbon dioxide equivalent.

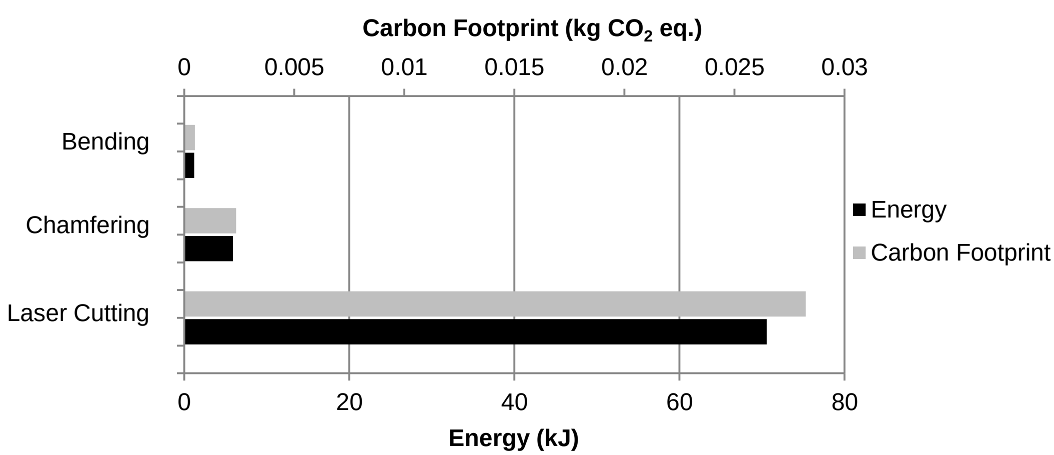


Figure 4.10: Process Energy Use and Carbon Footprint in Columbus, OH, USA for SC3a

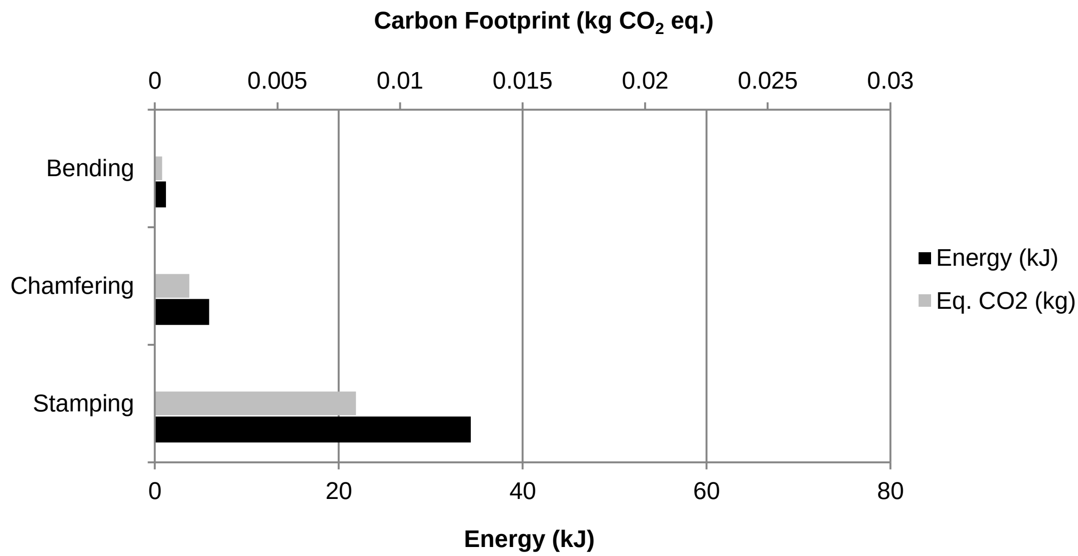
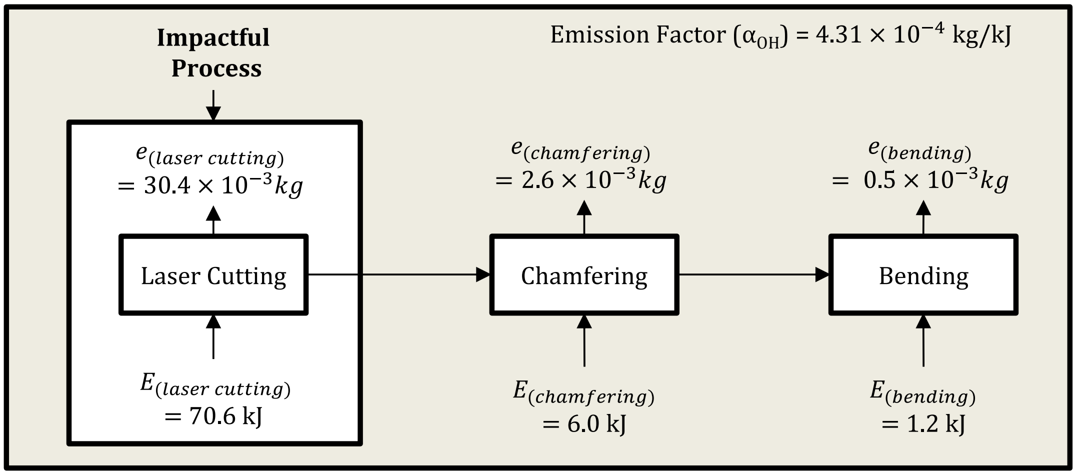
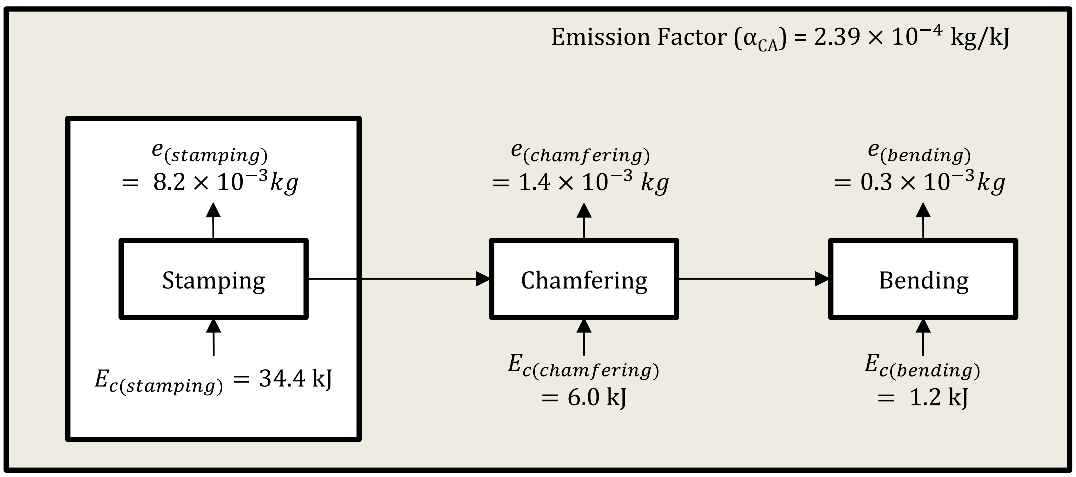


Figure 4.11: Process Energy Use and Carbon Footprint in Anaheim, CA, USA for SC3b

Figure 4.12 illustrates in more detail the process sequence associated with each supply chain. It can be seen that while the required energy amount of carbon footprint during the forming and machining processes in SC3a is greater than SC3b. The carbon dioxide emission factor in Ohio, USA, coal dependent for its energy generation, is 0.43×10^{-3} kg/kJ compared to 0.24×10^{-3} kg/kJ in California, USA which is natural gas dependent for its energy generation. Further investigation on processes utilized at each location is explored in Figure 4.12 (A) and (B). Since stamping consumes less energy than laser cutting, it could be a potential alternative to laser-cutting despite the higher impact associated with the power profile of Ohio.



(A)



(B)

Figure 4.12: Manufacturing Process Energy and Carbon Footprint in (A) Ohio, USA (SC3a) and (B) California, USA (SC3b)

The overall results for both alternatives are compared in Figure 4.13. The overall impact of SC3b is greater primarily due to the upstream process which took place in

China with employment of BOF. It can be seen that that production impact in terms of carbon footprint greatly surpasses that of transportation.

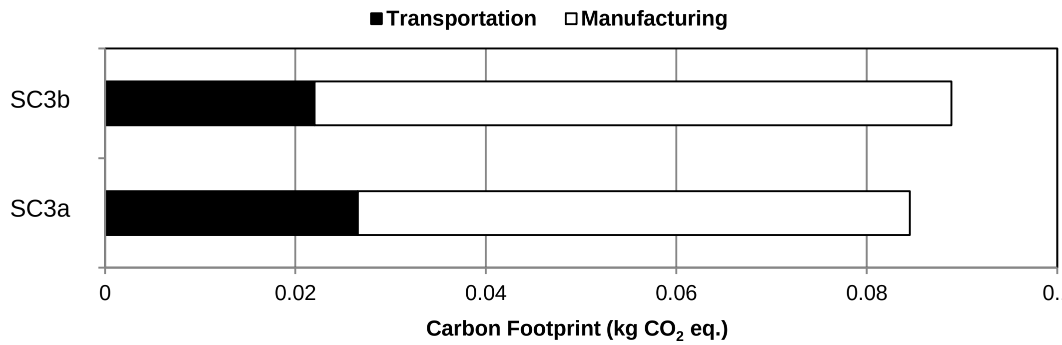


Figure 4.13: Carbon Footprint for Supply Chain Alternatives (SC3a) and (SC3b)

Summary of the results for SC3a and SC3b are reported in Table 4.3. All impactful factors are boldfaced for the two supply chain alternatives.

Table 4.3: SC3a and SC3b Results Summary

Entity Description	**SC3a**	**SC3b**
Total carbon footprint from manufacturing and transportation (kg)	8.44×10^{-2}	$\mathbf{8.89 \times 10^{-2}}$
Upstream carbon footprint (kg)	3.91×10^{-2}	$\mathbf{6.34 \times 10^{-2}}$
Carbon footprint from forming/machining (kg)	$\mathbf{1.89 \times 10^{-2}}$	0.35×10^{-2}
Total carbon footprint from manufacturing (kg)	5.80×10^{-2}	$\mathbf{6.69 \times 10^{-2}}$
Total travelling distance (km)	9991	13563
Carbon footprint from sea travel (kg)	5.71×10^{-3}	$\mathbf{12.75 \times 10^{-3}}$
Carbon footprint from rail travel (kg)	2.05×10^{-3}	0
Carbon footprint from road travel (kg)	$\mathbf{18.78 \times 10^{-3}}$	5.54×10^{-3}
Carbon footprint from rail/road travel (kg)	0	3.74×10^{-3}
Total carbon footprint from transportation (kg)	$\mathbf{2.64 \times 10^{-2}}$	2.20×10^{-2}
Upstream location emission factor (kg/kg)	0.29	**0.47**

Table 4.3: SC3a and SC3b Results Summary

Entity Description	SC3a	SC3b
Forming/machining emission factor (kg/kJ)	**0.400×10^{-3}**	0.238×10^{-3}
Furnace type	EAF	BOF
Forming/machining location power profile	**Coal-based**	Natural Gas-based

Figure 4.14 shows the carbon footprint of the transportation and manufacturing activities for the whole pedal assembly. It is clear that the manufacturing activities dominate the production of carbon dioxide equivalent in most components. However, when transportation involves airfreight transport, transportation activities then become the most impactful activities.

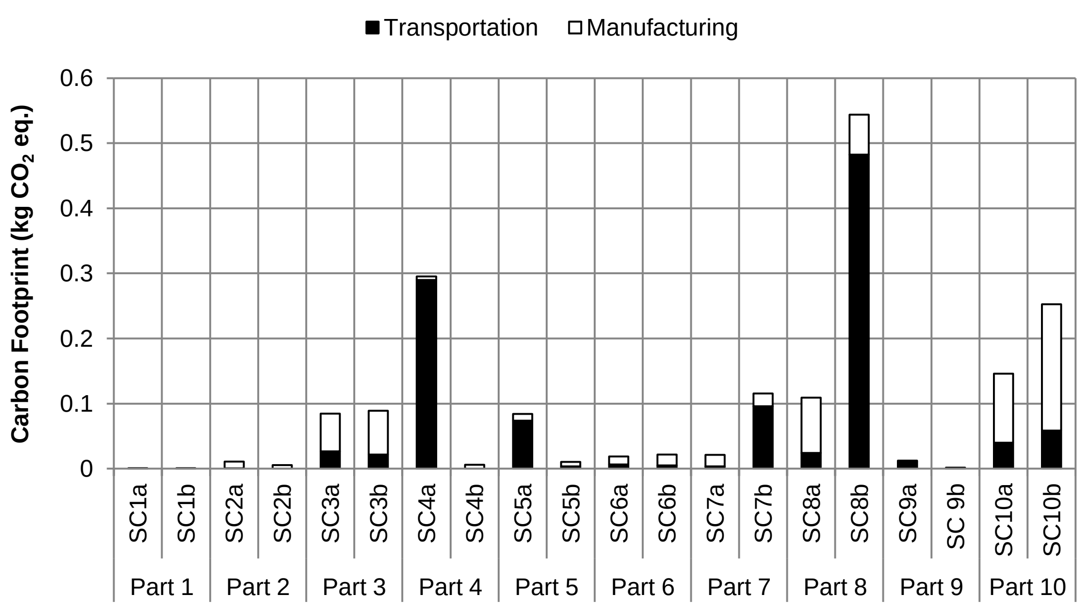


Figure 4.14: Carbon Footprint for Alternative Supply Chain Scenarios for Each Pedal Component

Figure 4.16 shows the best and worst alternative for each component. It is clear that in some cases, the impact of the worst alternative is greater than best alternative, e.g., Part 4, 5, 7, and 8. Thus, the method can greatly identify the most impactful processes and alleviate the production of carbon dioxide equivalent.

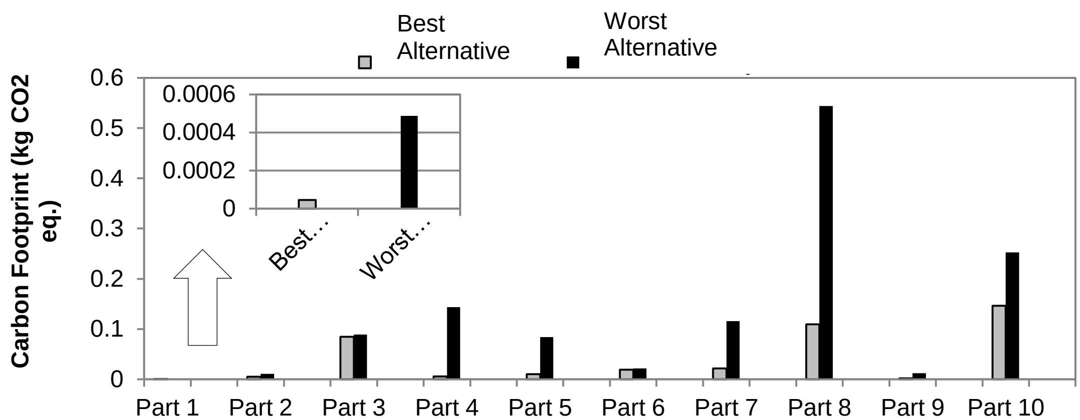


Figure 4.15: Best and Worst Alternatives of the Pedal Components

Finally, Figure 4.16 shows the overall performance in terms of carbon footprint for the complete assembly of the pedal. Again, it is clear that the worst assembly is greater than three times of that in the best assembly.

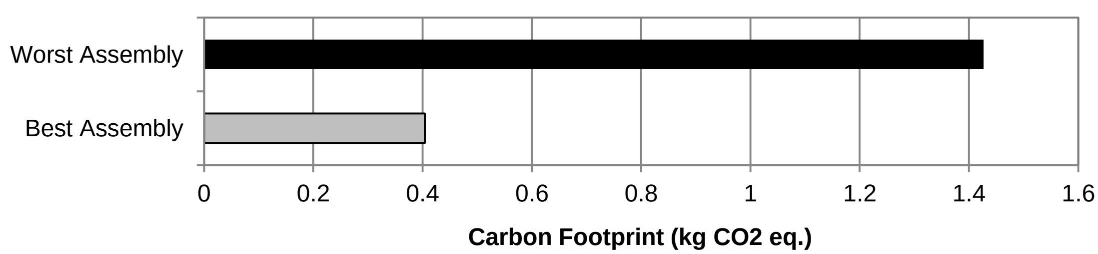


Figure 4.16: Overall Performance of the Whole Assembly

The analyses conducted in this chapter showed that the simultaneous consideration of manufacturing and transportation activities can impact the product environmental performance at the design development stage.

4.4. Summary and Conclusions

An application of the method described in Chapter 3 was presented herein to demonstrate the potential of the method in minimizing carbon footprint through the integration of the manufacturing process design and supply chain processes. The representative product used for the application is a bicycle pedal. The approach was demonstrated for the production of a bicycle pedal body plate (part 3), and applied to all of the pedal components, which revealed several interesting conclusions. First, for the part investigated, manufacturing process energy and carbon footprint appear to generally dominate transportation impacts. Second, material processing appears to have a greater impact on overall impacts than either part production or transportation. Lastly, it was found to be critical that cradle-to-gate manufacturing and supply chain effects are considered when making a decision on the basis of the energy use and carbon footprint. While SC3a resulted in more than five times the forming/machining manufacturing impacts than SC3b, it exhibited a reduction of about 60% in material processing impacts. Thus, SC3b had an overall carbon footprint estimated to be only 5% larger than SC3a which is within the margin of error for typical life cycle studies. Further analyses on supply chain transportation and manufacturing planning were also conducted. For supply chain networks, road travel dominated the supply chain carbon footprint despite the relatively shorter distance traveled compared to sea transport. The use of rail or intermodal rail/road can reduce the emissions of carbon dioxide equivalent by 65% and 58% respectively, which can yield to new conclusions, and, subsequently, new decisions.

For manufacturing analyses, observations regarding the effect of the location's power profile, i.e., emission factors, as well as planning of the manufacturing unit processes were made. Ohio, which is coal-based electricity generation, produces about 40% more of carbon dioxide equivalent per unit of energy compared to California, which relies primarily on natural gas in securing most of its electrical energy with regard to manufacturing unit processes; laser cutting associated with SC3a consumed twice the energy used by stamping associated with SC3b. As a result, even though carbon dioxide equivalent from Ohio is greater than that of California, the overall impact would be reduced in the case of utilizing stamping by capable facility in Ohio.

By iterating for the remaining components of the pedal, the overall environmental performance was shown to be enhanced in terms of energy consumption and carbon dioxide equivalent. This demonstration of the method motivates the need for continued development of such approaches to assist in more robust sustainable design and manufacturing decision making.

CHAPTER V – SUMMARY AND CONCLUSIONS

5.1. Chapter Overview

This chapter summarizes the content of this thesis and concludes all findings and results attained by this research. Highlights on limitations and recommended future work are presented. Broader impacts of this research are briefly described and discussed.

5.2. Summary of the Thesis

Environmental performance of human activities is correlated with how much energy is consumed and how it is generated. Increases of population, quality of life, and affluence have yielded a significant increase in energy consumption. While energy can be generated in a number of ways, including use of renewable resources, the primary resources for generating the majority of needed energy come from non-renewable resources, i.e., fossil fuels, which are accompanied by a number of environmental impacts that are endangering the current generation, and threating the well-being of future generations. GHG emissions represent one challenge and are reported to be a primary contributor to climate change. In 1962, Rachael Carson argued about the environmental impacts resulting from human activities in her book, *Silent Spring*, which attracted the attention of decision-makers, legislators, and the public. In 1970, EPA was created to regulate, monitor, and restrict the environment impacts resulting from human activities.

Transportation and industrial sectors rank second and third, respectively, to the electricity generation sector in terms of GHG emissions in the United States. Manufacturers have started to incorporate and adopt sustainability principles and practices in their activities in an effort to alleviate the environmental impacts and comply with government policies. Although efforts continue to understand the environmental impacts due to human activities and to propose methods and frameworks to enhance the environmental sustainability of products, processes, and systems, much of the focus is often placed on a single phase of the product life cycle. Hence, little research has been made to accurately predict impacts through simultaneous consideration of multiple stages of the product life cycle.

The research problem explored in this thesis intends to better understand the potential impact of energy consumption and associated carbon footprint on the environment through simultaneous consideration of manufacturing processes and supply chain network design from a cradle-to-gate life cycle perspective. Therefore, several objectives have been identified to address to address the problem described in Chapter 1 (Section 1.3). First, a comprehensive review composed largely of recent research literature has been reported to identify current research needs and support the novelty of this work. Second, development of parametric models to compute the energy consumption in manufacturing processes and supply chain network design, as well as the associated carbon footprint has been undertaken.

Synthesis of literature related to sustainable manufacturing and supply chain related research has been reported from the 1990s through 2011. It was concluded that most prior work on sustainable manufacturing research was either theoretically driven or centered on a particular process. Manufacturing process planning has also been identified to be an area that is under evaluated. Similarly, supply chain research lacks network design planning. Furthermore, several studies concluded current research is deficient in linking energy use and GHG emissions impacts during supply chain operations.

To reduce the environmental impacts of products, processes, and systems at the design stage, several approaches, methods, and tools have been developed. Current widely used methods include environmentally benign manufacturing (EBM), design for environment (DfM), and life cycle assessment (LCA).

Prior work was identified to have several shortcomings including: 1) Time intensity in collecting data, 2) Errors involved with collecting data, 3) Inaccuracy in defining the study goal and scope, 4) Variability of process model parameters, 5) Uncertainty of chemical and materials properties, and 6) Incomprehensive inventory databases. In addition, concurrent consideration of multiple stages of the product life cycle in the context of environmental performance is needed.

To address the limitations mentioned above, a process-based modeling approach has been utilized that considers manufacturing unit process and supply chain network models. The approach used carbon footprint as the environmental measure based on analytical models of energy consumption. For manufacturing processes, ten different parametric manufacturing process models were implemented in an Excel spreadsheet tool including metal casting, injection molding, open-die forging, turning, milling, laser cutting, and flame cutting. For the supply chain network design, routes, transportation modes, and mass to be transported were the factors considered in the models, also housed in the spreadsheet tool.

5.3. Conclusions from this Research

The conclusions identified by this research:

- **Conclusion #1:** Simultaneous consideration of manufacturing processes and supply chain network designs provide the opportunity to achieve better environmental performance for a given product, and can yield to better understanding of the environmental impacts generated by the manufacturing processes and supply chain activities at the design stage.
- **Conclusion #2:** The manufacturing upstream processes are often the most impactful in the cradle-to-gate life cycle of the product as demonstrated for the

pedal body plate and the other pedal components. Thus, it is imperative to utilize upstream processes that are not energy and carbon intensive, e.g., the EAF as opposed to the BOF. Wherever airfreight is employed, transportation becomes more impactful compared to manufacturing activities.

- **Conclusion #3:** Process planning can be conducted in a synchronized manner with supply chain design to replace impactful processes identified within the supply chains and manufacturing activities in pursuit of enhancing the overall environmental performance of the product.
- **Conclusion #4:** Global supply chains can utilize sea transport for the greatest possible reduction of carbon dioxide equivalent emission as compared to airfreight transportation. Local transportation is better utilized by either rail or intermodal rail/road travels which, can reduce the carbon dioxide equivalent emissions by 58% - 65%.

The review and future vision provided furnish a starting point for identifying future research needs and direction. The demonstrated application of the framework presented motivates researchers to continue to strive to meet the challenges of trade-off analysis when assessing competing objectives simultaneously with uncertain data and value-laden comparisons as in the case of design for environmentally sustainable manufacturing processes and supply chains.

5.4. Opportunities for Future Work

The opportunities for future improvements based on this research include:

- **Opportunity #1:** Additional phases of the product life cycle can be considered and interpreted on the basis of environmental performance, e.g. use phase, disposal, remanufacturing, and recycling.
- **Opportunity #2:** While energy consumption and associated GHG emissions are widely used as environmental indicators within the manufacturing sector, they do not represent a thorough consideration of the environmental performance. Consideration of other impacts such as solid wastes, water consumption, and material use can strengthen the conclusions made in this thesis as well as support the decision-making standards.
- **Opportunity #3:** Since social and economic measures are of great importance in sustainable manufacturing decision-making, other metrics should be identified, understood, and implemented into the framework. For example, shipping cost consideration of manufacturing and shipping costs can add new dimension in the process of decision-making.

5.5. Broader Impacts of this Work

The recommendations based on this research:

- **Impact #1:** The work presented in this thesis called for simultaneous consideration of manufacturing process and supply chain network designs in pursuit of understanding and reducing the environmental impacts from a cradle-to-gate life cycle perspective. In a broader sense, the demonstrated application of the framework motivates researchers to continue to strive to meet the challenges of trade-off analysis when assessing competing objectives simultaneously with uncertain data and value-laden comparisons as in the case of the design of environmentally sustainable manufacturing processes and supply chains.

- **Impact #2:** Product environmental sustainability reflects on its economic competency and value. The environmental performance can be translated and interpreted in the basis of dollar value as reported by research and targeted by manufacturers and decision-makers.

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APPENDICES

Appendix A

This appendix presents the manufacturing sequence for each component in the bicycle pedal components. The first column represents the manufacturing unit processes adopted. The second column gives a description of the operation parameter. The third column gives the symbol of the corresponding parameter. The fourth column provides relevant values to the given parameters and finally, the fifth column shows the units of the parameter.

Table A.1: Part 1 – Steel Ball

Operation	Process Parameter	Symbol	Value	Units
Stock Bar Production	Length of bounded volume	*l*	2.8	mm
	Diameter of bounded volume	*d*	2.4	mm
	Thickness	*t*	0	mm
	Void volume within bound volume		0	mm^3
	Material density	*d*	7.83×10^{-6}	kg/mm^3
	Mass of stock	*m*	9.92×10^{-5}	kg
	Specific energy required		11500	
	Energy consumption	E_C	**1.14**	**kJ**
Laser Cutting	Perimeter of the cut	*L*	7.54	mm
	Thickness of plates	*t*	2.4	mm
	Material constant	*K*	5000	$W/ cm^2/ s$
	Type of process		LASER	
	Weld spot diameter	*D*	0.5	mm
	Heat source density	*d*	10×10^6	W/ cm^2
	Minimum interaction time	t_{inter}	250×10^9	s
	Welding speed	*v*	2000000	mm/s
	Total operation time	t_{total}	3.77×10^{-6}	s
	Power consumption	*P*	1809.56	kW
	Energy consumption	$\boldsymbol{E_{laser}}$	$\mathbf{6.82\times10^{-3}}$	**kJ**

Table A.1: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Forging (Open-Die)	Strength coefficient	K	965	MPa
	Initial rod height	h_o	2.8	mm
	Final rod height	h_f	2.4	mm
	Initial rod diameter	d_o		mm
	Coefficient of friction	m	0.2	
	Initial rod radius	r_o	1.4	mm
	Final rod radius	r_f	1.2	mm
	True strain	e	0.1542	
	Strain-hardening exponent	n	0.14	
	Flow stress of the material	Y_f	742.74	MPa
	Forging force	F	0.0036	MN
	Velocity	v	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**1.79**	**KW**
	Actual power	P_{actual}	**2.51**	**KW**
	Energy consumption	$E_{forging}$	**0.012**	**KJ**

Table A.2: Part 2 – Plate Fixing Bolt

Operation	Process Parameter	Symbol	Value	Units
Stock Bar Production	Length of bounded volume	l	9.5	mm
	Diameter of bounded volume	d	9.5	mm
	Void volume within bounded volume	*V.V.*	0	mm^3
	Material density	d	7.83×10^{-6}	kg/mm^3
	Mass of stock	m	0.0053	kg
	Energy use per unit EAF		11500	
	Energy Consumption	E_C	**60.66**	**kJ**

Table A.2: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Drawing	Initial diameter	D_o	9.5	mm
	Final diameter	D_f	4.8	mm
	Initial area	A_o	70.88	mm2
	Final area	A_f	18.096	mm2
	Die angle	*alpha*	15	deg
	Coefficient of friction	μ	0.25	
	Strength coefficient	K	965	MPa
	Strain-hardening exponent	n	0.23	
	True strain	ε	0.26	
	Average flow stress of the material	Y_{avg}	575.53	MPa
	Drawing force	F	0.01422	MN
	Velocity	v	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**7.11**	**KW**
	Actual power	P_{actual}	**9.95**	**KW**
	Energy consumption	$E_{drawing}$	**0.1**	**KJ**
Forging (Open-die)	Strength coefficient	K	965	MPa
	Initial rod height	h_o	5.6	mm
	Final rod height	h_f	2.8	mm
	Initial rod diameter	d_o		mm
	Coefficient of friction	m	0.2	
	Initial rod radius	r_o	2.4	mm
	Final rod radius	r_f	4.75	mm
	True strain	e	0.6931	
	Strain-hardening exponent	n	0.23	
	Flow stress of the material	Y_f	886.99	MPa
	Forging force	F	0.0771	MN
	Velocity	v	500	mm/s
		eff.	0.4	
	Ideal power	P_{ideal}	**38.55**	**KW**
	Actual power	P_{actual}	**53.96**	**KW**
	Energy consumption	$E_{forging}$	**0.3**	**KJ**

Table A.2: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Thread Rolling	Length of cut	*L*	14.765485 47	mm
	Width of cut	*W*	0.75	mm
	Depth of cut	*d*	0.75	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	*p*	1	mm
	Number of teeth on cutter	*f*	1	
	Spindle speed	*n*	611	rpm
	Tool type - Sharp/ Dull		sharp	
	Feed rate	$P=W/D_c$	0.01875	mm/rev
	Number of tool pass		0.75	
	Cutting speed		1920	mm/min.
	Cutting time		0.9666	min.
	Rate of material removed		8.5921875	mm^3/min.
	Material removed		8.31	mm^3
	Power consumption		0.00066	kW
	Energy consumption	$E_{threading}$	**0.04**	**kJ**

Table A.3a: Part 3 – Body Plate

Operation	Process Parameter	Symbol	Value	Units
Stock Sheet Production	Length of bounded volume	*l*	234	mm
	Width of bounded volume	*w*	24	mm
	Thickness	*t*	3	mm
	Void volume within bounded volume	*vv*	0	mm^3
	Material density	*d*	7.83×10^{-6}	kg/mm^3
	Mass of stock	*m*	0.132	kg
	Energy use per unit EAF		11500.1	
	Energy consumption	E_C	**1517.75**	**kJ**

Table A.3a: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Cutting	Perimeter of the cut	L	686	mm
	Thickness of plates	t	3	mm
	Material constant	K	5000	W/ cm^2/ s
	Type of process		LASER	
	Weld spot diameter	D	0.5	mm
	Heat source density	d	10000000	W/ cm^2
	Minimum interaction time	t_{inter}	250×10^9	s
	Welding speed	v	2000000	mm/s
	Total operation time	t_{total}	0.000343	s
	Power consumption	P	205800	kW
	Energy consumption	$\boldsymbol{E_C}$	**70.5894**	**kJ**
Punching	Sheet thickness	T	3	mm
	Total length sheared	L	170.9	mm
	Ultimate tensile strength	UTS	579	MPa
	Punching force	F	2.04	MN
	Velocity	v	39.75	mm/s
	Efficiency	eff	0.4	
	Ideal power	P_{ideal}	80.95	kW
	Actual power	P_{actual}	113.33	kW
	Energy consumption	$\boldsymbol{E_{punching}}$	**8.55**	**KJ**
Chamfering	Length of cut	L	170.9	mm
	Width of cut	W	3	mm
	Depth of cut	d	3	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	3.175	mm
	Number of teeth on cutter	f	0	
	Spindle speed	n	1600	rpm
	Tool type - Sharp/ Dull		sharp	
	Feed rate	$P=W/D$	0.075	mm/rev
	Number of tool pass		0.9449	
	Cutting speed		15959	mm/min.
	Cutting time		1.3457	min.
	Rate of material removed		1143	mm^3/min
	Material removed		1538.12	mm^3
	Power consumption		0.07315	kW
	Energy consumption	$E_{chamfering}$	**5.906**	**kJ**

Table A.3a: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Bending	Length of the plate	L	234	mm
	Thickness of the plate	t	3	mm
	Strength coefficient	S	965	N/mm^2
	Strain-hardening coefficient	n	0.23	
	Bend angle	A	90	deg
	Punch radius	R	6	mm
	Die width	w	30	mm
	Coefficient of friction	μ	0.25	
	Energy consumption	$E_{bending}$	**1.22**	**KJ**

Table A.3b: Part 3 – Body Plate Process Flow II

Operation	Process Parameter	Symbol	Value	Units
Stock Sheet Production	Length of bounded volume	l	234	mm
	Width of bounded volume	w	24	mm
	Thickness	t	3	
	Void volume within bounded volume	vv	0	mm^3
	Material density	d	7.83×10^{-6}	kg/mm^3
	Mass of stock	m	0.132	kg
	Energy use per unit EAF		11500.1	
	Energy consumption	E_C	**1517.75**	**kJ**
Stamping	Sheet thickness	T	3	mm
	Total length sheared	L	686.9	mm
	Ultimate tensile strength	UTS	579	MPa
	Punching force	F	8.18	MN
	Velocity	v	63.5	mm/s
	Efficiency	eff	0.4	
	Ideal power	P_{ideal}	519.75	kW
	Actual power	P_{actual}	727.64	kW
	Energy consumption	$E_{stamping}$	**34.38**	**KJ**

Table A.3b: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Chamfering	Length of cut	L	170.9	mm
	Width of cut	W	3	mm
	Depth of cut	d	3	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	0.125	mm
	Number of teeth on cutter	f	0	
	Spindle speed	n	1600	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	$P=W/D$	0.075	mm/rev
	Number of tool pass		24	
	Cutting speed		628	mm/min.
	Cutting time		34.18	min.
	Rate of material removed		45	mm^3/min.
	Material removed		1538.12	mm^3
	Power consumption		0.003	kW
	Energy consumption	$E_{chamfering}$	**5.91**	**kJ**
Bending	Length of the plate	L	234	mm
	Thickness of the plate	t	3	mm
	Strength coefficient	S	965	N/mm^2
	Strain-hardening coefficient	n	0.23	
	Bend angle	A	90	deg
	Punch radius	R	6	mm
	Die width	w	30	mm
	Coefficient of friction	μ	0.25	
	Energy consumption	$E_{bending}$	**1.22**	**KJ**

Table A.4: Part 4 – Plate Fixing Screw

Operation	Process Parameter	Symbol	Value	Units
Stock Bar Production	Length of bounded volume	l	9.5	mm
	Diameter of bounded volume	d	6.7	mm
	Void volume within bounded volume	$V.V.$	0	mm^3
	Material density	d	7.87×10^{-6}	kg/mm^3
	Mass of stock	m	0.0026	kg
	Energy use per unit EAF		11500.1	
	Energy consumption	E_C	**30.32**	**kJ**
Drawing	Initial diameter	D_o	6.7	mm
	Final diameter	D_f	4.8	mm
	Initial area	A_o	35.26	mm^2
	Final area	A_f	18.1	mm^2
	Die angle	*alpha*	15	deg
	Coefficient of friction	μ	0.25	
	Strength coefficient	K	965	MPa
	Strain-hardening exponent	n	0.23	
	True strain	ε	0.26	
	Average flow stress of the material	Y_{avg}	575.53	MPa
	Drawing force	F	0.0069	MN
	Velocity	v	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**3.47**	**KW**
	Actual power	P_{actual}	**4.86**	**KW**
	Energy consumption	$E_{drawing}$	**0.0467**	**KJ**

Table A.4: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Forging (Open-Die)	Strength coefficient	K	965	MPa
	Initial rod height	h_o	3.4	mm
	Final rod height	h_f	1.7	mm
	Initial rod diameter	d_o		mm
	Coefficient of friction	m	0.2	
	Initial rod radius	r_o	2.4	mm
	Final rod radius	r_f	3.35	mm
	True strain	e	0.6931	
	Strain-hardening exponent	n	0.14	
	Flow stress of the material	Y_f	916.73	MPa
	Forging force	F	0.0408	MN
	Velocity	v	500	mm/s
	Efficiency	$eff.$	0.4	
	Ideal power	P_{ideal}	**20.41**	**KW**
	Actual power	P_{actual}	**28.57**	**KW**
	Energy consumption	$\boldsymbol{E_{forging}}$	**0.1**	**KJ**
Thread Rolling	Length of cut	L	15.08	mm
	Width of cut	W	0.5	mm
	Depth of cut	d	0.5	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	3.175	mm
	Number of teeth on cutter	f	1	
	Spindle speed	n	611	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	$P=W/D_c$	0.0125	mm/rev
	Number of tool pass		0.1575	
	Cutting speed		6094	mm/min.
	Cutting time		0.311	min.
	Rate of material removed		12.12	mm^3/min.
	Material removed		3.77	mm^3
	Power consumption		0.00093	kW
	Energy consumption	$E_{threading}$	**0.02**	**kJ**

Table A.5a: Part 5 – Spring Retainer Plate Process Flow I

Operation	Process Parameter	Symbol	Value	Units
Stock Sheet Production	Length of bounded volume	*l*	55.1	mm
	Diameter of bounded volume	*d*	17.5	mm
	Thickness	*t*	2.2	
	Void volume within bounded volume		0	mm^3
	Material density	*d*	7.83×10^{-6}	kg/mm^3
	Mass of stock	*m*	0.0166	kg
	Energy use per unit EAF		11500.1	
	Energy consumption	E_C	**191.1**	**kJ**
Laser Cutting	Perimeter of the cut	*L*	145.2	mm
	Thickness of plates	*t*	2.2	mm
	Material constant	*K*	5000	$W/ cm^2/ s$
	Type of process		LASER	
	Weld spot diameter	*D*	0.5	mm
	Heat source density	*d*	1×10^7	W/ cm^2
	Minimum interaction time	t_{inter}	250×10^{-9}	s
	Welding speed	*v*	2×10^6	mm/s
	Total operation time	t_{total}	7.26×10^{-5}	s
	Power consumption	*P*	31944	kW
	Energy consumption	$\boldsymbol{E_{laser}}$	**2.32**	**kJ**
Chamfering	Length of cut	*L*	32.6	mm
	Width of cut	*W*	2.2	mm
	Depth of cut	*d*	2.2	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	*p*	3.175	mm
	Number of teeth on cutter	*f*	0	
	Spindle speed	*n*	1600	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	$P=W/D_c$	0.055	mm/rev
	Number of tool pass		0.6929	
	Cutting speed		15959	mm/min.
	Cutting time		0.2567	min.
	Rate of material removed		614.68	mm^3/min.
	Material removed		157.78	mm^3
	Power consumption		0.0559	kW
	Energy consumption	$E_{chamfering}$	**0.86**	**kJ**

Table A.5a: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Bending	Length of the plate	*L*	145.2	mm
	Thickness of the plate	*t*	2.2	mm
	Strength coefficient	*S*	965	N/mm^2
	Strain-hardening coefficient	*n*	0.23	
	Bend angle	*A*	45	deg
	Punch radius	*R*	32	mm
	Die width	*w*	160	mm
	Coefficient of friction	*μ*	0.25	
	Energy consumption	$E_{bending}$	**0.2**	**KJ**

Table A.5b: Part 5 – Spring Retainer Process Flow II

Operation	Process Parameter	Symbol	Value	Units
Stock Sheet Production	Length of bounded volume	*l*	55.1	mm
	Diameter of bounded volume	*d*	17.5	mm
	Thickness	*t*	2.2	
	Void volume within bounded Volume		0	mm^3
	Material density	*d*	7.83×10^{-6}	kg/mm^3
	Mass of stock	*m*	0.016617328	kg
	Energy use per unit EAF		11500.1	
	Energy consumption	E_C	**191.1**	**kJ**
Stamping	Sheet thickness	*T*	2.2	mm
	Total length sheared	*L*	145.2	mm
	Ultimate tensile strength	*UTS*	579	MPa
	Punching force	*F*	1.27	MN
	Velocity	*v*	63.5	mm/s
	Efficiency	*eff*	0.4	
	Ideal power	P_{ideal}	80.57	kW
	Actual power	P_{actual}	112.8	kW
	Energy consumption	$E_{stamping}$	**3.91**	**KJ**

Table A.5b: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Chamfering	Length of cut	*L*	32.6	mm
	Width of cut	*W*	2.2	mm
	Depth of cut	*d*	2.2	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	*p*	3.175	mm
	Number of teeth on cutter	*f*	0	
	Spindle speed	*n*	1600	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	$P=W/D_c$	0.055	mm/rev
	Number of tool pass		0.6929	
	Cutting speed		15959	mm/min.
	Cutting time		0.2567	min.
	Rate of material removed		614.68	mm^3/min.
	Material removed		157.78	mm^3
	Power consumption		0.0473	kW
	Energy consumption	$E_{chamfering}$	**0.73**	**kJ**
Bending	Length of the plate	*L*	145.2	mm
	Thickness of the plate	*t*	2.2	mm
	Strength coefficient	*S*	965	N/mm^2
	Strain-hardening coefficient	*n*	0.23	
	Bend angle	*A*	45	deg
	Punch radius	*R*	32	mm
	Die width	*w*	160	mm
	Coefficient of friction	μ	0.25	
	Energy consumption	$E_{bending}$	**0.2**	**KJ**

Table A.6a: Part 6 – Body Top Process Flow I

Operation	Process Parameter	Symbol	Value	Units
Stock Sheet Production	Length of bounded volume	l	58.8	mm
	Width of bounded volume	w	28	mm
	Thickness	t	2.5	
	Void volume within bounded volume.		0	mm^3
	Material density	d	7.83×10^{-6}	kg/mm^3
	Mass of stock	m	0.0322	kg
	Energy use per unit EAF		11500.1	
	Energy consumption	E_C	**370.79**	**kJ**
Laser Cutting	Perimeter of the cut	L	173.6	mm
	Thickness of plates	t	2.5	mm
	Material constant	K	5000	$W/ cm^2/ s$
	Type of process		LASER	
	Weld spot diameter	D	0.5	mm
	Heat source density	d	1×10^7	W/ cm^2
	Minimum interaction time	t_{inter}	250×10^{-9}	s
	Welding speed	v	2000000	mm/s
	Total operation time	t_{total}	0.0000868	s
	Power consumption	P	43400	kW
	Energy consumption	$\boldsymbol{E_{laser}}$	**3.77**	**kJ**
Punching	Sheet thickness	T	2.5	mm
	Total length sheared	L	58.8	mm
	Ultimate tensile strength	UTS	579	MPa
	Punching force	F	0.5839	MN
	Velocity	v	39.75	mm/s
	Efficiency	eff	0.4	
	Ideal power	P_{ideal}	23.21	kW
	Actual power	P_{actual}	32.49	kW
	Energy	$\boldsymbol{E_{punching}}$	**2.04**	**KJ**

Table A.6a: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Chamfering	Length of cut	L	42.85	mm
	Width of cut	W	2.5	mm
	Depth of cut	d	2.5	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	3.175	mm
	Number of teeth on cutter	f	0	
	Spindle speed	n	1600	rpm
	Tool type - Sharp/ Dull		sharp	
	Feed rate	$P=W/D_c$	0.0625	mm/rev
	Number of tool pass		0.7874	
	Cutting speed		15959	mm/min.
	Cutting time		0.3374	min.
	Rate of material removed		793.75	mm^3/min.
	Material removed		267.81	mm^3
	Power consumption		0.0611	kW
	Energy consumption	$E_{chamfering}$	**1.24**	**kJ**
Bending	Length of the plate	L	173.6	mm
	Thickness of the plate	t	2.5	mm
	Strength coefficient	S	965	N/mm^2
	Strain-hardening coefficient	n	0.23	
	Bend angle	A	63	deg
	Punch radius	R	32	mm
	Die width	w	160	mm
	Coefficient of friction	μ	0.25	
	Energy consumption	$E_{bending}$	**0.12**	**KJ**

Table A.6b: Part 6 – Body Top Process Flow II

Operation	Process Parameter	Symbol	Value	Units
Stock Sheet Production	Length of bounded volume	l	58.8	mm
	Width of bounded volume	w	28	mm
	Thickness	t	2.5	
	Void volume within bounded volume		0	mm^3
	Material density	d	7.83×10^{-6}	kg/mm^3
	Mass of stock	m	0.0322	kg
	Energy use per unit (EAF)		11500.1	
	Energy consumption	E_C	**370.79**	**kJ**
Stamping	Sheet thickness	T	2.5	mm
	Total length sheared	L	232.4	mm
	Ultimate tensile strength	UTS	579	MPa
	Punching force	F	2.3077	MN
	Velocity	v	63.5	mm/s
	Efficiency	eff	0.4	
	Ideal power	P_{ideal}	146.54	kW
	Actual power	P_{actual}	205.15	kW
	Energy consumption	$E_{stamping}$	**8.08**	**KJ**
Chamfering	Length of cut	L	42.85	mm
	Width of cut	W	2.5	mm
	Depth of cut	d	2.5	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	3.175	mm
	Number of teeth on cutter	f	0	
	Spindle speed	n	1600	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	$P=W/D_c$	0.0625	mm/rev
	Number of tool pass		0.7874	
	Cutting speed		15959	mm/min.
	Cutting time		0.3374	min.
	Rate of material removed		793.75	mm^3/min.
	Material removed		267.81	mm^3
	Power consumption		0.0611	kW
	Energy consumption	$E_{chamfering}$	**1.24**	**kJ**

Table A.6b: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Bending	Length of the plate	*L*	173.6	mm
	Thickness of the plate	*t*	2.5	mm
	Strength coefficient	*S*	965	N/mm^2
	Strain-hardening coefficient	*n*	0.23	
	Bend angle	*A*	90	deg
	Punch radius	*R*	32	mm
	Die width	*w*	160	mm
	Coefficient of friction	*μ*	0.25	
	Energy consumption	$E_{bending}$	**0.1952**	**KJ**

Table A.7: Part 7 – Spring Retainer Screw

Operation	Process Parameter	Symbol	Value	Units
Stock Bar Production	Length of bounded volume	*l*	55	mm
	Diameter of bounded volume	*d*	8	mm
	Void volume within bound. volume	*V.V.*	0	mm^3
	Material density	*d*	7.87×10^{-6}	kg/mm^3
	Mass of stock	*m*	0.0217629 43	kg
	Specific energy required		11500.1	
	Energy consumption	E_C	**250.27602 41**	**kJ**

Table A.7: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Drawing	Initial diameter	D_o	8	mm
	Final diameter	D_f	4	mm
	Initial area	A_o	50.27	mm^2
	Final area	A_f	12.566	mm^2
	Die angle	*alpha*	15	deg
	Coefficient of friction	μ	0.25	
	Strength coefficient	K	965	MPa
	Strain-hardening exponent	n	0.23	
	True strain	ε	0.26	
	Average flow stress of the material	Y_{avg}	575.53	MPa
	Drawing force	F	0.01002	MN
	Velocity	v	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**5.01**	**KW**
	Actual power	P_{actual}	**7.01**	**KW**
	Energy consumption	$E_{drawing}$	**0.056**	**KJ**
Forging (Open-die)	Strength coefficient	K	965	MPa
	Initial rod height	h_o	6.76	mm
	Final rod height	h_f	4.76	mm
	Initial rod diameter	d_o		mm
	Coefficient of friction	m	0.2	
	Initial rod radius	r_o	2	mm
	Final rod radius	r_f	4	mm
	True strain	e	0.35	
	Strain-hardening exponent	n	0.14	
	Flow stress of the material	Y_f	833.36	MPa
	Forging force	F	0.0466	MN
	Velocity	v	500	mm/s
		eff.	0.4	
	Ideal power	P_{ideal}	**23.29**	**KW**
	Actual power	P_{actual}	**32.61**	**KW**
	Energy consumption	$E_{forging}$	**0.3104**	**KJ**

Table A.7: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Thread Rolling	Length of cut	*L*	75.4	mm
	Width of cut	*W*	0.5	mm
	Depth of cut	*d*	0.5	mm
	Hardness	D_c	45	HRC
	Milling cutter diameter	*p*	3.175	mm
	Number of teeth on cutter	*f*	15	
	Spindle speed	*n*	566	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate		0.3	mm/rev
	Number of tool pass	*U*	0.1575	
	Cutting speed	*U*	5646	mm/min.
	Cutting time		0.0699	min.
	Rate of material removed		269.56	mm^3/min.
	Material removed		18.85	mm^3
	Power consumption	*U*	0.0208	kW
	Energy consumption	$E_{threading}$	**0.0871**	**kJ**

Table A.8a: Part 8 – Body Process Flow I

Operation	Process Parameter	Symbol	Value	Units
Casting	Length of Bounded Vol.	l	72	mm
	Width of Bounded Vol.	w	61	mm
	Height of Bounded Vol.	h	24	mm
	Void Vol. w/in Bound. Vol.	V.V.	0	mm^3
	Material Density	d	0.0000027	kg/mm^3
	Mass of Plate	m	0.2846016	kg
	Specific Energy Required	CE	10.99	MJ/kg
	Energy Consumption	E_c	3127.771584	kJ

Table A.8a: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Drilling	Depth of cut	d	Unknown	mm
	Hole diameter	D	25	mm
	Hardness	H	35	HRC
	Spindle speed	vspindle	45	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	f	0.2	mm/rev
	Cutting speed	vcutting	3534.291735	mm/min.
	Cutting time	tcutting	34	min.
	Rate of material removal	MRR	4417.864669	mm^3/min.
	Material removed	MR	150207.3987	mm^3
	Power consumption	Pc	0.282743339	kW
	Energy consumption	$E_{drilling}$	576.7964112	kJ
Milling	Length of cut	L	100	mm
	Width of cut	W	300	mm
	Depth of cut	d	7	mm
	Hardness	Dc	45	HRC
	Milling cutter diameter	p	756	mm
	No. of teeth on cutter	f	15	
	Spindle speed	n	566	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate		0.3	mm/rev
	No. of tool pass	U	0.396825397	
	Cutting speed	U	1344274.93	mm/min.
	Cutting time		0.233701647	min.
	Rate of material removed		898581.6	mm^3/min.
	Material removed		210000	mm^3
	Power Consumption	U	73.6836912	kW
	Energy Consumption	$E_{milling}$	1033.2	kJ

Table A.8b: Part 8 – Body Process Flow II

Operation	Process Parameter	Symbol	Value	Units
Net Shape Casting	Length of Bounded Vol.	l	72	mm
	Width of Bounded Vol.	w	61	mm
	Height of Bounded Vol.	h	24	mm
	Void Vol. w/in Bound. Vol.		27628.59	mm^3
	Material Density	d	0.0000027	kg/mm^3
	Mass of Steel Plate	m	0.2100	kg
	Specific Energy Required	CE	10.99	MJ/kg
	Energy Consumption	$\boldsymbol{E_c}$	2307.948436	kJ
Boring	Length of Cut	L	72	mm
	Initial Diameter	Di	10.16	mm
	Final Diameter	Df	14.097	mm
	Feed Rate	f		mm/rev.
	Material Hardness			HRC
	Tool Type			
		π	3.14159265	
	Unit Power	U	120000	$in\text{-}lb/in^3$
		U	0.000827371	kJ/mm^3
	Energy Consumption	$\boldsymbol{E_{boring}}$	0.297874849	kJ
Milling	Length of cut	L	100	mm
	Width of cut	W	300	mm
	Depth of cut	d	7	mm
	Hardness	Dc	45	HRC
	Milling cutter diameter	p	756	mm
	No. of teeth on cutter	f	15	
	Spindle speed	n	566	Rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	P=W/D	0.3	mm/rev
	No. of tool pass	U	0.3968	
	Cutting speed	U	1344274.93	mm/min.
	Cutting time		0.2337	min.
	Rate of material removed		898581.6	$mm^3/min.$
	Material removed		210000	mm^3
	Power Consumption	U	73.68	kW

	Energy Consumption	$\boldsymbol{E_{milling}}$	1033.2	kJ

Table A.8b: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Tapping	Length of cut	L	2	mm
	Width of cut	W	3	mm
	Depth of cut	d	4	mm
	Hardness	Dc	40	HRC
	Milling cutter diameter	p	1	mm
	No. of teeth on cutter	f	1	
	Spindle speed	n	1	rpm
	Tool type - Sharp/ Dull		sharp	
	Feed rate	P=W/Dc	0.075	mm/rev
	No. of tool pass		3	
	Cutting speed		3.1415926 54	mm/min.
	Cutting time		80	min.
	Rate of material removed		0.3	mm^3/min.
	Material removed		24	mm^3
	Power Consumption		0.0000204	kW
	Energy Consumption	$\boldsymbol{E_{tapping}}$	0.09792	kJ

Table A.9: Part 9 – Nut

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Stock Bar Production	Length of bounded volume	l	3.9	mm
	Diameter of bounded volume	d	10	mm
	Void volume within bounded volume		0	mm^3
	Material density	d	7.83×10^{-6}	kg/mm^3
	Mass of stock	m	0.0023994 04	kg
	Specific energy required		11500	
	Energy consumption	E_C	**27.593143 98**	**kJ**

Table A.9: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Forging	Strength coefficient	K	965	MPa
	Initial rod height	h_o	4.2	mm
	Final rod height	h_f	3.9	mm
	Initial rod diameter	d_o		mm
	Coefficient of friction	m	0.2	
	Initial rod radius	r_o	6.1	mm
	Final rod radius	r_f	5.6	mm
	True strain	e	0.0741	
	Strain-hardening exponent	n	0.14	
	Flow stress of the material	Y_f	670.36	MPa
	Forging force	F	0.0787	MN
	Velocity	v	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**39.34**	**KW**
	Actual power	P_{actual}	**55.08**	**KW**
	Energy consumption	$\boldsymbol{E_{forging}}$	**0.4296**	**KJ**
Cutting	Perimeter of the cut	L	35.186	mm
	Thickness of plates	t	11.6	mm
	Material constant	K	5000	W/ cm^2/ s
	Type of process		LASER	
	Weld spot diameter	D	0.5	mm
	Heat source density	d	10000000	W/ cm^2
	Minimum interaction time	t_{inter}	250×10^9	s
	Welding speed	v	2000000	mm/s
	Total operation time	t_{total}	1.76×10^{-5}	s
	Power consumption	P	40815.57	kW
	Energy consumption	$\boldsymbol{E_{laser}}$	**0.7181**	**kJ**

Table A.9: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Drilling	Depth of cut	d	3.9	mm
	Hole diameter	D	7	mm
	Hardness	H	40	HRC
	Spindle speed	$v_{spindle}$	611	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	f	0.1	mm/rev
	Cutting speed	$v_{cutting}$	13437	mm/min.
	Cutting time	$t_{cutting}$	0.06	min.
	Rate of material removal	MRR	2351.4	mm^3/min.
	Material removed	MR	150.09	mm^3
	Power consumption	P_c	0.1505	kW
	Energy consumption	$\boldsymbol{E_{drilling}}$	0.5763	kJ
Threading	Length of cut	L	12.2521	mm
	Width of cut	W	0.75	mm
	Depth of cut	d	3.9	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	1	mm
	Number of teeth on cutter	f	1	
	Spindle speed	n	611	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate	$P=W/D_c$	0.01875	mm/rev
	Number of tool pass		0.75	
	Cutting speed		1920	mm/min.
	Cutting time		0.8021	min.
	Rate of material removed		44.6793	mm^3/min.
	Material removed		35.8377	mm^3
	Power consumption		0.00303	kW
	Energy consumption	$\boldsymbol{E_{threading}}$	**0.1462**	**kJ**

Table A.10a: Part 10 – Axle Shaft Process Flow I

Operation	Process Parameter	Symbol	Value	Units
Stock Bar Production	Length of bounded volume	*l*	91.0082	mm
	Diameter of bounded volume	*d*	25.4	mm
	Void volume within bounded volume		0	
	Material density	*d*	7.83×10^{-6}	kg/mm^3
	Mass of stock	*m*	0.361234204	kg
			11500	kJ/kg
	Energy consumption	E_C	**4154.193346**	**kJ**
Drawing	Initial diameter	D_o	2.56	mm
	Final diameter	D_f	4	mm
	Initial area	A_o	506.7074791	mm^2
	Final area	A_f	324.2927866	mm^2
	Die angle	*alpha*	0.2	deg
	Coefficient of friction	μ	0.25	
	Strength coefficient	*K*	1275	MPa
	Strain-hardening exponent	*n*	0.45	
	True strain	ε	0.446287103	
	Average flow stress of the material	Y_{avg}	611.6016295	MPa
	Drawing force	*F*	0.08851569	MN
	Velocity	*v*	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**44.25784495**	**KW**
	Actual power	P_{actual}	**61.96098293**	**KW**
	Energy consumption	$E_{drawing}$	**0.123921966**	**kJ**

Table A.10a: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Drawing	Initial diameter	D_o	3.955	mm
	Final diameter	D_f	8	mm
	Initial area	A_o	324.29	mm^2
	Final area	A_f	160.33	mm^2
	Die angle	*alpha*	0.2	deg
	Coefficient of friction	μ	0.25	
	Strength coefficient	K	1275	MPa
	Strain-hardening exponent	n	0.45	
	True strain	ε	0.7044	
	Average flow stress of the material	Y_{avg}	751.056	MPa
	Drawing force	F	0.0848	MN
	Velocity	v	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**42.41**	**KW**
	Actual power	P_{actual}	**59.38**	**KW**
	Energy consumption	$E_{drawing}$	**0.24**	**kJ**
Drawing	Initial diameter	D_o	38.02	mm
	Final diameter	D_f	79	mm
	Initial area	A_o	324.29	mm^2
	Final area	A_f	156.08	mm^2
	Die angle	*alpha*	0.2	deg
	Coefficient of friction	μ	0.25	
	Strength coefficient	K	1275	MPa
	Strain-hardening exponent	n	0.45	
	True strain	ε	0.7312	
	Average flow stress of the material	Y_{avg}	763.8	MPa
	Drawing force	F	0.0872	MN
	Velocity	v	500	mm/s
	Efficiency	*eff.*	0.4	
	Ideal power	P_{ideal}	**43.59**	**KW**
	Actual power	P_{actual}	**61.02**	**KW**
	Energy consumption	$E_{drawing}$	**2.4105**	**kJ**

Table A.10a: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Threading	Length of cut	L	11.25	mm
	Width of cut	W	0.5625	mm
	Depth of cut	d	0.5625	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	0.125	mm
	Number of teeth on cutter	f	0	
	Spindle speed	n	1600	rpm
	Tool type - Sharp/ Dull		sharp	
	Feed rate	$P=W/D_c$	0.0140625	mm/rev
	Number of tool pass		4.5	
	Cutting speed		628	mm/min.
	Cutting time		2.25	min.
	Rate of material removed		1.5820312 5	mm^3/min.
	Material removed		3.5596	mm^3
	Power consumption		0.000107	kW
	Energy consumption	$E_{threading}$	**0.0145**	**kJ**

Table A.10b: Part 10 – Axle Shaft Process Flow II

Operation	Process Parameter	Symbol	Value	Units
Casting	Length of bounded volume	l	91.0082	mm
	Diameter of bounded volume	d	25.4	mm
	Void volume within bounded volume		0	mm^3
	Material density	d	7.83×10^{-6}	kg/mm^3
	Mass of stock	m	0.36	kg
	Specific energy required		11500	
	Energy consumption	E_C	**4154.19**	**kJ**

Table A.10b: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Turning - "nut"	Length of cut	L	91.01	mm
	Initial diameter (D_o)	D_o	25.40	mm
	Final diameter (D_f)	D_f	20.32	mm
	Hardness	H	40	HRC
	Spindle speed (N)	N	1200	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate (f)	f	0.3	mm/rev
	Cutting edge angle	C_θ	15	degrees
	Edge radius	R	0	mm
	Depth of cut (d)	d	2.54	mm
	Cutting speed	v	95755.74	mm/min.
	Cutting time	t	0.25	min.
	Rate of material removal	MRR	65669.29	mm^3/min.
	Material removed	MR	16601.23	mm^3
	Power consumption	U	4.4655	kW
	Energy consumption	$E_{turning}$	**67.733**	**kJ**
Turning - "big thread"	Length of cut	L	8	mm
	Initial diameter (D_o)	D_o	20.32	mm
	Final diameter (D_f)	D_f	14.3	mm
	Hardness	H	40	HRC
	Spindle speed (N)	N	1200	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate (f)	f	0.3	mm/rev
	Cutting edge angle	C_θ	15	degrees
	Edge radius	R	0	mm
	Depth of cut (d)	d	3.01	mm
	Cutting speed	v	76604.6	mm/min.
	Cutting time	t	0.02	min.
	Rate of material removal	MRR	58927.22	mm^3/min.
	Material removed	MR	1309.49	mm^3
	Power consumption	U	4.0071	kW
	Energy consumption	$E_{turning}$	**5.34**	**kJ**

Table A.10b: (Cont'd)

Operation	**Process Parameter**	**Symbol**	**Value**	**Units**
Turning - "shaft"	Length of cut	*L*	72	mm
	Initial diameter (D_o)	D_o	20.32	mm
	Final diameter (D_f)	D_f	14.1	mm
	Hardness	*H*	40	HRC
	Spindle speed (N)	*N*	1200	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate (f)	*f*	0.3	mm/rev
	Cutting edge angle	C_θ	15	degrees
	Edge radius	*R*	0	mm
	Depth of cut (d)	*d*	3.11	mm
	Cutting speed	*v*	76604.6	mm/min.
	Cutting Time	*t*	0.2	min.
	Rate of material removal	*MRR*	60533.2	mm^3/min.
	Material removed	*MR*	12106.64	mm^3
	Power consumption	*U*	4.1163	kW
	Energy consumption	$E_{turning}$	**49.40**	**kJ**
Turning - "little thread"	Length of cut	*L*	7	mm
	Initial diameter (D_o)	D_o	20.32	mm
	Final diameter (D_f)	D_f	14.1	mm
	Hardness	*H*	40	HRC
	Spindle speed (N)	*N*	1200	rpm
	Tool type - Sharp/ Dull		Sharp	
	Feed rate (f)	*f*	0.3	mm/rev
	Cutting edge angle	C_θ	15	degrees
	Edge radius	*R*	0	mm
	Depth of cut (d)	*d*	3.11	mm
	Cutting speed	*v*	76604.6	mm/min.
	Cutting time	*t*	0.02	min.
	Rate of material removal	*MRR*	60533.2	mm^3/min.
	Material removed	*MR*	1177.03	mm^3
	Power consumption	*U*	4.12	kW
	Energy consumption	$E_{turning}$	**4.8023**	**kJ**

Table A.10b: (Cont'd)

Operation	Process Parameter	Symbol	Value	Units
Milling	Length of cut	L	11.25	mm
	Width of cut	W	0.5625	mm
	Depth of cut	d	0.56	mm
	Hardness	D_c	40	HRC
	Milling cutter diameter	p	0.125	mm
	Number of teeth on cutter	f	0	
	Spindle speed	n	1600	rpm
	Tool type - Sharp/ Dull		sharp	
	Feed rate	$P=W/D_c$	0.0141	mm/rev
	Number of tool pass		4.5	
	Cutting speed		628	mm/min.
	Cutting time		2.25	min.
	Rate of material removed		1.58	mm^3/min.
	Material removed		3.56	mm^3
	Power consumption		0.00011	kW
	Energy consumption	$E_{milling}$	**0.015**	**kJ**

Appendix B

Appendix B shows two alternative supply chains for each part. The first column indicates the part number as identified in appendix A

Part	SC	From	To	Transportation mode	Mass (Tonnes)	Average Distance (km)	kg CO_2/tonne-km	kg CO_2 eq.
1	1a	New Delhi, India	London, UK	Airfreight	9.92×10^{-8}	6724	602	4.02×10^{-4}
		London, UK	New York, NY, USA	Barge	9.92×10^{-8}	5587	31	1.72×10^{-5}
		New York, NY, USA	Austin, TX, USA	Road	9.92×10^{-8}	2432	62	1.49×10^{-5}
		Austin, TX, USA	Irvine, CA, USA	Road	6×10^{-8}	1928	62	7.17×10^{-6}
	1b	Pittsburg, PA, USA	Irvine, CA, USA	Intermodal road/rail	9.92×10^{-8}	3417	26	8.82×10^{-6}
2	2a	Luxemburg, Luxemburg	Wales – Cardiff, UK	Rail	1.46×10^{-6}	691	22	2.22×10^{-5}
		Wales – Cardiff, UK	Bridgeport, CT, USA	Deep-sea container	1.46×10^{-6}	5297	8	6.19×10^{-5}
		Bridgeport, CT, USA	Columbus, OH, USA	Road	1.46×10^{-6}	842	62	7.62×10^{-5}
		Columbus, OH, USA	Irvine, CA, USA	Road	1.5×10^{-6}	3161	62	2.94×10^{-4}
	2b	Beijing, China	Shanghai, China	Intermodal road/rail	1.46×10^{-6}	1066	26	4.05×10^{-5}
		Shanghai, China	Honolulu, HI, USA	Deep-sea container	1.46×10^{-6}	7964	8	9.30×10^{-5}
		Honolulu, HI, USA	San Francisco, CA, USA	Deep-sea container	1.46×10^{-6}	3855	8	4.50×10^{-5}
		San Francisco, CA, USA	Anaheim, CA, USA	Road	1.46×10^{-6}	651.2	62	5.89×10^{-5}
		Anaheim, CA, USA	Irvine, CA, USA	Road	1.5×10^{-6}	27.2	62	2.53×10^{-6}

Part	SC	From	To	Transportation mode	Mass (Tonnes)	Average Distance (km)	kg CO_2/tonne-km	kg CO_2 eq.
3	3a	Luxemburg, Luxemburg	Wales – Cardiff, UK	Rail	1.32×10^{-4}	691	22	2.01×10^{-3}
		Wales – Cardiff, UK	Bridgeport, CT, USA	Deep-sea container	1.32×10^{-4}	5297	8	5.59×10^{-3}
		Bridgeport, CT, USA	Columbus, OH, USA	Road	1.32×10^{-4}	842	62	6.89×10^{-3}
		Columbus, OH, USA	Irvine, CA, USA	Road	5.99×10^{-5}	3161	62	1.17×10^{-2}
	3b	New Delhi, India	London, UK	Airfreight	1.32×10^{-4}	6724	602	0.5342
		London, UK	New York, NY, USA	Barge	1.32×10^{-4}	5587	31	0.0229
		New York, NY, USA	Austin, TX, USA	Road	1.32×10^{-4}	2432	62	0.0199
		Austin, TX, USA	Irvine, CA, USA	Road	5.99×10^{-5}	1928	62	0.0072
4	4a	Luxemburg, Luxemburg	Wales – Cardiff, UK	Rail	2.63×10^{-3}	691	22	0.0401
		Wales – Cardiff, UK	Bridgeport, CT, USA	Deep-sea container	2.63×10^{-3}	5297	8	0.1117
		Bridgeport, CT, USA	Columbus, OH, USA	Road	2.63×10^{-3}	842	62	0.1376
		Columbus, OH, USA	Irvine, CA, USA	Road	1.2×10^{-6}	3161	62	0.0002
	4b	Pittsburg, PA, USA	Irvine, CA, USA	Intermodal road/rail	2.63×10^{-6}	3417	26	1.07×10^{-4}
					1.2×10^{-6}	3417	26	1.07×10^{-4}
5	5a	New Delhi, India	London, UK	Airfreight	1.66×10^{-5}	6724	602	6.72×10^{-2}
		London, UK	New York, NY, USA	Barge	1.66×10^{-5}	5587	31	2.88×10^{-3}
		New York, NY, USA	Austin, TX, USA	Road	1.66×10^{-5}	2432	62	2.51×10^{-3}
		Austin, TX, USA[2]	Irvine, CA, USA	Road	9.5×10^{-6}	1928	62	1.14×10^{-3}
	5b	Pittsburg, PA, USA	Irvine, CA, USA	Intermodal road/rail	1.66×10^{-5}	3417	26	1.48×10^{-3}
					9.5×10^{-6}	3417	26	8.44×10^{-4}

Part	SC	From	To	Transportation mode	Mass (Tonnes)	Average Distance (km)	kg CO_2/tonne-km	kg CO_2 eq.
6	6a	Luxemburg, Luxemburg	Wales – Cardiff, UK	Rail	3.22×10^{-5}	691	22	4.90×10^{-4}
		Wales – Cardiff, UK	Bridgeport, CT, USA	Deep-sea container	3.22×10^{-5}	5297	8	1.37×10^{-3}
		Bridgeport, CT, USA	Columbus, OH, USA	Road	3.22×10^{-5}	842	62	1.68×10^{-3}
		Columbus, OH, USA	Irvine, CA, USA	Road	1.5×10^{-5}	3161	62	2.94×10^{-3}
	6b	Beijing, China	Shanghai, China	Intermodal road/rail	3.22×10^{-5}	1066	26	8.94×10^{-4}
		Shanghai, China	Honolulu, HI, USA	Deep-sea container	3.22×10^{-5}	7964	8	2.05×10^{-3}
		Honolulu, HI, USA	San Francisco, CA, USA	Deep-sea container	3.22×10^{-5}	3855	8	9.94×10^{-4}
		San Francisco, CA, USA	Anaheim, CA, USA	Road	3.22×10^{-5}	651.2	62	1.30×10^{-3}
		Anaheim, CA, USA	Irvine, CA, USA	Road	1.5×10^{-5}	27.2	62	2.53×10^{-5}
7	7a	Luxemburg, Luxemburg	Wales – Cardiff, UK	Rail	2.17×10^{-5}	691	22	3.31×10^{-4}
		Wales – Cardiff, UK	Bridgeport, CT, USA	Deep-sea container	2.17×10^{-5}	5297	8	9.22×10^{-4}
		Bridgeport, CT, USA	Columbus, OH, USA	Road	2.17×10^{-5}	842	62	1.14×10^{-3}
		Columbus, OH, USA	Irvine, CA, USA	Road	5.8×10^{-6}	3161	62	1.14×10^{-3}
	7b	New Delhi, India	London, UK	Airfreight	2.17×10^{-5}	6724	602	0.0881
		London, UK	New York, NY, USA	Barge	2.17×10^{-5}	5587	31	0.0038
		New York, NY, USA	Austin, TX, USA	Road	2.17×10^{-5}	2432	62	0.0033
		Austin, TX, USA	Irvine, CA, USA	Road	5.8×10^{-6}	1928	62	0.0007

Part	SC	From	To	Transportation mode	Mass (Tonnes)	Average Distance (km)	kg CO_2/tonne-km	kg CO_2 eq.
8	8a	New York, New York, USA	Pittsburg, PA, USA	Road	2.84×10^{-4}	508	62	0.0089
		Pittsburg, PA, USA	Irvine, CA, USA	Road	7.12×10^{-5}	3417	62	0.0151
	8b	Montreal, Canada	Boston, MA, USA	Airfreight	2.1×10^{-4}	404	602	0.0511
		Boston, MA, USA	Salt Lake City, UT, USA	Airfreight	2.1×10^{-4}	3376	602	0.4268
		Salt Lake City, UT, USA	Riverside, CA, USA	Rail	2.1×10^{-4}	902	22	4.17×10^{-3}
		Riverside, CA, USA	Irvine, CA, USA	Road	7.12×10^{-5}	49	62	2.16×10^{-4}
9	9a	New Delhi, India	London, UK	Airfreight	2.39×10^{-6}	6724	602	9.71×10^{-3}
		London, UK	New York, NY, USA	Barge	2.39×10^{-6}	5587	31	4.16×10^{-4}
		New York, NY, USA	Austin, TX, USA	Road	2.39×10^{-6}	2432	62	3.62×10^{-4}
		Austin, TX, USA	Irvine, CA, USA	Road	1.2×10^{-6}	1928	62	1.43×10^{-4}
	9b	Beijing, China	Shanghai, China	Intermodal road/rail	2.39×10^{-6}	1066	26	6.65×10^{-5}
		Shanghai, China	Honolulu, HI, USA	Deep-sea container	2.39×10^{-6}	7964	8	1.53×10^{-4}
		Honolulu, HI, USA	San Francisco, CA, USA	Deep-sea container	2.39×10^{-6}	3855	8	7.40×10^{-5}
		San Francisco, CA, USA	Anaheim, CA, USA	Road	2.39×10^{-6}	651.2	62	9.69×10^{-5}
		Anaheim, CA, USA	Irvine, CA, USA	Road	1.2×10^{-6}	27.2	62	2.02×10^{-6}

Part	SC	From	To	Transportation mode	Mass (Tonnes)	Average Distance (km)	kg CO_2/tonne-km	kg CO_2 eq.
10	10a	Luxemburg, Luxemburg[1]	Wales – Cardiff, UK	Rail	3.61×10^{-4}	691	22	0.0055
		Wales – Cardiff, UK	Bridgeport, CT, USA	Deep-sea container	3.61×10^{-4}	5297	8	0.0153
		Bridgeport, CT, USA	Columbus, OH, USA	Road	3.61×10^{-4}	842	62	0.0189
		Columbus, OH, USA	Irvine, CA, USA	Road	2.8×10^{-6}	3161	62	0.0005
	10b	Beijing, China	Shanghai, China	Intermodal road/rail	3.61×10^{-4}	1066	26	0.0100
		Shanghai, China	Honolulu, HI, USA	Deep-sea container	3.61×10^{-4}	7964	8	0.0230
		Honolulu, HI, USA	San Francisco, CA, USA	Deep-sea container	3.61×10^{-4}	3855	8	0.0111
		San Francisco, CA, USA	Anaheim, CA, USA	Road	3.61×10^{-4}	651.2	62	0.0146
		Anaheim, CA, USA	Irvine, CA, USA	Road	2.8×10^{-6}	27.2	62	4.72×10^{-6}