Title

An Environmental and Economic Trade-off Analysis of Manufacturing Process Chains to Inform Decision Making for Sustainability

Author

Robinson, Stefanie L.

Publication Date

2013-12-01

An Environmental and Economic Trade-off Analysis of Manufacturing Process Chains to Inform Decision Making for Sustainability

by

Stefanie Lynn Robinson

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Engineering – Mechanical Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor David Dornfeld, Chair
Professor Alice Agogino
Professor Sara Beckman

Fall 2013

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346

An Environmental and Economic Trade-off Analysis of Manufacturing Process Chains to Inform Decision Making for Sustainability

Abstract

An Environmental and Economic Trade-off Analysis of Manufacturing Process Chains to Inform Decision Making for Sustainability

by

Stefanie Lynn Robinson

Doctor of Philosophy in Engineering – Mechanical Engineering

University of California, Berkeley

Professor David Dornfeld, Chair

Increasing costs, consumer awareness, and environmental legislation have driven industry to reduce its resource consumption and the impact from that consumption. So, both traditional economic objectives (e.g., cost, time, and quality) and environmental objectives (e.g., CO_2 emissions) have become strategically relevant for the manufacturing sector. For many manufacturing companies, production systems have a major influence on the environmental footprint of a product and therefore represent a major opportunity to minimize the company's overall environmental impact. Currently within industry, there is not an accurate, effective, or widely accepted method to assess the resource consumption of process chains used to manufacture a product. As a result, this information is often not considered when making decisions about what processes to use. A considerable part of the energy and resource demand in manufacturing is determined during production planning. An important component of this planning is determining the process chains to be used. Process chains are a combined sequence of specifically arranged, single processes used to manufacture a product. As manufacturing processes are very resource intensive, it is now necessary to assess the resource consumption as well as the economics of these process chains. Because of this, additional information must be considered when selecting the process chains used to manufacture a product.

Many life cycle assessment (LCA) tools focus on the materials and final disposition of a product, but do not include detailed information or data on the manufacturing required to fabricate the product. Sustainability impacts of discrete manufacturing processes and product value streams are needed to develop more complete LCAs. The development of a methodology and user tool to quantify sustainability impacts, leading to the identification of gaps and opportunities, is essential to facilitate decision making to support sustainability in manufacturing facilities.

To address these issues, this dissertation proposes an approach to evaluate and quantify the resource use in addition to the environmental and economic impacts associated with discrete manufacturing processes as part of a complex process chain. A methodology to evaluate multiple process chain configurations will be presented.

First, a database of industrial assessment metrics was compiled. This database allows users to sort and select from a list of key metrics in order to choose the metrics that are relevant for the performance that they want to measure. Next, an industrial assessment methodology was developed. This methodology gives users an overview of the key areas to address when conducting an industrial assessment. This methodology, which was applied to three case studies, can be used in combination with the key metrics.

In the second part of the dissertation, a resource consumption assessment and mapping methodology for complex manufacturing process chains was developed. This systematic methodology was developed to identify and quantify the resource consumption (energy, water, materials) for discrete manufacturing processes. The processes mapped include: welding (manual and robotic), cutting (plasma arc and laser), rework (air carbon arc cutting and hand grinding), and machining (milling).

Next, a model consisting of database modules for each process was developed. This model quantifies the sustainability impacts (energy, water, and material consumption, waste generation, emissions, and resource consumption cost) of manufacturing process chains. The model was validated using a case study with Caterpillar Inc. for a process chain including welding, plasma arc cutting, laser cutting, and milling.

Next, a process chain assessment tool was created. This tool enables manufacturers to assess the resource consumption and associated impacts of multiple fabrication process chain configurations. This enables a more comprehensive assessment compared to other software tools. Finally, a methodology modeled after the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) process was presented to show how to translate the results from the model and tool to an Environmental Value Stream Map and to translate those results into improvements in manufacturing systems. This methodology was validated on a machining operation in a Caterpillar facility.

This research has developed and evaluated an effective approach for the analysis of energy, water, and other resource use in multiple processes in a manufacturing process chain. This allows manufacturers to better understand the resource consumption and environmental and economic impacts of fabrication process chains used to make a product. This dissertation helps to provide the technical understanding and tools to enable designers and manufacturing engineers to create manufacturing systems that are truly more sustainable. The implementation of this work can be directly applied to assessing and optimizing manufacturing process chains and the work presented in this dissertation directly contributes to the realization of a sustainable and prosperous manufacturing sector.

Contents

List of Figures

List of Tables

Acknowledgments

There are many people that I would like to thank as my graduate studies come to an end. First, I must express my sincerest gratitude and appreciation to my adviser, Professor David Dornfeld. His mentorship, support, advice, and encouragement have been tremendous. He has given me many opportunities to grow professionally and personally, and his kindness and generosity have made working for him an absolute pleasure. I have been extremely fortunate to learn from Professor Dornfeld and could think of no better adviser to have.

I must also acknowledge Professor Alice Agogino and Professor Sara Beckman for being on my dissertation committee. Many thanks to them for the time that they took to review my dissertation and provide thoughtful and insightful feedback and edits. I would also like to thank Arianne Agogino for an extra set of eyes in acting as an editor for my dissertation.

I want to thank Professor Alice Agogino, Professor Homayoon Kazerooni, Professor Dennis Lieu, and Professor Sara Beckman for sitting on my qualifying examination committee. This opportunity was a wonderful learning experience and definitely helped to shape who I am today.

I want to thank the colleagues and collaborators that I have worked with-- you all have helped this project come to fruition. I want to thank Chee Ng for his inspiration and guidance in my work with mapping the processes and integrating them into the DMAIC methodology. A sincere thanks goes to Kirsten Mauritzson for working tirelessly with me on the Caterpillar case study as we progressed through the various TRL levels and deadlines. I would also like to thank the National Center for Defense Manufacturing and Machining, System Insights, Moneer Helu, and Nancy Diaz-Elsayed for their collaboration during the early part of my research with the Sustainable Aerospace Manufacturing Initiative.

My deepest gratitude goes to Jennifer Mangold--of whom I have had no better colleague or collaborator in graduate school. Her constant support, guidance, advice, and friendship have been a tremendous asset. Jennifer has always been happy to help me through a difficult problem, develop a new idea, or beautify my slides, even if that meant talking on the phone at a ridiculous time of the hour, or staying up late to help me, or putting her own work on hold to help me with mine. I am inspired by the projects and papers that we have co-created together and I look forward to our next joint professional venture. I would not have ended up in Berkeley if it wasn't for you and I certainly wouldn't be where I am today. Thank you for everything.

I would like to further thank Professor Homayoon Kazerooni for believing in me and for his continued support and encouragement throughout this process. I would also like to thank Professor Kyriakos Komvopoulos for believing in me and for giving me the opportunity to attend Berkeley. In addition, I would like to thank Professor George Johnson, Dr. Steven Chin, Hugo Ramirez, and Dr. George Gagnon for their support in the early stages of my graduate career. I also want to acknowledge the support of other coworkers and colleagues who supported me throughout the way: undergraduate students Alex Wong and Barbara Gao; visiting scholar Saskia Reinhardt; and Caterpillar colleagues: Brad Fix, Ted Norbits, Mike Noble, Mike Vogler, Matt Robinson, Ajay Yadav, Waldemar Gremplewski, Don Stickel, Karen Huber, Dan Adler, Yong Li, and Christie Ragle. A special thanks goes to Moneer Helu for your friendship and guidance throughout this whole graduate school process. Your continued willingness to always lend a hand or give advice is greatly appreciated. Another thanks goes to Margot Hutchins for helping with edits and for introducing me to MS Word styles and Barbara Linke for always being happy to give advice.

I would also like to thank Dave Madden at the Air Force Research Laboratory for his enthusiasm and support during the early stages of my research, for helping to shape my research directions, for opening up his home to me while I worked at AFRL, and for popcorn and smoothie nights!

Of course, none of this work would have been possible without generous financial support. Caterpillar Inc., Air Force Research Laboratory, and the Sustainable Manufacturing Partnership contributed tremendous resources that enabled my research. I would also like to thank the National Science Foundation for their support of my graduate work through a K-12 STEM fellowship and the Graduate Research Fellowship Program.

I also want to thank all of my friends and labmates at the Laboratory for Manufacturing and Sustainability for making my time in the lab fun. Whether it was rock climbing during a retreat, running up a mountain in Yosemite, or decorating cupcakes and cookies together, I can think of no better community to have joined for graduate school.

I am so very grateful for my family. I love you guys. Thank you for loving me and accepting me for who I am. Finally, my biggest thank you has to go to my wife-to-be (WTB!) and better half, Abbie, for being there for me and supporting me in the bad times and celebrating with me during the great times. Whether it was dropping off groceries, making me dinner, teaching me how to sail, making me laugh, or just wrapping your arms around me during the tough times, I cannot put into words how much your love and support means to me. I love you so much, and I cannot wait to see what this next chapter in life holds for us.

Chapter 1

Introduction

1.1 Resource Consumption Trends

As populations increase worldwide, and people strive for a better quality of life – including more and better things such as autos, electronics, shelter, food, health care and education), -- more and more energy, water and other resources are consumed.

Gross domestic product (GDP) is the market value of all officially recognized goods and services produced within a country in a given period of time. GDP per capita is often considered an indicator of a country's standard of living. If one looks at the relationship between one (arguably not perfect) measure of affluence (GDP/capita) and the efficiency of use of energy for the top 40 economies in the world (see Figure 1.1 below), one can see that as countries become more productive their energy efficiency drops. The impact of this reduced efficiency with affluence is seen on the environment – air, water and land, in social strife due to unequal distribution of resources, in health and well being of the people, and, for companies, increased cost of energy and other resources.

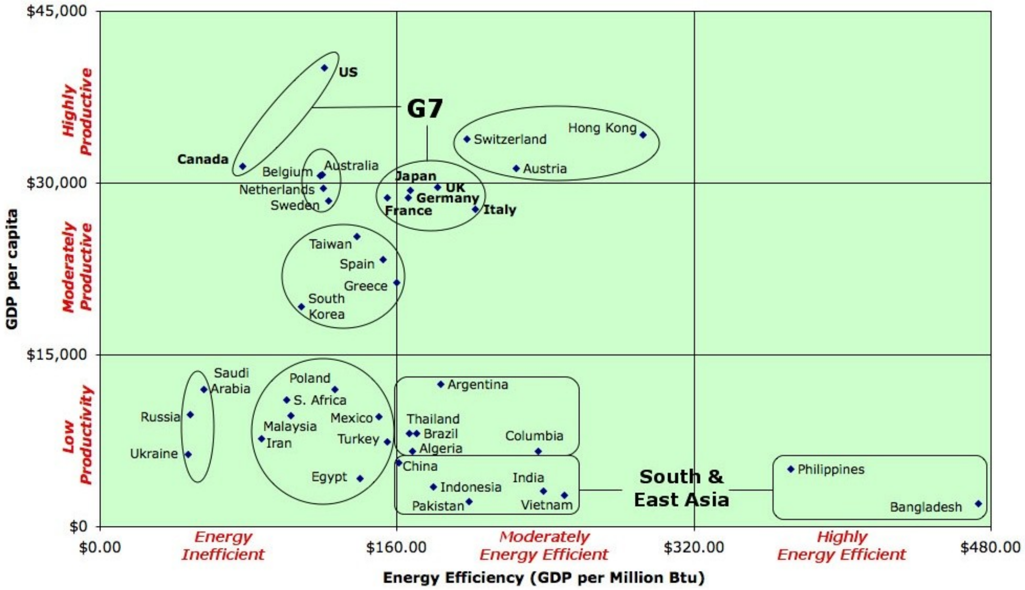


Figure 1.1: GDP per capita vs. Energy Efficiency (for the top 40 economies by GDP) (Wikipedia, 2005)

If this trend increases, and there is no reason to suggest that it will not, this is not sustainable. This trend underscores the need for improving the technology (both in creation and use of products) to ensure the aspirations of the world can be met, efficiently. Manufacturing plays an important role in this.

Society's use of resources has grown tremendously since the start of the Industrial Revolution. For example, the amount of energy consumed in the United States has increased exponentially (see Figure 1.2) (U.S. Energy Information Administration, 2012). Figure 1.2 shows the increasing consumption of energy in the United States over the past 234 years. Only the occurrence of the occasional recession causes the rate of increase to slow. The vast share of energy consumed in modern times has been from fossil fuel sources (e.g., petroleum, coal, and natural gas), all of which are relatively limited, nonrenewable resources; oil and natural gas may even be depleted by the middle of this century (Graedel & Allenby, 2003).

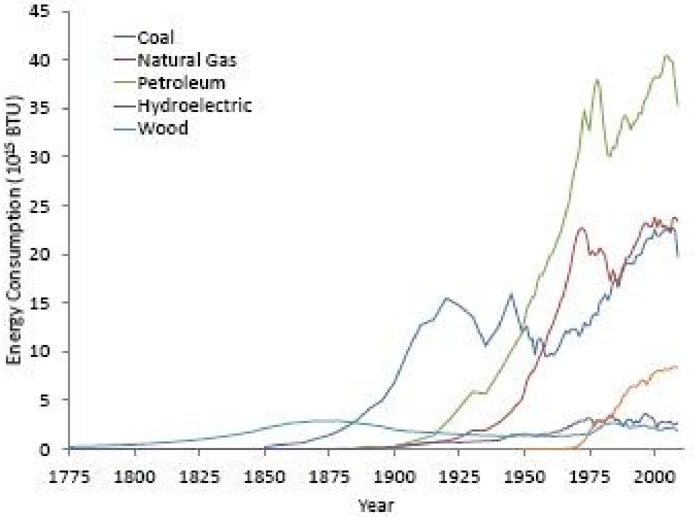


Figure 1.2: Historical energy consumption in the United States from 1775 – 2009 divided into each energy source (adapted from (U.S. Energy Information Administration, 2012)).

A similar trend can be observed in other essential engineering resources, such as minerals and materials. The growth of the use of these resources has also been exponential with the majority of the increase due to construction materials that have been used for the structures required for housing an increasing global population and the growing economy worldwide (see Figure 1.3) (Matos, 2009). Both trends are expected to continue increasing with the rise of developing economies in China, India, Brazil, and other countries.

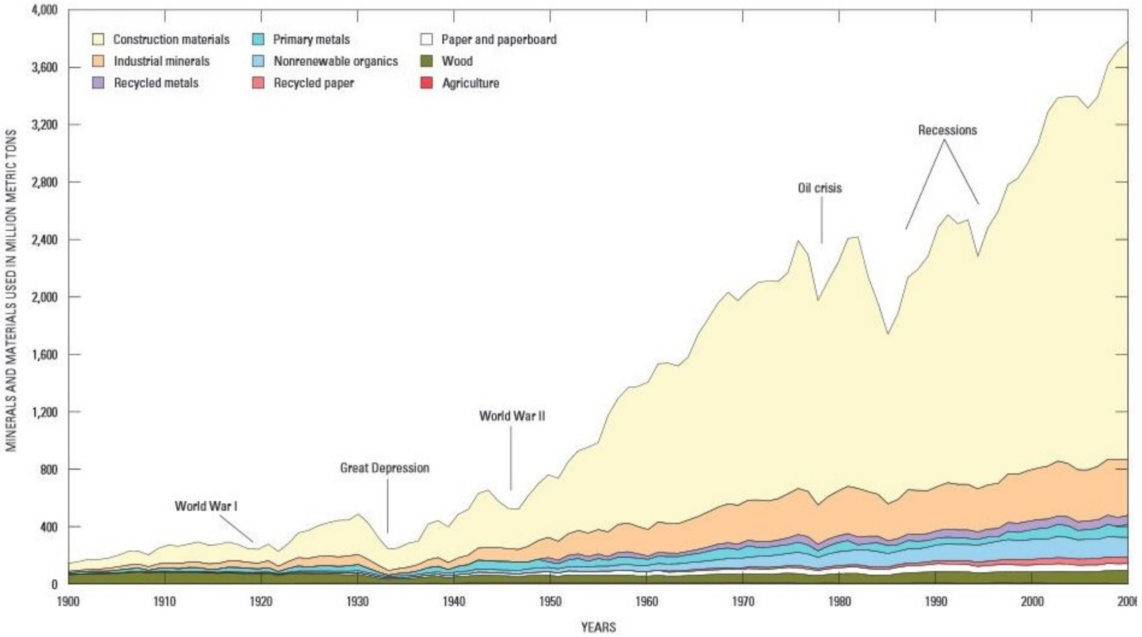


Figure 1.3: Minerals and materials used for physical goods in the United States from 1900 – 2006. Minerals and materials embedded in imported goods are not included. (Matos, 2009)

Water has seen increased use over the years. Available water resources continue to decline as a result of excessive withdrawal of surface- and ground-water, as well as decreased water run-off due to reduced precipitation and increased evaporation attributed to global warming (United Nations Environment Programme, 2007). According to the World Meteorological Organization, global water consumption increased six-fold between 1900 and 1995, which is more than double the rate of population increase in the last century (Pickard, 2009; UN Water, 2012). Water withdrawals are predicted to increase 50% by 2025 in developing countries, and 18% in developed countries (UNESCO, 2006).

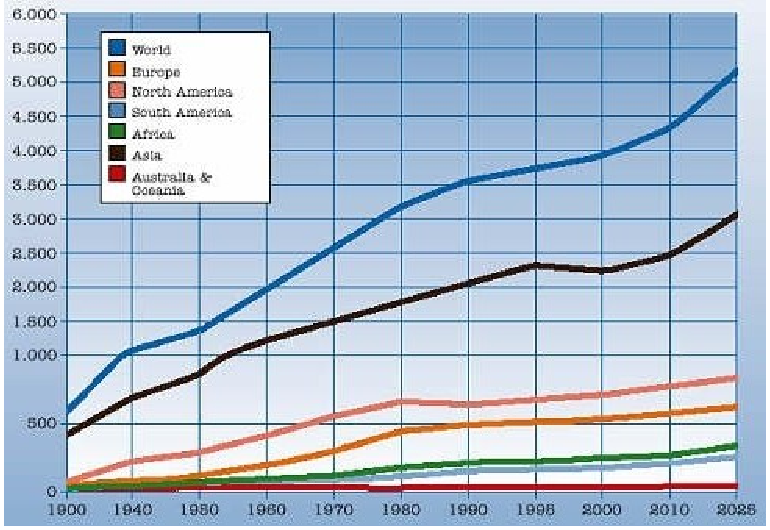


Figure 1.4: Global water consumption from 1900 – 2025 (by region, in billion m^3 per year) (World Resources Simulation Center, 2012)

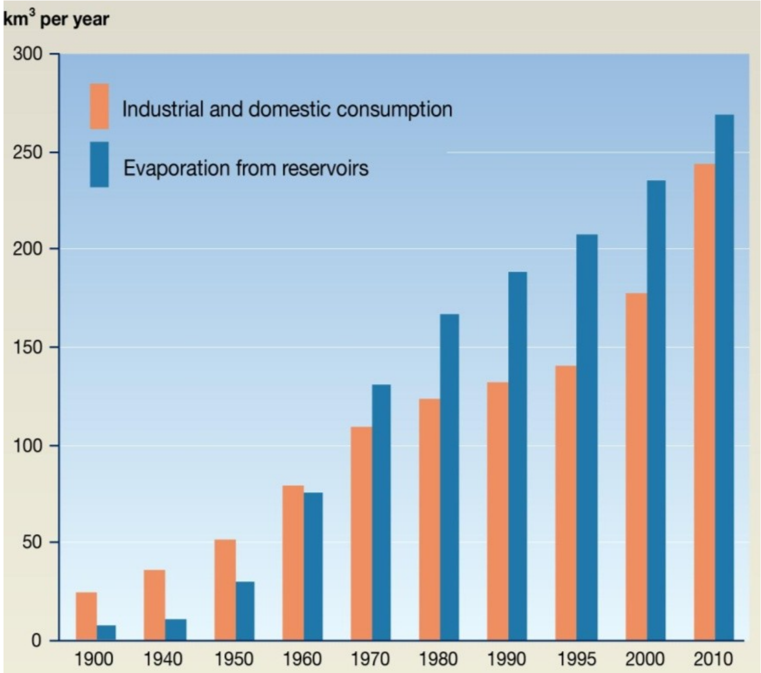


Figure 1.5: Industrial and domestic consumption compared with evaporation from reservoirs (Shiklomanov, 1999)

While water is “conserved” in the environment, meaning the water lost due to evaporation from reservoirs or consumed in production does not disappear. It often is not uniformly distributed, and excessive consumption in one area can severely affect the local region. Similarly, increasing demand from all users exacerbates shortages – whether the water used is returned to the environment locally or not.

1.2 Consumption of Resources in Manufacturing

Manufacturing today consumes a significant amount of energy, materials, water and other resources to produce the items consumers demand. These resources, to minimize the impact of their consumption on the environment, need to be used as efficiently and effectively as possible. That is, we need to ensure that the value created for these products is done with the least impact on the environment.

This means that the tools, processes, machines, systems, factories and enterprises that make up the manufacturing sector need to operate, at all levels, as efficiently and effectively as possible. Ultimately, this is a challenge for manufacturing engineers who are tasked with the implementation of advanced production technology. They must ensure that the technology is both resource and energy efficient in the production stage and that, when possible, the technology produces products that operate with as small an energy, or environmental, footprint as possible over their life cycles.

Manufacturing processes are very resource intensive. Energy is perhaps one of the most important process consumables that manufacturers must consider because of the scope of its use and its role in climate change. The industrial sector (a significant portion of which is manufacturing) consumes the largest share of energy in the United States. As of 2005, this represented 31% of the United States' total energy usage (U.S. Energy Information Administration, 2012). In addition, today's manufacturing enterprise consists of more than just factories producing goods. There are complex supply chains (input) feeding production and distribution networks (output) distributing the finished products. Transportation is an important element as are warehouses and distribution centers. Hence, the true impact of "manufacturing" is likely to be substantially greater than sector statistics suggest.

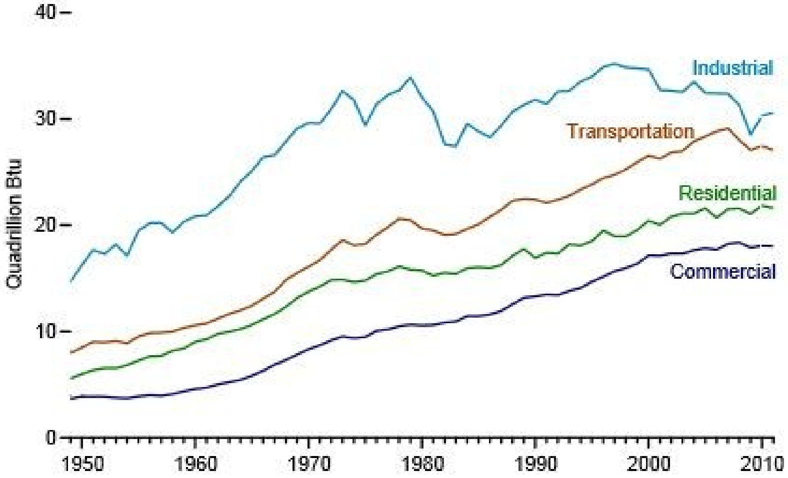


Figure 1.6: Total Consumption by End-Use Sector, 1949 – 2011 (U.S. Energy Information Administration, 2012)

Manufacturing activities were also responsible for 19% of the world's greenhouse gas (GHG) emissions as of 2004 (Herzog, 2009). Neither trend is expected to be abated in the near future. Instead, the U.S. Department of Energy predicted in 2011 that world energy consumption would increase 53% between 2008 and 2035 driven by the continually growing demand in the industrialized world and the expanding industrial economies in countries like India and China (Gruenshpect, 2011). According to a study conducted by McKinsey Global Institute (2007), the estimated untapped potential to increase energy efficiency is 16-22% of the global industrial end-use energy demand.

The utilization of energy varies from industrial sector to sector. Figure 1.7 below shows the more energy intensive sectors with, not surprisingly, process industries like petroleum and chemicals leading consumption. But, the manufacturing industries consume a significant amount of energy not related to process energy for feedstock conversion or heating. Industries such as transport equipment, machinery manufacturing, computer and electronics manufacturing use energy for direct production of consumer products. Manufacturing consumes a significant amount of energy, which results in significant global impact on CO_2. Thus it is important to look at reduction of energy consumption in manufacturing.

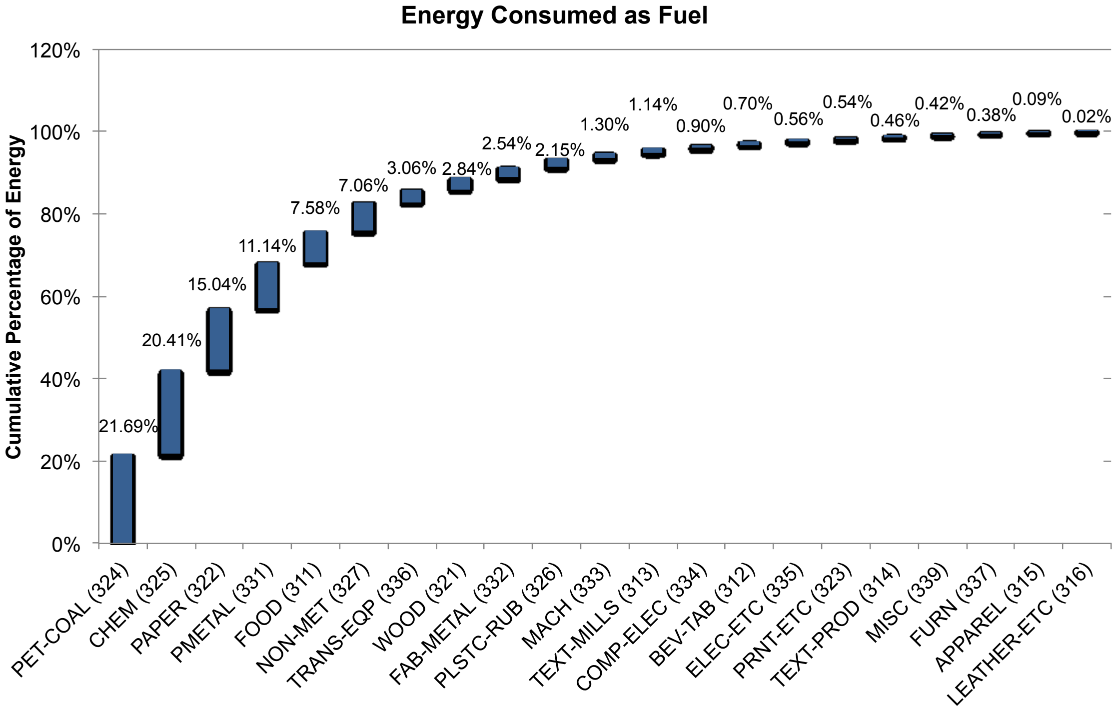


Figure 1.7: Cumulative percentage of energy consumption for the U.S. manufacturing sectors in 2006 (data sourced from (U.S. Energy Information Administration, 2009))

Energy is not the only resource at risk. Water and material use are also very important and used in great quantities in the manufacturing industry. In 2005, 4% of total water withdrawals came from industry (Barber, 2009). Domestic materials consumption increased by 30% in the industrial sector from 1975 to 2000 (Rogich, Cassara, Wernick, & Miranda, 2008).

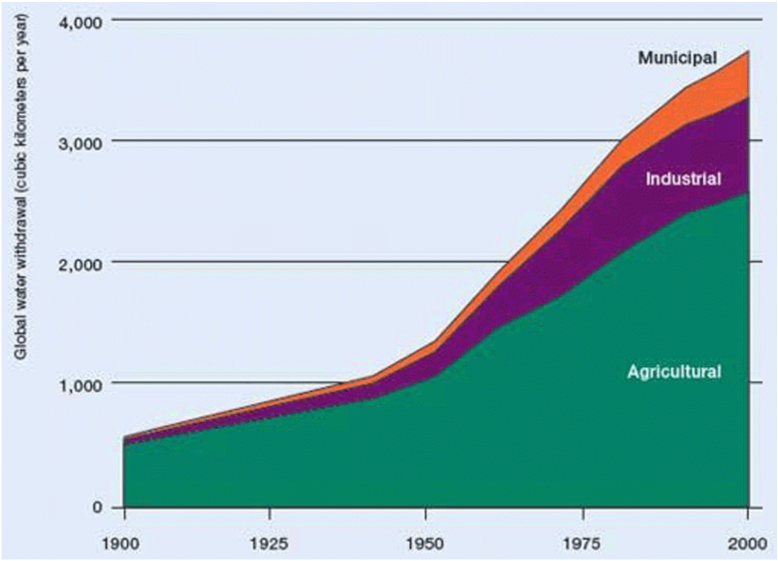


Figure 1.8: Trends in global water use by sector (Shiklomanov, 1999)

On the other hand, there are some situations in which the resources utilized in manufacturing and their impacts are relatively small or insignificant contributors to the life cycle impact of the product. This is true for products that have their biggest impact in the use phase, not rather than in the manufacturing phase. In these situations it is worthwhile to consider the potential for improved manufacturing techniques to reduce the impact of the product during its use phase. This is often referred to as leveraging (Dornfeld, 2011). Leveraging identifies manufacturing-based efficiencies in the product that are due to improved manufacturing capability but which, in the long run, have their biggest effects on the lifetime consumption of energy or other resources or environmental impacts (Dornfeld, 2011). Manufacturing should leverage improved product quality to drastically improve the environmental impacts and subsequently the total cost of ownership of their products. According to Dornfeld (2011), leveraging manufacturing means exploiting the trade-off between manufacturing and other life cycle stages by utilizing increased manufacturing resources through enhanced processes to generate even larger resource savings during subsequent life cycle stage.

Dornfeld (2011) also presents an example using the aircraft industry to illustrate the concept of leveraging. This example relates to improved machining tolerances and their impact on product performance. On an aircraft airframe (a large one like a B747 or the A380) savings in weight correspond directly to savings in fuel, and many other aspects of an aircraft scale with weight. If the machining process for large airframe components is under control and precision manufacturing principles are applied, a reduction in machining tolerances from approximately +/-150 microns to +/- 100 microns on the features of the airframe can account for a weight reduction of 4500 kg/aircraft and substantial fuel savings (8%) (Thompson, 1995). This allows an increase of 10% in passenger load (the engines don't need to carry as much plane), or increase in cargo payload and a substantial reduction in manufacturing cost of the aircraft (less material and improved assembly) and the accompanying reduction in scrap. And less fuel consumption means reduced CO_2 impact from aircraft operation. The accumulated savings over the life of the aircraft are incredible. The fuel consumption per km is estimated at 11.88 L/km (or about 5 gallon per mile). Thus, the CO_2 emission rate can be estimated at 30.64 kg/km ("Math! how much CO_2 is released by aeroplane?," 2007). A reduction in fuel consumption of 8% results in a reduction of almost 2.5 kg/km CO_2. And this is over the life of the aircraft – many millions of kilometers.

Manufacturing has had a significant influence on global development and growth, a trend that is likely to continue due to increased demand for consumer goods from a growing world population with improving quality of life. Thus, manufacturing plays a critical role within modern socio-economic systems, and will be a valuable contributor to wealth generation and job creation, especially in developing economies, for years to come. However, manufacturing activities also represent a significant burden on the environment. For example, in 2006, the U.S. manufacturing sector accounted for \$1.65 X 1012 (12.3%) of industry gross domestic product (U.S. Department of Commerce, 2013), but was responsible for 36% of carbon dioxide emissions within the U.S. industrial sector (U.S. Department of Commerce, 2010).

1.3 Sustainability and Manufacturing

1.3.1 What is Sustainability?

The concept of sustainability emerged from a series of meetings and reports in the 1970s and 1980s, and was largely motivated by environmental incidents and disasters as well as fears about chemical contamination and resource depletion. As pointed out in the 1987 Brundtland Report, Our Common Future (World Commission on Environment and Development, 1987):

> *"Major, unintended changes are occurring in the atmosphere, in soils, in waters, amount plants and animals. Nature is bountiful but it is also fragile and finely balanced. There are thresholds that cannot be crossed without endangering the basic integrity of the system. Today we are close to many of those thresholds."*

Thus, sustainability necessitates the need for a performance level that may be contrary to humanity's rational desire for continuous development and growth. This distinction was addressed in the term sustainable development, defined by the Brundtland Report as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). The 2005 United Nations World Summit further posited that three interdependent and mutually reinforcing pillars exist to support sustainable development: economic development, social development, and environmental protection (United Nations, 2005). These three interdependent pillars have been referred to as the triple bottom line (i.e., people, profit, and planet) and other related terms that evoke a holistic world view.

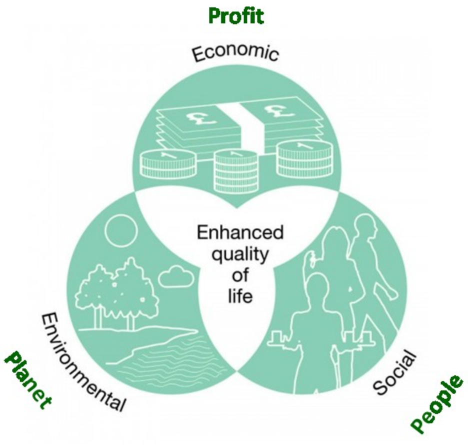


Figure 1.9: Three legs of sustainability or triple bottom line

1.3.2 Sustainable Manufacturing

According to Doug Jones, National President of Engineers Australia (Engineers Australia, 2013):

> *"It is up to engineers to consider sustainability in every project they design and construct and every product that is made. Sustainability is now a fundamental responsibility that all engineers must carry every day... We need to respond to the overarching responsibility for engineers in the application of our engineering education, training and experience to provide excellent sustainable engineering solutions for the benefit of our employees, clients and the community."*

Manufacturing is a business function, and, as such, engineers are well-versed in establishing the economic value of engineering solutions for manufacturing. Measuring environmental and social performance presents a more challenging engineering and business task. Sustainability-related impacts result from operations and activities that manufacturing processes and systems employ to convert input materials and energy into marketable products. Material and energy are necessary inputs of manufacturing processes and systems; wastes and emissions, which are generally classified as outputs, are, in turn, inputs to other industrial and natural systems, where their impact is felt socially, environmentally, and economically (see Figure 1.10) (Haapala et al., 2013).

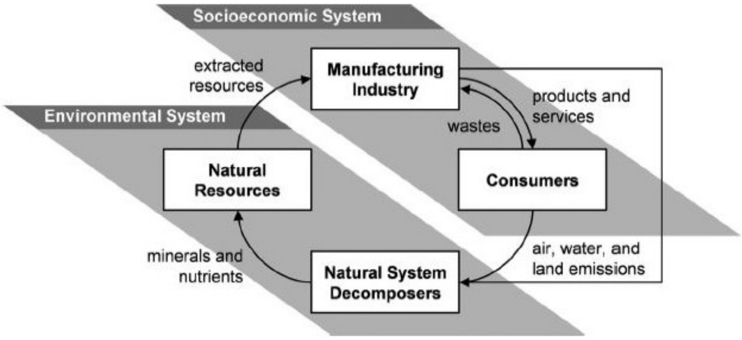


Figure 1.10: The role of the manufacturing industry in a sustainable system (Haapala et al., 2013)

Although widely accepted, the Brundtland Commission definition of sustainable development, presented above, is not an operational one for business and engineering decision makers in manufacturing. Mihelcic et al., proposed a definition relevant to engineering contexts as the "design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment" (Mihelcic et al., 2003).

According to the U. S. Department of Commerce (2012), sustainable manufacturing is "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound." Although many definitions have been proposed for sustainable manufacturing, a broadly accepted definition is not available to date.

Sustainable manufacturing requires simultaneous consideration of economic, environmental, and social implications associated with the production and delivery of goods. Fundamentally, sustainable manufacturing relies on descriptive metrics, advanced decision making, and public policy implementation, evaluation, and feedback (Haapala et al., 2013).

The research presented in this dissertation focuses specifically on developing metrics, methods and tools to address these issues. The methodologies and tools that this research specifically focuses on are aimed at advancing decision making to help the engineer to understand how to construct and operate systems that minimize negative environmental impacts and conserve energy and natural resources.

1.4 Business and Industry Drivers

Within industry there are several motivators for companies to reduce their energy and resource consumption as they try to build a more sustainable business practice. These concerns have come to the forefront in a number of ways. In no particular order, these include:

- *Pressure from Government* – this is from both individual governments at the state (like California) or national level as well as regional governments, like the European Union. Governmental pressure is often implemented as:
    - Regulations – recently a number of requirements for product performance, material composition, energy usage, etc. have been implemented
    - Penalties for lack of compliance which add cost of operations until the cause is resolved
    - Tax benefits and other incentives for complying or taking action
- *Cost reduction* – rising costs of energy and materials (also see bullet below)
- *Scarcity of resources/risk* – for processes or systems that rely on continuous supply of basic resources, including materials and water, reducing the dependency on these resources as well as reduced energy can reduce or eliminate risk from interrupted supplies or large cost fluctuation due to varying supply or demand or currency exchange rates
- *Continuous improvement* – improving process efficiencies is a key element
- *Operational efficiency* – wanting to be more efficient in their day to day operations
- *Interest in efficiency / reduced cost of ownership (CoO)* – reducing waste is a basic element of manufacturing
- *Pressure from society / consumers / customers* – consumers are increasingly aware of the need to reduce environmental impact of products, including their manufacture. For manufacturing machinery, the customer can be other manufacturers who are focused on reducing waste and consumption of energy and resources
- *Corporate responsibility* – wanting to do the right thing, wanting to be more transparent, and wanting to be more sustainable
- *Stakeholder expectations* – consumers' increasing awareness of sustainability and sustainable products, dealers' customers wanting information about the products that they are selling (consumer demand)

- *Market competitiveness* – companies are beginning to look at sustainability as a way to stay competitive, needing to keep up with competitors
- *Pressure from competitors* – in response to the societal and consumer drivers listed above, many companies use their efforts and advances in reducing the environmental impact and consumption of their products or systems as part of marketing strategies that show both reduced cost to operate and environmental benefits as an advantage
- *Maintain market leadership* – if you are already known as a leader in technology or performance you can add environmental leadership to your list
- *Standards and regulations* – looking ahead to a possible increase in legislation, limitations and penalties possibly being imposed by government to limit industry's energy use and environmental impact
    - Energy: GHG emission limitations
    - Water: Water discharge limitations
    - Waste: Spill and remediation requirements, hazardous material/waste shipping requirements
- *Risk avoidance* – supply chain reliability
- *Understand supply chain effects* (What's happening outside the facility?)—this is the hidden part of manufacturing – the part that is not directly controlled. Many examples of problems related to materials or other effects from unknown links in the supply chain exist. Most of these were unknown to the final producer and cause substantial problems (Dornfeld, Yuan, Diaz, Zhang, & Vijayaraghavan, 2013).

Many companies are finding that building sustainability, or at least green business practices, into their business plans makes good business sense. A recent survey from MIT Sloan and the Boston Consulting Group (2011) shows that overall this makes good sense, especially for more innovative companies. The first steps are waste reduction and resource efficiency improvement. More importantly, the more innovative companies see that part of the business case is that being sustainable is necessary to be competitive. This applies across many different industry sectors but is especially true for "manufacturing" companies – companies in the automotive, industrial goods and machinery, construction and commodities sectors (see Figure 1.11).

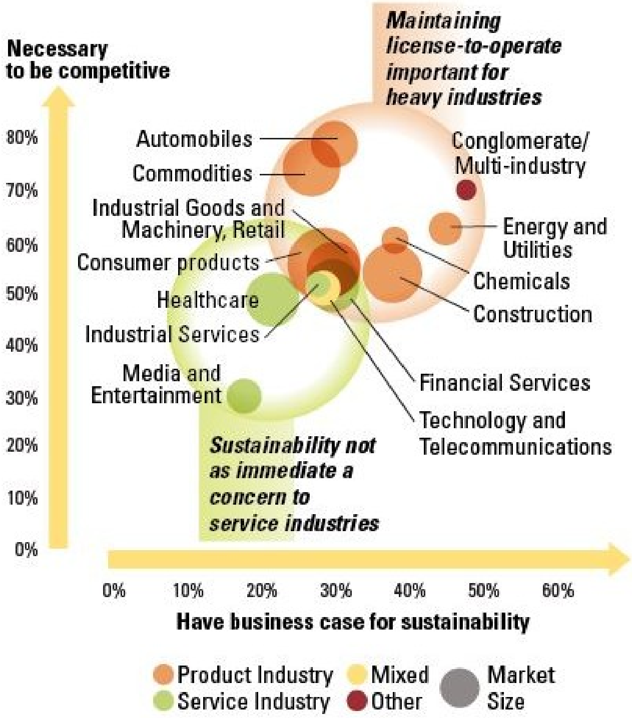
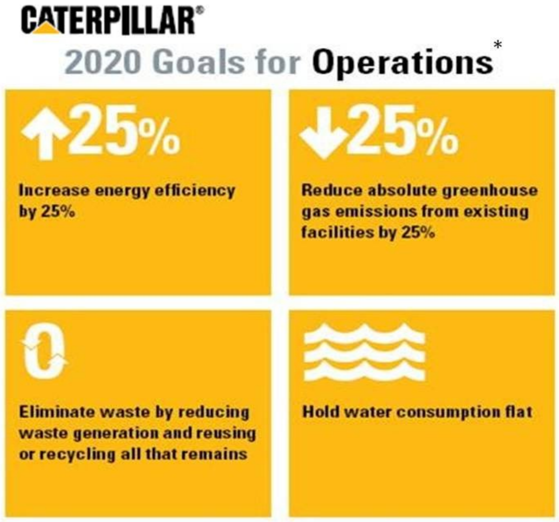


Figure 1.11: Sustainability "heat map" comparing industry segments on the basis of sustainability being necessary to be competitive and on the existence of a business case for it (MIT Sloan & The Boston Consulting Group, 2011)

The previous list above presented some of the motivations for why companies are reducing their energy and resource consumption and are building a more sustainable business practice. According to the survey results, some of the top business case drivers as to why companies adopt sustainable business plans are as follows:

- Improved brand reputation
- Increased competitive advantage
- Access to new markets
- Increased margins or market share due to sustainability positioning
- Reduced costs due to energy efficiency
- Better innovation of product/service offerings
- Improved perception of how well company is managed
- Reduced costs due to materials or waste efficiencies
- Improved regulatory compliance
- Improved ability to attract and retain top talent
- Enhanced stakeholder/investor relations
- Reduced risk
- Increased employee productivity

Faced with growing environmental concerns, mounting public pressure, and stricter regulations, manufacturers are developing plans to further incorporate sustainability into their practice. They also understand the importance of tracking their performance, and publicly committing themselves to reducing their resource consumption by striving to set and achieve sustainability-oriented goals. For example, Caterpillar Inc. published in their annual sustainability report their 2020 Goals for Operations. Caterpillar aims to increase energy efficiency by 25%, reduce absolute greenhouse gas emissions from existing facilities by 25%, eliminate waste by reducing waste generation and reusing or recycling all that remains, and holding water consumption flat (as shown in Figure 1.12).



*from 2006 levels

Figure 1.12: Caterpillar’s 2020 Goals for Operations (Caterpillar Inc., 2013)

Growing environmental concern has made it important for manufacturers to fully understand and characterize their processes, tools, and equipment to meet increasing regulations and customer demands.

1.5 Organization

This dissertation is organized as follows: Chapter 1 has discussed the motivation of this work including industry drivers for sustainable manufacturing. Chapter 2 will cover background material, the organization of manufacturing with some details on prior work in the literature, existing tools, and the specific parts of the manufacturing activity that is focused on in this work. Chapter 3 lays out the metrics, methodology, scope, and protocol required for process assessments. Chapter 4 introduces the background necessary for the Caterpillar case study, including detailed descriptions on the manufacturing processes use. Chapter 5 introduces a methodology for assessing manufacturing process chains. Chapter 6 looks at some examples of applying the methodology, and Chapter 7 summarizes and concludes the research and talks about future work.

Chapter 2

Manufacturing Systems and Analysis Tools

2.1 Manufacturing Processes and Systems

Manufacturing can be defined as the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes the joining of multiple parts to make assembled products (Groover, 2001). The processes that accomplish manufacturing involve a combination of machinery, tools, power, and manual labor, as shown in Figure 2.1a. Manufacturing is almost always carried out as a sequence of operations. Each successive operation brings the material closer to the desired final state. From an economic viewpoint, manufacturing is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations, as shown in Figure 2.1b. The main point here is that manufacturing adds value to the material by changing its shape or properties or by combining it with other materials that have been similarly altered (Groover, 2001).

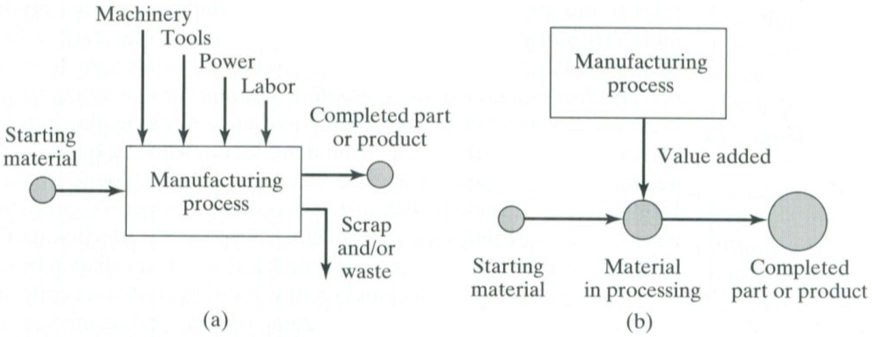


Figure 2.1: Alternative definitions of manufacturing: (a) as a technological process and (b) as an economic process (Groover, 2001)

Manufacturing covers a wide range of processes, machines, facilities and enterprise activities. For companies utilizing suppliers as part of their process they will also have complex supply, and distribution networks that must also be considered as part of "manufacturing." One convenient way to represent this complex "organism" is what one might call a "Google Earth" view of manufacturing (see Figure 2.2). This shows the range of manufacturing activities from the process and tooling level to the machinery and systems involved up to the factory and enterprise level. At each level the opportunities for impacting energy and resource use are different – some affecting the process, some the machinery performance, some the organization, etc. Starting at the factory level, there are various "scales" of systems and processing range from the enterprise level, to the factory level, to the production line in the factory, to individual machines and then down through tooling and setup on the machine. Finally, we see the tool/work process interface. At each of these levels, opportunities exist for green technology wedges. At the manufacturing level, one could focus on the plant/HVAC, food service/cafeteria, human relations and other office functions, management, packaging and shipping, and associated waste. At the processes and systems level this could include energy, water, materials, consumables, compressed air, and associated waste. Finally, at the machinery and tooling level this could include tool design, setup, operation, maintenance, and other waste.

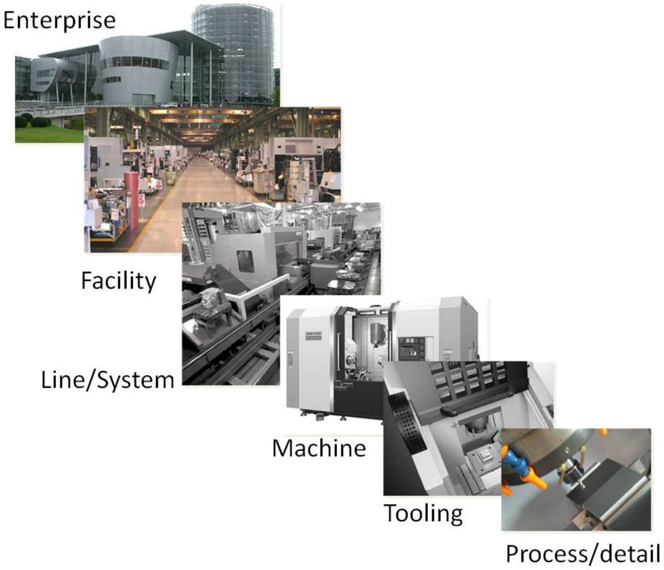


Figure 2.2: Different levels of the manufacturing hierarchy from the enterprise down to the process level. This is referred to as the "Google Earth" view of manufacturing (Dornfeld, Wright, Vijayaraghavan, & Helu, 2009).

The focus of this dissertation is on a specific section of this view of manufacturing, specifically the system level / line level within a factory. More detail on these various components of manufacturing will be discussed later. It will be seen that, at each level, a number of opportunities for improvement will exist.

Logically, the design of the product will greatly influence how it is manufactured, and what materials, processes, and systems it uses. While there are several definitions of the product life cycle, all include the four main stages (or phases) shown below in Figure 2.3: raw material extraction (removing constituent materials from the Earth or recycled products), manufacturing (converting new materials into products or remanufacturing older goods), use (using newly finished, reused, or remanufactured goods), and end of life (disposing of or recycling goods once obsolescence is reached) (Graedel & Howard-Grenville, 2005; Helu, 2013; Kalpakjian, 2006). Transportation is sometimes considered a separate life cycle phase, but transportation and distribution occur throughout the product life cycle. The complete supply chain is also an integral part of the product life cycle since these supply chains are required to produce, deliver, and collect a finished good for use or at end of life (Helu, 2013).

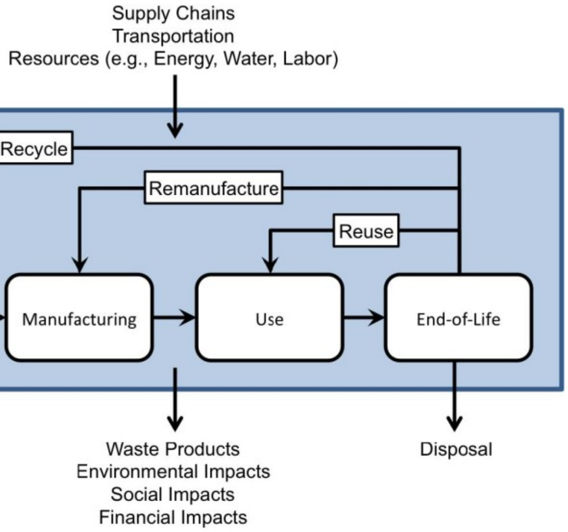


Figure 2.3: Schematic representation of the product life cycle (Dornfeld & Hutchins, 2013; Graedel & Howard-Grenville, 2005; Helu, 2013; Kalpakjian, 2006)

All phases are important and impact manufacturing. It is important to focus not just on the use phase of a product. As it has been shown in Chapter 1, the impact that the manufacturing phase has on resource consumption and the environment can be significant. For companies with diverse supply chains and distribution networks, the impact of transportation and associated facilities can play a large role. In this work, manufacturing is the focus, but one must be mindful of these other phases.

Another important consideration in the analysis is whether or not the major impact of the product is in the use or manufacturing phase as suggested above. Figure 2.4 illustrates the ranges of consumption and impact over the use and manufacturing phases of a product. The vertical axis shows the use phase consumption or impact (from low to high) and the horizontal axis shows the manufacturing phase consumption or impact (from low to high). Products that fall in the “high-high” quadrant are the least sustainable and products that fall in the “low-low” quadrant” are the most sustainable. For example, a typical automobile will have a much higher use phase impact than manufacturing phase. By contrast, a jacket would have a higher manufacturing phase impact than use phase impact.

To further explain Figure 2.4, the “high-high” quadrant is the worst case scenario and contains products that are the least sustainable, and one should avoid products with these features if possible. The two “high-low” quadrants represent products where one needs to either increase the efficiency of the product (with respect to design or using manufacturing leveraging – previously discussed in Chapter 1) or to improve the efficiency of the manufacturing process relative to use and manufacturing phases, respectively. Finally in the “low-low” quadrant are products that are the most sustainable, which is the best case scenario. This is the ultimate goal to achieve, to design products that have a low use phase impact as well as a low manufacturing phase impact.

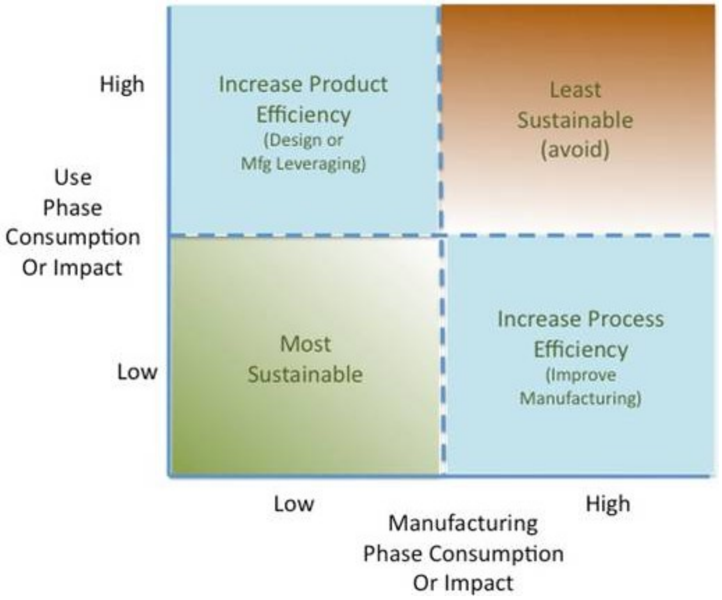


Figure 2.4: Regions of product performance (Dornfeld, 2013)

In order to reduce the rate of consumption or impact along either axis it is necessary to consider whether one comprehensive solution is feasible or, perhaps better, smaller incremental improvements are feasible. These smaller incremental improvements are referred to as “technology wedges” which, slowly over time, reduce the rate of consumption or impact. This can be applied to the use phase, manufacturing phase, or any phase in which more sustainable rates need to be achieved (see Figures 2.5 and 2.6). The “technology wedges” are based on a concept proposed by Pacala and Socolow to address the big gap between the present trajectory and impact of CO_2 on the atmosphere (business as usual -- BAU) and a sustainable level – and how to close this gap in 50 years (Pacala & Socolow, 2004). They argue that, rather than trying to find one “silver bullet” to correct this increasing mismatch between what we need and what we are doing, we should concentrate on “technology wedges” – small advances and improvements that, when added up, have the effect of a large change in the way we do business. Their wedges include efficiency improvements, carbon capture and storage from power plants, renewable power, etc. The specific wedges they propose are not the main interest here, but the idea has real merit.

These technology wedges make more sense in the context of manufacturing and sustainability. Figure 2.5 is a cartoon depicting the normal trend of consumption of a resource (water, energy, materials) or impact of that consumption (for example, GHG for energy) over time. A small reduction of either one results in a reduced rate of impact but does not provide enough change to achieve a sustainable situation. The application of technology wedges to, collectively bridge the gap between present rate of consumption or impact and a sustainable level is illustrated in Figure 2.6. With sufficient wedges, the gap can be closed. Individual wedges might be considered as "green" manufacturing steps (or "green" technology solutions). If there are sufficient greening steps, we can achieve sustainable manufacturing (as previously described in Chapter 1).

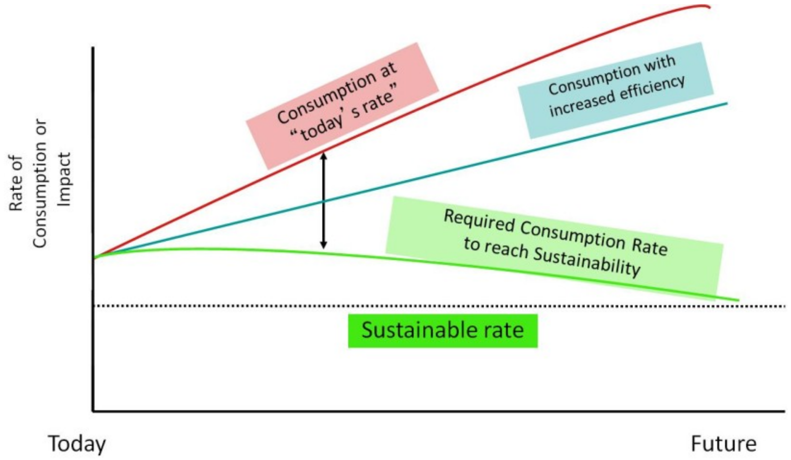


Figure 2.5: Illustration of consumption and impact over time (Dornfeld et al., 2013)

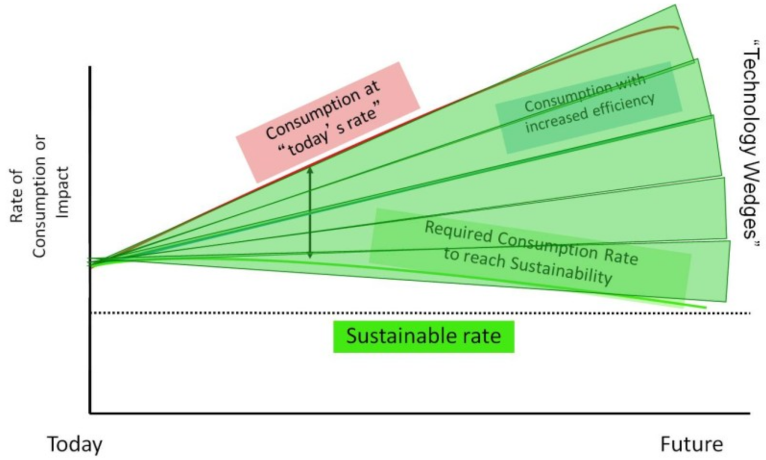


Figure 2.6: Illustration of sustainable consumption and technology wedges (adapted from (Dornfeld et al., 2013))

The goal of this research is to contribute a methodology for assessing the effectiveness of a specific "system-level" technology wedge.

2.2 Dimensions of Manufacturing

This section will look more closely at opportunities for improvement in manufacturing with respect to energy, material, water and other resource utilization. There are different dimensions to manufacturing which represent elements along a time line as going from product development to production similar to the product life cycle previously discussed (see Figure 2.3) or spatial elements such as the Google Earth view previously discussed (see Figure 2.2), moving from the enterprise level down to the process detail level. It is helpful to first define the different dimensions of the process, for example, time, space, product development, flexibility, etc. There is a continuum of influences on cost and material utilization as you go from product development through process chain design and then on to manufacturing. The main thing to realize is that at each one of these levels (Enterprise, Machine, etc.) there is a different set of issues that one is concerned about.

One of the first considerations in addressing green manufacturing strategies is to determine the extent of the product life cycle being addressed. Figure 2.7 illustrates the entire life cycle from extraction of material through material conversion (e.g., creating sheets and bars), manufacturing (e.g., forming, forging, cutting, and assembly), transport and distribution, use, and eventually reuse/remanufacture, recovery, or disposal. This is important since many consider only the middle "manufacturing" stage as the domain of interest. In fact, green manufacturing covers the entire spectrum since the embedded energy in the material used for production of machinery is dependent on the type and source of the material. Conversion adds energy and uses resources.

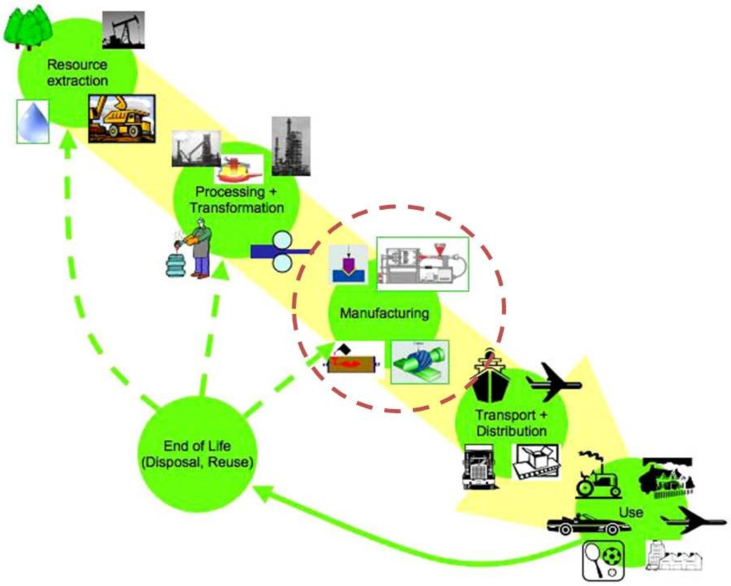


Figure 2.7: Phases of production and use (Dornfeld, 2010)

Most companies rely on complex supply chains and distribution networks so transportation and storage are important components of energy and resource use determination. Additionally, the end user, especially if the product is a machine tool or other production machinery or system, plays a significant role. So, really, green manufacturing and the technology wedges described above, are applicable all along the product life cycle.

Another axis of green manufacturing relates to the "control volume" over which metrics are applied and potential green technology wedges are implemented. Recalling the Google Earth view of manufacturing, if we zoom in on the level of process and machine (Figure 2.8) one can see that there are four potential levels of technology – the machine tool (and how it is built, and operated), the "macroplan" operation (or the sequence of operations on the machine(s) in production), the "microplan" operation (or the detailed process conditions for each step in the macroplan) and, finally, the systems of machines and how they operate together in the line or factory.

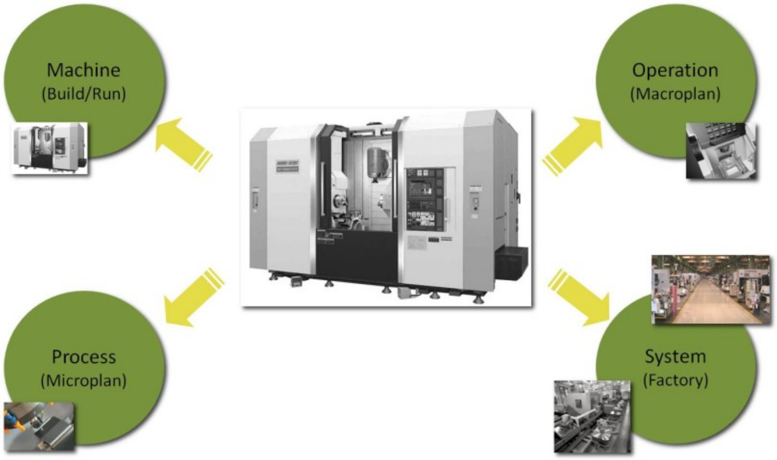


Figure 2.8: Greening… effects at different scales (Dornfeld, 2010)

At each of these levels there are a number of specific improvements or enhancements to be considered. For example, at the machine level, one can ensure that machine construction ensures minimum embedded energy, materials, resources per unit of performance (positioning accuracy, speed, thermal stability, etc. in machine tool frame and components), minimum operating energy (hydraulics, spindles, tables/axes, idle, energy recovery), and alternate energy sources for operation (fuel cell, solar, etc.) and energy storage/recovery capability. In addition, the working envelope can be optimized with minimized environmental requirements and machine work envelope/machine footprint minimization. One can also consider design for re-use/re-manufacturing/component upgrade.

At the process microplan level we can consider feeds/speeds for minimum energy roughing and finish machining, plans for minimum consumable use, efficient spindle/tooling design and optimized tool paths for high productivity and minimum energy. Several studies have already shown substantial energy reduction due to optimized tool paths in machining operations (Kong et al., 2011). At the system level we can consider energy "load balancing" over line/system and over the entire production facility or plant, resource/consumable optimization over the line, and minimized environmental impact over line/system and plant. Others demonstrated the potential energy savings resulting from system-level optimization to minimize machine idle time (and idle related energy consumption) while maintaining production levels constant (Diaz-Elsayed, 2013; Diaz-Elsayed, Jondral, Greinacher, Dornfeld, & Lanza, 2013).

Spatial and temporal views of manufacturing show the complex interactions between "where" manufacturing processes and activities are done and "when" they are done in the sequence. Figure 2.9 below represents an integrated view of manufacturing design levels and the decisions they contain, representing both the spatial and temporal elements of manufacturing.

Given the complexity and sophistication in the organization of manufacturing systems and processes, accurate environmental analysis requires a keen understanding of this organization. Manufacturing can be broken into "levels of study" across two orthogonal frameworks (Figure 2.9). From the perspective of the organization of the system, one can consider manufacturing processes as being composed of four levels, from the level of the individual devices where unit processes take place, through to that of the enterprise, incorporating all the activities in the manufacturing system, including supply chain externalities. Reich-Weiser et al. (2010) define these four levels are as follows:

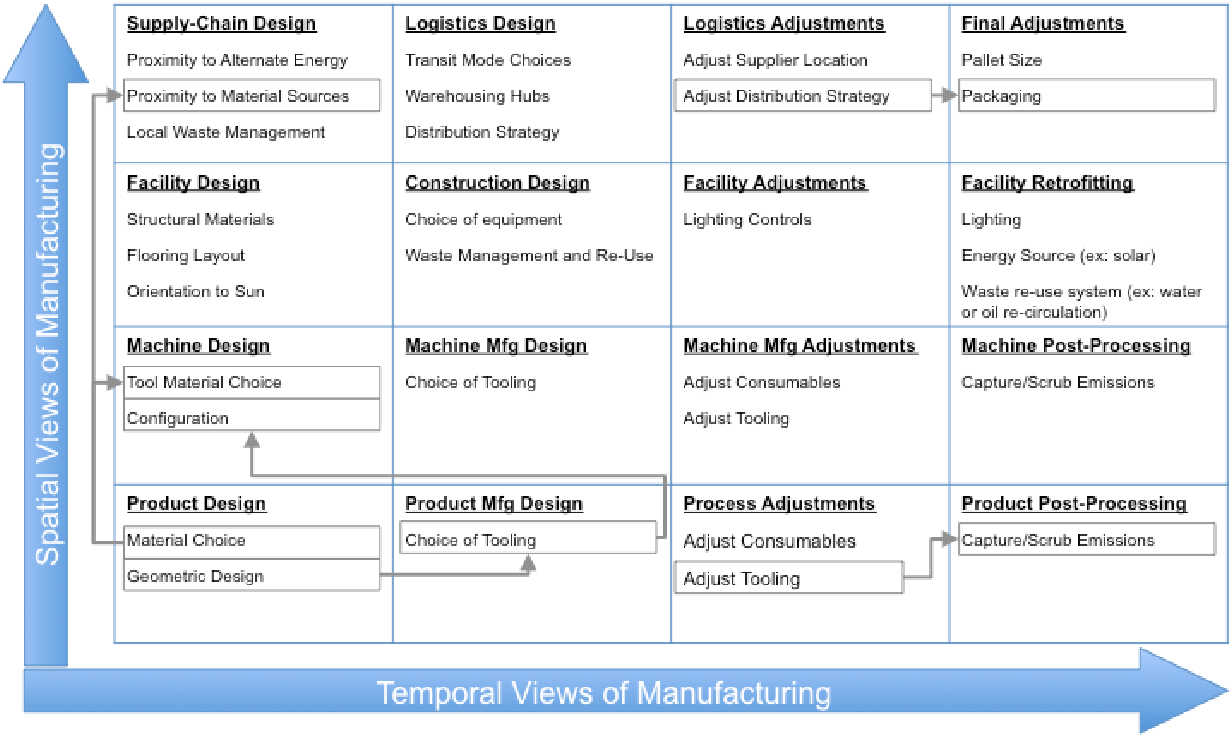
- Product feature – at this scale, product features are defined using specific process execution steps. Decisions on materials, modularity, and functionality are made that will influence all remaining decisions throughout the supply chain and manufacturing.
- Machine/device – defined as an individual device or machine tool in the manufacturing system, which is performing a unit process, this level includes support equipment such as gage systems, device level oil circulating systems, etc.
- Facility/line/cell – defined as a logical organization of devices in a facility acting in series or parallel to execute a specific activity (such as manufacturing a part or assembly). This also includes any distinct physical entity housing multiple devices, which may or may not be logically organized into lines, cells, etc.
- Supply-chain – the entire manufacturing enterprise, consisting of all the individual facilities, the infrastructure required to support the facilities, as well as the transportation and supply chain externalities.

An equally compelling and orthogonal view of manufacturing can be made through the design to manufacturing life cycle of the process being considered. Here, one starts with the design of the product, and works their way through the design of the manufacturing process, to process optimization, and finally post-process finishing and abatement. These levels are temporal in nature, and indicate the degree of control over the environmental impact of the manufacturing process. Reich-Weiser et al. (2010) define these four levels as follows:

- Product design – the earliest in design and manufacturing. At this stage there is the most opportunity to influence environmental impacts and decisions throughout all future stages. At Level 1, critical decisions on part precision, materials, and design for assembly/recycling are made. Here there is scope to design the product as well as its manufacturing process to satisfy specific requirements in all the criteria.

- Process design – the product design is fixed; however here a manufacturing process to suit this design is created. Flexibility to optimize the system is limited to known tools and processes that work with the specified design. Here there is extensive control over the performance of the process in all the criteria as allowed by the product design.
- Process adjustments – the basic manufacturing process is fixed, but small changes to the process through process parameter selection and optimization are used to control the critical features such as precision, burr formation, and energy or consumable consumption.
- Post-processing – post-process finishing and abatement processes are used in controlling the part-precision and the environmental impact; at this level there is no control over the process as it has already been designed.

Figure 2.9 illustrates the interaction between the four temporal and spatial levels described above. Moving up and to the right in the figure indicates a loss of decision-making flexibility (Reich-Weiser et al., 2010).



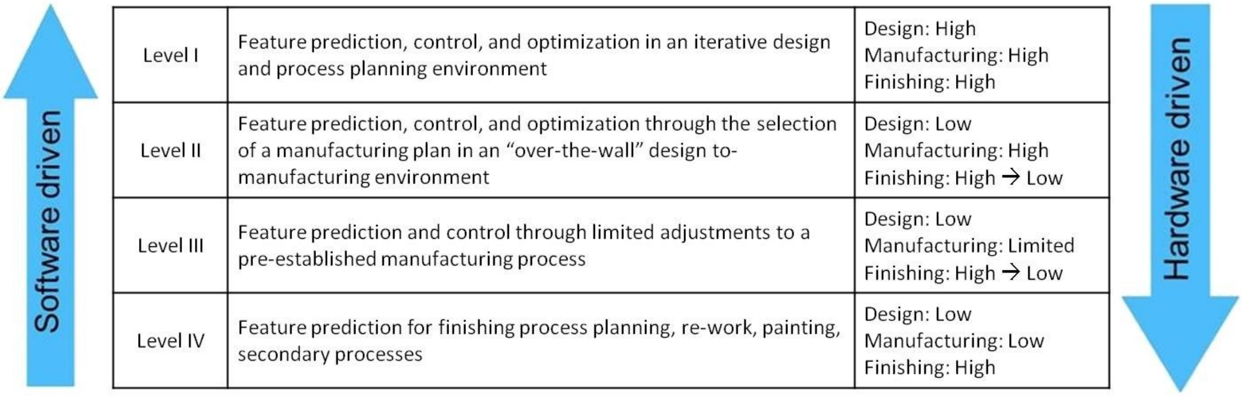
Supply-Chain Design Proximity to Alternate Energy Proximity to Material Sources Local Waste Management	**Logistics Design** Transit Mode Choices Warehousing Hubs Distribution Strategy	**Logistics Adjustments** Adjust Supplier Location Adjust Distribution Strategy	**Final Adjustments** Pallet Size Packaging
Facility Design Structural Materials Flooring Layout Orientation to Sun	**Construction Design** Choice of equipment Waste Management and Re-Use	**Facility Adjustments** Lighting Controls	**Facility Retrofitting** Lighting Energy Source (ex: solar) Waste re-use system (ex: water or oil re-circulation)
Machine Design Tool Material Choice Configuration	**Machine Mfg Design** Choice of Tooling	**Machine Mfg Adjustments** Adjust Consumables Adjust Tooling	**Machine Post-Processing** Capture/Scrub Emissions
Product Design Material Choice Geometric Design	**Product Mfg Design** Choice of Tooling	**Process Adjustments** Adjust Consumables Adjust Tooling	**Product Post-Processing** Capture/Scrub Emissions

Figure 2.9: An integrated view of manufacturing design levels and the decisions they contain (Reich-Weiser et al., 2010). *Arrows* represent the flow of information from one decision to another.

From these hierarchies – which span temporal and organizational levels – one can get a sense of the complexity involved in information capture and transfer in manufacturing systems. For effective decision-making, we need to understand both what quality and quantity of information need to pass between the levels and how decisions early on will percolate through the spatial and temporal levels.

Another consideration is the level of flexibility or control one has at different stages of the process (see Figure 2.10). If the levels of influence along the path from design to production are represented in four distinct levels - design, manufacturing process planning, production, and secondary operations/finishing, the level with the most flexibility as seen with respect to design and accompanying manufacturing processes, is level I. At this level little is finalized in either domain. At level II, manufacturing plan development, the design is more or less fixed and the task is to determine the production process to achieve it. At level III, on the factory floor, the machinery of production is in place and there is no flexibility for design changes at this point and limited process flexibility. Finally, at level IV, the final stages of production are implemented and there is no flexibility. Capable software tools that capture these design and production interactions will allow the maximum flexibility.

In general, the most effective way to address performance and impact in a product is to address this at the design stage. At that stage, one usually has the most flexibility. After design, process plans are developed, sequences of operations are set and the basic parameters of manufacturing are determined. At this point, there is not much flexibility in the design but some changes can be tolerated. Once production begins with real machines operating in real factory environments, little can be done to accommodate product variations for improvement. But, much can be done within manufacturing.



Level I	Feature prediction, control, and optimization in an iterative design and process planning environment	Design: High Manufacturing: High Finishing: High
Level II	Feature prediction, control, and optimization through the selection of a manufacturing plan in an "over-the-wall" design to-manufacturing environment	Design: Low Manufacturing: High Finishing: High → Low
Level III	Feature prediction and control through limited adjustments to a pre-established manufacturing process	Design: Low Manufacturing: Limited Finishing: High → Low
Level IV	Feature prediction for finishing process planning, re-work, painting, secondary processes	Design: Low Manufacturing: Low Finishing: High

Figure 2.10: Levels of influence along the path from design to production (adapted from (Dornfeld, 2004))

Finally, there is still another angle to this discussion – at what point along the path from design to production are the considerations determined that define resource and energy consumption? And, which among those considerations have the largest impact? Looking at the potential for improvement in resource consumption of manufacturing processes, one can anticipate that a considerable part of the energy and resource demand in manufacturing is determined during the production planning process. Figure 2.11 shows schematically the possibilities of influencing costs, and how the costs increase with the successive life phases of a product. One can see that the greatest influence and savings potential is located in the early phases of the production planning process.

It can be seen that these two curves in Figure 2.11 run in opposite directions. In the beginning phases, in which the engineer/designer has the most influence, the least is known about the future costs. It is obvious that during project and product planning the costs of a vaguely defined product are known only very roughly, whereas the possibilities of influencing these are the greatest. At the beginning of the product development process alternative paths can be chosen. At its end the lifecycle, costs of the product are largely set, even if they are still not known. In the phases of production, use, and disposal, still another cost optimization can be carried out. This optimization is of the individual processes, based on the development outcome. For example, if an automobile engine or drive train is fully developed then there is reduced leeway as far as manufacturing and operating costs are concerned. By a clever choice of production processes, or with especially cautious driving, one could still save on costs. The largest part of the lifecycle costs, however can be changed little, since they can be influenced only at the beginning of the lifecycle. It cannot be emphasized enough the importance of the early life phases for the product's success.

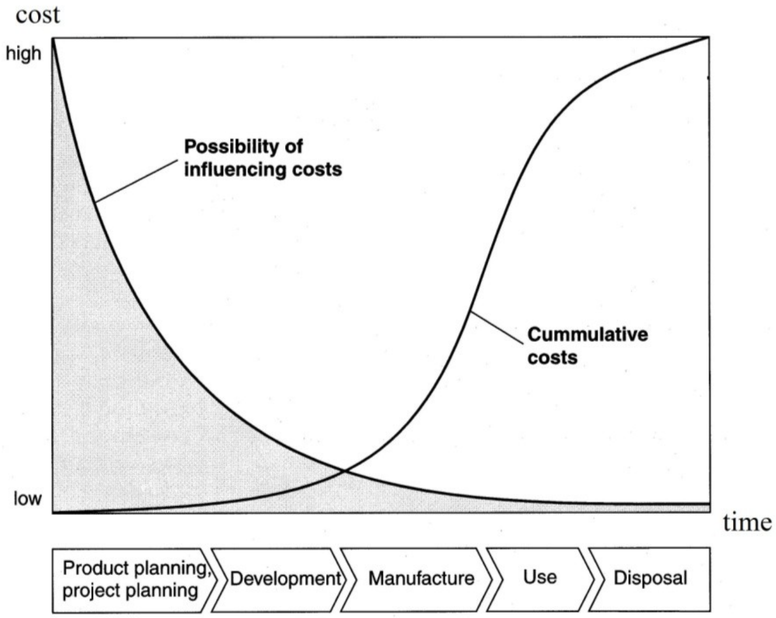


Figure 2.11: Possibilities of influencing and establishing costs over the lifecycle of a product: The "dilemma of product development" (an example of a new design) (adapted from (Ehrlenspiel, Kiewert, & Lindemann, 2007))

Finally, there is still another angle to this discussion – at what point along the path from design to production are the considerations determined that define resource and energy consumption? And, which among those considerations have the largest impact? Using similar logic as with the discussion above on Figure 2.11, if one zooms in on the product development to manufacturing phases, looking at the potential for improvement in resource consumption of manufacturing processes, one can anticipate that a considerable part of the energy and resource demand in manufacturing is determined during the production planning process (the phase in between the product development and manufacturing phases). The resources referred to here are energy, water, materials, etc. In Figure 2.12, one can see that the greatest influence and savings potential is located in the early phases of the production planning process (shaded area), also referred to as the process chain design. Here, resource costs include both resource consumption and cost ($). Although this traditional view is correct in many situations, it should not be interpreted that there is little need to consider manufacturing in terms of energy and resource efficiency. That is, process chain design is important along with other temporal considerations.

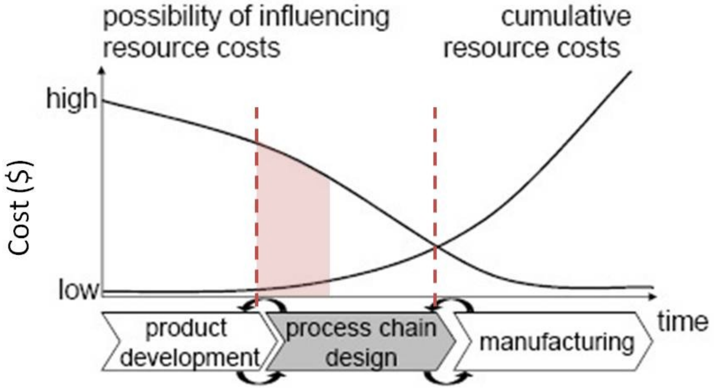


Figure 2.12: Resource costs and influencing possibilities during the production planning process (adapted from (Ehrlenspiel et al., 2007; Schrems, Eisele, & Abele, 2011))

As seen above, the process chain design phase links the product development and manufacturing phase. In the product development phase one is essentially looking at material selection and defining the performance of the product which will then have a large determination on which manufacturing processes can be used. The material section is greatly driven by the design phase and the desired function and performance of the product. As mentioned above, this greatly determines which manufacturing processes can be used, which in turn greatly drives the resource consumption of the manufacturing phase. Figure 2.13 below further shows how interconnected design and manufacturing are and how it is very important for communication regarding decisions made early in the product development cycle and the amount of influence that this has on resource consumption.

Figure 2.13 shows the flow of how materials are selected. In thinking about material selection, you have various materials and properties, design, and fabrication/manufacturing. One needs to balance all three. It is a given fact that if you have a design, one will infer some materials with certain material properties, then there will be some fabrication that will dictate the consumables. Functionality and performance drive design which drives material selection which drives manufacturing which then drives consumables. There is the material that goes into the process and then the fabrication process dictates the additional use of materials (tooling/consumables) as well as water and other resources.

As illustrated in the Google Earth view of manufacturing, there is a number of places (phases and interfaces between phases – for example, at the process level or the interface between process and tooling) to affect the impact. With that in mind, then, the product development process will influence several of these phases. If we represent the product development as in Figure 2.13 below, product development has, as its goal, the definition of certain product functions and performance specifications. In that sense, material selection will be one important decision. That clearly influences the manufacturing process selection and operating parameters. Defining the performance of the product will have an impact on its use phase resource consumption (for example, how an automobile manufacturing process capability, as with surface finish or tolerances in an internal combustion engine, will affect fuel consumption). In the process chain and design of the manufacturing phase one attempts (or should attempt) to leverage manufacturing to improve product use phase performance (if it's a use phase heavy impact product in which the manufacturing use is a small portion of the life cycle impact) and thus affect the performance of the product over time.

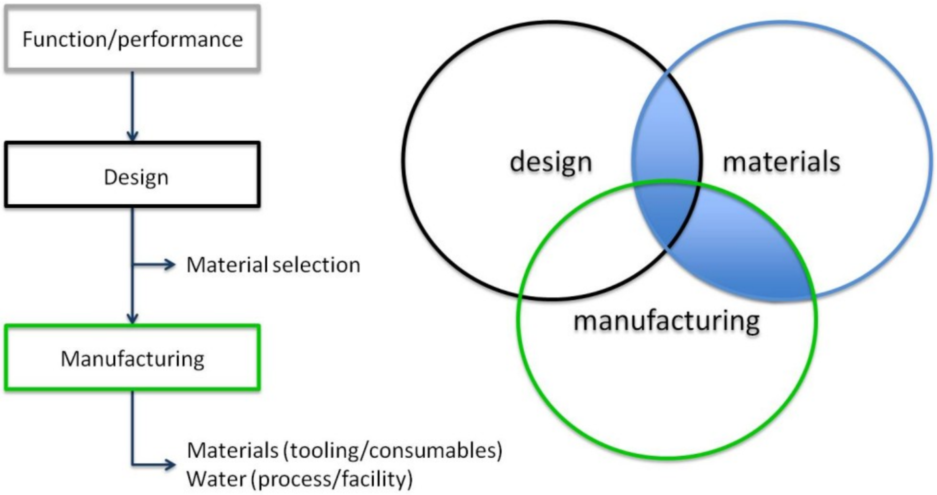


Figure 2.13: Influences on resource consumption within design and manufacturing

The specific focus of this research is on methodologies and analyses to influence process chain design with respect to resource consumption. This is accomplished, first, at the individual process level.

2.3 Production Systems

The term 'manufacturing system' is broad. Groover (2013) defines it as "a collection of integrated equipment and human resources that performs one or more processing and/or assembly operations on a starting work material, part, or set of parts. The integrated equipment consists of production machines, material handling and positioning devices, and computer systems". Manufacturing systems include both automated and manually operated systems. The distinction between the two categories is not always clear because many manufacturing systems consist of both automated and manual work elements (e.g., a machine tool that operates on a semiautomatic processing cycle but must be loaded and unloaded each cycle by a human worker). A production line consists of a series of workstations arranged so that the product moves from one station to the next, and at each station a portion of the total work is performed on it, as shown in Figure 2.14 (Groover, 2013). Although one tries to distribute and balance the work at each station to insure equal cycle times at each station, this is usually not possible and, hence, the production rate of the line is limited by its slowest station. In order to assess the performance of a production line, a series of variables and relationships can be used. These relations will not be discussed in depth here, but some basic terms and performance characteristics that define how material flows through the system will be covered.

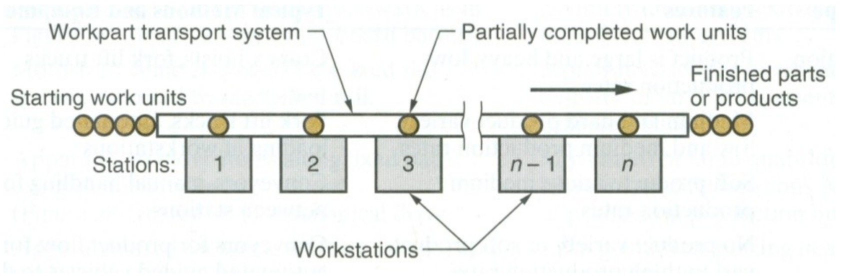


Figure 2.14: General configuration of a production line (Groover, 2013)

Process planning involves, according to Groover (2013), determining the most appropriate manufacturing processes and the sequence in which they should be performed to produce a given part or product specified by design engineering. Process planning includes (a) deciding what processes and methods should be used and in what sequence, (b) determining tooling requirements, (c) selecting production equipment and systems, and (d) estimating costs of production for the selected processes, tooling, and equipment. Process planning is one of the main functions within the manufacturing engineering department, whose overall goal is to optimize the production operations in a given organization.

In addition to process planning, the scope of manufacturing engineering usually includes other functions such as: providing staff support to the operating departments (parts fabrication and product assembly) to solve technical production problems, continuous efforts to reduce production costs, increasing productivity, improving product quality, and working with product designers to develop product designs that not only meet functional and performance requirements, but that also can be produced at reasonable cost with minimum technical problems at the highest quality possible in the shortest amount of time (also known as design for manufacturability). Figure 2.15 shows a typical sequence of processes required in part fabrication.

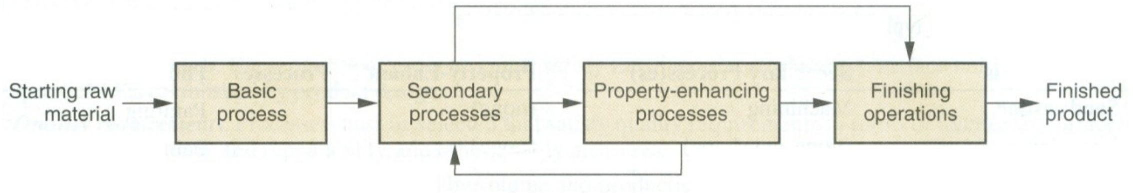


Figure 2.15: Typical sequence of processes required in part fabrication (Groover, 2013)

During the production planning phase, the specific processes used to manufacture the product need to be determined. The combination of these processes are called process chains which can be defined as a combined sequence of specifically arranged, single processes that are used to manufacture a product. The sequence is determined by the number of specific operations needed to complete the production steps as well as any precedence requirements (specific steps that must be done in a specific sequence – for example for a hole of a precise size at a precise location it might include: drill pilot hole, drill hole, ream hole – in that sequence.)

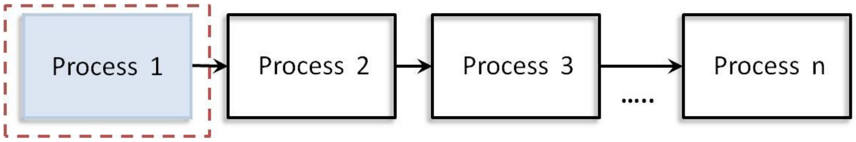


Figure 2.16: Schematic representation of a process chain

Systems of processes as illustrated in Figure 2.16 above are referred to as process chains. A representation of a typical process chain is illustrated in Figure 2.17 below.

Figure 2.17: Representation of a typical process chain (Machsources, 2012)

These process chains are a series of interconnected individual processes with measurable performance characteristics. Some of these characteristics will be reviewed below.

Performance characteristics of a manufacturing operation indicate the rate of flow of parts, the time it might take to process a specific batch of similar parts, the amount of work materials required by the process, etc. and, of course, quality measures. These help engineers and managers determine how much can be produced in a period of time, how long it might take to set up the operation and what kind of yield might be expected. Operation cycle time is defined as the time that one work unit spends being processed or assembled. It is the time between when one work unit begins processing (or assembly) and when the next unit begins. The cycle time is the time that an individual part spends at the machine. But not all of this time on the machine (at the process) is productive. In a typical processing operation, such a machining, cycle time consists of: (1) actual machining operation time, (2) workpart handling time, and (3) tool handling time per workpiece. Takt time is the pace at which the customer is demanding the part or product. In other words, takt time is how often one should produce one part or product, based on the rate of sales, to meet customer requirements. Takt time can be an external customer for whom one is producing the part or an internal customer (for example, another production line waiting for input from the previous line.) Takt time is calculated by dividing the customer demand rate per day (in units), into the available working time per day (in seconds).

In addition to production rates (assuming the line is fully functional), it is important to understand how often the facility, or process, or line, is able to produce. Utilization is the amount of output of a production facility relative to its capacity. Availability is a common measure of reliability for equipment. It is especially appropriate for automated production equipment. Availability is defined using two other reliability terms, *mean time between failure* (MTBF) and *mean time to repair* (MTTR). The MTBF indicates the average length of time the piece of equipment runs between breakdowns. The MTTR indicates the average time required to service the equipment and put it back into operation when a breakdown occurs. Availability is typically expressed as a percentage between the MTBF and MTTR.

To understand how long it might take for a batch of like products to pass through the production line, engineers determine the manufacturing lead time (MLT). MLT is the total time required to process a given part or product through the plant. Work-in-progress (WIP) is the quantity of parts of products currently located in the factory that are either being processed or are between processing operations. WIP is inventory that is in the state of being transformed from raw material to finished product. A fixed cost is one that remains constant for any level of production output (e.g., cost of production equipment, insurance, and property taxes). A variable cost is one that varies in proportion to the level of production output (e.g., direct labor, raw materials, and electric power to operate the production equipment).

Once the performance characteristics of the production line are understood, it is usually required to determine if the resources in production are being efficiently used. For example, is the flow of materials efficient or are there unnecessary steps included that cause a larger than needed cycle time? One common method used in industry to optimize these types of systems is value stream mapping. Value stream mapping (VSM) is a lean manufacturing technique used to analyze and design the flow of materials and information required to bring a product or service to a consumer (Wikipedia, 2013). Value stream mapping will not be covered in detail here, but an example value stream map is shown in Figure 2.18. By plotting the entire production chain, and material flows, non-productive time or excessive wastage of material can be easily seen and then corrected.

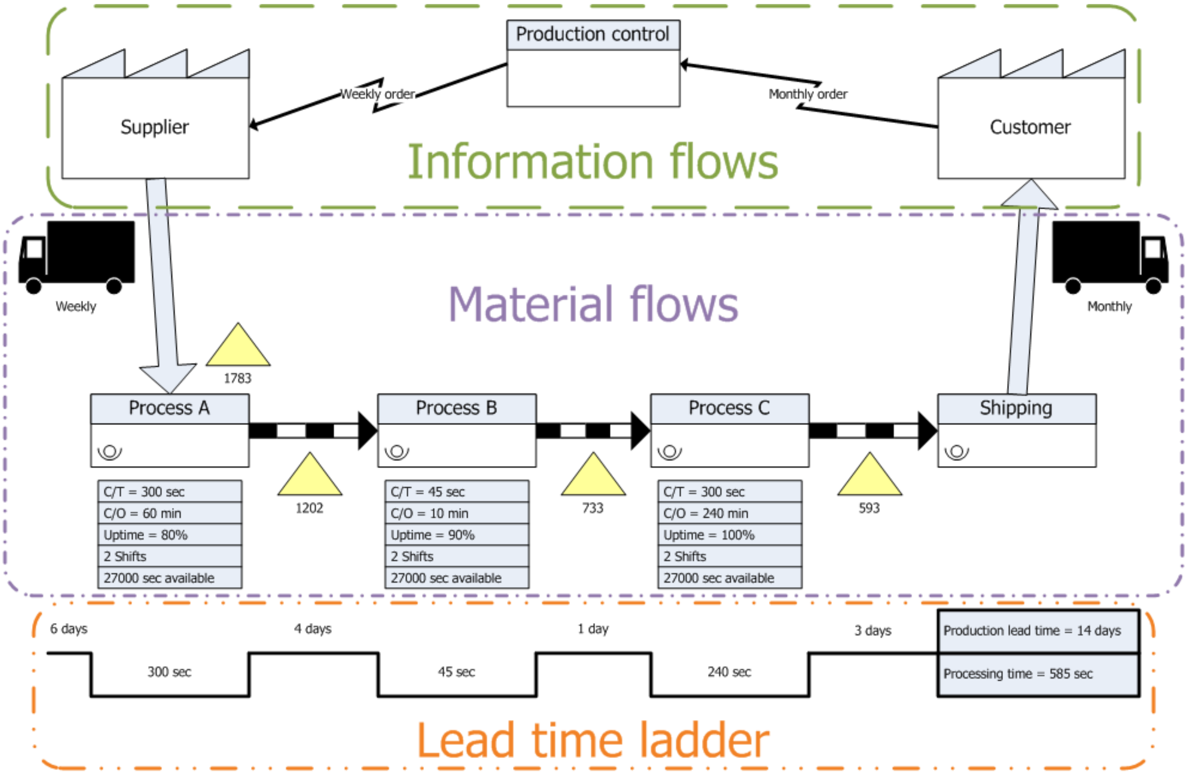


Figure 2.18: Schematic of typical parts of a value stream map (Wikipedia, 2013)

A typical process chain would exist at the system/line level of the Google Earth view (see Figure 2.2). As previously discussed, there are opportunities to make changes on all levels of the Google Earth view for manufacturing, but the research presented in this dissertation is focused on the system/line level and looks specifically at how to improve the process chain with respect to economic and environmental impact, for an existing facility. The assumption is that the manufacturing process chain (or system of production for a specific class of mechanical products) is determined and in operation in a production facility. This is the case with the Caterpillar production line that motivates this dissertation work. As such, this research can be used to consider improvements to various parts of the production process line to improve both quality and throughput, but at the same time gain an understanding of any impacts on the economic or environmental performance of the line.

The importance of determining all of the resources coming into and out of the system at all stages has been emphasized earlier in this dissertation. Primarily, manufacturers are concerned with determining the levels of resource, material and energy utilization and the associated costs so that an assessment of production cost as well as environmental impact can be determined. A second, significant concern (and the focus of this dissertation) is on determining which elements or process steps can be swapped or traded/replaced without penalty as part of the attempts to improve the operation of the production system. The ultimate goal is to understand how process technologies can trade-off without penalty to the overall effectiveness of the process chain from both a manufacturing and environmental viewpoint.

2.4 Balancing Process Chain Effectiveness and Environmental Impact

To remain globally competitive, manufacturers must increase the flexibility and speed of production systems and their supplier networks, while also reducing environmental impacts, material, and energy requirements (U.S. Environmental Protection Agency, 2003). These changes require a transformation from manufacturing practices based on experience and best practices towards science-based modeling, decision making, and production. This research presents a methodology for sustainability characterization to bridge the tools and data needed for sustainable manufacturing to help companies make this transformation towards more informed decision-making.

Many companies are trying to understand how process technologies can trade-off without penalty to the overall effectiveness of the process chain from both a manufacturing and environmental viewpoint. As a result, they are trying to balance these two constraints but at a higher level of abstraction and for larger systems. For example Siemens has developed what they refer to as the Eco Care Matrix (ECM) (see Figure 2.19). This ECM is used to determine system development strategy for large processing plants so that both environmental improvement is realized as well as economic gain.

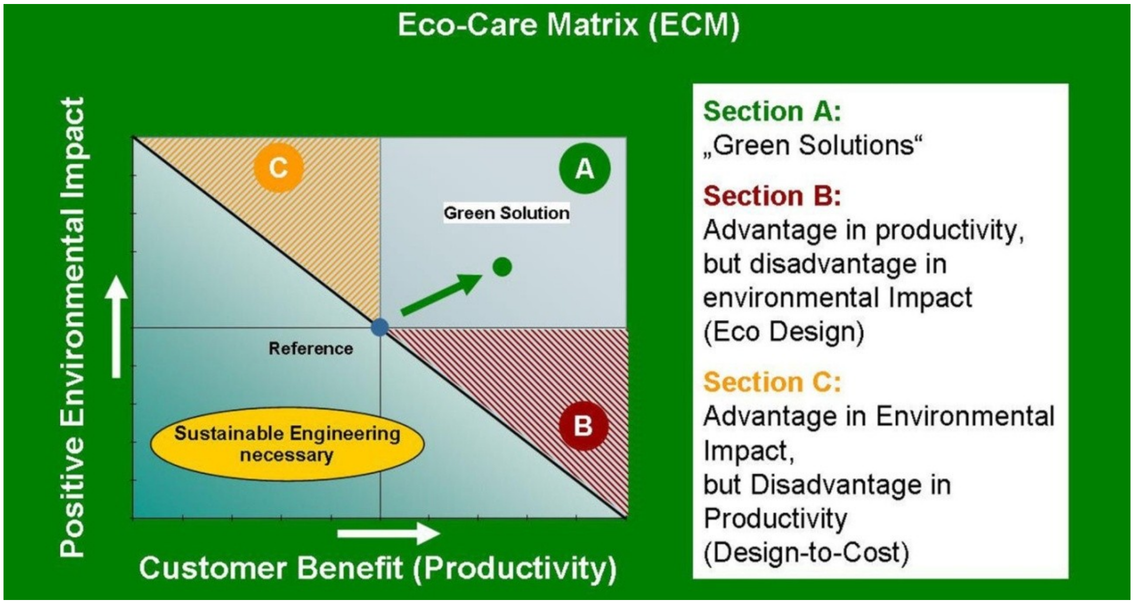


Figure 2.19: Siemens' Eco-Care Matrix (Siemens, 2010)

The ECM describes both dimensions of economic performance (horizontal) and environmental impact (vertical). An existing technology/product/solution is set as a reference in the center of the ECM. The to-be developed green solutions should be better in both eco-dimensions, i.e., eco-nomical and eco-logical. To describe the economical dimension it is favorable to use system costs e.g., CAPEX (capital expenditure) and OPEX (operating expense). The eco-logical dimension is described by the life cycle assessment (LCA) methodology and environmental impact categories (e.g., acidification potential, global warming potential, and eutrophication potential) (Wegener, Finkbeiner, Geiger, Olsen, & Walachowicz, 2009).

The ECM matrix works by first establishing a baseline or a reference point, as described above and then a way of measuring improvement. The approach illustrated in the Eco Care Matrix is a systems view, whereas the focus in this research is on the individual process and process chain level. One must establish a baseline for the performance of the system/process and track the potential improvements/changes. The ECM gives a broad overview as to where one is with one's system, but does not indicate specifically how to improve the system. The focus of this research is to do this kind of a trade-off analysis but at a much more detailed process level.

Within the Google Earth view, as previously discussed, there are many different levels within manufacturing ranging from the process/detail level to the enterprise level, all having an effect on the manufacturing impact. If one wanted to try to make a trade-off between the various impacts within the manufacturing phase, one might create an "eco-route map" (or a "resource-route map") in order to plan the journey through the manufacturing phase. Figure 2.20 shows the basic principle of the "eco-route map" showing the current process/systems and the desired improved process/systems. In order to achieve a more sustainable system, one must make trade-offs between savings/value and environmental benefit. Ideally one would optimize for both.

In order to make these trade-offs, one must have a baseline or an assessment of the current status of their system. Often it is useful to have metrics to measure the performance of the system. Some examples could be consumption, yield, waste/output, and recovery. Once the current status of the system is known, a strategy for improvement can be established. This strategy is the future state of the system that achieves a desired level of performance with respect to the list of metrics that were established during the baseline assessment of the system. This strategy establishes a path to move the system from the current state to the desired state (i.e., less sustainable to more sustainable).

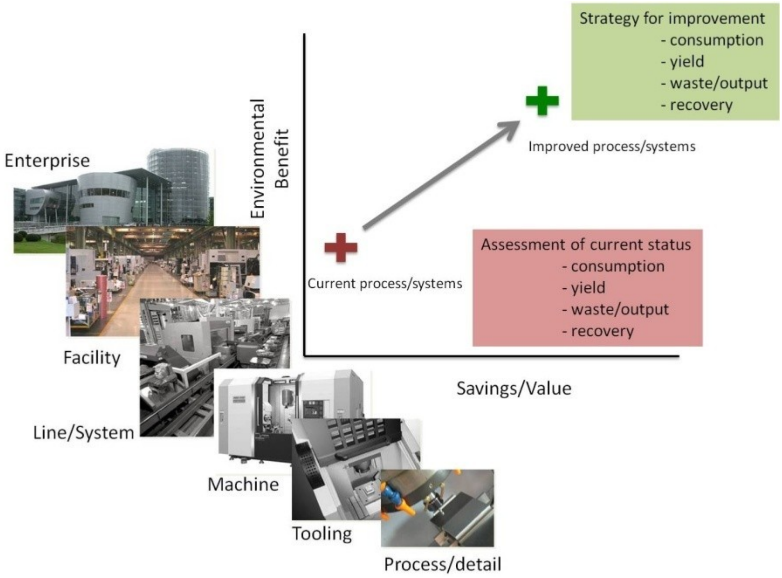


Figure 2.20: Eco-route map (Robinson & Dornfeld, 2013)

The path from the current process/system being examined to the improved process/system can be described on many levels. Figure 2.21 below shows the path as a journey through the different levels of manufacturing. For example, in order to get from the current state to the improved state, many "mini-strategies" can be utilized in looking at the various levels of manufacturing and how addressing each of those levels could move the system from the current state to the improved state. In deciding on the strategy, one must ask, where is the best place for improvement/investment within the organization? At which level(s) is the biggest opportunity for the largest effect on impact/value?

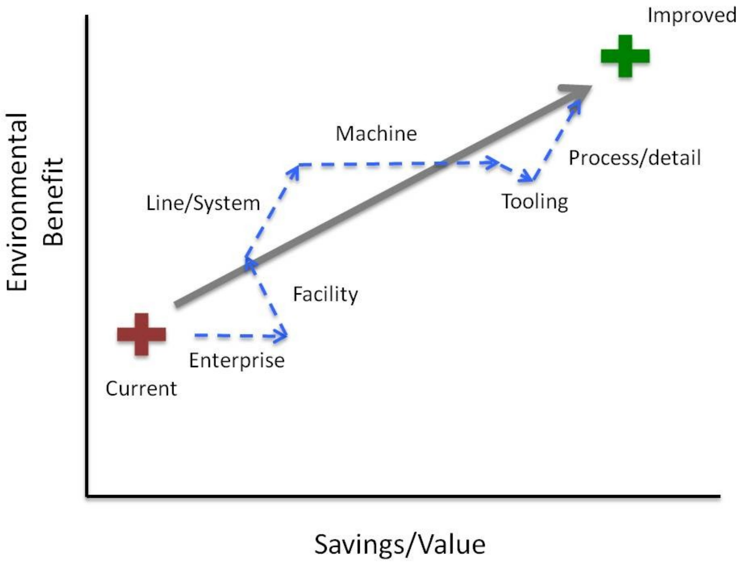


Figure 2.21: Eco-route map (Robinson & Dornfeld, 2013)

In order to answer this question, one should zoom in on the various levels to determine which improvement strategies can be most effectively utilized. For example, if one concentrates on the line/system level, one could look at things like: process sequence, line layout, hybrid processes, environment, and automation in order to improve. If one zooms in on the machine level, one could look at things like: operating energy and resources, standby energy and resources, machine structural design/mass-stiffness, environment, and automation in order to drive improvement.

In addition to looking at the system as a composition of levels of manufacturing, one could also zoom in on a specific level and define an eco-route map to address a specific level. For example, if one zoomed in on the system/line level, then they would be looking at the process chain level (as described earlier). They would be looking at a system/line composed of processes. One could then map this process chain or line of processes onto an eco route map (see Figure 2.22).

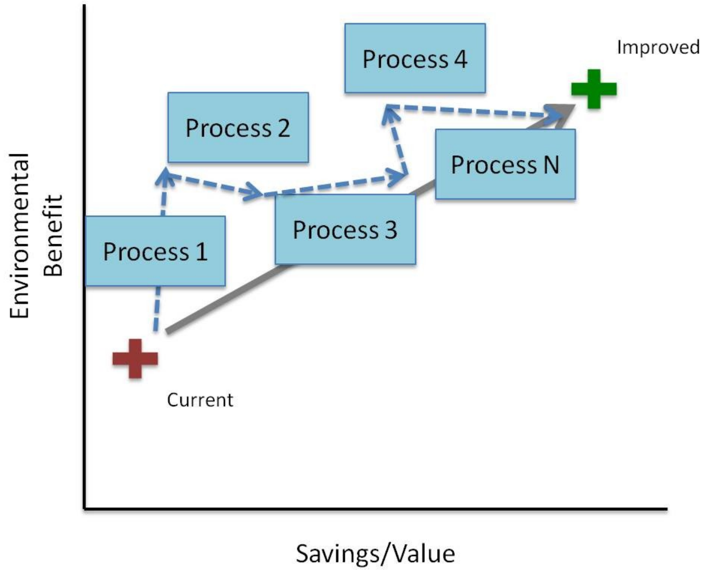


Figure 2.22: Eco-route map (Robinson & Dornfeld, 2013)

If one looks at the system from this point of view, then in order to get from the current state to the future state, it is necessary to go through a series of processes. One now needs to determine how to improve the combination of this series of processes in order to reach a more sustainable state. The question one must ask at this point, is, how can the most effective potential process changes/replacement or enhancements be determined?

To do this, it is necessary to assess the entire process chain. But, this cannot be done all in one step. In order to assess the process chain, one must zoom in on each individual process in the process chain to determine the individual inputs and outputs of each process before stringing the processes back together to identify the inputs and outputs to the process chain (see Figure 2.23). The research presented in this dissertation aims to do exactly this, to develop methodologies to assess manufacturing process chains in order to enable trade-off analysis for improved decision making. This particular methodology will be covered in more detail in Chapter 5.

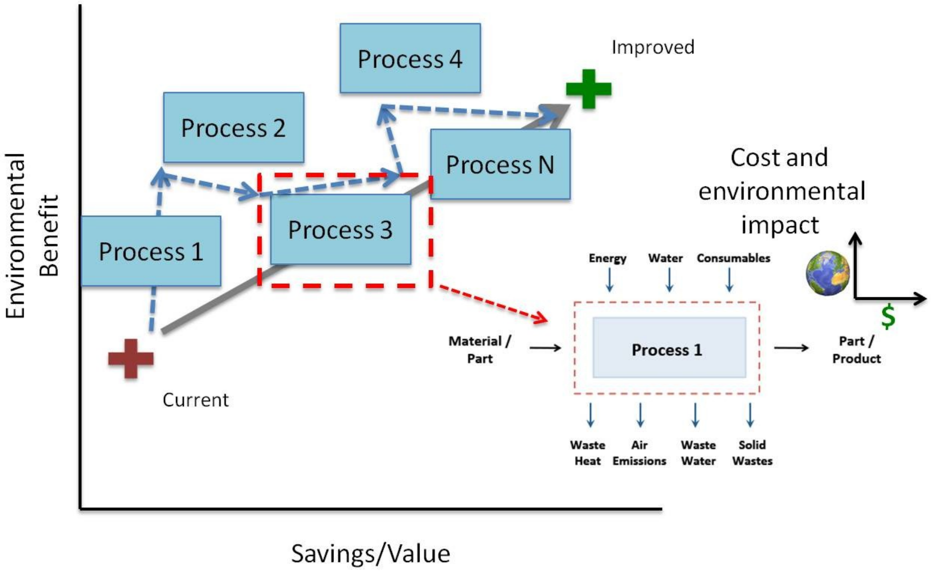


Figure 2.23: Eco-route map (Robinson & Dornfeld, 2013)

2.5 Prior Work on Manufacturing Energy and Resource Efficiency Analysis

The interest in understanding and improving the energy and resource efficiency of manufacturing has been growing over the last few years. The bulk of the literature focuses on studying several specific aspects, for example (1) facility level, (2) process-chain level, and (3) process level (Duflou et al., 2012). The relevant literature addressing work on analyzing the process chain and process levels will be reviewed here. As the facility level is outside the scope of this research it is not covered here. With respect to system optimization (as has been discussed in this chapter so far) there are a number of optimization techniques that have been developed for optimizing the flow and performance of manufacturing systems. But, with the exception of environmental value stream mapping (EVSM) these techniques do not address the environmental and resource issues associated with the systems.

2.5.1 Process Chain Level

Reviewing the literature around resource consumption of manufacturing process chains, it is obvious that there has been little work in the area of assessing resource consumption in process chain design. Much of the literature addresses the optimization with respect to traditional resources that are optimized in a process chain: time, money, throughput, production rate, etc. Several studies have created a modeling framework for process chain assessment (Schrems et al., 2011; Zhang, Wang, Yue, Jiang, & Zhao, 2011). However these are very high level concepts that do not address specific considerations that should be made when implementing these frameworks. Others are limited in scope and only focus on setting up a framework to estimate the energy consumption of machining process chains (Herrmann & Thiede, 2009; Weinert, Chiotellis, & Seliger, 2011). Some studies took this idea one step further and discussed how an energy modeling framework would be applied to a case study application (Schlosser et al., 2011; Thiede & Herrmann, 2011). However, little can be gathered from these studies because they do not actually apply the framework to the case study. Reinhart et al. (2011) carry out the application of the framework that they developed, but there is limited transparency as the results are displayed in an aggregate resource efficiency value, making it hard to see where the impacts are coming from.

2.5.2 Process Level

There have also been some studies that have looked at the resource consumption of individual manufacturing processes. They are similar in nature to the process chain assessment papers just discussed in the previous section. The only differences being that these studies only focus on assessing individual processes. Some studies suggest assessment frameworks to look at the energy consumption of specific individual processes (Duflou, Kellens, & Dewulf, 2011; Kellens, Dewulf, Overcash, Hauschild, & Duflou, 2012; Kuhrke, Schrems, Eisele, & Abele, 2010). Others specifically look at modeling the energy used in machining processes (Dahmus & Gutowski, 2004; Dietmair & Verl, 2010; Kara & Li, 2011; Verl et al., 2011). All of the papers mentioned that focus on individual processes consider only energy and no other resources. Much of the literature looks at characterizing the relationship between energy consumption and process variables for milling. Other work looks at assessing traditional material removal processes (turning and milling).

It is also important to note that these studies do not consider the environmental impacts of this resource consumption or the associated costs of the resource consumption. In summary, fabrication process chains are not well characterized with respect to resource consumption as they are not well represented or addressed in the literature. Additionally, there is a lack of data and data quality available with respect to the resource consumption tracked. Because of this, the resource consumption of manufacturing process chains is currently not able to be fully assessed. As a result, there is an inability to fully consider resource consumption when selecting among different fabrication process chain combinations.

2.6 Capability of Existing Assessment Tools

Due to the variety and quantity of definitions, tools and indicators, it has become more and more challenging to have an overview of existing work. This is especially true when it comes to the sustainability assessment in specific areas, e.g., for the assessment of manufacturing systems. There have been many reviews of life cycle assessment (LCA) software tools, but the focus of this review is on LCA software and assessment tools used to evaluate the performance of manufacturing systems. The suitability of existing assessment tools and their deficits are discussed in some detail here. Many have reviewed software tools used to assess manufacturing processes (Duflou, Kellens, Renaldi, Guo, & Dewulf, 2012; Duflou et al., 2011; Kellens et al., 2012; Mani, Madan, Hyun Lee, Lyons, & Gupta, 2012; Schabert, 2010).

Manufacturing industries lack the measurement tools and the needed databases to measure and effectively compare the performance of manufacturing processes, resources and associated services with respect to sustainability. The current use of ad-hoc methods and tools to assess and describe sustainability of manufactured products does not account for manufacturing processes explicitly and, hence, this results in inaccurate and ambiguous comparisons (Mani et al., 2012).

There are a number of approaches to addressing this challenge that have been proposed or tried in the past. Some are too complex and some are not sufficiently detailed to do the necessary analysis. The necessary analysis will consider both manufacturing characteristics (thru-put, quality, reliability, line availability, etc.) as well as environmental characteristics (material/water/energy use, source of materials and social impacts, environmental impact – GHG, etc.) This section will review some of the more prominent approaches and indicate benefits and limitations.

Performance measurement in general identifies the gaps between the current and desired performance, and provides an indication of the progress made towards closing the gaps. Performance indicators are used to organize data into formats that are easy for understanding, analyzing, and comparing purposes. Companies then use these indicators to set targets and monitor their performance. Traditionally, manufacturing related performance indicators provided information on the productivity and throughput, cost, quality, material, etc.

Performance measurements for sustainable manufacturing should include performance indicators and corresponding metrics (these at times can also be one and the same). A number of indicators have been proposed in the past for sustainability performance measurement (OECD, 2011).

It is well understood that the currently available LCA tools like GaBi (PE International, 2013) and SimaPro (Product Ecology Consultants, 2013), use Life Cycle Inventory (LCI) databases which are typically limited only to primary material production (e.g., sheets, and foils) and recycling processes (Kellens et al., 2012). General approximations made today for sustainability ignore the manufacturing-process related LCI and therefore result in inaccurate planning for cross comparisons and decision making. It has been shown that publically available LCI databases lack unit process data for most manufacturing processes and where the quality of what is available is often quite deficient (Kellens et al., 2012).

Software tools used for determining sustainability help reduce the amount of time taken for sustainability assessment. The tools generally rely on different LCI databases. From a review of the various environmental assessment software tools, it was observed that measurement of impact assessment for a product was based on the LCI database provided by different organizations. The major deficiency in these LCI databases is that details up to the level of individual manufacturing processes are not included. Furthermore, the information is region specific and the scientific basis of the LCI is unknown. For example, although LCI information is available for cast or rolled steel process, there is no information related to the numerous operations being performance on the sheet such as punching, blanking, shearing, and bending, etc. (Mani et al., 2012). Presently available software tools that depend on LCI databases are therefore incomplete when it comes to assessing manufacturing processes for sustainability. Mani et al. evaluated several LCA based software tools: GaBi (PE International, 2013), SimaPro (Product Ecology Consultants, 2013), Design for Manufacture and Assembly (DFMA) (Boothroyd Dewhurst Inc., 2012), Eco Materials Adviser (Granta Design, 2012), and a Product Lifecycle Management (PLM) tool (PTC, 2012) and found that manufacturing process specific LCI is not available.

At all of these different levels (facility, process-chain, process) there exist some tools to help those in industry. In this section, "tools" refers to any methodology, framework, model, metrics, software tool etc. to assist one in trying to understand the performance of their manufacturing system with respect to any aspect of the three pillars of sustainability – economic, environmental, and social.

Duflou et al. (2012) showed that there are very large discrepancies on the energy demand and related environmental impact of discrete part manufacturing processes obtained by different assessment methods (Kellens et al., 2012). The accuracy of currently available data records on manufacturing processes in LCI databases, such as EcoInvent2.0, is highly process type dependent. For some records the quality of data entries leaves significant space for improvement. The quality of LCI database coverage of manufacturing processes could also be improved by further subdividing process categories based on applied materials, machine tool architecture and capacity as well as process parameters (Duflou et al., 2012).

The EcoInvent database (Swiss Centre for Life Cycle Inventories, 2013), is one of the most widely consulted sources of consistently and transparently documented lifecycle inventory (LCI) data. In this database, in contrast to materials and chemicals production, manufacturing processes, as used for discrete part manufacturing, are unfortunately less well documented in terms of the overall environmental impact. On the one hand, the coverage of the wide range of available manufacturing processes is rather limited to more conventional processes, such as drilling, turning, milling, etc. Commonly used processes, such as electrical discharge machining and rapid prototyping processes, are lacking in the database. On the other hand, most of the available data on manufacturing processes are incomplete: the focus is often limited to theoretical energy consumption, and data on potential process emissions are rarely found (Steiner & Frischknecht, 2007).

Another available source of LCI data is input-output databases. Among others, examples can be found for the USA (Product Ecology Consultants, 2003), Denmark (Weidema et al., 2005), The Netherlands (Product Ecology Consultants, 2004), and Japan (Product Ecology Consultants, 2006). The disadvantage of input-output databases for LCA is that processes are aggregated, i.e., at the level of product groups rather than individual products. Consequently, the impact of individual manufacturing processes cannot be extracted from this category of data.

At the very high level, encompassing the whole factory planning view, Chen, Schudeleit, Posselt, & Thiede, 2013 performed a review and evaluation of tools for factory sustainability assessment aimed at guiding factory planners towards the sustainability indicators and aspects they need to consider during the factory development phase. Figure 2.24 shows a summary of the tools evaluated. The authors concluded that there are many different existing tools for factory level assessments, but no tool exists that fulfils all evaluation criteria in order to support factory planning. Most tools can be used for specific planning cases, but not for general use. Tools also used different indicator units and scales. The authors also suggested finding a balance between a tool that was overly simple and a tool that was overly complex as the deficit of moving towards a tool that just unifies and simplifies the measuring system is that the assessment accuracy decreases likewise.

\+ = Criteria fulfilled
O = Fulfilled with restrictions
\- = Criteria not fulfilled
^{1}dependent on the adaption process

Year	**Assessment tools**	Rapid assessment	Application on factory level	Generic applicability	Holistic view of sustainability
1997	**Barometer of Sustainability**	+	-	O^1	-
1999	**Dow Jones Sustainability Index**	-	+	O	O
1999	**GRI Reporting Framework**	-	+	O	+
2002	**IChemE Sustainability Metrics**	-	+	-	+
2002	**Rapid Plant Assessment Tool**	+	+	O	-
2004	**Sustainability Assessment in Mining and Minerals Industry**	-	O	-	+
2005	**Composite Sustainable Development Index**	+	+	O^1	+
2006	**ITT Flygt Sustainability Index**	+	+	-	+
2007	**Ford of Europe's Product Sustainability Index**	-	-	-	+
2009	**GM Metrics for Sustainable Manufacturing**	+	+	-	+
2009	**Sustainable Development Framework**	-	-	O^1	+
2010	**Rapid Basin-wide Hydropower Sustainability Assessment Tool**	+	-	-	+

Figure 2.24: Evaluation of tools and evaluation criteria fulfillment (Chen et al., 2013)

The lack of thorough analysis of manufacturing processes often results in optimization opportunities not being recognized. As mentioned earlier, many traditional manufacturing processes are not well represented in these software tools and datasets. In addition, the fact that newly emerging, non-conventional production processes are increasingly energy intensive strengthens the need for reliable and statistically rigid datasets. There is a growing need for a reliable methodology, tools, and data. Since this dissertation concentrates on the system/line -- process chain level, the review of existing assessment tools from that perspective is greatly lacking. My research aims to fill this gap and propose a methodology to document and analyze the economic and environmental impacts of manufacturing process chains.

In conclusion, an assessment tool is needed which enables the cross company comparison, gives a holistic view of sustainability's three pillars, and has a manageable complexity level and is adaptable at the process chain/line level.

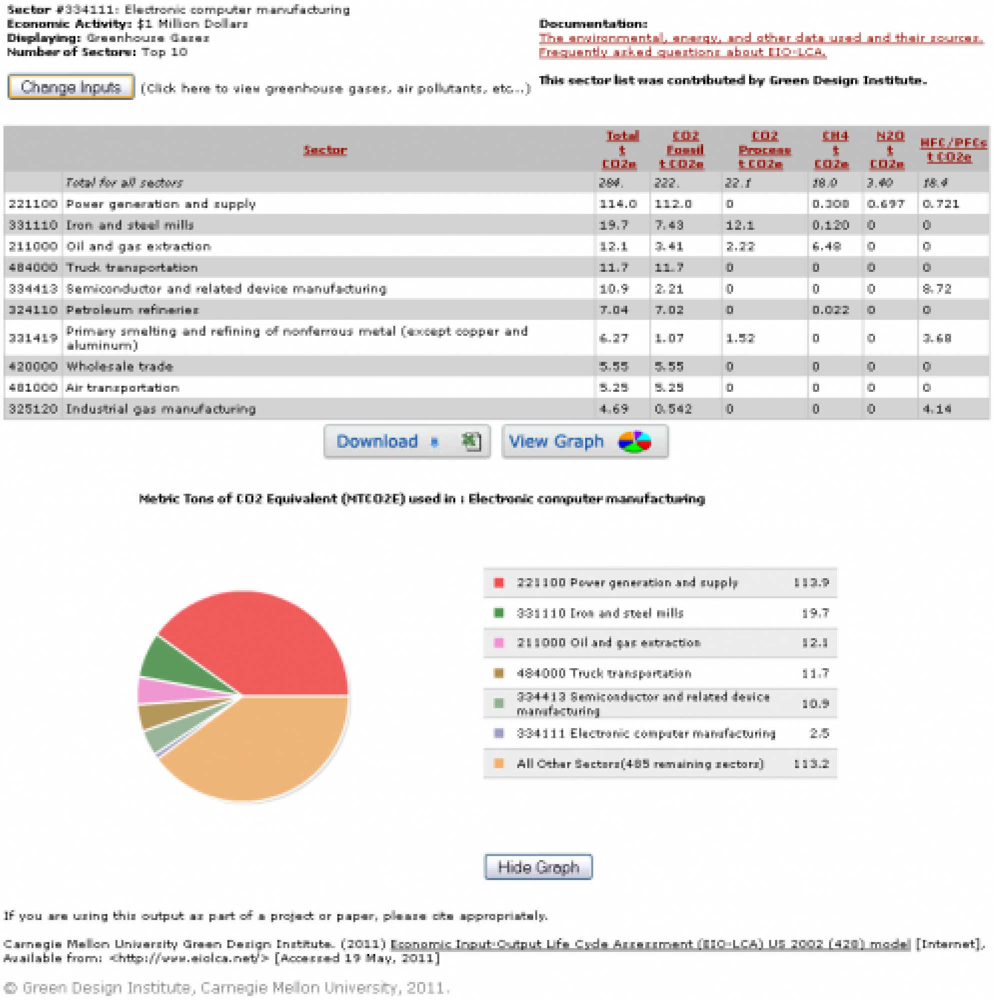
This research proposes a methodology that will enable manufacturers to evaluate the sustainability performance of fundamental manufacturing processes ensuring reliable and consistent comparisons. This dissertation discusses a methodology for sustainability characterization to allow manufacturers to objectively assess and compare different manufacturing processes and process chains for sustainability.

2.7 Review of Existing Assessment Tools

Although the existing literature of research on assessment tools is not large, there are some tools available that have been applied to manufacturing processes and systems. It is instructive to review some of the more prominent ones as a basis for understanding what is useful. A review of existing assessment tools (methodologies, frameworks, metrics, and software) was conducted as part of this research to find features (based on the opinion of the author) that are important to include when designing assessment tools and to also note areas (from the author's perspective) in which more work needs to be done with respect to assessment tools and methodologies. These tools covered varying levels from supply chain to facility to product. Some of the tools reviewed are highlighted in more detail below.

2.7.1 Economic Input-Output Life Cycle Assessment (EIO-LCA)

Description: The Economic Input-Output Life Cycle Assessment (EIO-LCA) method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy. The web-based tool uses either the producer price (cost to the manufacturer for raw materials and production) or the purchaser price (producer price plus transportation to final sale location and retail margin). The models and sectors are updated every 5 years.



Sector #334111: Electronic computer manufacturing
Economic Activity: $1 Million Dollars
Displaying: Greenhouse Gases
Number of Sectors: Top 10

(Click here to view greenhouse gases, air pollutants, etc...)

Documentation:
The environmental, energy, and other data used and their sources.
Frequently asked questions about EIO-LCA.

This sector list was contributed by Green Design Institute.

	Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
	Total for all sectors	*284.*	*222.*	*22.1*	*18.0*	*3.40*	*18.4*
221100	Power generation and supply	114.0	112.0	0	0.308	0.697	0.721
331110	Iron and steel mills	19.7	7.43	12.1	0.120	0	0
211000	Oil and gas extraction	12.1	3.41	2.22	6.48	0	0
484000	Truck transportation	11.7	11.7	0	0	0	0
334413	Semiconductor and related device manufacturing	10.9	2.21	0	0	0	8.72
324110	Petroleum refineries	7.04	7.02	0	0.022	0	0
331419	Primary smelting and refining of nonferrous metal (except copper and aluminum)	6.27	1.07	1.52	0	0	3.68
420000	Wholesale trade	5.55	5.55	0	0	0	0
481000	Air transportation	5.25	5.25	0	0	0	0
325120	Industrial gas manufacturing	4.69	0.542	0	0	0	4.14

Metric Tons of CO2 Equivalent (MTCO2E) used in : Electronic computer manufacturing

🟥	221100 Power generation and supply	113.9
🟩	331110 Iron and steel mills	19.7
■	211000 Oil and gas extraction	12.1
■	484000 Truck transportation	11.7
🟩	334413 Semiconductor and related device manufacturing	10.9
🟪	334111 Electronic computer manufacturing	2.5
🟧	All Other Sectors(485 remaining sectors)	113.2

If you are using this output as part of a project or paper, please cite appropriately.

Carnegie Mellon University Green Design Institute. (2011) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model [Internet]. Available from: <http://www.eiolca.net/> [Accessed 19 May, 2011]

© Green Design Institute, Carnegie Mellon University, 2011.

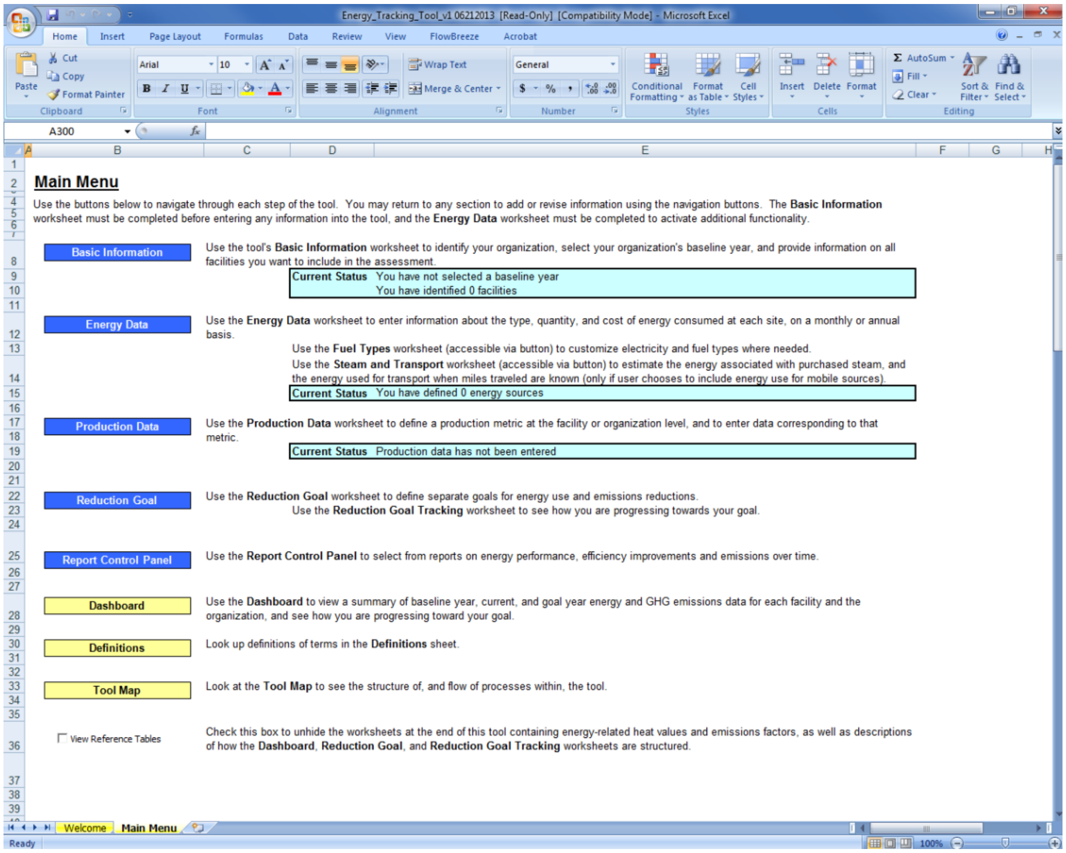
Figure 2.25: Screenshot of EIO-LCA software tool ("EIOLCA sample output," 2011)

Review: The EIO-LCA provides the environmental footprint of commodities and services during the manufacturing phase. An analysis of the use phase may be conducted by considering the resource inputs of a cell individually (e.g., water, and coolant), but the tool cannot incorporate cell inputs that must be measured directly such as electricity. Since the EIO-LCA sectors are particularly broad, the environmental impact of resource inputs should be analyzed from values taken from the literature to make it more applicable. Results from the EIO-LCA tool can be used for comparison purposes if desired.

Pros	Cons
• The tool is free to use. • Results can be generated rapidly for any one product or service. • The tool accounts for the circularity effects of product production, such as the use of steel machinery to make steel. • Outputs are comprehensive and include emissions, energy consumption, economic activity, water use, and toxic releases. • Uses publicly available data. • A hybrid approach may be used in which the user modifies the economic inputs.	• The impacts are related to the manufacturing phase of the commodity or service. To analyze a process, the inputs would have to be assessed individually. • Assessments contain aggregate data. The sectors are also aggregated such that it may be the case that highly pollutant and environmentally friendly industries are represented by one sector. • Assumes that products are produced in the United States. • Uncertainty in original data is transferred to the tool. • Some of the data are incomplete since the tool takes data that must be reported by firms. Therefore, impacts such as toxic releases represent a lower bound. • Assumes a linear trend between price and impact. • The tool uses old data making the results unreliable for industries in which the technology is changing rapidly.

2.7.2 Energy Star Energy Tracking Tool (ETT)

Description: The ENERGY STAR Energy Tracking Tool (ETT) is an Excel workbook that provides manufacturers with a simple means for tracking their energy performance over time and progress toward goals. The tool enables users to track energy use, energy intensity (i.e., MMBtu/Unit of Production), energy cost, greenhouse gas emissions, and progress towards goals for up to 15 years. It considers the location of the facility in order to accurately report the greenhouse gas emissions associated with electricity usage.



Main Menu

Use the buttons below to navigate through each step of the tool. You may return to any section to add or revise information using the navigation buttons. The **Basic Information** worksheet must be completed before entering any information into the tool, and the **Energy Data** worksheet must be completed to activate additional functionality.

Use the tool's **Basic Information** worksheet to identify your organization, select your organization's baseline year, and provide information on all facilities you want to include in the assessment.

Current Status You have not selected a baseline year
You have identified 0 facilities

Use the **Energy Data** worksheet to enter information about the type, quantity, and cost of energy consumed at each site, on a monthly or annual basis.

Use the **Fuel Types** worksheet (accessible via button) to customize electricity and fuel types where needed.

Use the **Steam and Transport** worksheet (accessible via button) to estimate the energy associated with purchased steam, and the energy used for transport when miles traveled are known (only if user chooses to include energy use for mobile sources).

Current Status You have defined 0 energy sources

Use the **Production Data** worksheet to define a production metric at the facility or organization level, and to enter data corresponding to that metric.

Current Status Production data has not been entered

Use the **Reduction Goal** worksheet to define separate goals for energy use and emissions reductions.

Use the **Reduction Goal Tracking** worksheet to see how you are progressing towards your goal.

Use the **Report Control Panel** to select from reports on energy performance, efficiency improvements and emissions over time.

Use the **Dashboard** to view a summary of baseline year, current, and goal year energy and GHG emissions data for each facility and the organization, and see how you are progressing toward your goal.

Look up definitions of terms in the **Definitions** sheet.

Look at the **Tool Map** to see the structure of, and flow of processes within, the tool.

☐ View Reference Tables

Check this box to unhide the worksheets at the end of this tool containing energy-related heat values and emissions factors, as well as descriptions of how the **Dashboard**, **Reduction Goal**, and **Reduction Goal Tracking** worksheets are structured.

Figure 2.26: Screenshot of Energy Star Energy Tracking Tool Interface (Energy Star, 2012)

Review: The main advantage of using this tool is that the data for fuel source emissions are centralized and in the case of electricity, region-specific. The data sources are well-documented and reliable so they can be used for emissions calculations in the manufacturing cell assessments. The methodology for automatically generating the reports can be adopted for increased efficiency. The limited availability of metrics, though, limits the use of ETT in the assessments.

Pros	Cons
• Automatically generates user-defined reports. • Can input 15 years of historical data. • Checks for common user input errors. • Outputs emissions specific to the region and energy mix. • The user can customize the fuel sources. • The user inputs goals to see how they compare to actual resource use and production. • The data sources are well documented.	• The tool provides a limited number of metrics. • Navigation through the tool is cumbersome; the data input cells are not centralized. • Production metrics are only defined to create the energy intensity metrics. The tool does not include more relevant examples of production efficiency metrics. • The scope of the tool is too broad; it was created for tracking facility-wide energy and emissions.

2.7.3 Global Reporting Initiative (GRI)

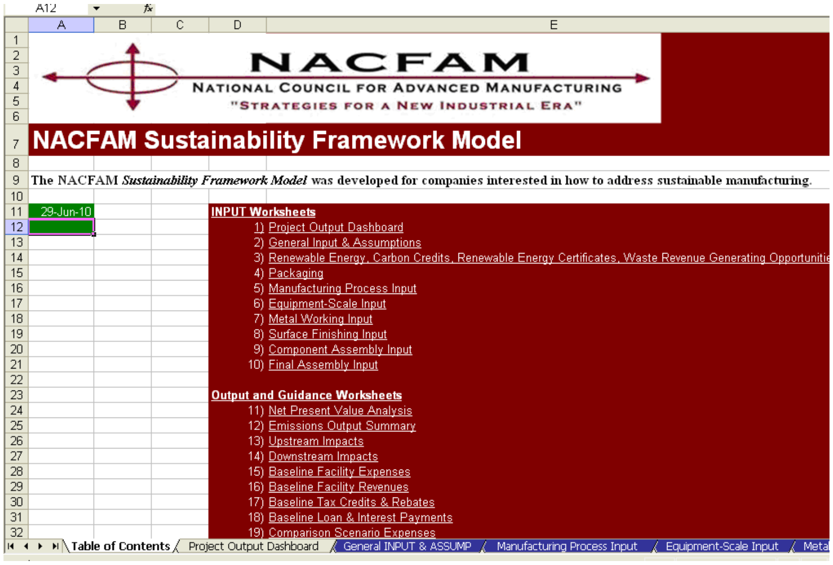
Description: The Global Reporting Initiative (GRI) provides a framework for sustainability performance reporting. The reporting guidelines provide performance indicators (qualitative and quantitative information) as well as a methodology for assessing the completeness and quality of the sustainability performance report.

Review: It is clear that relevant performance indicators from the GRI indicators are included in the list of metrics produced for the manufacturing cell assessments. The most relevant performance indicators that should be considered are the environmental indicators, though the evaluator must note that the indicators are generally too broad for the assessments that will be conducted. The economic, social (labor practices and decent work), and product responsibility performance indicators should be considered as secondary in importance and relevance. Also reference the sector supplements for additional performance indicators. Assess the completeness and quality of the assessments using the GRI guidelines.

Pros	Cons
• Provides guidance for assessing the completeness and quality of the report. • Provides additional information for each performance indicator such as its relevance and a high-level explanation of ways in which to obtain the data/information. • Does not restrict the scope or boundary of the analysis.	• The majority of the performance indicators are broad and therefore not specific to a manufacturing facility. • Does not provide the technical details or support related to the data acquisition of performance indicators. The compilation of energy and water performance indicators, for example, typically assumes the use of utility bills otherwise a general definition is provided.

2.7.4 National Council for Advanced Manufacturing (NACFAM) Sustainability Framework Model

Description: The NACFAM Sustainability Framework Model provides a flexible tool that allows for a comparative assessment based on both financial and environmental metrics that is aimed towards strategy development, manufacturing product design, manufacturing process strategy development, and manufacturing implementation. The framework is flexible and can be applied on single projects or multiple projects simultaneously and in combination. The framework's flexibility extends to its scope, which can range from one process all the way to an entire facility or corporation. The overall goal of this framework is to provide an analysis means that can connect cost reduction and sustainability even if data may be lacking. To this end, an Excel spreadsheet is provided to guide the use of this tool.



NACFAM Sustainability Framework Model

The NACFAM *Sustainability Framework Model* was developed for companies interested in how to address sustainable manufacturing.

29-Jun-10

INPUT Worksheets

1) Project Output Dashboard
2) General Input & Assumptions
3) Renewable Energy, Carbon Credits, Renewable Energy Certificates, Waste Revenue Generating Opportunitie
4) Packaging
5) Manufacturing Process Input
6) Equipment-Scale Input
7) Metal Working Input
8) Surface Finishing Input
9) Component Assembly Input
10) Final Assembly Input

Output and Guidance Worksheets

11) Net Present Value Analysis
12) Emissions Output Summary
13) Upstream Impacts
14) Downstream Impacts
15) Baseline Facility Expenses
16) Baseline Facility Revenues
17) Baseline Tax Credits & Rebates
18) Baseline Loan & Interest Payments
19) Comparison Scenario Expenses

Figure 2.27: Screenshot of NACFAM Sustainability Framework tool (National Council for Advanced Manufacturing, 2011)

Review: The NACFAM Sustainability Framework Model is not actually a model but really just a framework. Outside of eGRID factors (that define the impact of drawing electricity from the local power grid in the United States) and embodied energy values for materials usage taken from a literature source, no data or modeling is behind the toolkit. Rather, the framework provides a nice tool for data entry that has some simple underlying calculations to determine the difference in environmental impact (metrics include air pollutants, hazardous and solid waste, material usage, chemical usage, water usage, and electricity and natural gas usage) and financial performance (e.g., rate of return, net present value, and payback period) between two or more scenarios. These calculations are then extended to determine the financial impacts due to changes in the environmental impacts. It is important to stress, though, that both the environmental and financial analyses are based entirely on user-input data that NACFAM advises may be either "estimates, educated guesses," or expert data – it is in this way that the framework may be used with limited data.

Pros	Cons
• Environmental metrics do a good job of capturing key impacts of manufacturing. • Extension of analysis to include the financial impacts due to a change in environmental impact allows decision-makers to consider financial cost of proposed technology or strategy solution. • Framework provides nice way to organize data entry and calculations. • Framework enables analysis at different scope levels and may be transferred down to the cell-level. • Allows for analysis of upstream and downstream strategies.	• Metrics may aggregate all impacts across analysis such that it is difficult to determine problem areas. • Analysis is based entirely on experience of assessors who may be inexperienced such that poor data is used. • Data that are used in the framework are limited and lacks consistency across all parts of the analysis. • Generality of framework to enable analysis at different scope levels means that results may lack necessary level of detail for smaller scope analyses. • Upstream and downstream strategies are limited to materials usage and waste generation. • Embodied energy approach is used for materials usage analysis meaning that the analysis suffers from aggregation and generalization limitations; also, because an embodied energy approach is used for each air pollutant as well as energy usage, the emissions due to electricity usage are probably not included in the analysis. • Social factors are not included and some parts of the supply chain (e.g., transportation and some materials and chemicals) are neglected.

2.7.5 The Organization for Economic Co-operation and Development (OECD) Sustainable Manufacturing Toolkit

Description: The OECD Sustainable Manufacturing Toolkit is an approach that offers guidance to companies to facilitate internal analysis of sustainability performance as well as comparative analysis useful for decision-makers. The toolkit focuses on performance at the facility level considering both the materials and the product mix utilized within the facility. This approach is meant to augment existing efforts (such as the GRI and EU Eco-Management and Audit Scheme) and is aimed for use by non-experts. The ultimate output of the OECD toolkit is 17 “core indicators of sustainability” based on 44 identified data sources that concentrate on land use/biodiversity, energy use, water use, material use, greenhouse gases, and residuals. To aid data collection and indicator calculation, OECD offers an Excel spreadsheet where the assessors may enter all 44 identified data sources.

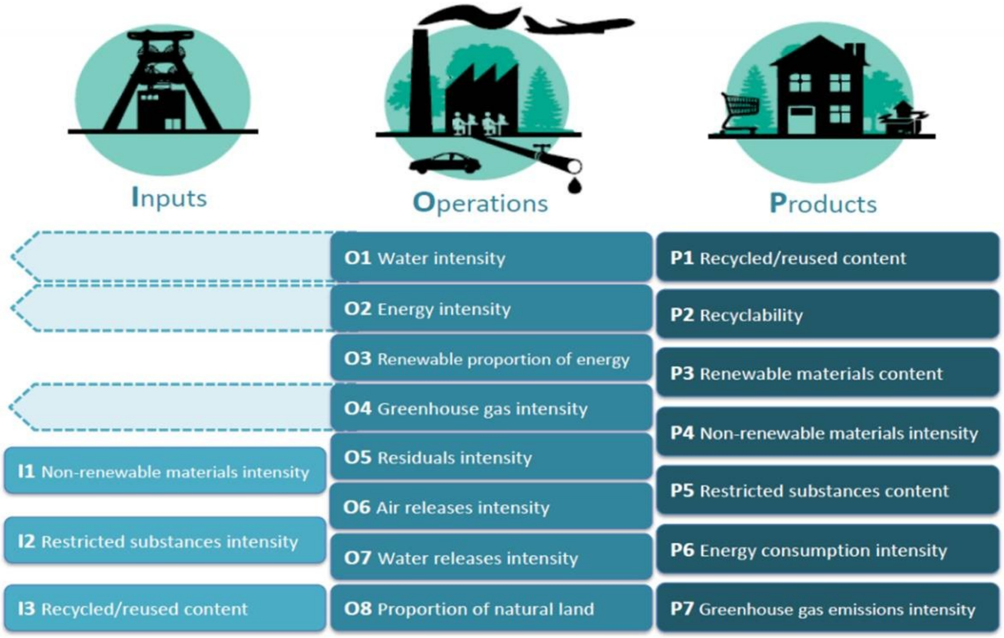


Figure 2.28: OECD core indicators of sustainability (OECD, 2011)

Review: The OECD Sustainable Manufacturing Toolkit advocates a value-stream mapping approach where a facility is broken down into individual processes to consider each input and output. The majority of the toolkit is essentially a guide for non-experts with a focus on concepts, data collection, and calculation. The core indicators that are offered do not consider the ultimate impact of the facility's sustainability performance (e.g., the assessment will indicate that a particular amount of chemicals is used, but it will not indicate how harmful that may or may not be) as OECD views this to be outside the scope and expertise of those conducting the assessment. The scope of the analysis is fluid – OECD advises that while it is best to consider an entire supply chain or all products and processes in a facility, only first tier or more important aspects may be considered in the interest of limited resources. The OECD also strongly advocates normalization using the purchasing power parity (PPP – adjusts for price levels in different countries), value-added (the difference in the factor gate price and the cost of all inputs) or gross output (value of sales). It is important to note that the OECD toolkit does not offer any data but rather emphasizes a methodology to gather and use relevant data.

Pros	Cons
• Designed to be used by non-experts. • Normalization using PPP value-added or gross output allows decision-makers to consider financial cost of proposed technology or strategy decision. • Environmental metrics do a good job of covering most environmental impacts. • Focus on amount of resource use rather than impacts is helpful for a general manufacturing audience who may be initially uninterested in environmental impact. • Methodology and included spreadsheet allow for comparative analysis. • Value-stream mapping approach may help indicate particular areas and flows of high impact.	• Lacks technical detail and advocates a more generalized (i.e., less accurate) approach. • Normalization by PPP value-added or gross output may conflate differences in value of manufactured goods. • Some important environmental metrics are not considered (e.g., compressed air usage). • Social indicators are not considered and economic factors are only considered through the normalization process. • Some of the 44 data sources lack specificity to facility – instead of asking how much a facility may use, it asks how much can a facility use. • Indicators may be too aggregate such that it may be difficult to understand true problem areas. • Facility-level analysis that is not easily translated to cell-level.

2.7.6 TechSolve Energy, Environment, Economy (E3) Approach

Description: The TechSolve E3 approach enables the reduction of energy, cost, and waste per unit output for a facility or corporation. The approach is composed of five main components: a lean review, an energy audit, a greenhouse gas evaluation, a "clean" review (i.e., a review of water, energy, and resources as well as waste and emission streams), and a post-assessment recommendation. The metrics that drive this approach are categorized in three areas: economic (e.g., savings, jobs created and retained, and capital infusion), energy (energy used and conserved as well as the emissions due to energy usage), and environment (air emissions, solid waste, material intensity, water usage, and hazardous waste). The PartView tool developed by TechSolve drives the E3 approach by applying value-stream mapping to find inefficiencies in the production process. The results of this approach are presented in a "spider web" diagram with an associated indicator value that describes a facility or organization's commitment to sustainability.

Review: The TechSolve E3 approach is a facility-level audit that seeks to find areas of inefficiency that can be addressed by particular technologies and processing strategies. These solutions are supported by relevant financial analyses that determine the potential savings due to correcting identified inefficiencies and opportunities. One interesting aspect of the TechSolve approach is the use of feature-based analyses where the impacts and inefficiencies of individual features may be studied. While the TechSolve approach covers many of the major environmental impacts of manufacturing, the solutions it presents are primarily motivated by financial arguments. Also, the methodology lacks transparency because the data sources and values are unknown.

Pros	Cons
• Value-stream mapping approach may help indicate particular areas and flows of high impact. • Environmental metrics do a good job of capturing key impacts of manufacturing. • Social impacts are included in economic metrics (e.g., jobs created and retained). • Feature-based approach may add extra granularity to analysis. • Overall sustainability indicator and "spider web" diagram may help classify facility and operation. • Financial analysis may allow decision-makers to consider financial implications of environmental changes.	• Facility-level analysis that may not be easily transferred to cell-level. • Some important environmental metrics are not considered (e.g., compressed air usage). • Analysis is weighted towards financial performance. • Data source is unclear and therefore difficult to evaluate and validate. • Overall sustainability indicator and "spider web" diagram are highly subjective.

This review has provided an understanding of the level, features and metrics of the more prominent analysis tools. This basic understanding will be used in the research presented in the next chapter.

2.8 Conclusions

This chapter began by introducing the background necessary for this research. This included details on manufacturing systems and process chains and their operation. The different dimensions of manufacturing with respect to the spatial and temporal view were then reviewed to illustrate the multiple facets and interactions existent in manufacturing. Some basic terms and definitions of production systems were introduced in order to understand how manufacturing system performance is assessed. Finally, literature relevant to work that has been done in this area and the capabilities of existing assessment tools was reviewed and some of the more prominent capabilities pointed out.

It has been shown that manufacturing processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products, but are still poorly documented in terms of their environmental footprint. The lack of thorough analysis of manufacturing processes has as consequence that optimization opportunities are often not recognized and that improved manufacturing systems in terms of ecological footprint have only been targeted for a few common processes.

Overall conclusion - there is a serious lack of tools. Although some tools exist, they are generally not very broad, do not cover manufacturing processes in depth, and they do some things but often do not do them very well – especially with respect to process design and optimization. The existing tools are complicated, time intensive, lack specific manufacturing data, and do not include the manufacturing process level. Companies do not have the man-power to solve this problem as the tools are typically too complicated, too expensive, or require too much expertise or specialization to use. There is a lack of data within the datasets; there either are no data, or if there are data, they are an estimate and not directly related to the process being assessed or not available for the specific process that is needed.

The work in this dissertation is motivated by the need for engineers to be able to quickly and easily assess the resource consumption of process chains within the factory. This information can be used early in the design process to consider the environmental and economic impacts and trade-offs associated with the manufacturing process chains used to manufacture products. The outcomes of this research can be used to make more informed decisions when selecting manufacturing processes for production.

The next chapter introduces the development of assessment metrics and procedures for use in this research.

Chapter 3

Development of Industrial Assessment Metrics and Procedures

The previous chapters have defined the importance of manufacturing with respect to environmental and energy issues, defined the complexity of manufacturing with respect to the enterprise, factory, system, machine, process, and tooling levels, reviewed the operational metrics for manufacturing system productivity and efficiency, and reviewed some tools for considering the utilization and impact of energy and other resources in these systems.

Although a number of different approaches have been proposed, from the perspective of this work they usually are not sufficiently detailed to allow an accurate assessment of the system for decision making or, for example, a trade-off analysis.

3.1 Precision Manufacturing Case Study

It is important to develop a set of metrics for process analysis in manufacturing and to construct a methodology, or protocol, to apply in industry. A research project as part of a US Air Force initiative provided an opportunity to do this. This research was conducted to support the Air Force ManTech Sustainable Aerospace Manufacturing Initiative (SAMI). In the early part of this research, a project in conjunction with the National Center for Defense Manufacturing and Machining, Air Force Research Laboratory, and System Insights looked at three different manufacturing environments with the goal of developing metrics, methodology, scope, and protocols for process analysis. An overarching goal of this work was to support the Air Force's efforts to measurably decrease the use of non-renewable materials, including energy, without affecting the quality or performance of defense systems. As part of a series of studies, three different manufacturing facilities were looked at. Each facility had a slightly different product mix (defense system and medical instrument components, aircraft components, and jet engine components). This section will describe some of the motivation and details of this project with the goal of characterizing these systems/processes.

After reviewing the assessment protocols and tools previously discussed in Chapter 2, a list of possible metrics was developed as well as an initial assessment protocol. The metrics development will be discussed in section 3.4 and the assessment protocol development will be discussed throughout the chapter. The assessment protocol will then be tested at the three facilities and the results will be reported. In conclusion, the pros and cons of the methodology and what was learned from this work will be discussed.

An ultimate goal for the SAMI program was to develop assessment tools to evaluate the sustainability of manufacturing facilities within the aerospace industrial base and to establish a baseline or standard against which manufacturing or machining processes can be compared. The goal of the research presented in this chapter was to inform the development of a standardized methodology to assess manufacturing facilities at the cell and process level and to collect data to help establish this baseline.

The initial steps of this work were to develop an assessment tool and conduct onsite assessments at aerospace supply-chain facilities. This work will establish a baseline for future assessments and identify opportunities for improved energy efficiency, reduced water consumption, reduced waste streams, and the initiation for environmentally friendly manufacturing processes.

In order to achieve these goals and as a result of the insufficiency of existing tools, it was necessary to develop a set of industrial assessment metrics and procedures. The resources that this study focused on assessing were:

- tooling,
- energy,
- industrial fluids,
- raw material,
- waste, and
- human impacts.

Methodology

Environmental assessment approach

An environmental assessment is generally a mass and energy balance analysis where a unit process or set of unit processes of interest are identified and enclosed into a box from which all input and outputs are individually measured. Figure 3.1 schematically shows the general methodology. The inputs represent all material and energy needed to run the unit processes within the box while the outputs represent all material and energy that are eliminated as either waste or finished products.

Figure 3.1: Schematic representation of environmental assessment methodology (adapted from (Horvath, 2009))

3.2 Resource Flows in Machining

Because the Sustainable Aerospace Manufacturing Initiative was primarily focused on machining technologies, the mass and energy balance approach was applied to specific machining equipment within the facility. Figure 3.2 shows the inputs and outputs of a standard machining operation including tooling and preparation, machine tool construction and maintenance, work materials production, the material removal process itself, part cleaning, cutting fluid preparation and other general facility inputs. It also identifies the portions of the overall system that were specifically investigated in this assessment.

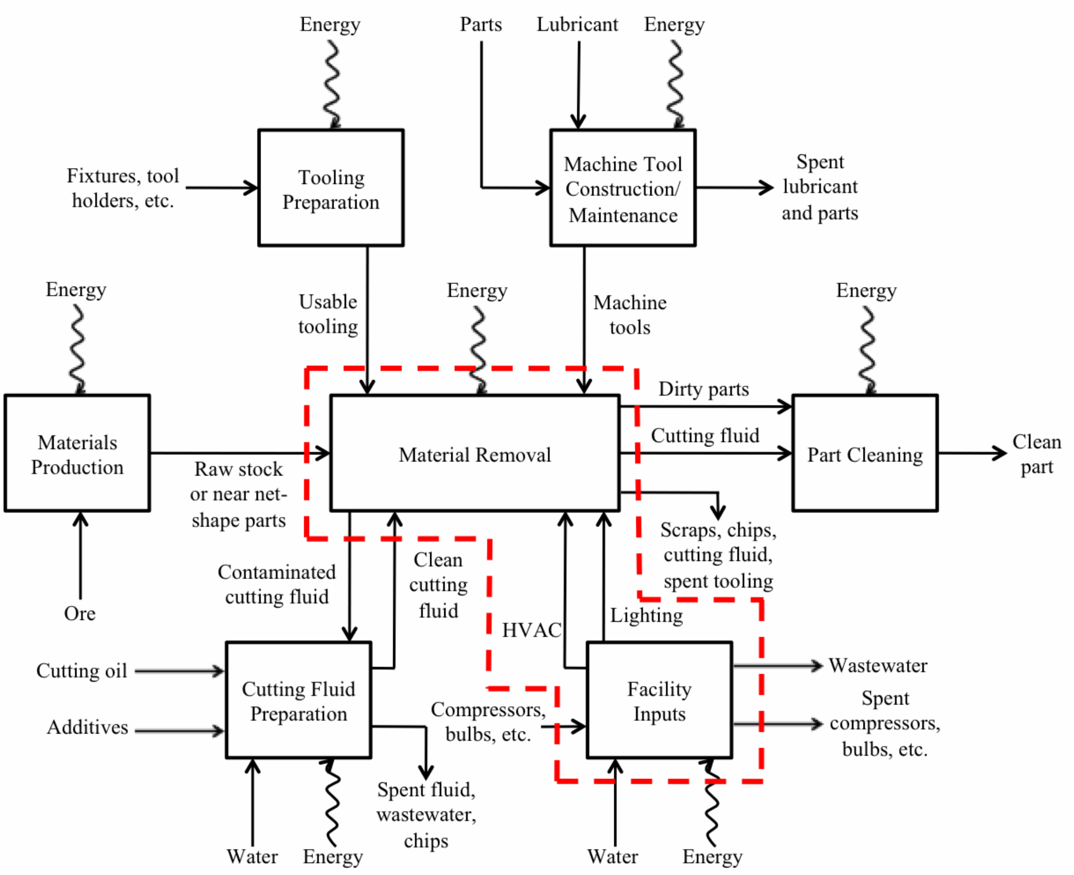


Figure 3.2: Comprehensive systems view of a standard machining process (adapted from (Helu & Dornfeld, 2013)). The dashed box identifies the bounds of the presented analysis.

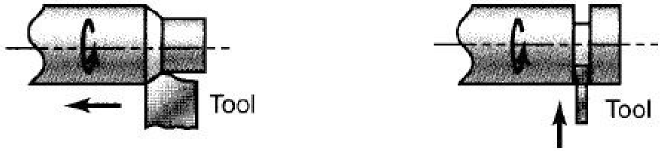
Machining

This section presents a basic introduction to the fundamentals of machining processes and will present the basic concepts relevant to all machining operations.

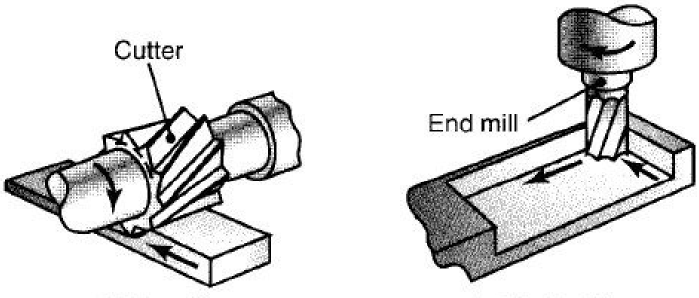
Machining is a subtractive process. The process of cutting a material to achieve a finished form that meets design specifications is called machining. Machining can be further defined as follows: cutting, in which layers of material are mechanically separated from a workpiece in the form of chips by means of a cutting tool (Klocke, 2011). Machining processes accomplish material removal by producing a chip or physically separating the material (Kazanas & Lerwick, 2002). Analyzed as a system, machining consists of three basic elements: the material to be shaped, secured in a way that permits it to be processed; a cutting point or edge that is attached to or part of a tool body; and the machine tool itself, some mechanism for controlling the interaction between the workpiece and the cutting tool (Kazanas & Lerwick, 2002).

Some of the more common cutting processes which remove material from the surface of a workpiece by producing chips are as follows and can also be seen below in Figure 3.3:

- *Turning*, in which the workpiece is rotated and a cutting tool removes a layer of material as the tool moves to the left,
- *Cutting off*, in which the cutting tool moves radially inward and separates the right piece from the bulk of the blank,
- *Slab milling*, in which a rotating cutting tool removes a layer of material from the surface of the workpiece, and
- *End milling*, in which a rotating cutter travels along a certain depth in the workpiece and produces a cavity.



Straight turning   Cutting off



Slab milling   End milling

Figure 3.3: Some example of common machining operations (Kalpakjian & Schmid, 2001)

In order to analyze these processes in detail, a two-dimensional model is presented in Figure 3.4 below. In this idealized model, a cutting tool moves to the left along the workpiece at a constant velocity, v, and a depth of cut, t_o. A chip is produced ahead of the tool by plastically deforming and shearing the material continuously along the shear plane.

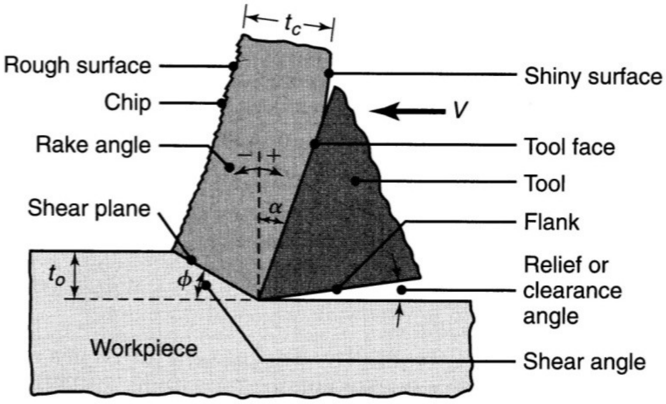


Figure 3.4: Schematic illustration of a two-dimensional cutting process, also called orthogonal cutting. Orthogonal cutting with a well-defined shear plane is also known as the M.E. Merchant model. Note that the tool shape, the depth of cut, t_o, and the cutting speed, v, are all independent variables. (Kalpakjian & Schmid, 2001)

The tool moves with a constant velocity, v through the workpiece and with a cutting force, F_c, and a feed force, F_f (shown in Figure 3.6). As the tool moves into the workpiece with a depth of cut t_o, forces F_c and F_f cause the work material ahead of the tool to be compressed. The area under compression is in a state of plastic deformation; within this area is a section referred to as the shear zone. Material failure within the shear zone occurs at a plane called the shear plane. The shear plane occurs at the shear angle Φ, here shown as approximately a 45° angle but which, in practice can vary over a wide range depending on the uncut chip thickness and the tool rake angle. The work material moves up and over the face of the cutting tool and separates from the parent material. The cutting action causes the work material in the shear plane to be compressed and flow up and over the face of the tool. The deformation occurs in both the chip and in a shallow zone in the workpiece below the cutting tool as shown in Figure 3.5.

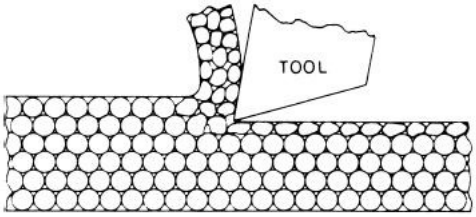


Figure 3.5: Deformation in the chip and workpiece resulting from machining (Kazanas & Lerwick, 2002)

To round out the discussion of terms and concepts, the cutting portion is the active part of the tool where the cutting tool is defined by the location of the primary cutting edge, or rake face, and flank face of the tool. The idealized cutting tool is made up of two faces: A rake face and a flank face, which intersect in a line, the cutting edge. The angle between these two faces is designated as the tool angle β. Figure 3.6 shows an idealized cutting tool. The rake face or tool face is the face of the cutting edge over which the chip flows. The flank face, or clearance face, is the face on the tool that passes over the new workpiece surface (the cut surface). The angle of the clearance face insures that it does not contact the cut surface. These terms make it clear that the cutting tool should always be regarded in connection with the workpiece. This means that considerable importance should be attached to process kinematics.

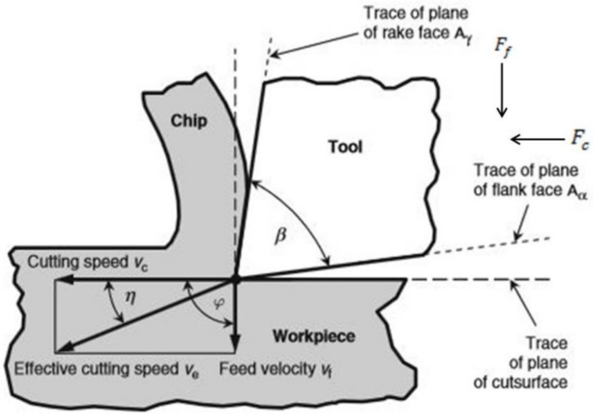


Figure 3.6: Description of the idealized cutting tool (Klocke, 2011)

To simplify the process kinematics, one can focus on a selected cutting point. This allows one to summarize the spatial velocity fields relative to one point. At the selected cutting point, the velocity fields can be represented as a summation of vectors representing the principal directions of movement of the tool, cutting speed, and feed. These vectors can be summarized in turn by vector addition in one total vector. Usually, the workpiece is assumed to be fixed; all motions are carried out by the tool. This results in a velocity vector referred to as the effective cutting speed, v_e. It can be divided into two components; the cutting velocity v_c in the cutting direction and the feed velocity v_f in the feed direction. To position the components of effective cutting speed clearly, two angles are defined:

- The effective cutting speed angle η as the angle between the effective cutting direction and the direction of primary motion (see Figure 3.6 above).
- The feed motion angle ϕ as the angle between the feed direction and the direction of primary motion (see Figure 3.6 above).

Similarly, as previously discussed and as seen above in Figure 3.6, the principal forces in the cutting process can be identified along these directions. That is, a cutting force, F_c, and a feed force, F_f, as shown in the figure. The cutting force and distance of motion of the tool in applying this force are the basic components of the cutting energy, and, with cutting speed (distance/time) the basic components of the cutting power. This will be referred to as "processing energy consumption" or processing power P_p in the discussion to follow. The cutting energy is provided by the motors and gearing systems driving the tool motion. In the milling process this would be provided by the spindle motor powering the cutting tool. In addition to the cutting energy, the feed motion, for example in milling, is provided by the motors driving the axes of the machine tool table on which the workpiece is fixtured during machining.

Material removal rate (MRR), a measure of process productivity, is determined by the rate at which the cutting tool moves through the workpiece. In the case of milling this would be determined by the engagement of the tool with the workpiece (axial depth of engagement *x* width of the tool if the tool is fully engaged in the work) *x* the feed rate of moving the tool through the work. The term "specific energy" is often used with machining processes relative to the energy required to remove a specific volume of a specific work material and is a measure of the "machinability" of a material. Specific energy, and hence machinability, can vary by a factor of 10X when comparing the machining of aluminum (which is generally very machinable) to titanium (which is generally difficult to machine). Machinability of steels is somewhere in the middle but can be as challenging as titanium depending on the alloy of the steel.

The specific energy is the energy consumed divided by the material removal during that machining step – energy/MRR expressed in units of HP-min/in^3 or W-sec/mm^3. If this is measured at the motor, then there will be losses due to inefficiency of the motor that must be considered. Additionally, the specific energy in machining will be influenced by the sharpness of the cutting tool – the radius of the corner of the tool at the chip-tool interface. Due to temperatures in cutting, abrasion, etc. the tool will become progressively worn and this will reduce the inefficiency of the chip forming process and cause cutting and feed forces to increase, resulting in higher cutting energy for the same MRR.

All of these characteristics cannot be independently controlled in the machining process (for example, volume and shape of material removed during machining) and, thus, some variability will be seen in the power consumed for a specific machining process compared to a similar machining process on a different machine tool, or with different tooling (shape, composition, coating, degree of wear). Once a baseline is established for the system being assessed, these parameters could be set to minimize energy consumption for those parameters that cannot be changed, if so desired.

3.3 Measuring Resource Flows

For the purposes of simplifying the initial validation of the assessment approach, the current assessment focused primarily on the electrical energy flowing to the material removal process (i.e., consumed by the spindle and axis motors of the machine tools themselves) and the compressors in the facility as well as the material waste from the material removal process (e.g., rejected product). The primary metrics that capture the environmental impact of these flows include electrical energy consumption of processing and non-processing activities as well as the resultant carbon emissions, power factors, energy costs, and scrap rate of the facility and equipment.

While some of the identified metrics are relatively straightforward to measure (e.g., scrap rate), others (specifically electrical energy consumption and power factors) require the deployment of monitoring equipment. To determine the electrical energy consumption, the electrical power demand must be monitored, which can be challenging depending on the component that one wishes to monitor and whether it requires AC or DC power. Most equipment in a facility typically requires 3-phase AC power from the facility source, and thus overall electrical energy consumption can be monitored through the use of a wattmeter calibrated and setup for a 3-phase, 3-load, 3-wire measurement (see Figure 3.7). We must emphasize that the derivation of AC power is not as straightforward as multiplying current and voltage as it is for DC power. However, a good wattmeter performs the relevant calculations for the user, which allows for a straightforward measurement of electrical power demand.

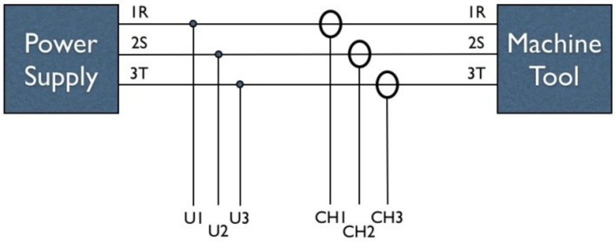


Figure 3.7: A schematic of a 3-phase, 3-load, and 3-wire measurement used to monitor input electrical energy consumption (Vijayaraghavan & Helu, 2013)

When measuring AC power demand, one must distinguish between apparent, real, and reactive power. Real power represents the portion of overall power demand that is used for productive work. Reactive power represents the portion of overall power demand that is not used in productive work (i.e., losses in the system). Apparent power is the root mean square voltage and current, and it represents the overall power demand from the electrical grid. However, it is important to note that the absolute sum of real and reactive power does not equal apparent power since AC power is sinusoidal in nature and can reverse as well. Nonetheless, the power factor is the ratio of the real to apparent power and is used to represent the efficiency of the electrical circuit. Machine tools typically have a low power factor (~60%) due to the resistive losses in motors. But, this does not generally adversely affect facilities since machine tools represent only one portion of the overall electrical system. A good wattmeter will also measure the power factor.

Whether or not a wattmeter is employed, current must be measured using a variety of devices called ammeters, which rely on the changes that fluctuations in current induce in magnetic fields. While many ammeters require that the sensor be placed into the circuit, the best ammeters for industrial assessment employ the Hall effect so that they are non-contact and generally enjoy a high degree of accuracy if they are properly sized for the circuitry. Hall effect sensors are essentially coils placed a known distance around a wire to be measured. These coils output a voltage change that is induced by the change in magnetic field that is caused by a change in current in the wire. Despite their high accuracy, there are integration challenges for Hall effect sensors, particularly in AC circuits. Specifically, these sensors are unidirectional and must be placed relative to the direction of current flow. However, the direction of AC current is not always intuitive due to current reversals. Also, the size of the coils typically dictates accuracy – smaller diameter coils are generally more accurate. Furthermore, many wattmeters must measure each phase of current in a particular order so that the algorithms it uses to determine AC power are used correctly. These issues require that a certain amount of testing be performed when implementing Hall effect sensors.

Voltage must also be measured using another family of devices called voltmeters, which essentially measure voltage by placing a large resistor in series with the circuit. This resistor allows the voltmeter to sample a small amount of current, the amount of which is proportional to the voltage drop. The accuracy of these measurements is dependent on several factors including temperature and voltage fluctuations. Therefore, it is important to ensure constant operating conditions when performing these measurements. Also, Wheatstone bridge circuits are ideally used to ensure greater precision in measurement.

Once the electrical power demand is determined, the electrical energy consumption is simply the measured power integrated over a time interval. The subsequent carbon emissions can also then be calculated by multiplying the electrical energy consumption by the relevant carbon emissions factor based on the local energy mix of a facility's electricity provider – the electricity provider generally provides the carbon emissions factor. The electrical energy costs may also be determined by using the facility's electricity provider's pricing schedule. For each of these calculations, the real power is typically used since electricity is charged based on the real power. However, a full understanding of the overall environmental impact demands that the power factor must also be monitored to capture any electrical inefficiency in the facility or equipment of interest.

Comparison of Different Machines and Processes

The previous section discussed the assessment of one unit process or set of unit processes. However, since the purpose of this investigation is to assess the environmental impact of the production of a part and there are several methods for producing the part (e.g., various machine tools and process parameters) a functional unit must be defined in order to make a fair comparison across different systems. The functional unit therefore standardizes the inputs and outputs for any given system.

Possible functional units that were considered include a standard time, the functional life of the machine tool, the production of one part, or the processing of a batch of parts. Ultimately, since the level of automation and the processing rate varies across machine tools, the environmental impacts were analyzed for the production of one part. Under ideal circumstances, there would be a standardized part to test across all equipment. In the absence of that, one has to try to normalize for different part characteristics. One way that this work addressed this was when comparing different machines and processes to assess at each facility, the different machines and processes chosen to be assessed were ones producing the same part so that a direct comparison could be made.

Instrumentation

The assessment methodology broadly consists of automated data collection using appropriate sensors, and manual data collection using pre-defined sensors. Automated data collection was performed for energy consumption of the machine tools and the process equipment. Details of the automated data collection are as follows:

Equipment Used: Yokogawa CW240 Clamp-on Power Meter

Figure 3.8: Yokogawa CW240 Clamp-on Power Meter

Connection: The power meter was used to measure the power drawn from the grid by the equipment by measuring the current and voltage drawn by the equipment from the grid. The voltage was measured using standard voltage leads, and the current was measured using current transformers (CTs). The CTs were chosen based on the size of the estimated loads (for example, 200A CTs for loads less than 200A).

Data Logging: Data were logged using compact flash memory at a sampling frequency of 1 Hz.

Data Collected: The following data values were collected:

Voltage (three-phase) [V]
Current (three-phase) [A]
Power [W]
Energy [J]
Power Factor [%]

Duration: Power data were measured for an adequate duration to capture several part cycles or a representative length of an equipment's operation time (such as a compressor).

3.4 Metrics Development

In the words of Lord Kelvin, "To measure is to know. If you cannot measure it, you cannot improve it." So, essentially, if you cannot measure what you have made, you do not know whether you have made it or not ("Lord kelvin quotations," 2008).

While Figure 3.2 identifies the basic material and energy flows into and out of a machining process, these must be eventually linked with traditional manufacturing process parameters defining, for each operation, data on part production time, machine operation time, warm up time, down time, etc. This is referred to as data on "functional units of the production of a part" on the particular process of interest.

Thus, these additional metrics were defined around the functional unit of the production of a part. Facility data, when available, were amortized over the number of machine tools and parts produced. The metrics fell into the following categories:

- Power demand and energy consumption (e.g., idle power demand and processing energy consumption per year)
- Production efficiency/overall equipment effectiveness (e.g., availability and efficiency)
- Process consumables and facility overhead charges (e.g., coolant consumption, water consumption, and tool life)
- Process waste (e.g., rework rate and scrap rate)
- Economic (e.g., return on investment)
- Human safety (e.g., max noise level and injuries per year)

The entire list of metrics can be seen in Appendix A.

3.4.1 Relevant Variables

Measurements were broken up into time periods for production cell operation and relevant variables. Three periods of operation were defined for the analysis:

a. Processing – cumulative time over a shift during which the machines in the cell are being productive
b. Idle – cumulative time over a shift during which the machines in the cell are not being productive
c. Warm-up – cumulative time over a shift during which the machines in the cell run at full or partial load to achieve sufficient stability (e.g., thermal stability for precision processes)

The relevant variables are the variables required to derive and define the list of metrics presented in section 3.4.2 below. The relevant variables are defined and listed in Table 3.1 below. The full definitions, units, and the nature of the data and their sources are defined in Appendix A.

Table 3.1: Relevant variables required to define each metric

Name	Variable	Definition
Cell footprint	A_{cell}	The footprint of the cell or machine tool being analyzed
Average cell	A_{avg}	The average footprint of a cell or machine tool in a facility

footprint		
Total facility floor space	A_{total}	The total amount of floor space in a facility
Compressed air usage	CA	The amount of compressed air used by the cell or machine tool being analyzed
Demand on air compressor	D_{comp}	The average demand placed on the air compressor (i.e., the amount of time it is functional relative to the operation time)
HVAC energy	E_{HVAC}	The amount of energy consumed by HVAC systems in the facility
Lighting energy	E_{light}	The amount of energy consumed by the lighting systems in the facility
Powered cell time	h_{cell}	The total time that a cell or machine tool is powered on irrespective of productivity
Total facility powered time	$h_{facility}$	The sum of the powered cell time for each cell or machine tool in a facility
Total mass of fixture material	$m_{fixutre}$	The total mass of each material type in a fixture for a cell or machine tool
Total mass of material in all processed parts	m_{parts}	The total mass of all material processed in a cell or machine tool
Total mass of replacement part material	$m_{replacement}$	The total mass of each material type in a replacement part for a cell or machine tool
Noise level	n	Noise level during production
Injuries per year	N_I	Total number of injuries in a facility per year
Process loss per cell	$N_{process}$	Total mass of chips generated from the processing that occurs in one cell over a specified time period
Idle power	P_i	Power demand during idle periods
Processing power	P_p	Power demand during processing periods
Warm-up power	P_w	Power demand during warm-up periods
Water consumed for cleaning	R_{clean}	The amount of water consumed to clean processed parts
New coolant oil consumed	R_{cool}	The amount of new coolant oil consumed
Coolant oil recycled	$R_{cool,r}$	The amount of coolant oil that is recycled
Lubricating oil consumed	R_{lube}	The amount of lubricating oil consumed
Water consumed for coolant	R_{water}	The amount of water consumed through the use of coolant
Lifetime savings	$S_{savings}$	Total amount of savings over the entire lifetime of a technology solution

Investment cost	$S_{investment}$	Total investment required to implement a technology solution
Sick days per year	SD	Total number of sick days in a facility per year
Tool life	T	The life of a tool in a cell or machine tool
Cycle time	$t_{c,design}$	Designed (or ideal) cycle time per part
Calendar time	$t_{calendar}$	Total calendar days over a specified time period
Planned downtime	$t_{d,planned}$	Total planned downtime during t_s
Unplanned downtime	$t_{d,unplanned}$	Total unplanned downtime during t_s
Idle time	t_i	Total elapsed time during idle periods
Processing time	t_p	Total elapsed time during processing periods
Operation time	t_s	Total operation time during a specified time period
Warm-up time	t_w	Total elapsed time during warm-up periods
Production volume	V_s	Total processed parts over t_s
Scrapped volume	V_{scrap}	Total processed parts that are scrapped over t_s
Reworked volume	V_{rework}	Total processed parts that are reworked over t_s
Hazardous waste	W_{HAZ}	Amount of hazardous waste that must be disposed of over a specified time period
Solid waste	W_{solid}	Amount of solid waste that must be disposed of over a specified time period; this variable does not refer to waste items associated with the completed part or tools (e.g., tools, chips, and fixtures) but rather other waste items such as gloves, packaging, etc. that are disposed of through standard garbage disposal

3.4.2 Metrics

Now that we have introduced the relevant variables required to define each metric, metrics were developed for the following categories: power demand and energy consumption, production efficiency/overall equipment effectiveness (OEE), process consumables and facility overhead charges, process waste, economic, and human safety. These categories encompass the various resources and outputs being investigated in this study. The list of metrics was determined based upon conversation with facility engineers, observation of the machinery, and knowledge of manufacturing systems. This list is meant to serve as a comprehensive database of metrics (to choose from) that could be considered for assessing the performance of various pieces of a facility or process/cell (with respect to the focus of this study).

The metrics are defined below in their respective sections. For the full description and summary of the metrics, please refer to Appendix A for details.

3.4.2.1 Power Demand and Energy Consumption

The metrics for power demand and energy consumption are defined and listed in Table 3.2 below. The full definitions, units, and the nature of the data and their sources are defined in Appendix A.

Table 3.2: Power demand and energy consumption metrics

Metric	Variable	Definition
Idle power demand	P_i	Same as measured variable
Warm-up power demand	P_w	Same as measured variable
Peak power demand	$P_{p,max}$	This is the maximum steady-state value during the processing period
Component power demand	$P_{comp,i}$	Power demand for each identified relevant component, j; equation may be used if sub-metering is difficult
Cutting power demand	P_{cut}	Power demand due to the requirements of the cutting process
Processing energy consumption per year	E_p	Total energy consumed during all processing periods over one year
Idle energy consumption per year	E_i	Total energy consumed during all idle periods over one year
Warm-up energy consumption per year	E_w	Total energy consumed during all warm-up periods over one year

3.4.2.2 Production Efficiency/Overall Equipment Effectiveness (OEE)

The metrics for production efficiency/overall equipment effectiveness (OEE) are defined and listed in Table 3.3 below. The full definitions, units, and the nature of the data and their sources are defined in Appendix A.

Table 3.3: Production efficiency/overall equipment effectiveness (OEE) metrics

Metric	Variable	Definition
Availability	a	A measurement of uptime irrespective of quality, performance, and scheduled downtime
Performance efficiency	$\eta_{performane}$	A measurement of the actual operating speed of machine relative to its designed operating speed irrespective of availability or quality

Process utilization	$u_{process}$	A measurement of the schedule effectiveness that compares the actual operation time to the total calendar time irrespective of system performance
Quality	q	A measurement of the total number of good to bad parts

3.4.2.3 Process Consumables and Facility Overhead Charges

The metrics for process consumables and facility overhead charges are defined and listed in Table 3.4 below. The full definitions, units, and the nature of the data and their sources are defined in Appendix A.

Because many of the variables associated with consumables and overhead charges are usually known at the facility level, we must first define a scaling factor that will assign these flows to each cell or machine based on its relative size (larger machine tools or cells generally have larger impact) and processing time (longer processing times generally increase impact). This scaling factor, K, has been defined as follows:

$$K = \left(\frac{A_{cell}}{A_{avg}}\right)\left(\frac{h_{cell}}{h_{facility}}\right).$$

This scaling factor was informed by the previous work of Diaz et al. (2010) and should be used with any metric or variable known only at the facility level.

Table 3.4: Process consumables and facility overhead charges metrics

Metric	Variable	Definition
Coolant oil consumption	R_{cool}	Same as measured variable; this metric refers only to new coolant oil and should not count recycled coolant oil
Recycled coolant	r_{cool}	The proportion of recycled coolant that is used in the cell relative to new coolant
Lubricating oil consumption	R_{lube}	Same as measured variable
Water consumption for coolant	R_{water}	Same as measured variable
Water consumption for cleaning	R_{clean}	Same as measured variable
Tool life	T	Same as measured variable
Fixturing	F	The amount of material used to create a fixture relative to the amount of material it is used to process; each type of material in the fixture should be accounted for separately
Replacement parts	R	The amount of material in the new cell or machine tool parts relative to the amount of material the cell or machine tool processes over the life of the new part; each type of

		material in the replacement part should be accounted for separately
Compressed air usage	CA	Same as measured variable
Effective compressor energy consumption	$E_{comp,eff}$	An estimate of the average energy consumed by the air compressor for the cell
Effective HVAC energy consumption	$E_{HVAC,eff}$	An estimate of the average energy consumed by the HVAC system for the cell
Effective lighting energy consumption	$E_{light,eff}$	An estimate of the average energy consumed by the lighting system for the cell

3.4.2.4 Process Waste

The metrics for process waste are defined and listed in Table 3.5 below. The full definitions, units, and the nature of the data and their sources are defined in Appendix A.

Table 3.5: Process waste metrics

Metric	Variable	Definition
Rework rate	N_{rework}	The number of parts that are processed through the cell that need to be reworked relative to the total number of parts processed
Scrap rate	N_{scrap}	The number of parts that are processed through the cell that are scraped relative to the total number of parts processed
Process loss	$N_{process}$	Same as measured variable; each type of material should be specified individually
Hazardous waste	W_{HAZ}	Same as measured variable; this metric should include any used coolant and lubricating oil that must be treated as hazardous material as well as any associated contaminated water; each type of hazardous waste should be specified individually
Solid waste	W_{solid}	Same as measured variable

3.4.2.5 Economic

As a measure of economic value, using the metric of return on investment was suggested. This metric is one that the companies being studied were commonly using as a measure and was included in the analysis to represent this. The metric for economic considerations are defined and listed in Table 3.6 below. The full definition, units, and the nature of the data and their source are defined in Appendix A.

The economic metric presented below is dependent on the technology solution that is being evaluated using the assessment protocol/tool.

Table 3.6: Economic metrics

Metric	Variable	Units	Source	Definition
Return on investment	ROI	n/a	$\frac{S_{savings}}{S_{investment}}$	The dollar amount saved by the technology solution relative to the cost of the technology solution

3.4.2.6 Human Safety

The metrics for human safety are defined and listed in Table 3.7 below. The full definitions, units, and the nature of the data and their sources are defined in Appendix A.

Table 3.7: Human safety metrics

Metric	Variable	Units	Source	Definition
Maximum noise level per cycle	n_{max}	dB/cycle	Variable	Maximum measured noise value over one cycle
Injuries per year	$N_{I,cell}$	injuries	$K*N_I$	Total number of injuries per year in the facility scaled to an individual cell
Sick days per year	SD_{cell}	days	$K*SD$	Total number of sick days per year in the facility scaled to an individual cell

The metrics developed in this section were used to inform the development of the assessment methodology and also to serve as a checklist of possible items that one could measure in a facility.

3.5 Development of Assessment Methodology

Three sustainability assessments of various manufacturing facilities were performed in order to inform the development of the assessment methodology as well as to establish a baseline for resource consumption for a manufacturing cell. Two of these assessments will be detailed in this section, Remmele Engineering and GKN aerospace, and a third, General Electric Aviation will be briefly covered. These facilities offer a good range of typical machining processes and conditions for precision components.

3.5.1 Remmele Engineering

Remmele Engineering, located in Big Lake, Minnesota, is a contract manufacturing facility with a core business of providing manufactured components to the aerospace, defense, and medical device industries. Remmele provides machined components for the Aerospace industry including Airframe assemblies, space system assemblies, composite manufacturing tooling, radar systems, and missile launcher components and assemblies. The goals of the assessment were to establish a baseline resource usage of machines to create gripper component, do a comparative analysis of resource use between machine tools, and to compare older and newer machines. The specific processes studied were two machine tools performing similar machining operations; the Hydromat Rotary Transfer Machine Tool and the Citizen Swiss Machine Tool. The basis of comparison for this study was a gripper component part that both machines tools made.

Assessment Protocol

The goal of the assessment was to evaluate a specific machining operation with regard to energy and resources consumed as well as the resultant waste streams. The assessment process has three phases: 1) Pre-Assessment Survey completed by Remmele employees prior to site visit, 2) an on-site assessment conducted by the assessment team, and 3) review of the gathered data and preparation of a formal report.

Prior to visiting the facility, the assessment team sent ahead a pre-assessment questionnaire for the facility employees to fill out ahead of time (see Appendix B). The pre-assessment questionnaire contained questions about facility information and general energy usage. The main categories of the questionnaire were:

- General information (e.g., organization name, contact person, e-mail)
- Organizational information (e.g., number of employees, number of operating hours per day)
- Energy (e.g., if energy audits are conducted, if energy metering is used)
- Energy data plant level (e.g., purchased power, fuel used)
- Resource consumption projects implemented (if applicable)
- Energy bill (e.g., please attach bill)
- Energy cost (e.g., demand charges, purchased electricity cost)
- Utilization of renewable energy sources (if applicable)

The questionnaire was sent ahead of time to ensure data quality so that the facility employees would have sufficient time to gather the information needed to complete the questionnaire and to allow time questions and clarification if needed. Sending the questionnaire ahead of time also allowed the assessment team to spend more time on the factory floor assessing the facility and not tracking down employees or data that are typically available at the enterprise level.

Upon arriving at the facility, the team had a kick off meeting in which they explained the purpose of the assessment, introduced assessment team members, and went through the pre-assessment questionnaire. Unfortunately the facility employees did not have a chance prior to the visit to fill out the pre-assessment questionnaire, so this information was also obtained during the assessment. This did not affect the overall outcome of the study, but it did slow the progress of the assessment as this required extensive time from the assessment team to track down employees and data. This also required additional time on site from the assessment team to review the questionnaire results to determine where to focus the assessment before they could begin. During the kick off meeting, the assessment team also identified key personnel at the facility to seek out for specific information (e.g., energy bills and purchasing records).

After the kick off meeting, the assessment team broke into three groups. Each group focused on collecting a specific section of data.

Group 1: Obtained data to complete the pre-assessment questionnaire (facility information and general energy usage). This questionnaire can be found in Appendix B. After group 1 collected this information, they assisted group 2 with collecting any remaining data needed.

Group 2: Obtained data to complete the process level assessment and metrics sheet (see Appendix C). The process level assessment and metrics sheet contained questions to ask about the following categories:

- Line-level (e.g., line production capacity/day)
- Machine-level (e.g., which processes are being assessed)
- Production management (e.g., part handling time, planned cycle time)
- Utilization management (e.g., OEE)
- Rejection management (e.g., average rejection quantity, rework quantity)
- Machine tool energy consumption (e.g., rated power, total idle duration)
- Processing power (e.g., overall input power, control system power)
- Material processing (e.g., type of material processed, weight of finished workpiece)
- Consumables (e.g., coolant, oil)
- Tooling (e.g., type of cutting tools used, tool life)
- Utilities
    - Compressors (e.g., type of compressed air, total number of compressors present)
    - HVAC (e.g., capacity of system, operating power consumption)
    - Coolant circulation system (e.g., rated input power)
    - Waste management (e.g., metal scrap, coolant waste, solid waste)
- Maintenance check points (e.g., is lubrication oil level checked periodically?)

Group 3: Hooked up energy monitoring devices and collected energy data from the machine tools and compressor. An energy measurement checklist, listing some guidelines for taking measurements can be found in Appendix D. This checklist included items such as ensuring that the energy meter is working, connecting the current and voltage clamps, checking for directionality, and collecting the cycle time of all supporting equipment.

During this assessment, the team evaluated two similar machining operations. The team assessed the machining of the “Jaw Moving Ins” part. This component is machined on both a Hydromat Rotary Transfer Machine Tool and a Citizen “Swiss style” Machine tool depending on machine tool availability and other production requirements (so-called “Swiss style” as it was developed by the Swiss watch industry for precision production of watch components). The Hydromat Rotary Transfer Machine Tool is a multiple station piece of equipment that incorporates 10 independent positions allowing simultaneous machining or transfer of the component in each operation. The second machine tool is a bar fed Citizen Swiss Style Machine Tool. This piece of equipment machines only one component during each machining cycle.

During the assessment, the team utilized energy monitoring equipment, shop floor personnel interviews, historical records, and an understanding of common shop practices in order to conduct a complete analysis of the machining process.

Analysis

Using the methodology previously described above, we can categorize the consumption of resources into 4 categories: Tooling, Industrial Fluids, Raw Material, and Energy.

Tooling

The Citizen Swiss machine tool utilized 18 different tools with tool life ranging from 100 pieces to 3,000 pieces. Per part tooling costs ranged from less than $0.02 per part to more than $0.32 per part. The total tooling costs were estimated at $1.56 per part.

Table 3.8: Citizen Swiss Tooling Data (tool pricing circa 2010)

Tool Life (# of parts)	**Tool Description**	**Cost of Tool**	**Tooling cost per jaw**
1000	INSERT, GROOVING .0620W, NG2062RK-KC5025	$13.10	$0.01
1000	INSERT, DIAMD 0.008CR, CCGT32505LF-KC5025	$8.95	$0.01
300	INSERT 35DEG .0156CR, VBGT331LF-KC5010	$13.90	$0.00
250	ENDMILL .0800D .002CR, MWI 4FLT SC	$22.13	$0.09
3000	ENDMILL .0787D .0079CR, MITS 4FLT SC	$57.68	$0.02
300	ENDMILL, BALL.0315D, 4FLT.090 REACH MWR03-144	$26.06	$0.09
200	DRILL .0312D, MWI R03-115	$10.38	$0.05
1000	T-SLOT SAW.4600D X.025, MWI R03-134 REV D	$156.13	$0.16
250	ENDMILL .2500D, HTA 3FLT SC	$41.06	$0.16
1000	BRUSH ABRASIVE, NYLON BRUSH 2.5000D	$10.14	$0.01
1000	DOVETAIL, .2500 60 DEG., MWI R03-026	$53.25	$0.05
500	DRILLMILL, .1250D, HRVY 30DEG 15408	$24.13	$0.05
500	SAW 3/4 X .021 X 1/4, SWM750-10204 20T F/RAD	$109.20	$0.22
1000	T-SLOT SAW.4600D X.025, MWI R03-134 REV D	$156.13	$0.16
1000	ENDMILL .1250D, NIA 5FLT SC	$16.68	$0.02
500	ENDMILL .2500D, HTA 6FLT STUB SC	$27.17	$0.05
100	ENDMILL .0472D, MWI#R03-208 4FLT .0944RC	$32.81	$0.33
300	ENDMILL, BALL .0200D, .090 REACH	$27.56	$0.09
		Tooling cost per part	**$1.56**

The Hydromat machine tool utilized 21 different tools with tool life ranging from 200 pieces to 50,000 pieces per tool and per part tooling costs range from a fraction of a cent to more than $0.16 per part. The total tooling cost per part is estimated at $0.77 per part.

Table 3.9: Hydromat Tooling Data (tool pricing circa 2010)

Tool Life (# of parts)	**Tool Description**	**Cost of Tool**	**Tooling cost per jaw**
2000	Kennametal VBGT331 KC5010 (R.0156")	$12.62	$0.00
400	MA Ford 7MM dia., 0.035" CR 4flt.	$48.62	$0.12
200	MITGI .0472" endmill # R03-208	$32.81	$0.16
3500	T-SLOT SAW.4600D X.025, MWI MITGI R03-134 REV D	$156.13	$0.04
5000	MITGI Dovetail Cutter # R03-026 Rev. A	$53.25	$0.01
2500	Fraisa 0.059" 1.5mm 2 flute M5752.120	$52.97	$0.02
800	MITGI Chamfer tool #R03-218 60 DEG	$24.23	$0.03
3000	Robb-Jack Saw 1.25 x 0.021 with full radius	$121.15	$0.04
1200	Javelin TR4S47 6flute 45degre e-mill	$27.17	$0.02
800	MITGI drill # R03-115	$10.38	$0.01
6500	MILL, FORM, MWI 4LT MWR03-136	$217.88	$0.03
400	ENDMILL, BALL.0315D, 4FLT.090 REACH MWR03-144	$48.88	$0.12
2000	MITGI END MILL R03-194	$43.00	$0.02
800	Sandvik insert MACR 3 070-L 1025	$26.63	$0.03
50000	Sandvik tool holder SMALR 1616K 3	$88.29	$0.00
20000	Sandvik Ball head screw replacement	$12.50	$0.00
4800	Harvey Tool R0.0365 & side mill per REI drawing # VL-0947-T-20 Rev C	$85.25	$0.02
5000	MITGI 0.035" diameter 4 flute ball endmillTialN coated, MITGI # R03-018	$32.75	$0.01
2500	Mitgi 0.059 End mill #R03-025	$33.19	$0.01
3000	T-SLOT SAW 0.4600D X 0.0245, MWI MITGI R03-189	$122.94	$0.04
3000	MITGI 0.0236" diameter 4 flute ball endmillTialN coat, MITGI # R03-017	$31.44	$0.01
		Tooling cost per part	**$0.77**

Increased spindle speeds and additional room for tooling provides a measurable sustainable advantage in the area of tool life. The tooling cost per part on the Citizen Swiss Machine was more than twice that of the Hydromat on the component that was analyzed. In this case superior machine tool capabilities not only improved overall productivity by reducing the cycle time by more than 90%, it also improved tool life by more than 100%. In performing an economic analysis of the metrics measured for this assessment, tooling demonstrated the most significant opportunity for return on investment.

Industrial Fluids

Coolant (used in the cutting process to lubricate and flush away chips), spindle oil (lubricates the machine spindle), way oil (reduces friction on the "ways" – the rails on which the machine axes move), and hydraulic oil (used to activate clamps) were the industrial fluids that were identified to be directly consumed in the machining process of the component analyzed. The consumption of industrial fluids was not metered or physically measured, therefore common practices and limited historical data were used to estimate industrial fluid consumption for each process. Industrial fluids in these machining processes are part of closed systems and the fluids are not "consumed" in the traditional sense. Coolant is lost in evaporation and carried off, spindle oil is evaporated or carried off, and the way oil and hydraulic oils are changed out periodically as their cleaning and lubricating properties deteriorate.

Hydromat

The Hydromat machine tool consumed approximately 55 gallons of NuCut Lite bio lube coolant per month across all components machined in the cell. 100% of the coolant was recycled. In order to allocate the coolant to a particular component, we must normalize the coolant consumption based on this component running 100% of the available operating time for the machine tool. Assuming an 89% efficiency consistent with past operating efficiency data and a 45 second cycle time we can estimate that there are approximately 51,264 available cycles for this component per month. Distributing the 55 gallons of coolant used per month across all cycles, we can estimate that 4.05 mL of coolant is consumed per cycle.

> 24 hours / day X 30 days / month X 3600 seconds / hour X 1 cycle / 45 seconds = 57,600 cycles / month
>
> 57,600 cycles X 0.89 efficiency = 51,264 cycles
>
> 55 gallons / month X month / 51,264 cycles = 0.00107 gallons / cycle
>
> 0.00107 gallons / cycle X 3785 mL / 1 gallon = 4.05 mL / cycle

The hydraulic oil was changed in the system once every 6 months. Approximately 1 gallon of hydraulic oil is replaced during the change. The Hydraulic oil consumed per cycle can be estimated similarly to the coolant.

> 24 hours / day X 30 days / month X 3600 seconds / hour X 1 cycle / 45 seconds = 57,600 cycles / month
>
> 57,600 cycles X 0.89 efficiency = 51,264 cycles / month
>
> 51,264 cycles / month X 6 months = 307,584 cycles / 6 months
>
> 1 gallons / 6 months X 6 months / 307,584 cycles = 3.251 e-6 gallons / cycle
>
> 3.251 e-6 gallons / cycles X 3785 mL / 1 gallon = 0.012 mL hydraulic oil/ cycle

Way Oil is added to the system as needed. It was estimated that 1.5 gallons of way oil was added per week.

> 24 hours / day X 7 days / week X 3600 seconds / hour X 1 cycle / 45 seconds = 13,440 cycles / week

13,440 cycles /week X 0.89 efficiency = 11,961 cycles / week

1.5 gallons / week X 1 week / 11,961 cycles = 0.1.25 e-4 gallons / cycle

1.25 e-4 gallons / cycle X 3785 mL / 1 gallon = 0.47 mL way oil/ cycle

Spindle oil is added to the system as needed. It was estimated that approximately ½ gallon of spindle oil is added to the system every 60 days.

24 hours / day X 30 days / month X 3600 seconds / hour X 1 cycle / 45 seconds = 57,600 cycles / month

57,600 cycles X 0.89 efficiency = 51,264 cycles / month

51,264 cycles / month X 2 months = 102,528 cycles / 2 months

0.5 gallons / 2 months X 2 months / 102,528 cycles = 4.88 e-6 gallons / cycle

4.88 e-6 gallons / cycles X 3785 mL / 1 gallon = 0.018 mL spindle oil / cycle

Citizen Swiss

The Citizen Swiss machine tool consumed only 2 gallons (7.6 liters) of NuCut Lite bio lube coolant per week across all components machined in the cell. 100% of the coolant was recycled. In order to allocate the coolant to a particular component, we must again normalize the coolant consumption based on this component running 100% of the available operating time for the machine tool. Assuming an 80% efficiency consistent with past operating efficiency data and a 787 second cycle time we can estimate that there are approximately 768 available cycles for this component per week. Knowing that approximately 2 gallons of coolant is added to the machine tool per week allows us to calculate a per cycle consumption of 12.34 mL of coolant consumed per part.

24 hours / day X 7 days / week X 3600 seconds / hour X 1 cycle / 787 seconds = 768 cycles / week

768 cycles X 0.80 efficiency = 614 cycles

2 gallons / week X week / 614 cycles = 0.00326 gallons / cycle

0.00326 gallons / cycle X 3785 mL / 1 gallon = 12.34 mL / cycle

Way Oil is added to the system as needed. It was estimated that 0.5 pints of way oil was added every three days.

24 hours / day X 3 days X 3600 seconds / hour X 1 cycle / 787 seconds = 329 cycles / 3 days

329 cycles / 3 days X 0.80 efficiency = 263 cycles / 3 days

0.5 pints / 3 days X 3 days / 329 cycles = 0.00151 pints / cycle

0.00151 pints / cycle X 473 mL / 1 pint = 0.714 mL way oil/ cycle

It was approximated that 1 pint of spindle oil is added to the system per week.

24 hours / day X 7 days / week X 3600 seconds / hour X 1 cycle / 787 seconds = 768 cycles / week

768 cycles X 0.80 efficiency = 614 cycles

1 pint / week X week / 614 cycles = 0.00163 pints / cycle

0.00163 pints / cycle X 473 mL / 1 pint = 0.77 mL / cycle

Table 3.10: Industrial fluid summary

	Hydromat	Citizen	% Difference
Coolant	4.05 mL / Cycle	12.34 mL / Cycle	204%
Hydraulic Oil	0.012 mL / Cycle	No Info Available	N/A
Way Oil	0.47 mL / Cycle	0.714 mL / Cycle	52%
Spindle Oil	0.018 mL / Cycle	0.77 mL / Cycle	4178%

Material

The raw material required to machine the part was fairly consistent across both machine tools with the bar fed Citizen Swiss machine tool requiring slightly less material. The scrap rate for the component was consistent across both machine tools and accounted for less than 1% of the production volume on average. Due to the small size, relatively short cycle time, and minimal material costs, no rework is performed on the part analyzed. Any quality concern results in a scrapped component.

Hydromat

The Hydromat machining process utilizes a small cylindrical blank as the starting stock for the component analyzed during the assessment. The material was a 17-4 pH stainless steel and the blank weighed approximately 0.281 oz. The finished component weighed in at 0.037 oz. The final part accounted for 13% of the original blank.

Citizen Swiss

The Citizen Swiss machine tool is a bar fed operation utilizing 12' sections of bar stock. The bar stock including cut off is 1.125 inches in length and the stock is 0.250" in diameter. At a density of 0.283 lbs / cu in, the weight of the blank can be calculated at:

$$0.283 \text{ lb} / \text{in}^3 \text{ X } (\pi\ 0.250 \text{ in}^2 / 4) \text{ X } 1.125 \text{ in} = 0.0156 \text{ lbs}$$

$$0.0156 \text{ lbs X } 16 \text{ oz} / 1 \text{ lb} = 0.250 \text{ oz}$$

The finished component in the Citizen Swiss machining operation accounted for 15% of the original material.

Energy

The energy consumed at the machine input was measured for two separate Hydromat machine tools as well as a Citizen Swiss machine tool using the procedures and equipment previously described in section 3.3. While the Hydromat machine tools consumed energy at an increased rate, the significant decrease in cycle time more than adjusted for the increased rate of consumption. Figure 3.9 shows the average energy consumed per cycle for the two Hydromat machines measured as well as the Citizen Swiss Machine Tool.

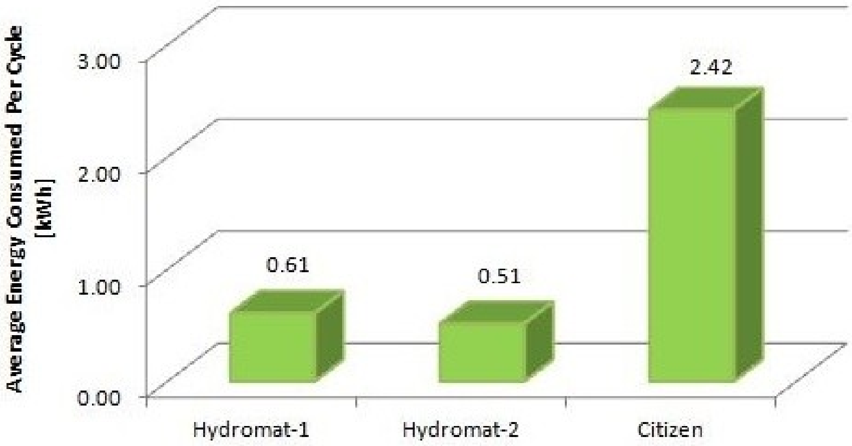


Figure 3.9: Average energy consumption per cycle for the Hydromat machines and Citizen Swiss machine

Remmele Assessment Results and Discussion

The assessment highlighted in this section served to assess the sustainability of two separate machining processes, each focused on making a similar component, and to provide a comparative analysis between the two processes. A Hydromat Rotary Transfer Machine Tool and a Citizen Swiss Machine Tool were compared on the basis of energy and resource consumption as well as the resultant waste streams produced from the machining operations.

The assessment revealed that not only did the Hydromat produce a 17 times increase in cycle time productivity over the Citizen Swiss Machine Tool, it did so utilizing only 25% of the energy per part. Due to the increased spindle speed capability, there was also an approximate 50% reduction in tooling consumption. Industrial fluid consumption was also reduced and while in some cases the consumption was relatively small, the relative consumption was reduced by several orders of magnitude.

In summary, the raw material, tooling, industrial fluids, and electrical energy required to machine the evaluated component were all reduced as compared to the Citizen Swiss machine. It should be noted that while the significant capital investment, multiple machining station configuration, and complexity in part set up and programming of a Hydromat machine tool make it impractical for low volume machining, it has obvious advantages for high volume production work. If the volume exists to support the operation, the machine tool not only provides a productivity increase, it does so at a significant reduction in energy and material resources.

3.5.2 GKN Aerospace

GKN Aerospace, located in St. Louis, MO, is a first tier supplier to the global aviation industry. A leader in the manufacture of highly complex composite and metallic aerostructures and engine products, GKN is equally focused on military and civil markets. Their manufacturing plant focuses primarily on milling, reaming, and drilling operations in its production of parts for the aerospace market. The goals of this assessment were to analyze the resource consumption of a Magnum machining test cell for the production of a test piece and to obtain data to assist in establishing a baseline for future assessments. The specific machining process studied was the production of a test piece using the Cincinnati H5-1000 Machine Tool.

Assessment Protocol

Prior to the assessment, the assessment team sent ahead a pre-assessment questionnaire (see Appendix B) for the facility to fill out ahead of time. Unfortunately, the facility was unable to complete the questionnaire, but during the kick off meeting and subsequent meetings key personnel were identified that could obtain answers to the questions at hand.

The manufacturing cell chosen for the assessment was the Magnum cell which holds three 5-axis horizontal Cincinnati H5-1000 machining centers. The machines run 24 hours a day, 7 days a week, and the machine tool the test part was run on is used primarily for the roughing of parts. It is equipped with a flow and a load meter, which were installed by Southside Engineering. With the load meter, one can compute the power demanded by the machine tool with a correctional power factor.

On the first day of the assessment, the team was able to run multiple tests on the machining center. The main power line was measured with the Yokogawa to compare to the load provided by the Karen Engineering unit. We were interested in running three tests in which the spindle and table axes were run. For the first experiment we monitored the machine tool power at a spindle speed of 2,000 rpm and jogged all 5-axes while the coolant was turned “on.” During the second experiment we monitored the machine tool power at a spindle speed of 2,000 rpm, ran the same program, except for this time the coolant was turned “off.” We attempted to do sub metering of the coolant and spindle/axis drives, but found that there were multiple AC/DC conversions in the electrical network, and while AC power should be measured with the wattmeter accessibility prevented us from doing so.

On the second day of the assessment the test part was run. The part was estimated to have a run time of 7 hours, but after several cutting tools broke, the feed was reduced and the part ran for approximately 10 hours. This was the first time that the facility had run the test part, but it will be used in the future to test cutting tool and machine center performance. The test part was a titanium workpiece with initial dimensions of approximately 22” L x 2.75” H x 5.5” W. The part was machined to a final volume of roughly 170 in^3. Two wattmeters were hooked up to the machine tool; the Yokogawa measured the input of the spindle and axis drives (as previously discussed in section 3.3) and GKN’s power meter measured the main power line.

As the part was machined, the assessment team spoke to a representative of the GKN Environmental Safety and Health group, who was able to show us incident, waste, and noise pollution reports. Power data were also obtained from the compressor serving the facility over the course of a few hours in 30 minutes increments. Finally, we toured the coolant recycling room.

At the conclusion of the assessment, the team compiled a list of information the team was to request through electronic communication once approved and if available:

- Tool list for the test part including description, cost, tool life, and estimated # of regrinds
- Information on worker conditions
    - Safety incident rate
    - Noise study results
- Waste stream information
    - Landfill waste generated
    - Any estimate as to how much is allocated to the machining portion of the business
- Cell information
    - Cell footprint
    - Average Cell footprint
    - Part volume for the cell or cells
    - Description of parts produced and quantities
    - Scrap for the cells
    - Rework for the cells
    - Equipment Utilization estimates for the cell
- Energy data
- Maintenance schedule and frequency for changing all fluids (other than coolant)
- Information on previous and planned initiatives
    - Peak leveling
    - Machine tool retrofits
- Description of part cleaning process and an estimate of water used to clean the sample part
- Compressor
    - Power
    - Flow rate

Not all data were available; as a result only the data that were available are included in the analysis section.

Analysis

Based on the collected information from the assessment protocol, we were able to analyze the resource consumption of the Magnum test cell according to five categories: tooling, energy, industrial fluids, raw material and waste, and human impacts. First, though, we focused on the size, productivity, and utilization of the cell in order to place this baseline in context. Table 3.11 shows a summary of this data. The Magnum test cell has an FMS (automated pallet transfer) system, and the cell footprints shown in Table 3.11 include this system. Part production, rework, and scrap rate data were collected from taken from October 20 to December 20, 2010. Utilization data were obtained from December 13 to December 17, 2010.

Table 3.11: Productivity and utilization data collected for the magnum test cell

Variable Name	Value	Units
Part Production	30.5	[parts/month]
Rework	9.8	[%]
Scrap Rate	0	[%]
Utilization with Mag 5	79	[%]
Utilization without Mag 5	90	[%]

Tooling

To machine the test part, five different cutting tools are required. In general, tools are re-ground four times before disposal. The tool life for the Magnum test cell ranged from 0.59 to 6.96 parts, and the per part tooling costs ranged from $12.15 to $202.75. The total tooling costs were estimated to be $370.54 per part.

Table 3.12: Magnum test cell tooling data

Cutter	Quantity	Diameter	Tool Life Metrics			Cost Metrics	
			Tool Life	Processing Time	Parts Produced	Cost of Tool	Tooling Cost
	[-]	[in]	[min]	[min]	[parts]	[$]	[$/part]
1	2	1.25	180	306	0.59	119.62	202.75
2	2	0.75	160	188	0.85	86.00	101.18
3	1	0.50	160	70	2.29	61.87	27.02
4	1	1.25	160	23	6.96	191.00	27.44
5	1	0.75	160	25	6.40	77.74	12.15

Energy Consumption and Power Demand

The electrical energy consumed by the Magnum test cell was measured by running the GKN test part through the cell. The cycle time to run the part was 36000 seconds. The electrical energy cost was \$0.09/kWh and the associated carbon footprint was 1.76 lbs of CO2/kWh. Table 3.13 shows a summary of the electrical energy consumed to produce the test part in the Magnum test cell. Based on this analysis, Figure 3.10 shows how the average electrical energy consumed per part would decrease for a given reduction in the cycle time to produce the part.

Table 3.13: Summary of electrical energy metrics for the magnum test cell

Per Part Metrics		
Average Power Demand	23.86	[kW]
Maximum Power Demand	35.61	[kW]
Specific Energy Consumed per Part (SEC)	238.59	[kWh]
Carbon Footprint per Part	419.92	[lbs CO_2]
Energy Cost per Part	37.79	[\$]
Annualized Energy Usage & Footprint		
Yearly Energy Usage	143154.09	[kWh]
Energy Cost per Year	12883.87	[\$]
Carbon Footprint per Year	251951.20	[lbs CO_2]

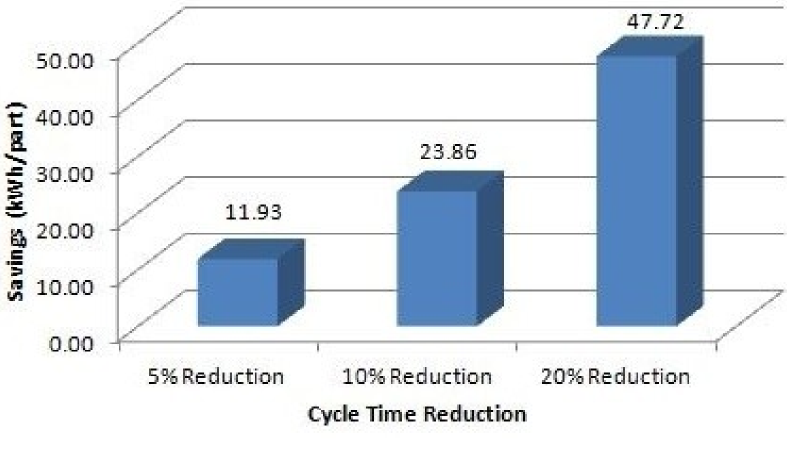


Figure 3.10: Average energy savings per part for a reduction in cycle time

In addition to the summary presented in Table 3.13, we also studied the effect of cell utilization on electrical energy usage by scaling our results assuming an 80% utilization. Figure 3.11 shows the yearly savings in energy costs due to utilization improvements from an 80% utilization rate, while Figure 3.12 shows how the average electrical energy consumed per part would decrease for a given reduction in the cycle time to produce the part for 80% utilization rate.

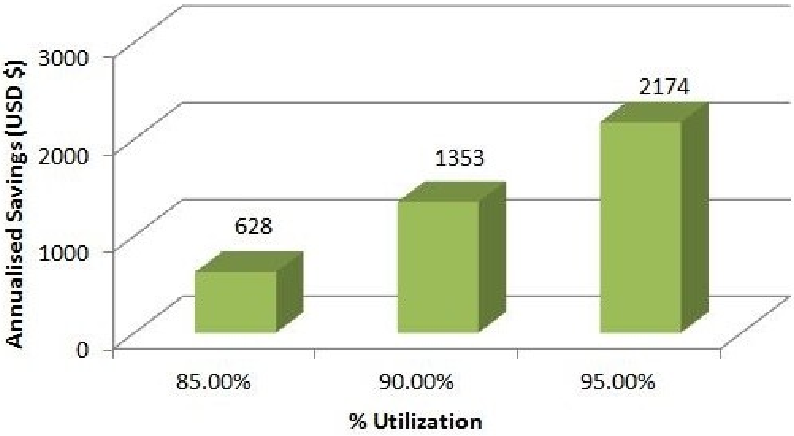


Figure 3.11: Yearly savings in energy costs by utilization improvement

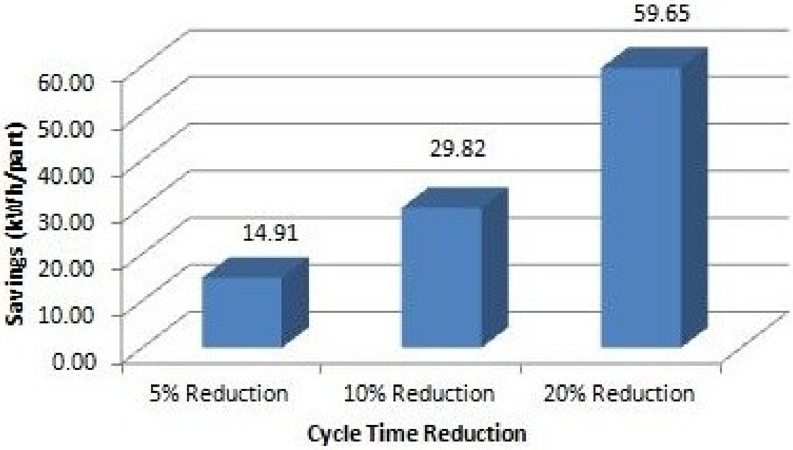


Figure 3.12: Average energy savings per part for a reduction in cycle time using an 80% utilization rate

Compressors at the GKN facility distribute compressed air for multiple machine tools within the plant, (i.e., no one compressor is allotted to a particular machine tool). The energy and power demand provided herein is for the South Balcony compressor. The data for this compressor were gathered over the course of 16 days, December 1 – December 16, 2011.

The metrics provided below show the total energy consumed by the compressor, the average daily energy consumption and the average power demand. Once information is available regarding the machine tools that are serviced by this compressor and their compressed air requirements, the energy consumed for the Magnum cell in particular can be calculated.

Table 3.14 South Balcony compressor energy and power metrics

Variable Name	Value	Units
Energy Consumption	114,170.943	[kWh]
Average Daily Energy Consumption	7,136	[kWh]
Average Power Demand	297	[kW]

Figure 3.13 shows facility level electric energy consumption from January through November 2010.

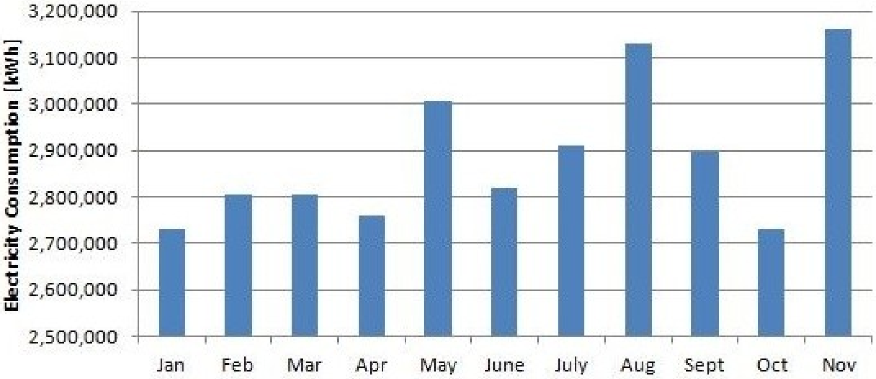


Figure 3.13: Facility level electric energy consumption for January through November of 2010

Industrial Fluids

Coolant, spindle oil, way oil, and hydraulic oil were the industrial fluids that were identified to be directly consumed in the machining process of the test piece analyzed. The consumption of industrial fluids was not metered or physically measured, therefore common practices and limited historical data were used to estimate industrial fluid consumption for each process. Industrial fluids in these machining processes are part of closed systems and the fluids are not "consumed" in the traditional sense. Coolant is lost in evaporation and carried off, spindle oil is evaporated or carried off, and the way oil and hydraulic oils are changed out periodically as their cleaning and lubricating properties deteriorate. Figure 3.14 shows monthly new coolant consumption from January through November 2010.

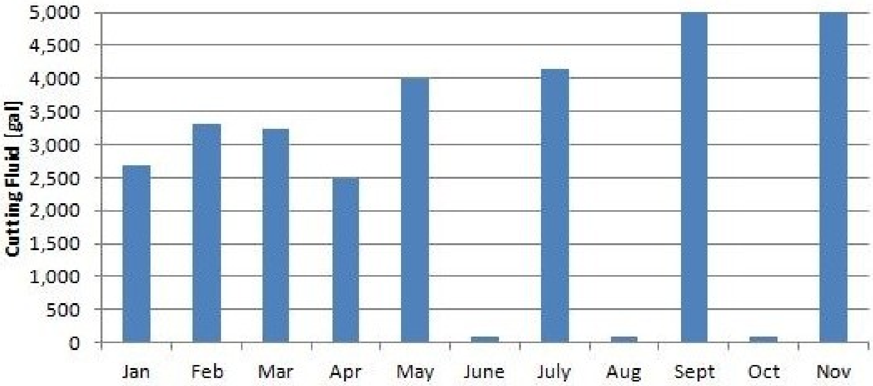


Figure 3.14: New coolant consumption for the machine for January through November of 2010

The metrics provided below show the average amount of new coolant consumed as well as the average amount of oil consumed for Mag 4, 5, and 6.

Table 3.15: Average industrial fluid consumption

Variable Name	Value	Units
New Coolant Consumed	2,747	[gal/month]
Mag 4 Oil Consumption	6	[gal/month]
Mag 5 Oil Consumption	1.6	[gal/month]
Mag 6 Oil Consumption	5.9	[gal/month]

Raw Material and Waste

Below is monthly metal chip removal data for aluminum and titanium from January through November 2010. Aluminum is used much more extensively than titanium; in fact it is used more than twice as much.

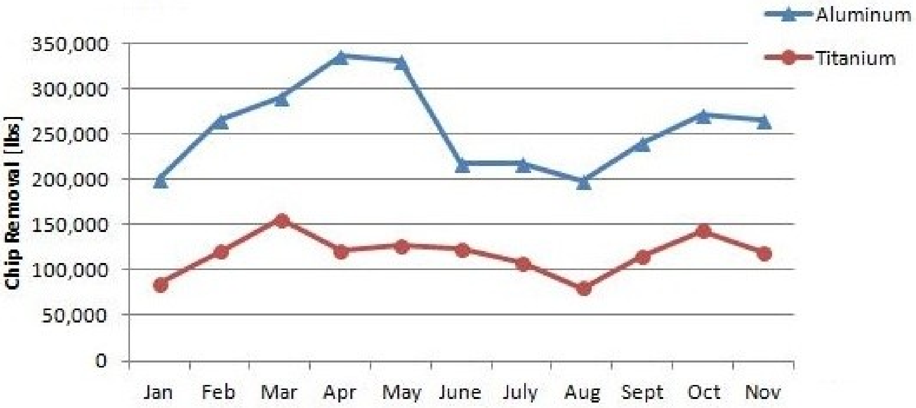


Figure 3.15: Metal chip removal for aluminum and titanium from January through November 2010

Table 3.16 below shows the average amount of aluminum and titanium chips removed per month.

Table 3.16: Average metal chip removal

Variable Name	Value	Units
Aluminum Chip Removal	257,869	[lbs/month]
Titanium Chip Removal	118,438	[lbs/month]

Figure 3.16 shows data for solid waste sent to the landfill from January through November 2010.

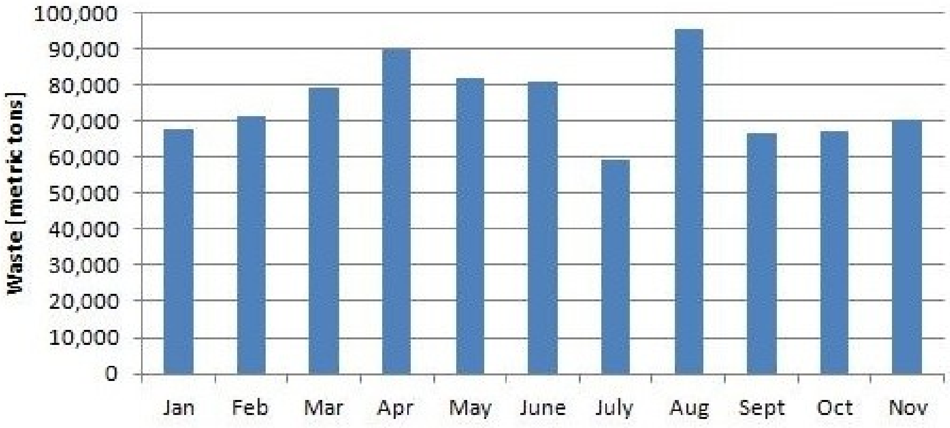


Figure 3.16: Monthly solid waste (landfill) production

Figure 3.17 shows data for liquid waste produced from January through November 2010.

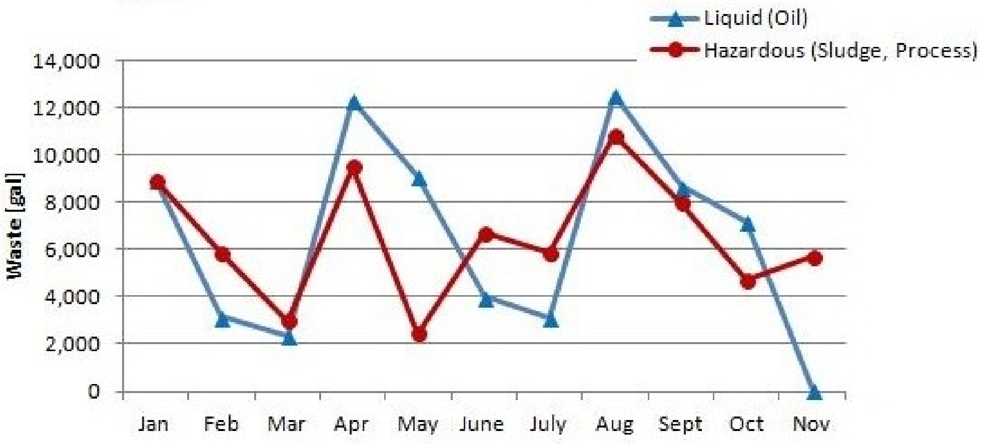


Figure 3.17: Monthly liquid waste production

The metrics provided below show the average amount of solid waste, liquid waste, and hazardous waste produced each month.

Table 3.17: Average waste production

Variable Name	Value	Units
Solid Waste (landfill)	75,438	[metric tons/month]
Liquid Waste (oil)	6,500	[gal/month]
Hazardous Waste (sludge, process)	6,491	[gal/month]

Human Impacts
Of the various human impacts in the manufacturing environment, we were able to find the average noise level in the facility. This was found to be 86 dB.

GKN Assessment Results and Discussion
The purpose of this assessment was to determine the sustainability of a green machining test cell and collect data in order to establish a baseline performance. In order to assess the sustainability of the green machining test cell, a test piece was run in the Magnum machining cell and data were collected to analyze the resource consumption of the Magnum test cell according to five categories: tooling, energy, industrial fluids, raw material and waste, and human impacts. The tooling costs were estimated to be $370.54 per part. The test part run through the Magnum cell consumed 238.59 kWh of energy to produce over a cycle time of 36,000 seconds. Consumables used were difficult to establish for the Magnum cell due to a lack of information in order to assign the facility level data to the cell level. Nonetheless, the data highlighted in this report can be used to help establish a baseline or standard to which manufacturing or machining processes can be compared against. Based on this baseline, process level improvements can be explored to increase the resource efficiency of the Magnum cell. For example, cycle time reductions and utilization improvements can both have a substantially positive impact on overall electrical energy and cost savings.

A third assessment was conducted, but due to confidentiality restrictions of the facility, the results were not able to be released, so a very brief overview is provided in the next section.

3.5.3 General Electric Aviation

General Electric (GE) Aviation is the world's leading producer of large and small jet engines for commercial and military aircraft. They also supply aircraft-derived engines for marine applications and provide aviation services. Their engine blades and vanes (all engine programs) manufacturing facility is located in Madisonville, KY. The goals of the assessment were to establish a baseline for the resource usage of machines to create finished airfoils and to compare older and newer machines. The specific processes studied were grinding, smear electrical discharge machining, and current electrical discharge machining for a turbine airfoil hole drilling line. In general, the results of this assessment validated the feasibility of the methodology.

3.6 Advantages and Disadvantages of Methodology

There are a number of observations that came up during this research exercise that illustrated advantages and disadvantages to an idealized methodology. Most assessment methodologies only look at the facility level making it very difficult to translate this data to the cell level. The assessment approach developed here allows the user to zoom in on specific cells and machine tools, draw a box around the process, and evaluate all of the inputs and outputs specific to that system using a comprehensive list of metrics (see Appendix A). The assessment was placed in the context of the manufacturing process, allowing for better reasoning and decision-making upstream.

Most assessment tools cannot incorporate inputs that must be measured directly, such as electricity, whereas this tool incorporates these inputs into the analysis, allowing for a very detailed analysis.

Other assessment tools use very broad categories and often lump metrics together into one main area. This does not allow for the user to be able to separate out specific metrics. The assessment tool in this work keeps specific categories and metrics separate, allowing the user to have flexibility in their analysis.

On the other hand, most facilities may not have existing energy monitoring devices available, making energy monitoring at the cell level difficult. Even if the facility is able to obtain energy monitoring devices, every machine tool is different and every electrical supply to the machine is different (even within the same facility). This would make it very difficult for workers in a facility to hook up the energy monitoring devices to the power supply without specific training and electrical systems knowledge.

Due to the level of data collection (as well as if a facility is not already outfitted with energy monitoring devices), assessing an entire facility with respect to their machine tools (depending on the size of the facility) could prove to be time consuming. Since all facilities differ, one blanket approach will not work. The methodology will have to be changed and adapted to accommodate different facilities, again requiring worker knowledge and/or training (making it difficult for a non-expert to use the tool). Following from this, reliability of data are dependent on the person conducting the assessment.

The groups gathered the data from various sources: direct measurement (energy monitoring devices, stopwatches), interviews (machine operators, financial/purchasing department personnel, facility engineers), and paper trails (tool lists, log books, energy bills). Since the uncertainty in the data is dependent on the source, the uncertainty in the data varies. Also, for shared process equipments such as compressors, the usage must be amortized per device based on planned estimates, not actual usage.

Lastly, it is important to note that it can be difficult to obtain data without interrupting production on the facility floor.

3.7 Conclusions

The work detailed here focused on a combination of facility level and machine level assessments. From the experiences gained with these studies it was possible to develop the protocol for conducting assessments and test the validity of the metrics. As a result of this work, a comprehensive list of metrics was developed, different measurement approaches were explored, and different ways of looking at performance indices were discussed. The assessment methodology discussed in this section focused on five main categories:

- tooling,
- energy,
- industrial fluids,
- raw material and waste, and
- human impacts.

This methodology can be used for a variety of purposes:

- to assess the energy and resource consumption of separate machining operations,
- to provide a comparative analysis between two processes,
- to serve as a guideline for which data to collect from a machining cell, and
- to establish a baseline or standard to which manufacturing or machining processes can be compared against.

The data collected during this work can be used to help establish that baseline. Using this baseline, process level improvements can be explored to increase the resource efficiency of the process or cell being analyzed. For example, the analysis conducted in the GKN Aerospace study showed how cycle time reductions and utilization improvements can both substantially provide electrical energy and cost savings.

This work served as a starting point to establish a standardized assessment methodology and baseline. More assessments and data are needed to further refine the methodology and to establish a standardized baseline. The examples shown in the sections above described the procedures used for analysis of a narrowly defined set of manufacturing processes – usually machining – in the context of a machined part. In reality, most manufacturing processes are a part of a larger series of processes in a production chain, each adding a specific feature or modification. The focus of the next chapter is investigated, in detail, at a more complicated process chain. This is motivated by a research project with Caterpillar. Caterpillar was seeking to understand the potential benefits/impact of changes in a multi-station production process chain. The objective was to maintain, or improve, the production process (e.g., throughput and reduced costs) while at the same time noting any benefits in resource or energy consumption by making a change to one of the specific process steps.

Chapter 4

Manufacturing Process Chains

The previous chapters focused on machining and generally, individual processes. In reality, manufacturing process chains often include multiple different processes all working together in sequence to convert an incoming material or component into a finished structure or component.

4.1 Introduction to Fabrication Process Chains and Decision-Making

Fabrication processes are not well characterized with respect to resource consumption. There have been some initial attempts at this but, in general, they are not well represented nor are they addressed in the literature. Importantly, they are not addressed at a level to allow engineering decision making about the effectiveness of the resources used in the process relative to the production specifications. There is a lack of data and data quality available about their resource consumption. As a result, the resource consumption of many fabrication process chains currently cannot be assessed. Consequently, there is an inability to consider resource consumption when selecting among different fabrication process chain elements or combinations.

This research focuses on assessing the resource consumption of fabrication process chains for Caterpillar. Fabrication at Caterpillar refers to building large metal structures from plate or structural steel using a series of cutting, bending, and assembling processes. Figure 4.1 shows a sample fabrication process chain. The input is metal plate and the output is a large welded structural component for construction machinery.

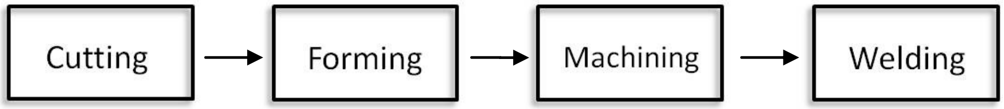


Figure 4.1: General fabrication process chain

Fabrication process chains are used to manufacture construction and mining equipment and used in fabrication shops for structural work on buildings, bridges, and ship building and repair.

Sales of construction equipment by the world's 50 largest manufacturers grew by 25 percent last year - to $182 billion. This was a new record for the industry as the previous high was $168 billion in 2008 (Barbaccia, 2012).

When deciding on the process chains to use to manufacture a product, there is typically more than one way to feasibly make the same product. If several manufacturing process chains are able to produce a product, a decision will have to be made as to which process chain to use. In Figure 4.2 we see three different process chain combinations available to make a product. The path at the top represents process chain 1, middle is process chain 2, and bottom is process chain 3.

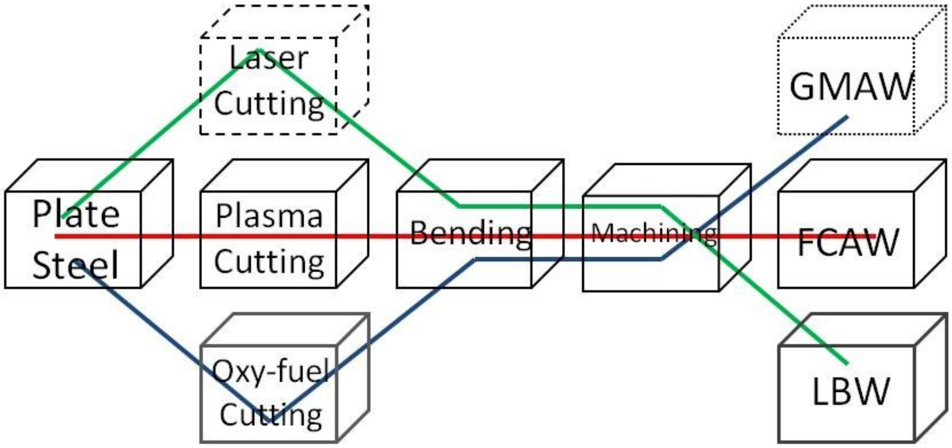


Figure 4.2: Process chain combinations (GMAW = Gas Metal Arc Welding, FCAW = Flux Cored Arc Welding, LBW = Laser Beam Welding) (adapted from (Chien & Dornfeld, 2010))

Currently in industry, process chain decisions are typically made by taking into account considerations such as production costs, cycle times, quality, efficiency, customer demand and capacity, as well as whether the manufacturing technology being considered is appropriate. At a higher level, considerations with respect to precedence must be taken into account. Here precedence refers to determining what process must be done first, second, third, etc. to insure a logical sequence of manufacturing. For example, if one is drilling a hole, it is usually necessary to first drill a pilot hole of smaller diameter and then follow this with the appropriate drill size. Thus, the pilot hole must precede the desired hole. Figure 4.2 above indicates both the processes needed and the required sequence, or precedence, required. In addition, however, as previously discussed in Chapter 1, manufacturing processes are very resource intensive. Because of this, additional information needs to be considered when selecting the process chains used to manufacture a product.

One of the goals of this research is to fill in and provide this piece of the puzzle so that a more complete picture of the process chain is known. This research proposes that in order for industry to make more informed decisions about the process chains that they are selecting when deciding how to manufacture a product; they need to take into account the resource consumption of the process chains.

Figure 4.3 shows a holistic picture of process chain decision making process/selection process. Along the top of Figure 4.3 are the key metrics that industry currently considers when making decisions about process chain selection. Along the right side of Figure 4.3 are the proposed additional elements one must consider in order to have a holistic view of the impact of the decision and for industry to make more informed decisions. It is also important to consider potential health hazards to address situations that directly impact the worker(s) besides waste and emissions or other production characteristics.

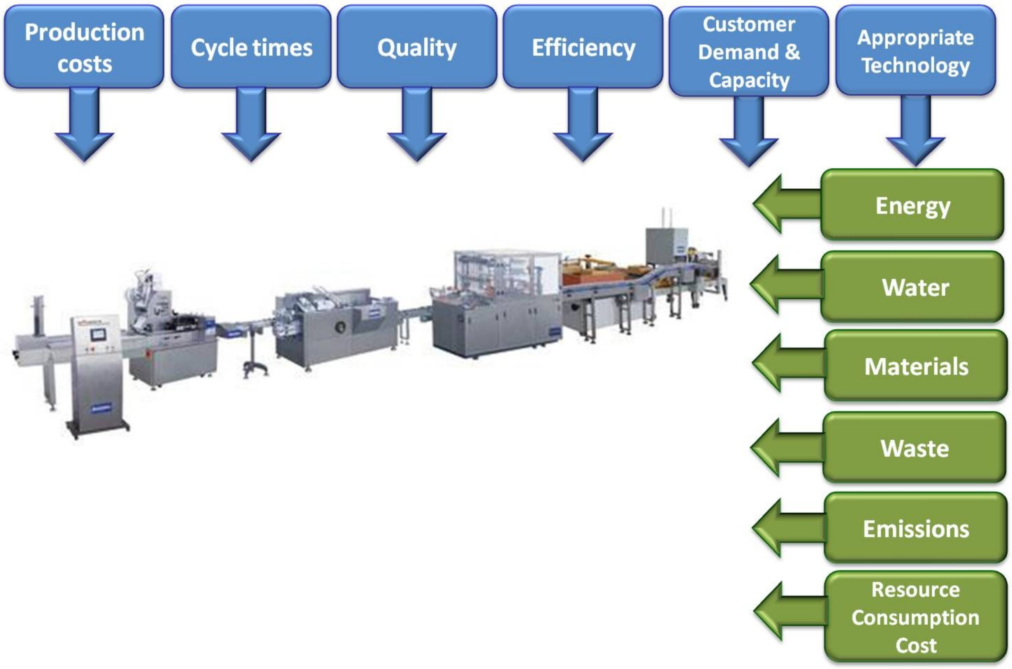


Figure 4.3: Holistic picture of process chain decision making process/selection process

Any environmental assessment needs to address as well the potential health hazards associated with manufacturing. In particular, welding has been long studied due to the heat, particulate and other emissions resulting from the process. Yeo & Neo, 1998 suggest a health hazard scoring system based on air emissions as a way of choosing welding processes, but does not assess any resource consumption. Shama (2005) framed the considerations of conducting a life cycle assessment on ship building, but fails to point out how to assess the specific welding processes. Drakopoulos, Salonitis, Tsoukantas, & Chryssolouris, 2009 looked at some welding and cutting processes used in ship hull repair, but used a life cycle assessment software tool to conduct the analysis. Unfortunately the results of this study are not very accurate as the use phase of these processes is not well represented or characterized in the life cycle inventory databases that the LCA software uses. Although health hazards are not specifically addressed in this research as they are outside of the scope of study, they should be considered when making process selection decisions as with any technology decision. It is also important to note that these studies do not consider the environmental impacts of this resource consumption or the associated costs of the resource consumption.

In summary, fabrication processes are not well characterized with respect to resource consumption as they are not well represented or addressed in the literature and there is a lack of data and data quality available about their resource consumption. Because of this, the resource consumption of fabrication process chains currently cannot be assessed. As a result, there is an inability to consider resource consumption when selecting among different fabrication process chain combinations.

In order to address this, the research objectives of this work are to:

- evaluate the resource consumption and environmental impacts of fabrication process chains at a process level and in combination for the chain
- evaluate the associated economic impacts due to the resource consumption of fabrication process chains, and
- develop a model to evaluate the resource consumption of multiple process chain configurations
- suggest a strategy for evaluating trade-offs between alternatives

4.2 Background on the Caterpillar Process Chain Case Study

Taking the metrics, organizational structure, and evaluations developed earlier, a case study of a more complex process chain used in the manufacturing of heavy machinery was done. Caterpillar Inc., (or CAT) the world's largest manufacturer of construction and mining equipment (with 20% of the market share) provided the test case for this. A more in depth discussion of the actual case study is given in Chapter 6.

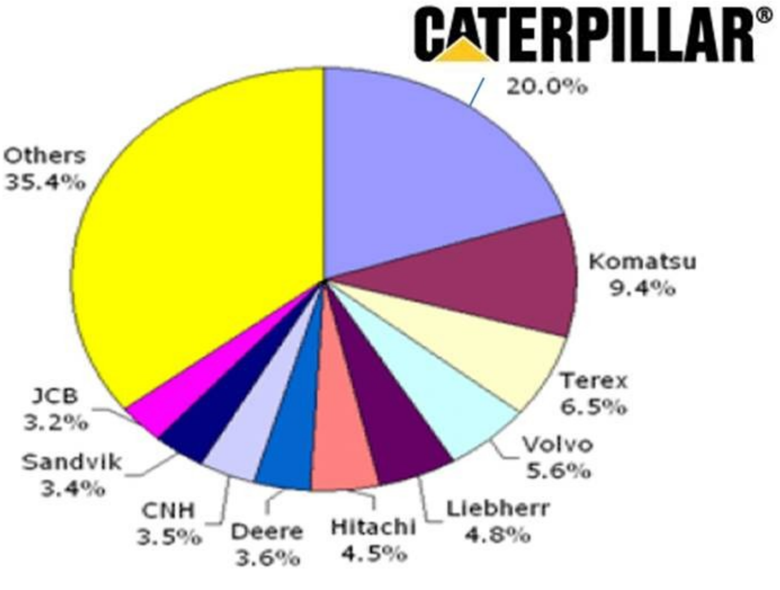


Figure 4.4: Market share of construction and mining equipment industry (Barbaccia, 2012)

A recent report from Report Linker (2013) indicates that the global construction machinery demand is expected to grow at a yearly rate of 6.5% through 2015 to reach a value in excess of \$170 billion. Hence, the product manufacturing needed to support this demand is substantial with Caterpillar, at 20% market share in 2010, seeing some \$34 billion in sales.

The system analyzed is for the production of the D6 track-type tractor (see Figure 4.5). The Caterpillar D6 track-type tractor is a medium size bulldozer. This is in comparison to the D11 track-type tractor which is a large size bulldozer (see Figure 4.7). In specific, the production of the top ROPS (roll over protective structure) canopy component on the D6 track type tractor was studied (shown in Figure 4.6). This component was chosen because it encompassed all of the most basic fabrication processes, served as a great example fabrication process chain, was not too complex to fabricate, and served as a good test case for the model development. The D6 canopy is the part used to develop the resource consumption process chain model presented in the Chapter 6.

Figure 4.5: Caterpillar Inc. D6 track-type tractor (Wikipedia, 2012)

Figure 4.6: D6 canopy component

Figure 4.7: Caterpillar Inc. D11 track type tractor showing the canopy component placement as part of the larger assembly/finished product, the D11 is the largest in the D series track type tractors manufactured by Caterpillar.

4.3 Production Chain and Process Details

The manufacturing process chain for the D6 canopy is very challenging due to both the complexity and the size of this structure. There are many different variations of the process chain that can take place. Figure 4.8 shows a complete schematic of different variations of the process chains used to make the D6 canopy.

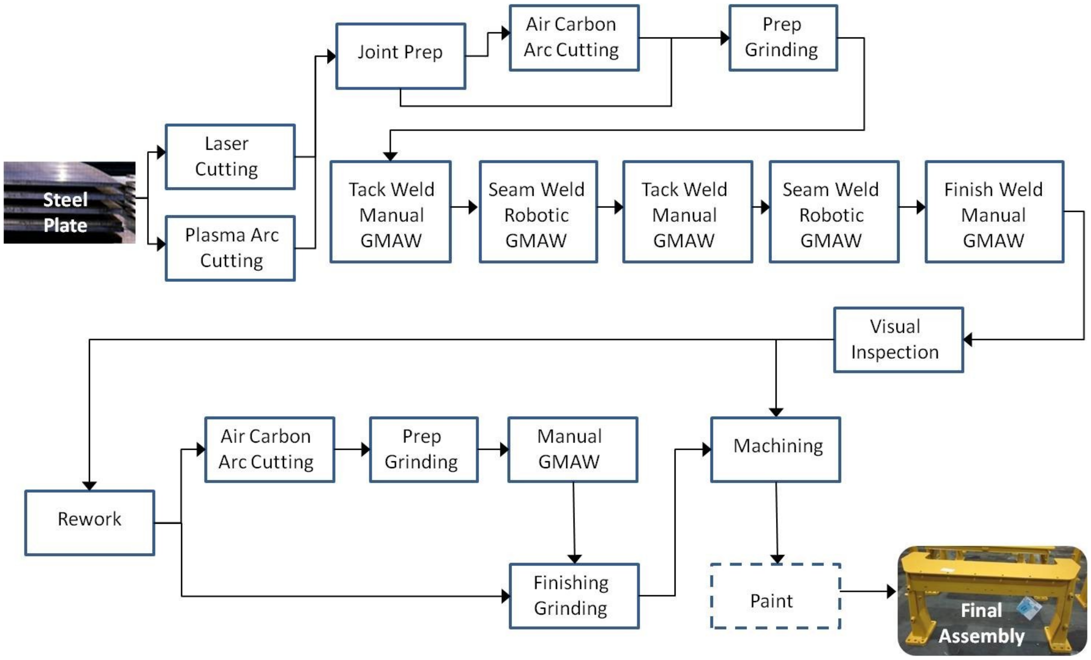


Figure 4.8: Possible process chain configurations for D6 canopy production (GMAW = Gas Metal Arc Welding)

The basic production sequence is summarized as follows:

- Steel plate enters into first operations, which means that the steel plate is prepared for the part. This is done by cutting the steel plate into the various pieces required to make the part. The cutting is done by either laser cutting or plasma arc cutting.
- After the steel plate is cut to size from the raw material (into pieces to be assembled), the edges of the pieces are prepared for welding (assembly). This is referred to as the joint prep stage. During the joint prep stage the edges of the freshly cut steel pieces are prepared in order to be welded. This means that if two pieces of steel are to be joined together (by welding), the edges where the welding will take place need to be prepared to a certain geometry and finish in order to have a successful weld at the joint (where the two pieces are joined). Joint prep can be done by air carbon arc cutting or by hand grinding (prep grinding step).
- Once the joint prep is completed and the edges of the parts are prepared for welding, the pieces move to the welding cell. In the welding cell the pieces of steel are assembled through a series of welding steps.
- First, the pieces are manually tack welded together (to hold them in place) using gas metal arc welding
- They next move into the robot welding cell where the pieces that were just tacked together are then seam welded using robotic gas metal arc welding. This step completes the weld for the pieces that were tacked together.
- Next more pieces are added to the assembly via manual tack welding
- Then that assembly moves into another robotic welding cell for a seam weld.
- Finally the assembly moves to the final station where a worker inspects the assembly and manually welds any remaining sections that need to be completed.
- After the welding is completed, the assembled canopy pieces are staged in a line for visual inspection. In the visual inspection step, the assembled parts are visually inspected using weld quality and aesthetic standards.
- If the part is free from defects, it then moves to the machining station where some very small amount of machining takes place and then the assembly heads off to the paint department for a fresh coat of Caterpillar yellow paint. Then the part is complete and ready for final assembly with the rest of the finished components to complete the assembly of the entire D6 tractor.

If during the visual inspection, defects or problems with the welds or appearance are found, then the assembly enters back into the manufacturing line and goes through a rework process. The rework process has a number of possible options depending on what is found in the visual inspection. The possible rework steps occur 1) if welds need to be redone or 2) if welds or spatter needs to be cleaned up for aesthetic standards. (Weld spatter is little droplets of molten material that are generated at or near the welding arc (OTC, 2012)).

In option 1, after visual inspection, the part would enter the rework portion of the process chain and first the weld needing to be replaced would be removed (gouged out) using air carbon arc cutting. Then the edges being welded together would be prepared (joint prep). This is done by hand grinding (prep grinding step). After the joint edges are prepared, the weld is redone using manual gas metal arc welding. Next the weld is cleaned up if needed using hand grinding (finishing grinding step) and then the assembly heads off to the machining station and then off to paint and then off to final assembly.

In option 2, after visual inspection, the part would enter the rework portion of the process chain and the welds that needed to be cleaned up or the spatter that needed to be removed would be taken care of by hand grinding (finishing grinding step). Then the assembly would move on to the machining station and then off to paint and then off to final assembly.

Note that in Figure 4.8, the paint process is in a dash lined box. This indicates that for this research, the paint process is out of scope and will not be covered in this study.

To review, the individual processes that are part of the process chain examined above include: laser cutting, plasma arc cutting, air carbon arc cutting, gas metal arc welding, grinding, and machining.

As background on the technology and capabilities, each process is described in more detail below.

4.3.1 Thermal Cutting

In addition to mechanical means, a piece of material can be separated into two or more parts or into various contours by the use of a heat source that melts and removes a narrow zone in the workpiece; this is known as thermal cutting. The sources of heat can be torches, electric arcs, or lasers. Plasma arc cutting and laser cutting are amongst the most common technologies for first operations/steel plate cutting.

4.3.1.1 Laser Cutting

In laser cutting, the source of energy required to cut the workpiece is provided by a laser (light amplification by simulated emission of radiation) which focuses optical energy on the surface of the workpiece. On projection of this highly focused, high-density energy on the workpiece, the heat generated melts and evaporates the material in a controlled manner. There are primarily two types of industrial cutting lasers: 1) gaseous state CO_2 laser and 2) solid state Nd: YAG (neodymium: yttrium-aluminum-garnet) laser. In the case of CO_2 lasers, light amplification is done in a CO_2 gas enclosure and is transported to the cutting nozzle by means of mirrors, whereas, for solid state lasers the light amplification is conducted in the Nd: YAG crystal and the beam is transported to the desired location by means of optic fiber. Due to the capability for energy absorption on steel surfaces, Nd: YAG lasers can overcome the limitation of CO_2 lasers to cut workpieces with reflective surfaces. For cutting applications, CO_2 lasers up to 7KW and ND: YAG lasers up to 4KW are available commercially.

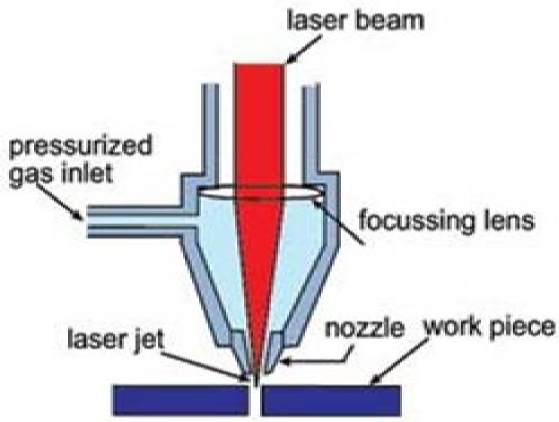


Figure 4.9: Schematic of laser cutting process (Aviation Metals Inc, 2013)

Laser cutting is typically used in combination with a high-pressure gas stream (assist gases), e.g., oxygen, nitrogen, and argon. These gas streams have the important function of blowing away molten and vaporized material from the workpiece surface before it can solidify. The assist gas surrounds the laser beam, as shown in Figure 4.10. Cuts have been made on 1” (25mm) carbon steel using CO_2 lasers. Since the beam spreads out quickly and the laser energy is harder to focus, cuts in material less than 3/8” (9.5mm) thick are most common. As the metal thickness increases, the required laser power increases and the cutting speed decreases. Because of the precision usually required, the cut is often computer-programmed. Laser cutting is done with automatic-type equipment, usually CNC, similar to automated machining processes.

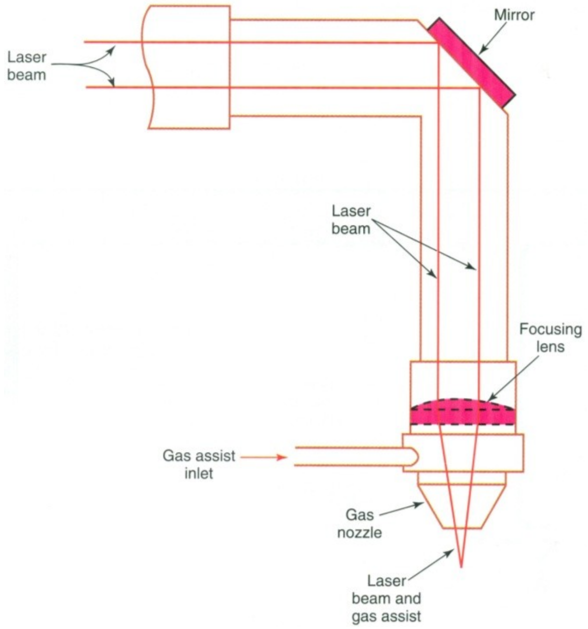


Figure 4.10: Schematic of a laser cutting torch with an assist gas system incorporated (Althouse, 2004)

Important physical parameters in the laser cutting process are the reflectivity and thermal conductivity of the workpiece surface and its specific heat and latent heats of melting and evaporation. The lower these quantities, the more efficient the process is. The cutting depth may be expressed as:

$$t = \frac{CP}{vd}$$

where t is the depth and C is a constant for the process, P is the power input, v is the cutting speed, and d is the laser spot diameter. Peak energy densities of laser beams are in the range of 5 to 200 kW/mm^2.

The laser cutting used in the process chain studied is CO_2 laser cutting.

Arc Cutting

Arc cutting processes are based on the same principles as arc welding processes. A variety of materials can be cut at high speeds by arc cutting. As in welding, these processes also leave a heat-affected zone, which needs to be taken into account, particularly in critical applications.

4.3.1.2 Plasma Arc Cutting

Plasma-arc cutting produces the highest temperatures of arc cutting processes. They are used for the rapid cutting of nonferrous and stainless-steel plates. The cutting productivity of this process is higher than that of oxyfuel-gas methods. It produces a good surface finish, narrow kerfs, and is the most popular cutting process utilizing programmable controllers employed in manufacturing today (Kalpakjian & Schmid, 2001). Plasma-arc cutting (PAC) is a thermal cutting process in which an inert gas is blown at high speed out of a nozzle, while simultaneously initiating an electrical arc between the nozzle and workpiece thereby turning some of the gas to plasma. The temperature within the plasma is in the order of 15,000°C causing the metal to be melted by the heat of the plasma arc. Then the molten metal is blown away from the cut by the high velocity of the shielding gas. Figure 4.11 shows a schematic of the plasma arc cutting process and Figure 4.12 shows an illustration of a simplified plasma arc cutting station.

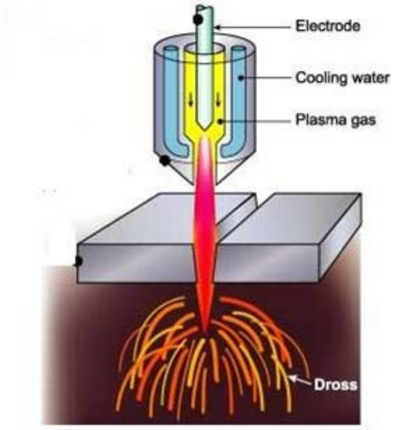


Figure 4.11: Schematic of plasma arc cutting process (TWI, 2012)

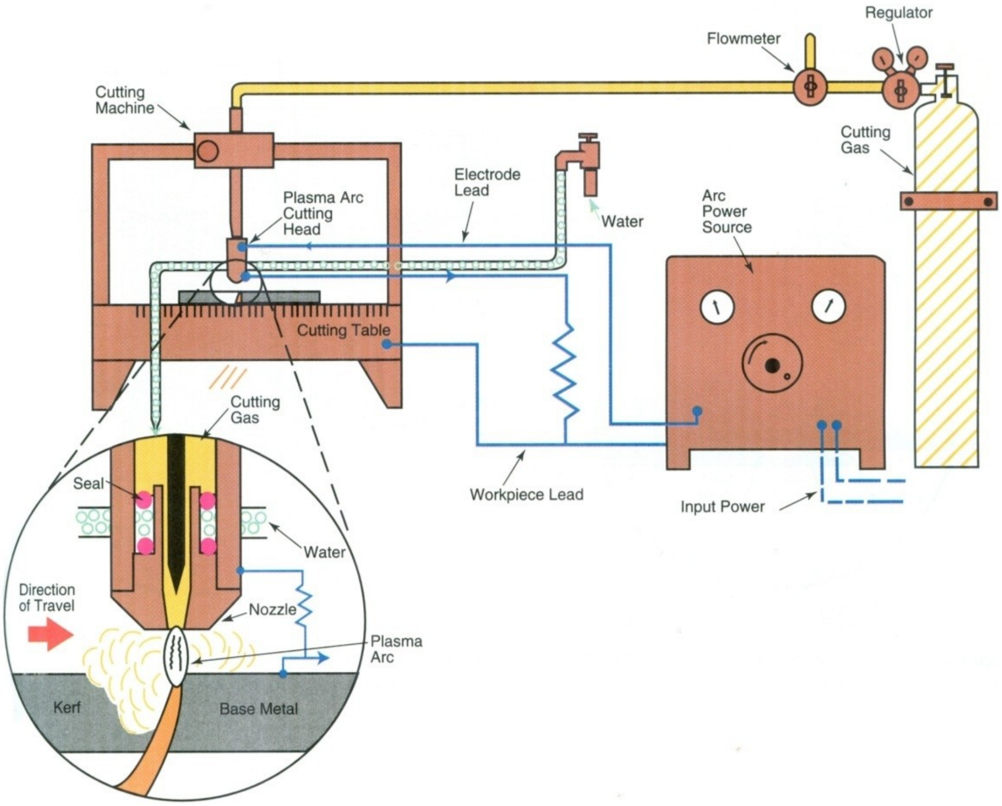


Figure 4.12: Schematic of a simplified station for plasma arc cutting (Althouse, 2004)

Plasma arc cutting requires a special water-cooled cutting nozzle. It makes use of a tungsten electrode connected to a source of dc power, compressed gas, and suitable controls. Plasma arc cutting is usually used along with automated cutting devices. The current is controlled by devices on the power sources. Water flow to cool the torch is usually manually adjusted by the welder.

The plasma arc cutting system studied in this research uses a dual-flow cutting process, one gas is used for the plasma and one gas is used as the shielding gas. Nitrogen is often used as the plasma gas. The shielding gas typically used for mild steel is CO_2 or compressed air. For aluminum, an argon and helium mixture can be used as the shielding gas. Figure 4.13 shows a dual-flow plasma arc cutting torch nozzle.

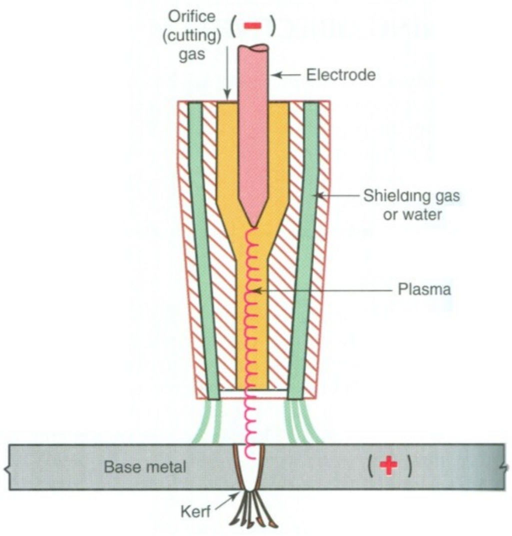


Figure 4.13: A dual-flow plasma arc cutting torch nozzle. The orifice (cutting) gas becomes a plasma in the arc stream. The shielding gas or water flows out around the plasma orifice through a number of holes. (Althouse, 2004)

Figure 4.14 shows the type of equipment required for a plasma arc cutting station, typical of an industrial setup.

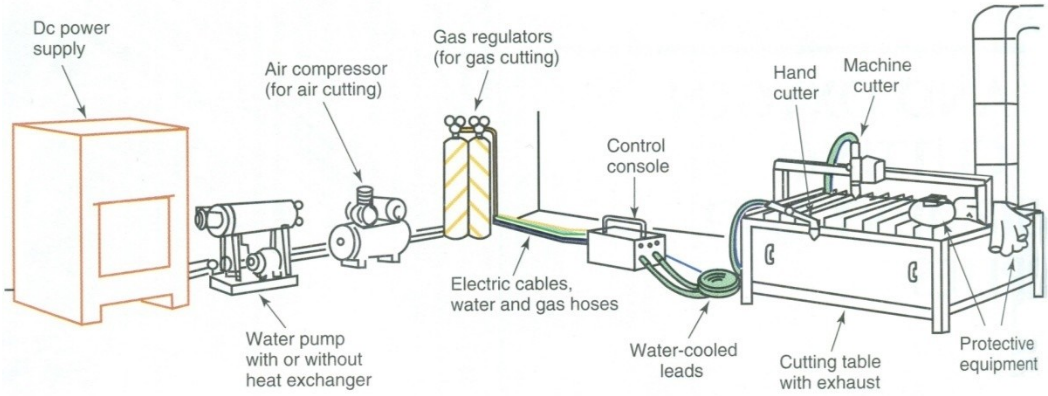


Figure 4.14: A drawing of the type of equipment required for a plasma arc cutting station (Althouse, 2004)

Plasma arc cutting is a very noisy process. The operator or welder must be protected from the noise by the use of earplugs or industrial “ear muffs.” It is sometimes necessary to use a “walkie-talkie” type of communication system where plasma arc cutting is being done. The welder must also be protected with an approved helmet, gloves, protective clothing, and other required safety equipment.

4.3.2 Welding

Welding is a ubiquitous process, used in manufacturing facilities worldwide for assembly of structural and other components of products. Welding processes can be divided into two major categories: fusion welding and solid-state welding. Fusion welding can be defined as the melting together and coalescing of materials by means of heat. The thermal energy required for these welding operations is usually supplied by chemical or electrical means. Filler metals, which are metals added to the weld area during welding, may or may not be used. This process constitutes a major category of welding; it comprises consumable- and nonconsumable- electrode arc welding and high-energy-beam welding processes (Kalpakjian & Schmid, 2001).

In arc welding, the heat required is obtained from electrical energy. The process involves either a consumable or a nonconsumable electrode (rod or wire). An arc is produced between the tip of the electrode and the workpiece to be welded, by the use of an AC or a DC power supply. This arc produces temperatures of about 30,000°C (54,000°F) to melt the metal (Kalpakjian & Schmid, 2001). The "arc welding" category includes several processes, as described below.

Shielded metal-arc welding (SMAW) is one of the oldest, simplest, and most versatile joining processes. About 50% of all industrial and maintenance welding is currently performed by this process (Kalpakjian & Schmid, 2001). The electric arc is generated by touching the tip of a flux-coated electrode against the workpiece and then withdrawing it quickly to a distance sufficient to maintain the arc. The electrodes are in the shape of a thin, long stick, so this process is commonly known as stick welding. The heat generated melts a portion of the tip of the electrode, of its coating, and of the base metal in the immediate area of the arc. A weld forms after the molten metal, a mixture of the base metal (workpiece), the electrode metal, and substances from the coating on the electrode, solidifies in the weld area. The electrode coating deoxidizes the weld area and provides a shielding gas to protect it from oxygen in the environment (Kalpakjian & Schmid, 2001).

Gas metal-arc welding (GMAW), commonly referred to as MIG (metal inert gas), is an electric arc welding process in which an arc is struck between a consumable wire electrode and a workpiece. The weld area is shielded by an atmosphere of inert gases such as argon and helium, or by carbon dioxide, or other gas mixtures. The consumable bare wire is fed automatically through a nozzle into the weld arc.

Flux-cored arc welding (FCAW) is similar to gas metal-arc welding, with the exception that the electrode is tubular in shape and is filled with flux. That is, it has a similar flux material as shielded metal arc welding (SMAW, or "stick" welding) except that the flux is internal to the continuous rod of filler material rather than on the outside as in stick welding.

To accomplish fusion of metals, a source of high-density heat energy is supplied to the workpiece surface and the resulting temperatures are sufficient to cause localized melting of the base metals. If a filler metal is added, the heat density must be high enough to melt it also. Heat density can be defined as the power transferred to the work per unit surface area, W/mm_2. The time to melt the metal is inversely proportional to the power density.

Power density can be computed as the power entering the surface divided by the corresponding surface area:

$$PD = \frac{P}{A}$$

where PD = power density, W/mm^2; P = power entering the surface, W; and A = surface area over which the energy is entering, mm^2.

Productivity is often measured as arc time (also called arc-on time). This is the proportion of hours worked that arc welding is being accomplished:

$$Arc\ time = \frac{time\ arc\ is\ on}{hours\ worked}$$

This definition can be applied to an individual welder or to a mechanized workstation. For manual welding, arc time is usually around 20%. Frequent rest periods are needed by the welder to overcome fatigue in manual arc welding, which requires hand-eye coordination under stressful conditions. Arc time increases to about 50% for machine, automatic, and robotic welding (Groover, 2013).

To calculate the power consumed in the welding operation:

$$P = IE$$

where P = power, W; E = voltage, V; I = current, A;

Three distinct zones can be identified in a typical welded joint, as shown in Figure 4.15.

1) *Base metal*
2) *Heat-affected zone*
3) *Weld metal*

The metallurgy and properties of the second and third zones strongly depend on the type of metals joined, the particular joining process, the filler metals used (if any), and welding process variables. A joint produced without a filler metal is called autogeneous, and its weld zone is composed of the resolidified base metal. A joint made with a filler metal has a central zone called the weld metal and is composed of a mixture of the base and the filler metals.

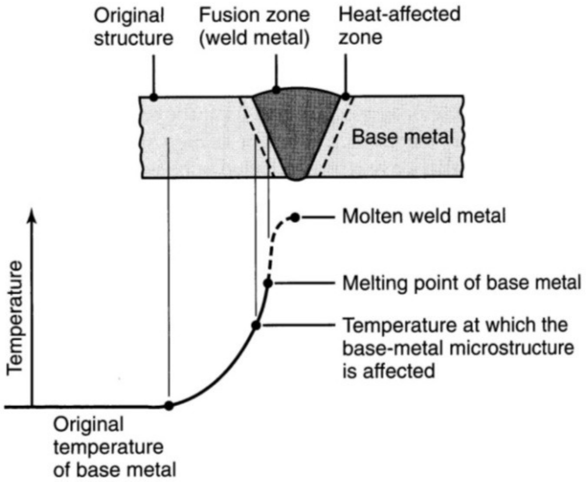


Figure 4.15: Characteristics of a typical fusion-weld zone in arc welding (Kalpakjian & Schmid, 2001)

Typical types of joints produced by welding and their terminology are shown in Figure 4.16.

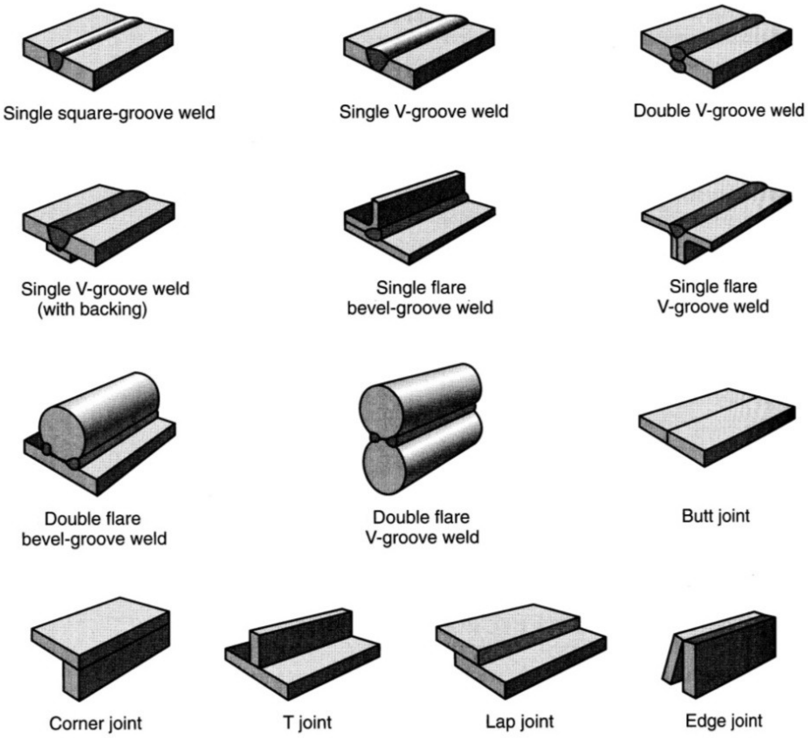


Figure 4.16: Examples of welded joints and their terminology (Kalpakjian & Schmid, 2001)

When welding, typically energy efficiency is the most important factor for reducing environmental impact from welding equipment. Welding consumables on the other hand, generates welding slag, fumes and /or stub ends depending on the type of consumable. Welding fumes, primarily from the arc and combustion process of the flux, can be hazardous and should be kept away from the welder's breathing zone. Fume components contributing to the health hazard are mainly heavy metals and fluorides.

There are a number of other hazards specific to welding:

- Burns
- Electrical hazards: electric shock
- Eye hazards: radiation, foreign bodies, particulate fumes
- Fume and gas inhalation
- Noise

In short, the inputs required for the welding process include electricity, an electrode, and a welding machine. The outputs from the welding process can be characterized as radiation, heat, fumes, gases, and waste. Depending on the specific welding process used, some inputs and outputs vary, as indicated by dashed lines in Figure 4.17. Inputs that are not present in all welding processes are indicated with dashed lines. Welding consumables can generate welding slag, fumes, and/or stub ends depending on the type of consumable used. Welding fumes can be hazardous and should be kept away from the welder's breathing zone.

Fume components contributing to the health hazard are mainly heavy metals and fluorides. One can find reasonable data in the literature on the magnitude of these outputs and their measurable impacts on people as previously discussed (Yeo & Neo, 1998).

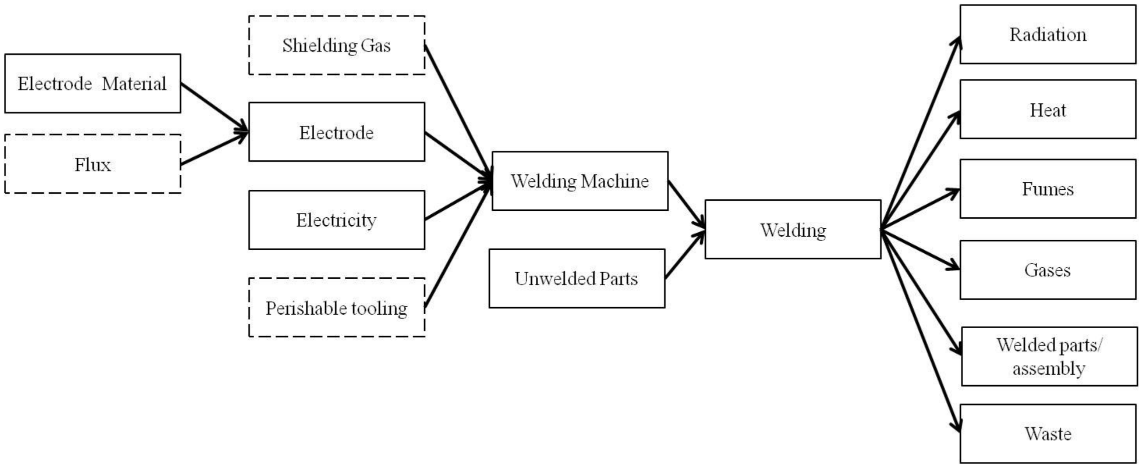


Figure 4.17: Simplified inputs/outputs of the welding process

The specific type of welding used in the process chain studied is manual and robotic gas metal arc welding.

4.3.2.1 Gas Metal Arc Welding

Gas metal-arc welding (GMAW), commonly referred to as MIG (metal inert gas), is a fusion welding process in which an electric arc is formed between a solid, continuous, consumable wire electrode (weld wire) and the workpiece. This heats the workpiece metal, causing it and the wire to melt, and join. The resulting joint is comprised of both base material and the filler metal. The weld area is shielded by an atmosphere of inert gases such as argon and helium, or by carbon dioxide, or other gas mixtures. This shielding gas "shields" the process from contaminants in the air. The consumable bare wire is fed automatically through a nozzle into the weld arc by a wire-feed unit. This process is suitable for welding most ferrous and nonferrous metals and is used extensively in the metal-fabrication industry. Because of the relatively simple nature of the process, the training of operators is easy. The process is versatile, rapid, and economical, and welding productivity is double that of the SMAW process (Kalpakjian & Schmid, 2001). The GMAW process can be automated easily and lends itself readily to robotics and to flexible manufacturing systems.

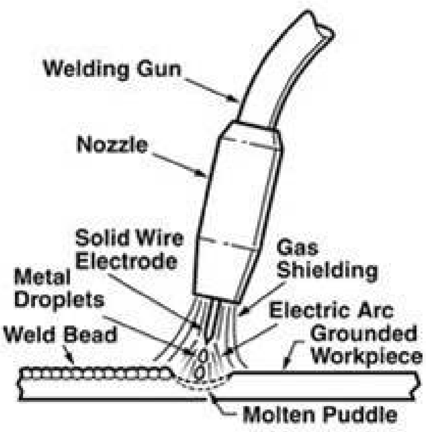


Figure 4.18: Schematic of gas metal arc welding process (adapted from (Groover, 2013))

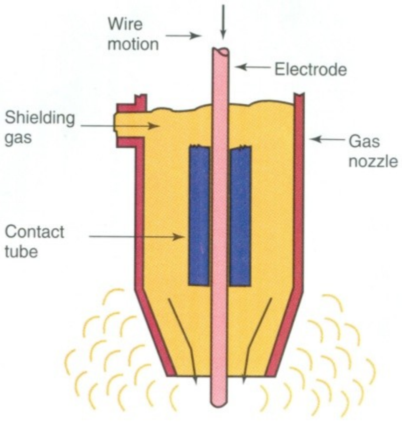


Figure 4.19: Schematic view of gas metal arc welding gas nozzle and electrode (Althouse, 2004)

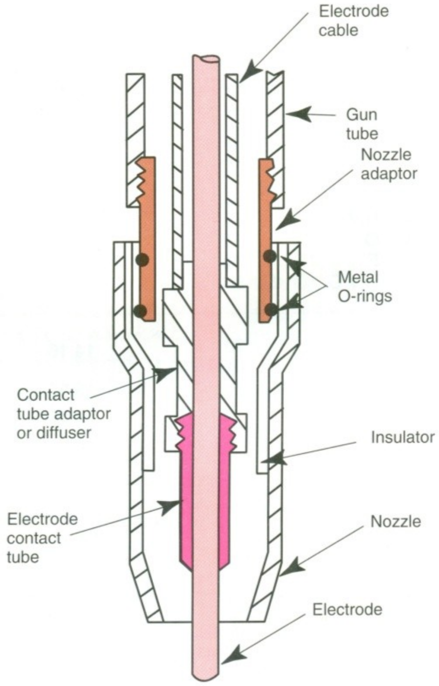


Figure 4.20: A schematic drawing of the nozzle end of a GMAW torch (Althouse, 2004)

As shown in Figure 4.21, a shielding gas cylinder, regulator, flow meter, and hose provide a flow of shielding gas to the arc. Shielding gases such as carbon dioxide, argon, or helium may be used. An electrode-feeding device continuously supplies metal electrode. A cable carries the electrode wire, current, and shielding gas to the torch and arc. The torch usually has a trigger-type switch for starting and stopping the electrode feed and gas flow.
A constant voltage dc welding power supply is used with this process. The desired voltage is set on the power supply. Current is changed by adjusting the feed speed of the wire. Speed controls for the wire are usually mounted in the wire-feed mechanism. Shielding gas volume adjustments are made at a gas flow meter on the regulator. The kind of shielding gas used usually depends on the metals being welded.

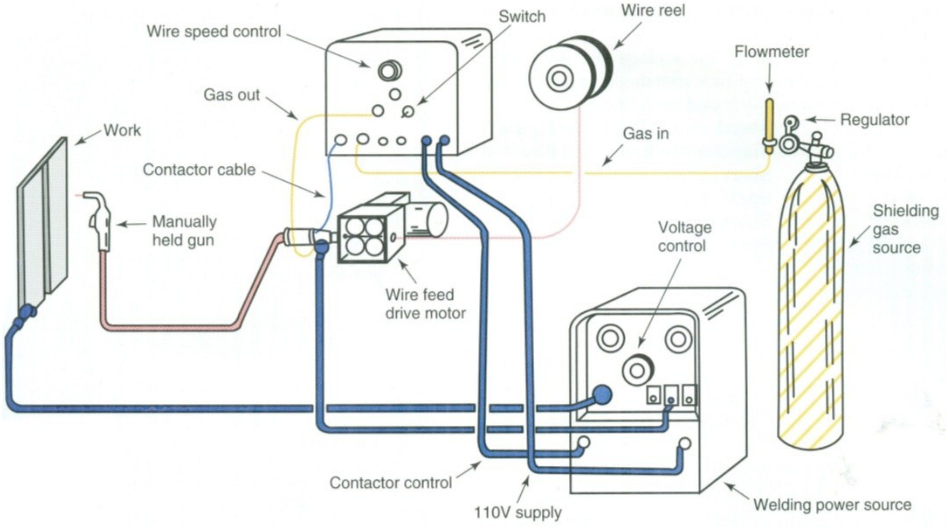


Figure 4.21: Diagram of the equipment and set up for a manual gas metal arc welding system (Althouse, 2004)

When performing GMAW, the welder:

1. Selects the electrode size
2. Sets the desired voltage
3. Adjusts the shielding gas flow
4. Adjusts the rate of electrode feed
5. Controls the torch movement and electrode extension (the electrode extension is distance from the torch tip to the arc.)

The welder must wear an approved helmet, gloves, and welder's clothing. The welding area must have good ventilation.

4.3.3 Joint Prep/Rework Operations

If during the visual inspection step of the process chain, defects or problems with the welds or appearance are found, then the assembly enters back into the manufacturing line and goes through a rework process. Rework is the process of redoing a previous step in the process.

Some possible reasons that a part or assembly would end up needing rework is due to weld quality or appearance (aesthetic reasons).

As a result of thermal and microstructural changes, a welded joint may develop various discontinuities. Welding discontinuities also can be caused by an inadequate or careless application of proper welding technologies or by poor operator training.

The major discontinuities that affect weld quality are:

- Porosity
- Slag inclusions
- Incomplete fusion and penetration, and

- Weld profile

These will not be covered in depth here, but as a quick example of what a worker might look for during the visual inspection step, incomplete fusion and penetration and the weld profile will be detailed here. Incomplete fusion (lack of fusion) produces poor weld beads, such as those shown in Figure 4.22. Incomplete penetration occurs when the depth of the welded joint is insufficient.

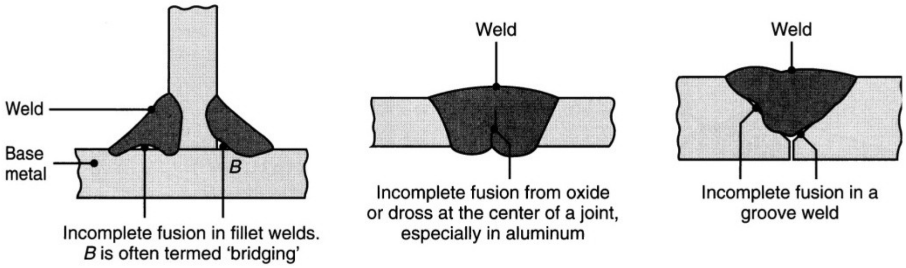


Figure 4.22: Examples of various discontinuities in fusion welds (Kalpakjian & Schmid, 2001)

Weld profile is important not only because of its effects on the strength and appearance of the weld, but also because it can indicate incomplete fusion. Underfilling results when the joint is not filled with the proper amount of weld metal (Figure 4.23a). Undercutting results from the melting away of the base metal and the consequent generation of a groove in the shape of a sharp recess or notch (Figure 4.23b). If it is deep or sharp, an undercut can act as a stress raiser and can reduce the fatigue strength of the joint; possibly leading to premature failure. Overlap is a surface discontinuity (Figure 4.23b) usually caused by poor welding practice or by the selection of improper materials. Lastly, a good weld is shown in Figure 4.23c.

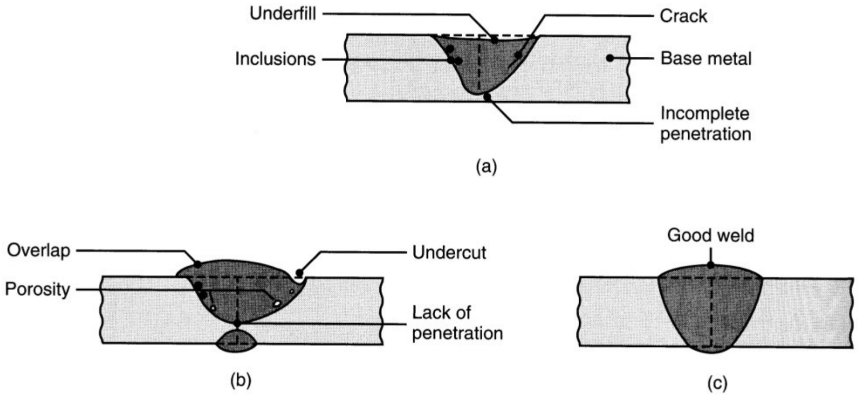


Figure 4.23: Examples of various defects in fusion welds (Kalpakjian & Schmid, 2001)

Weld profiles that are unacceptable because of any of the defects shown above need to be repaired before the welded component can be accepted. This, usually, requires the removal of the unacceptable weld material. One effective process for removal of this is air carbon arc cutting (or gouging). This is described in the next section.

4.3.3.1 Air Carbon Arc Cutting

Air carbon arc cutting is as the name implies a form of arc cutting (as previously described above). Also a form of thermal cutting, in this process, the intense heat of the arc between a carbon-graphite electrode and the workpiece melts a portion of the workpiece. Simultaneously, a high-velocity stream of compressed air is passed through the arc to blow away the melted portion of the metal. A schematic of the process is shown in Figure 4.24. Although essentially "gouging" the process is efficient in removing unwanted material and leaving a reasonable groove for redepositing new material. It relies on the skill of the operator to ensure a smooth and defined groove geometry from the gouging process. This process is used especially for gouging and scarfing (removal of metal from a surface). However, this process is noisy, and the molten metal can be blown substantial distances and cause safety hazards (Kalpakjian & Schmid, 2001).

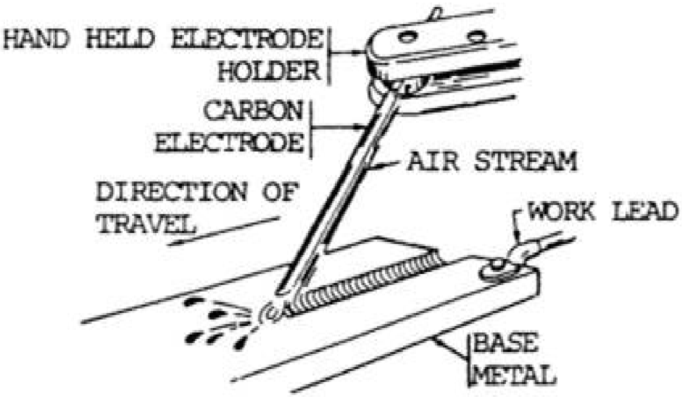


Figure 4.24: Schematic of air carbon arc cutting process (The Whole Weld World, 2011)

Figure 4.25 shows a typical station for air carbon arc cutting and gouging. The electrical supply may be either direct current (dc) or alternating current (ac). An electrode lead (flexible cable) connects the electrode holder to the welding machine. A workpiece lead (ground cable) connects the base metal to the welding machine.

The air jet may be supplied from either a compressed air cylinder or an air compressor. The air line is attached to the electrode holder. A lever-operated valve in the electrode holder controls the air flow. The welder operates the electrode holder manually. This process can be used for either cutting or gouging metal.

Current is regulated by adjustments on the welding machine. The arc length is controlled by the welder. The length of the carbon electrode between the air jet nozzle and the arc must be maintained at such a distance that the air jet will be effective in blowing away the molten metal.

This cutting process produces considerable sparking. The welder must be protected by gloves, helmet, and clothing. Excellent ventilation is needed. Good fire prevention practices must be followed.

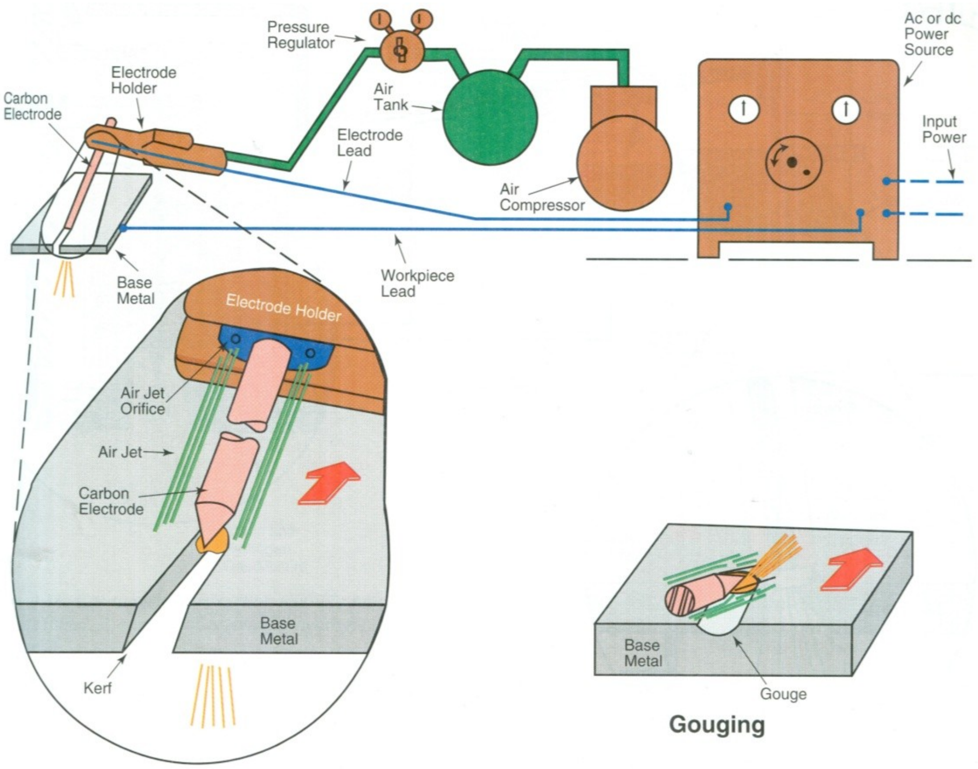


Figure 4.25: Schematic of typical station for air carbon arc cutting and gouging (Althouse, 2004)

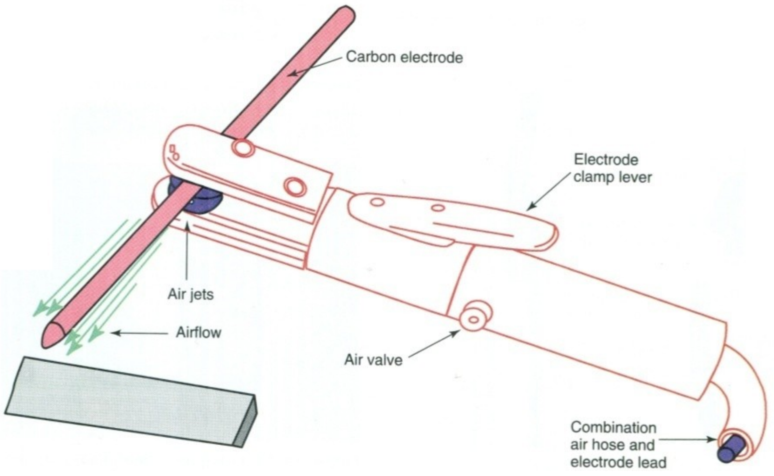


Figure 4.26: Schematic of an air carbon arc electrode holder with a carbon electrode installed. (Note the air jet orifices under the electrode.) (Althouse, 2004)

4.3.3.2 Grinding

Grinding is a chip-removal process that uses an individual abrasive grain as the cutting tool. An abrasive is a small, hard particle having sharp edges and an irregular shape, unlike the cutting tools described in the machining section in Chapter 3 and below in section 4.3.4. In this study, grinding is used mainly for removing unwanted weld beads and spatter, but can also be used in joint preparation for welding. As used in manufacturing operations, abrasives generally are very small when compared to the size of cutting tools and inserts that were described in the machining section of Chapter 3 and below in section 4.3.4. Also, abrasives have sharp edges, allowing the removal of very small quantities of material from the workpiece surface. Consequently, a very fine surface finish and dimensional accuracy can be obtained using abrasives as tools. The size of an abrasive grain is identified by a grit number, which is a function of sieve size: the smaller the grain size, the larger the grit number. For example, grit number 10 is regarded as very coarse, 100 as fine, and 500 as very fine. Sandpaper and emery cloth are also identified in this manner, as you can observe the grit number printed on the back of the abrasive paper or cloth.

Grinding-wheel wear is an important consideration because it adversely affects the shape and dimensional accuracy of ground surfaces – similar to the wear on cutting tools. Grinding-wheel wear generally is correlated with the amount of workpiece material ground by a parameter called the grinding ratio, G, and defined as:

$$G = \frac{volume\ of\ material\ removed}{volume\ of\ wheel\ wear}$$

Grinding ratios in practice vary widely, ranging from 2 to 22 and even higher, depending on the type of wheel, workpiece material, grinding fluid, and process parameters (such as depth of cut and speeds of wheel and workpiece).

4.3.3.2.1 Hand Grinding

A disc grinder, also known as a side grinder or angle grinder, is a handheld power tool using an abrasive disc, similar to a grinding wheel (bonded abrasives) that can be used for cutting, grinding and polishing.

Figure 4.27: Commonly found handheld disc grinder

4.3.4 Machining

Machining was previously discussed in some detail in Chapter 3. This section will focus specifically on milling as this was the specific type of machining process focused on for this portion of the study.

4.3.4.1 Milling

Milling is a cutting process in which material is removed by a rotating multiple tooth cutter typically aided by cutting fluids. In milling, the tool progressively generates a surface by removing chips from a workpiece as it is fed into a rotating tool and these chips are swept away by the rotation of the cutter. Because both workpiece and cutter can be moved in more than one direction at the same time, surfaces having almost any orientation can be machined. The milling process is used to machine external surfaces, slots, produce flat, contoured, or shaped surfaces using multi-toothed milling cutters or end mills (Kalla, Twomey, & Overcash, 2009). This is a versatile process with a high metal removal rate. Consequently, chip disposal in milling and the effectiveness of cutting fluids are important. An example of a current technology computer numerically controlled (CNC) milling machine is given in Figure 4.28. Details of the milling mechanism are illustrated in Figure 4.29.

Figure 4.28: Computer numerical control (CNC) milling machine with 3-axis control, tool changer and control panel (Haas Automation Inc, 2013)

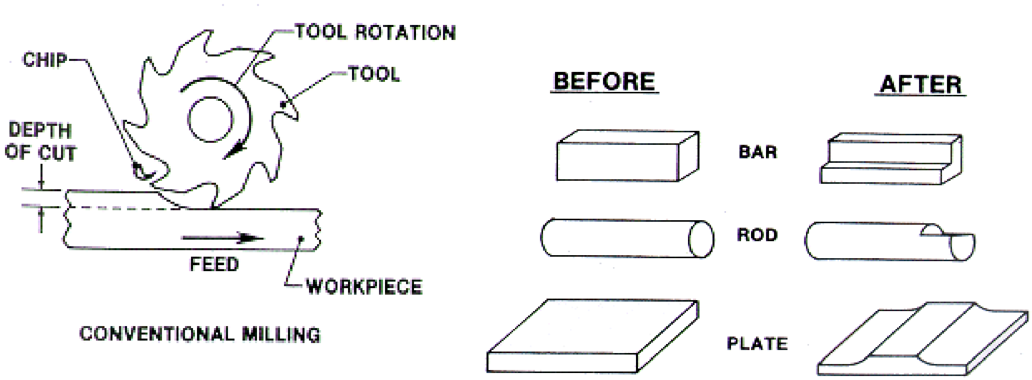


Figure 4.29: Process Schematic of Peripheral Milling (Todd, Allen, & Alting, 1994)

End Milling

End milling is a multipoint cutting process in which material is removed from a workpiece by a rotating tool. The material is usually removed by both the end and the periphery of the tool. Generally, the cutter rotates about an axis perpendicular to the surface. On occasion, a single-point tool, such as a fly cutter, may be used (Todd et al., 1994). The process uses a rotating cutter to produce a machined surface and creates small, discontinuous chips. It uses vertical and horizontal milling machines. It removes materials with the face and/or periphery of the cutter. It uses a wide variety of tools, including square end mills, ball end mills, shell end mills, and t-slot mills. End milling can produce slots, angles, pockets, radii, and many other workpiece geometries.

Process Schematic

In end milling, the tool rotates rapidly, and the workpiece is moved relative to the tool, or the tool is moved relative to the workpiece. The teeth on the end and the periphery of the tool cut the material. The process schematic for end milling can be seen below in Figure 4.30.

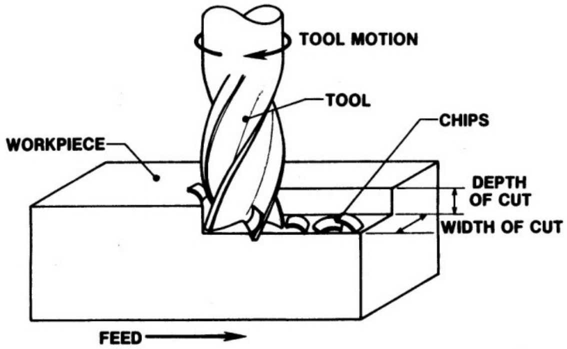


Figure 4.30: Process schematic for end milling (Todd et al., 1994)

Setup and Equipment

A vertical milling machine is commonly used in end milling, but a horizontal machine can also be used. The tool is mounted in a chuck or collet and the workpiece is secured by a clamp like device on the bed of the milling machine. A picture of a typical manual vertical milling machine can be seen below in Figure 4.31.

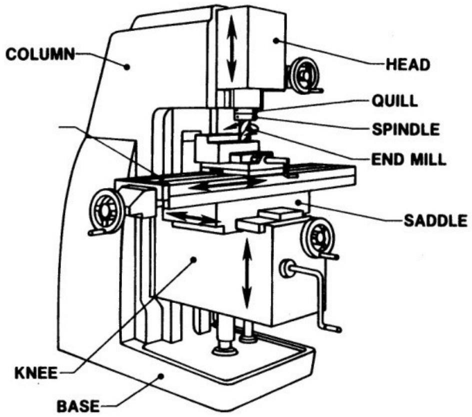


Figure 4.31: Schematic illustration of a typical manual vertical milling machine (Todd et al., 1994)

Various factors can affect process results. The tolerances and surface finishes produced depend on the following:

- tool geometry and sharpness,
- cutting speed and feed rate,
- rigidity of the tool, workpiece, and machine,
- alignment of machine components and fixtures, and
- cutting fluid

With respect to tool geometry, the four critical angles on the cutter are the end cutting edge angle, axial relief angle, radial relief angle, and rake angle. Figure 4.32 below shows the graphical representations of each of these angles.

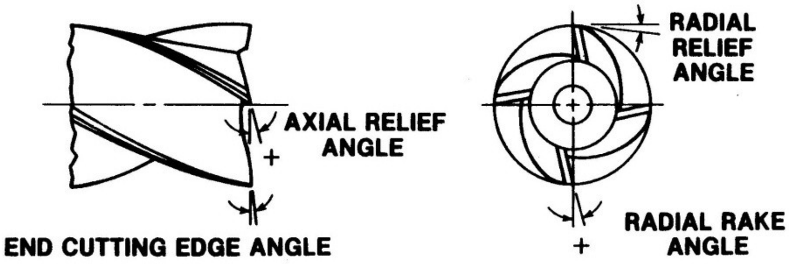


Figure 4.32: Tool geometry schematic showing the four critical angles on the cutter (Todd et al., 1994)

When talking about process conditions, the cutting and feed speeds depend on the material being machined. Softer materials, such as plastics and aluminum, may be machined at fairly high cutting speeds with good feed rates. Harder and tougher materials, such as cast iron and stainless steel, require lower cutting speeds and decreased feed rates.

Cutting fluids used in milling include mineral oil, fatty oil, water-soluble oil, sulfurized mineral oil, and chemical and synthetic oil. Spraying or flooding the tool and workpiece is the most common form of lubrication.

In looking at the power requirements for end milling, unit power is based on the horsepower required to remove one cubic inch of material per minute. Generally, the power required is proportional to the hardness of the material being machined. Less horsepower is required to remove one cubic inch per minute of plastic or aluminum than is required to remove one cubic inch per minute of mild steel or stainless steel.

$$machine\ hp = unit\ power\ \times removal\ rate\ \left(\frac{in^3}{min}\right)$$

Figure 4.33 shows a schematic of the variables needed for calculating milling time and positioning time.

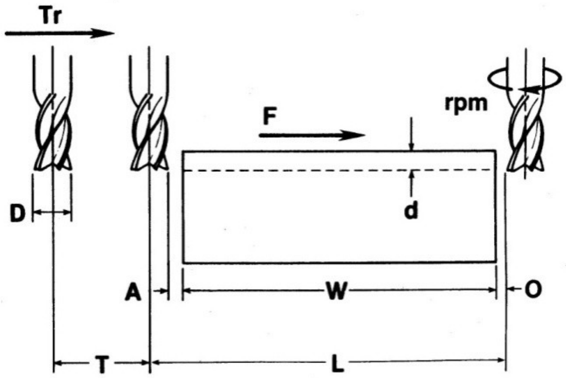


Figure 4.33: Schematic of milling process variables (Todd et al., 1994)

Where:

Length of cut (in.) = L
Diameter of cutter (in.) = D
Depth of cut (in.) = d
Length of workpiece (in.) = W
Approach = A
Rapid traverse distance = T
Rapid traverse rate = T_r
Number of teeth in cutter = N
Cutter feed rate (ipm) = F
Cutting speed (sfpm) = V
Feed per tooth (in.) = f
Overtravel = O

To calculate the milling time, $milling\ time\ = \frac{L}{F}$

To calculate the traverse time, $traverse\ time\ = \frac{T_d}{T_r}$

To calculate the revolutions per minute, $rpm\ = \frac{4\times V}{D}$

To calculate the feed rate, $feed\ rate\ = f\ \times N\ \times rpm$

4.4 Conclusion

This chapter introduced fabrication process chains as well as the concept of assessing the resource consumption of process chains in order to assist in decision making. Background material was given on the Caterpillar process chain case study including the production chain and process details. A detailed background on the individual processes used in the process chains was presented; the details and operating characteristics of the principal processes in the chain, laser cutting, plasma arc cutting, gas metal arc welding, air carbon arc cutting/gouging, hand grinding, and machining were presented. The full details of the Caterpillar case study covering these processes will be covered in Chapter 6.

Chapter 5

Assessment Methodologies for Manufacturing Process Chains

5.1 Historical Information and Background

Caterpillar’s 2020 sustainability goals established bold targets for CAT operations, products, services and solutions. To drive sustainable development transformation in the Caterpillar organization, Caterpillar established a comprehensive set of aggressive 2020 sustainability goals in 2007. The vision is to contribute, through their diverse businesses, to a society in which people’s basic needs are not only met but fulfilled in a way that sustains the environment. The 2020 sustainability goals are relative to a 2006 base. As the Caterpillar enterprise overall makes gains towards achieving the 2020 sustainability goals, there is still a number of gaps and challenges in achieving these targets.

The development of tools and a deployment strategy focused on improving manufacturing sustainability to meet the 2020 operational sustainability goals is essential. This project was initiated to develop a methodology to identify and quantify the energy and waste streams in discrete manufacturing processes performed in Caterpillar facilities. The methodology developed showed that developing a detailed understanding of the energy and waste stream footprints of discrete manufacturing processes performed in Caterpillar facilities will enable the identification of high impact process improvement projects. This would allow Caterpillar to chart a research and development strategy to develop tools that will address energy efficiency and waste stream reduction opportunities to better equip team Caterpillar in meeting 2020 operational sustainability goals.

The strategy chosen by Caterpillar is typical of other leading manufacturing companies who have targets for reductions in resource use and process/production impact. Although the work in this study focuses on a specific process chain used by Caterpillar, the process chain utilized and the general output requirements of the process chain are not atypical of a wide range of manufacturing enterprises – from construction machinery to agricultural machinery to transportation and so forth. This is especially true where manufacturing involves producing structural components (automobile frames, for example). In that sense, it is expected that the results of this work will be applicable over a wide range of manufacturing environments.

Understanding the current gaps and opportunities in discrete manufacturing processes performed in-house is a critical aspect in the process of meeting the 2020 goals. With the enterprise's focus on implementing sustainable development, the development of a methodology to identify and quantify gaps and opportunities is essential to defining a deployment strategy and the development of tools and technologies to improve manufacturing sustainability in Caterpillar manufacturing facilities.

A methodology is developed in this research to enable Caterpillar to perform a baseline measurement of energy and waste stream generation for discrete manufacturing operations. This will allow Caterpillar to quantify current sustainability impacts and improvement opportunities. Research and development projects may then be proposed to develop tools and technologies to improve the sustainability footprint in the manufacturing facilities.

The objective of the research was to develop a systematic methodology to identify and quantify the energy and waste stream for discrete manufacturing processes as part of a process chain. It was desired to validate the developed methodology by using the methodology to perform an analysis on a machining operation in a Caterpillar facility. The resource consumption mapping (energy and waste stream mapping) and analysis methodology developed in this work can then be used to identify and quantify existing gaps in current manufacturing processes. Eventually, resource consumption mapping can be performed for all discrete manufacturing processes performed in Caterpillar facilities to allow Caterpillar to obtain (a) a baseline of current energy and waste stream generation data for each discrete manufacturing process; (b) a detailed list of potential energy efficiency improvement and waste stream reduction projects. The resource consumption mapping and analysis methodology developed in this work can be used to identify, quantify and analyze current energy consumption and waste stream generation for most discrete manufacturing processes. Then, sustainability tools can subsequently be developed based on the analysis to bridge the gaps identified.

This chapter will present a resource consumption assessment and mapping methodology for manufacturing process chains and will present a methodology developed in a step-by-step guide, with an example provided for each step in the process.

5.2 Input-output Analysis and Resource Consumption Mapping (Energy and Waste Stream Mapping)

It is not possible to assess the entire process chain all at once. In order to assess a manufacturing process chain, the process chain must be broken up into pieces (individual processes). Each manufacturing process needs to be analyzed individually to understand what is going on within each process, before putting them together into the entire system (process chain).

In order to assess a manufacturing process chain, this research proposes to draw a box around the physical manufacturing process and to analyze everything that flows in and out of that process.

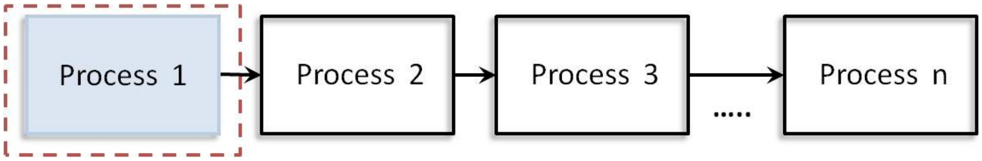


Figure 5.1: Process chain assessment methodology

One method to do this is input-output analysis. Input-output analysis is a methodology that looks at the flows in and out of a system. This methodology can be used to look at the resources that flow in and out of a system (e.g., energy, water, and waste). Figure 5.2 shows a sample input-output analysis for a manufacturing process. The first step is to draw a boundary around your process. The next step is to document the resources that flow in and out of the system.

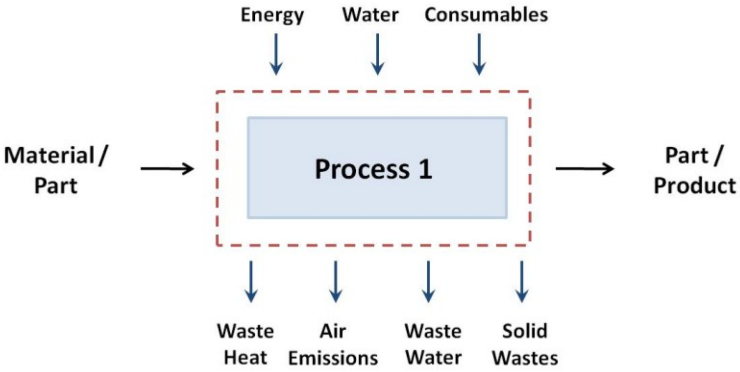


Figure 5.2: General input-output analysis schematic for process 1

This input-output analysis can then be expanded into a fully documented process map for the manufacturing process.

Each process map identifies the material and natural resource inputs to the process and the part and waste stream outputs from the process. This creates a roadmap for identifying the impacts to be quantified for sustainability considerations. Process maps can be created to assist in the modeling of manufacturing processes. Some facilities may have processes that vary slightly from the pictured flow. In general, these processes are typical of any company manufacturing heavy construction equipment or stationary mechanical equipment.

The process map format is color coded for ease of review and to clearly distinguish the inputs and outputs. Incoming to the process, raw materials and parts are shaded black, electricity streams are yellow, water streams are blue, compressed air is white with black outline, and gases are light green. The manufacturing process is light blue, with subcomponents identified within the process as appropriate. Depending on the level of data typically available, incoming and outgoing streams are directed either from the overall process or from the sub-process level. Outgoing product/piece parts are orange, waste typically sent to a landfill is maroon, waste typically recycled is green, airborne emissions are gray, radiant emissions (heat) are red, and wastewater is blue. An example of the process map format is shown below in Figure 5.3.

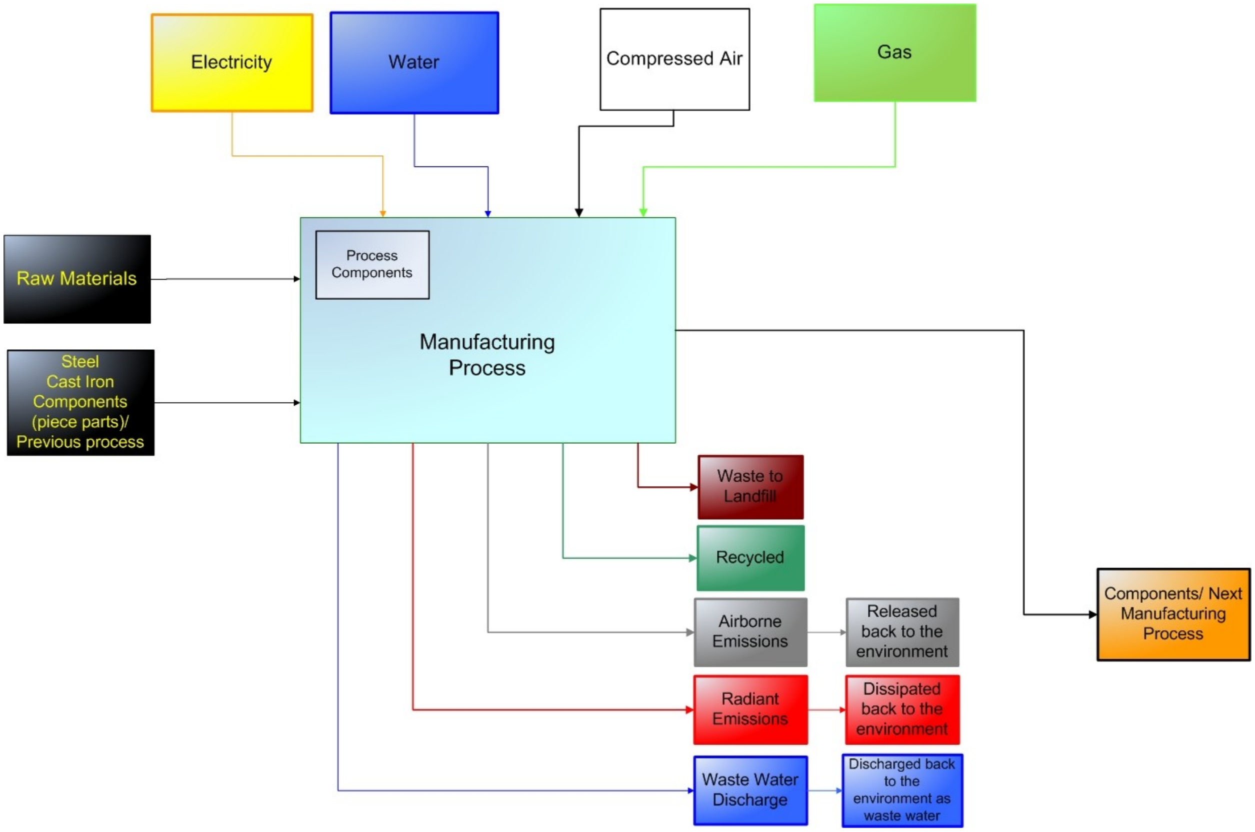


Figure 5.3: General process map format

The input-output analysis and process map can then be used to represent what is going on within a specific process.

For example, Figure 5.4 shows a specific process map created for gas metal arc robotic welding. Notice that this mapping methodology gives a very detailed view of the inputs and outputs of the system.

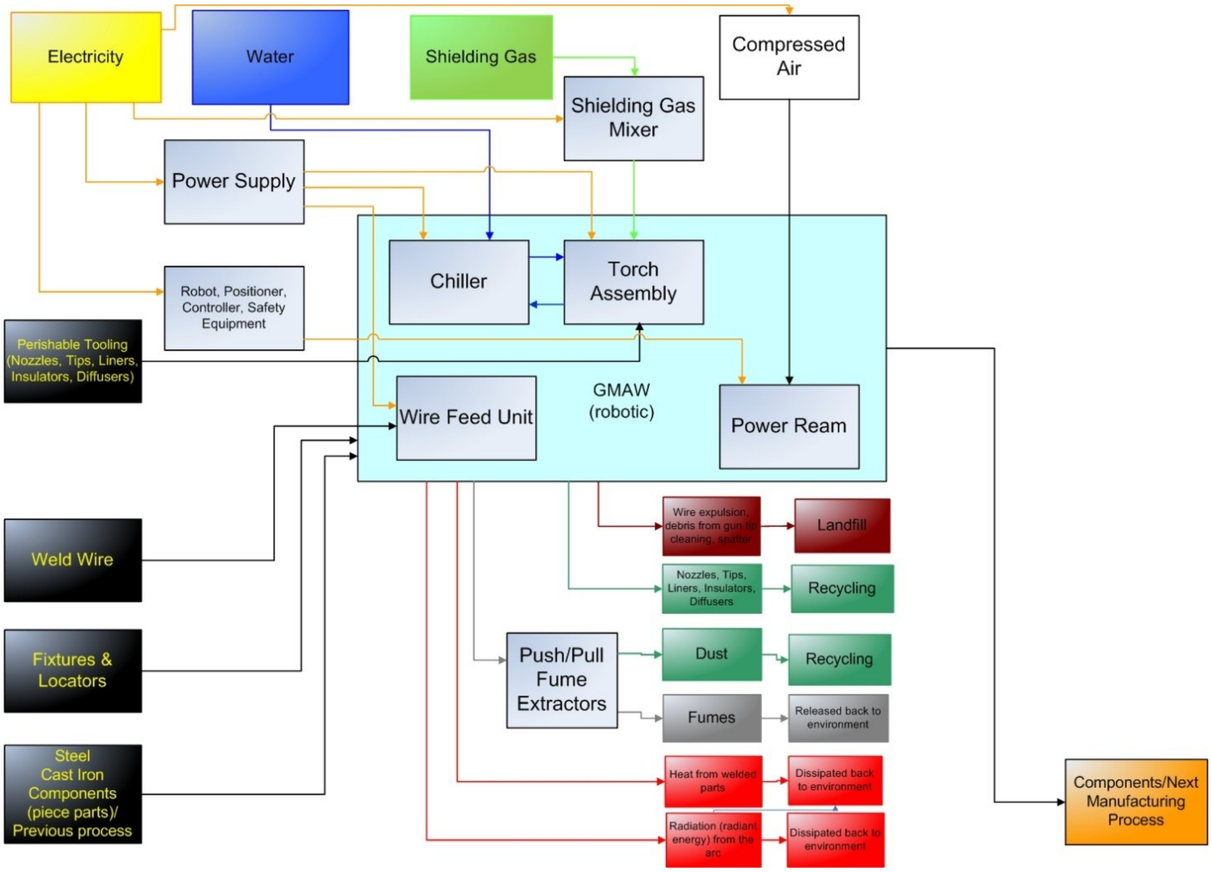


Figure 5.4: Robotic gas metal arc welding (GMAW)

Now that Figure 5.4 represents everything going on within the system, one can represent the system with an input-output analysis flow diagram as shown in Figure 5.5. This then allows us to see what process data are needed in order to assess the process in question.

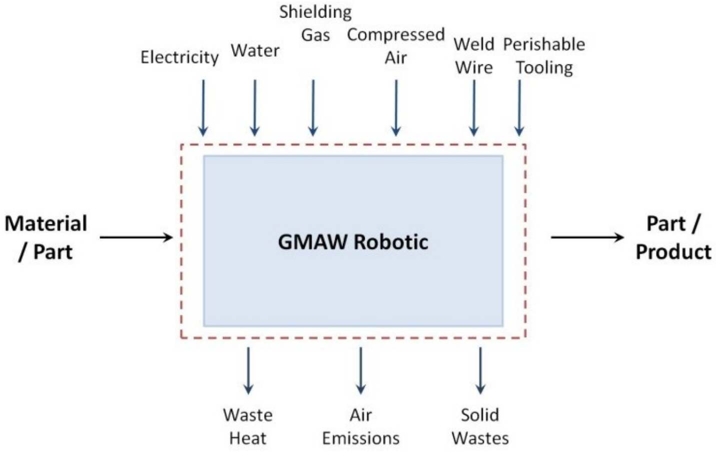


Figure 5.5: Input-output analysis schematic for robotic gas metal arc welding (GMAW)

Now that we have mapped the system in question, we would want to populate the boxes with process specific data. We would then repeat this process for every process in the process chain.

Once we have assessed all of the inputs and outputs of each process and obtained data for all of the inputs and outputs, we can then evaluate the resource consumption of each process individually. From here we can then develop resource consumption profiles for each process (Figure 5.6).

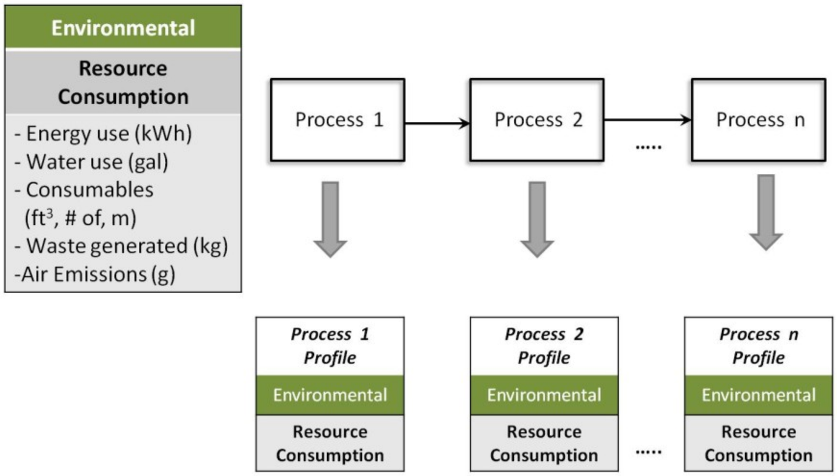


Figure 5.6: Process resource consumption

Once we have the resource consumption profiles for each of the manufacturing processes, we can establish a database module to for each process. These database modules can then be used to represent the various manufacturing processes that make up the process chain.

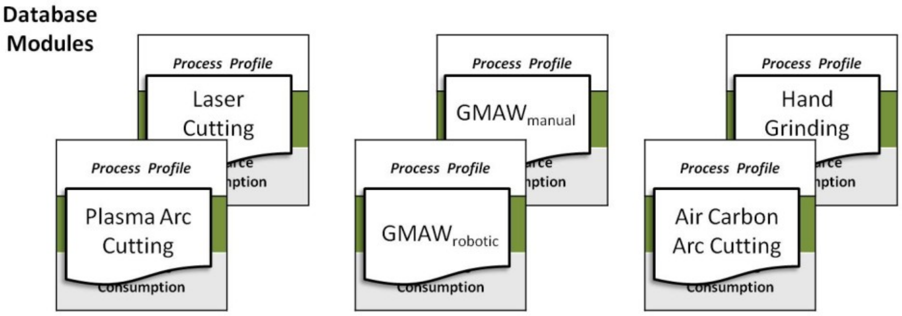


Figure 5.7: Process chain database modules

Now that we have assessed the resource consumption for the processes, we can evaluate the environmental and economic impacts of that resource consumption (Figure 5.8).

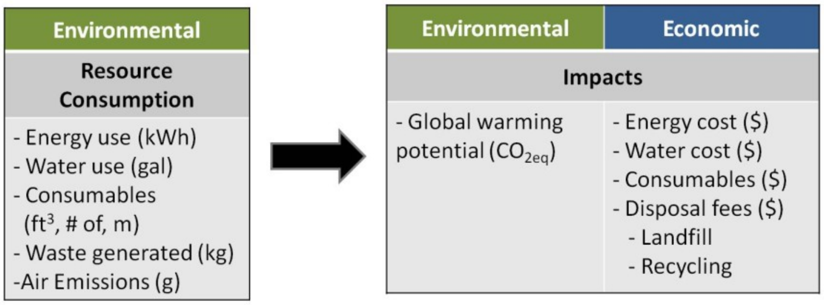


Figure 5.8: Environmental and economic impacts

Once we have calculated the environmental and economic impacts we can string together the process chain database modules to represent the various process chains that we want to assess (Figure 5.9). This then allows us to compare different process chain combinations with respect to resource consumption and economic and environmental impacts (Figure 5.10).

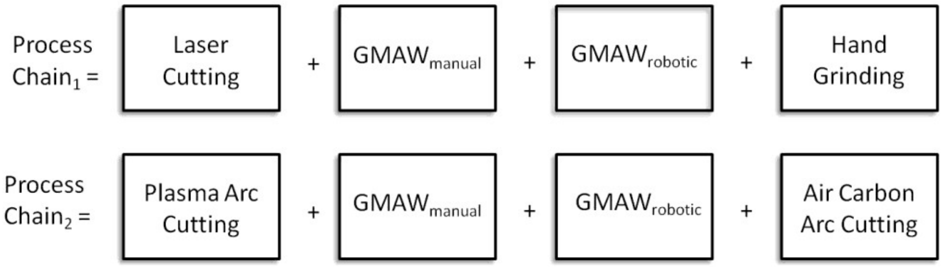


Figure 5.9: Process chain comparison

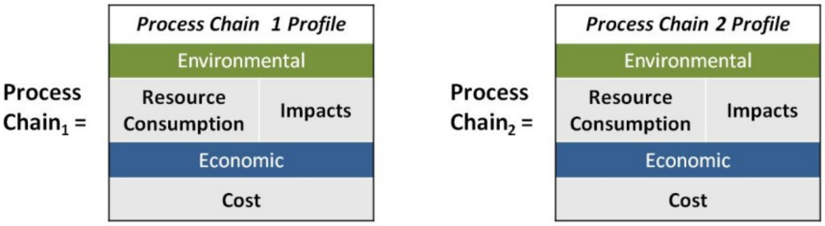


Figure 5.10: Process chain comparison results

This methodology allows us to assess individual processes and process chains. In conclusion, this section introduced a methodology to assess and map the resource consumption of manufacturing processes. The next section will discuss how to apply this assessment and mapping methodology in an industrial context.

5.3 Application of Resource Consumption Assessment and Mapping Methodology

This section will introduce a methodology to map the resource consumption of manufacturing processes that is modeled after the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) process. The developed methodology was validated on a machining process in a Caterpillar facility. The methodology developed will be presented in the following sections. A brief description and an example will be provided with each step of the process.

All of the steps in the methodology are listed below for reference, but, steps 1 – 2.5 of the methodology will be covered in this chapter and steps 2.6 – 5 of the methodology will be covered in the next chapter.

1. Define
2. Measure
    - 2.1. Create/review resource consumption map (energy and waste stream map)
    - 2.2. Identify key inputs and outputs that can be measured
    - 2.3. Modify resource consumption map
    - 2.4. Define operational definitions
    - 2.5. Collect data during production

    - 2.6. Compile data into an Environmental Value Stream map
3. Analyze
    - 3.1. Perform a Pareto Analysis (optional)
        - 3.1.1. Assign a unit cost ($/x) to each resource category
        - 3.1.2. Identify the biggest opportunity based on total cost ($) of waste generated
    - 3.2. Perform an appropriate root cause analysis
        - 3.2.1. Ishikawa diagram
        - 3.2.2. 5 Whys
    - 3.3. Compile Possible Root Causes Identified
4. Improve
5. Control

1. Define

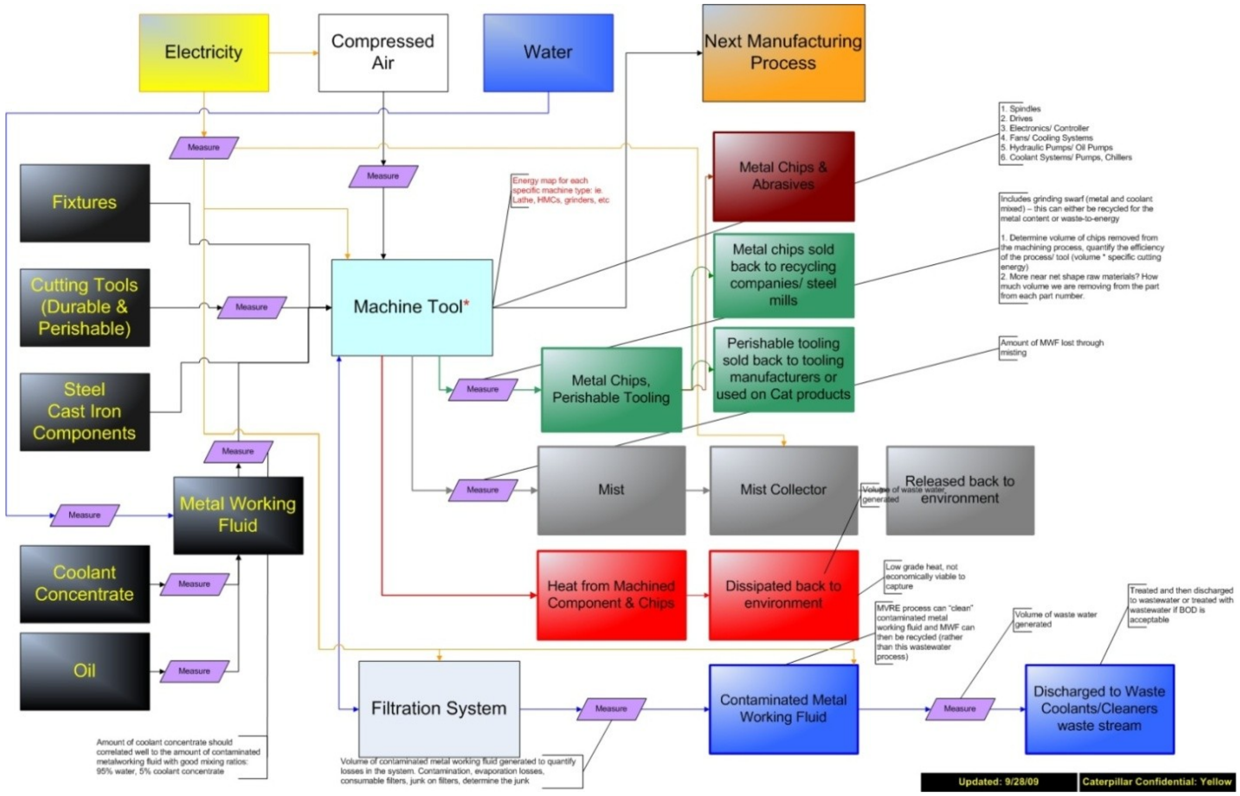
The Define phase ensures that the problem/process selected to go through the DMAIC process improvement methodology is linked to the organization's priorities and has management support (Shankar, 2009). The Define phase starts with identifying a problem that requires a solution and ends with a clear understanding of the scope of the problem and evidence of management support. To begin, the focus and scope of the assessment has to be clearly stated. The specific manufacturing process of interest has to be identified and the boundary (in-scope and out-of-scope) of the assessment explicitly stated. At this point, a goal is also set of which performance parameters to improve upon (e.g., a target to reduce resource consumption by 5%). Once the manufacturing process is selected, the boundary clearly defined, and the goal set, the current state of the selected process can be measured.

2. Measure

The purpose of the Measure phase is to gather baseline information about the process that has been identified as needing improvement. Baseline information about the process is used to better understand what exactly is happening in the process and where the problems lie. The Measure phase can be broken up into a six step process to compile and present the resource consumption map (energy and waste stream map) for the manufacturing process of interest in a visual and easy to understand format.

2.1 Create/review resource consumption map (energy and waste stream map)

If a resource consumption map already exists in the organization for the selected process, in this step, the map would be reviewed for accuracy and updated as needed. If a resource consumption map does not exist for the selected process, one would be created following the methodology previously presented in section 5.2. An example of what an existing resource consumption map in an organization for a machining process might look like is illustrated in Figure 5.11. Since this is the "measure" step of the process, one additional feature that can be added to the resource consumption map in this step is measurement points. As shown in Figure 5.11, purple boxes indicating possible measurement points for inputs and outputs of the system have been added to the resource consumption map. Also note that additional comments (specific to the company or process) can be added to the map as well (small text boxes in Figure 5.11).



Energy map for each specific machine type: ie. Lathe, HMCs, grinders, etc

1. Spindles
2. Drives
3. Electronics/ Controller
4. Fans/ Cooling Systems
5. Hydraulic Pumps/ Oil Pumps
6. Coolant Systems/ Pumps, Chillers

Includes grinding swarf (metal and coolant mixed) – this can either be recycled for the metal content or waste-to-energy

1. Determine volume of chips removed from the machining process, quantify the efficiency of the process/ tool (volume * specific cutting energy)
2. More near net shape raw materials? How much volume we are removing from the part from each part number.

Amount of MWF lost through misting

Volume of waste water generated

Low grade heat, not economically viable to capture

MVRE process can "clean" contaminated metal working fluid and MWF can then be recycled (rather than this wastewater process)

Volume of waste water generated

Treated and then discharged to wastewater or treated with wastewater if BOD is acceptable

Amount of coolant concentrate should correlated well to the amount of contaminated metalworking fluid with good mixing ratios: 95% water, 5% coolant concentrate

Volume of contaminated metal working fluid generated to quantify losses in the system. Contamination, evaporation losses, consumable filters, junk on filters, determine the junk

Updated: 9/28/09

Caterpillar Confidential: Yellow

Figure 5.11: Existing resource consumption map (energy and waste stream map) for machining process

To review, the resource consumption map shows all the resource inputs and outputs (color coded) of the discrete manufacturing process.

The color coding for the resources are as follows:

- Black: Inputs to the system
- Yellow: Electrical energy
- White: Compressed air
- Blue: Water
- Red: Heat energy
- Green: Recyclable outputs
- Brown: Landfill outputs
- Grey: Emissions to Air
- Purple: Possible measurement points for inputs and outputs

2.2 Identify key inputs and outputs that can be measured

After the selection of an appropriate resource consumption map for the discrete manufacturing process of interest, a thorough review of the resource consumption map is performed. During the review process, key inputs and outputs that can be quantified are highlighted. Figure 5.12 illustrates an example of the inputs and outputs of interest that can be measured from the machining center.

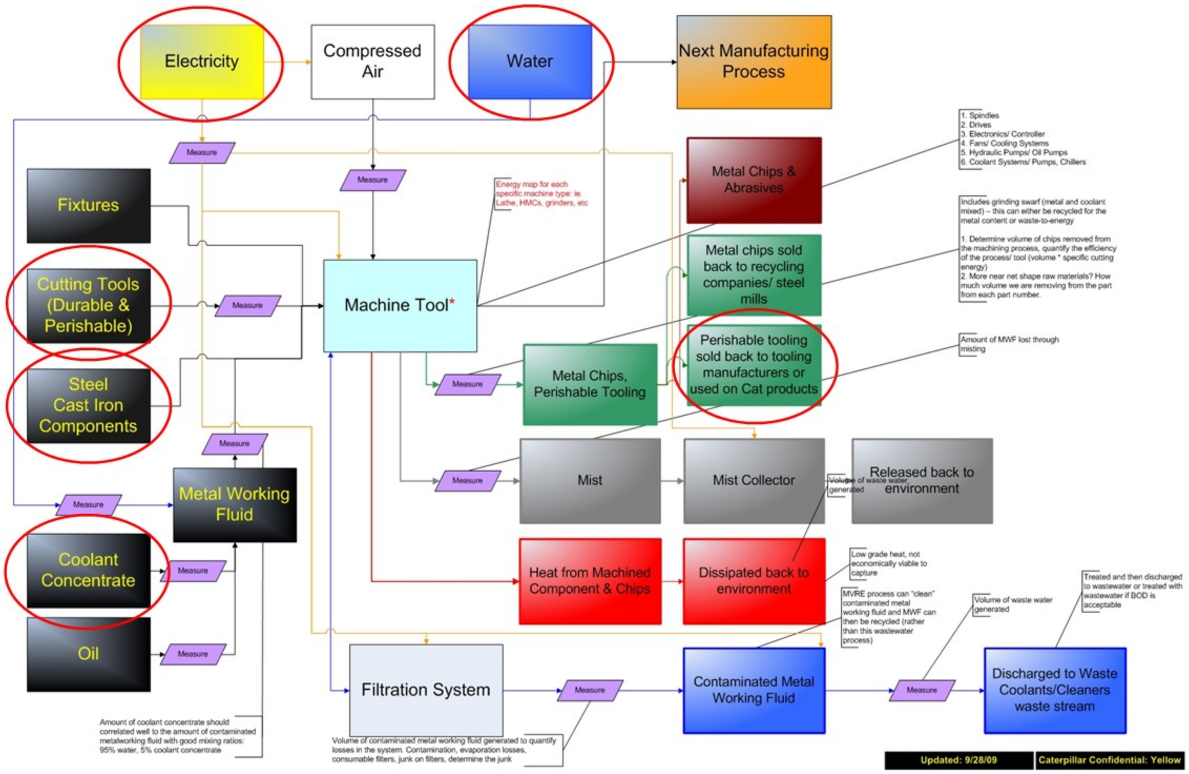


Figure 5.12: Key inputs and outputs that can be measured from the machining center are circled in red

2.3 Modify resource consumption map (energy and waste stream map)

After the key inputs and outputs are identified, the resource consumption map for the discrete manufacturing process of interest can be further reduced to more accurately reflect the boundary and scope of the assessment. The inputs and outputs that cannot be quantified appropriately and/or are not of interest can be removed from the resource consumption map (if desired). Figure 5.13 shows an example of a reduced resource consumption map for the machining center.

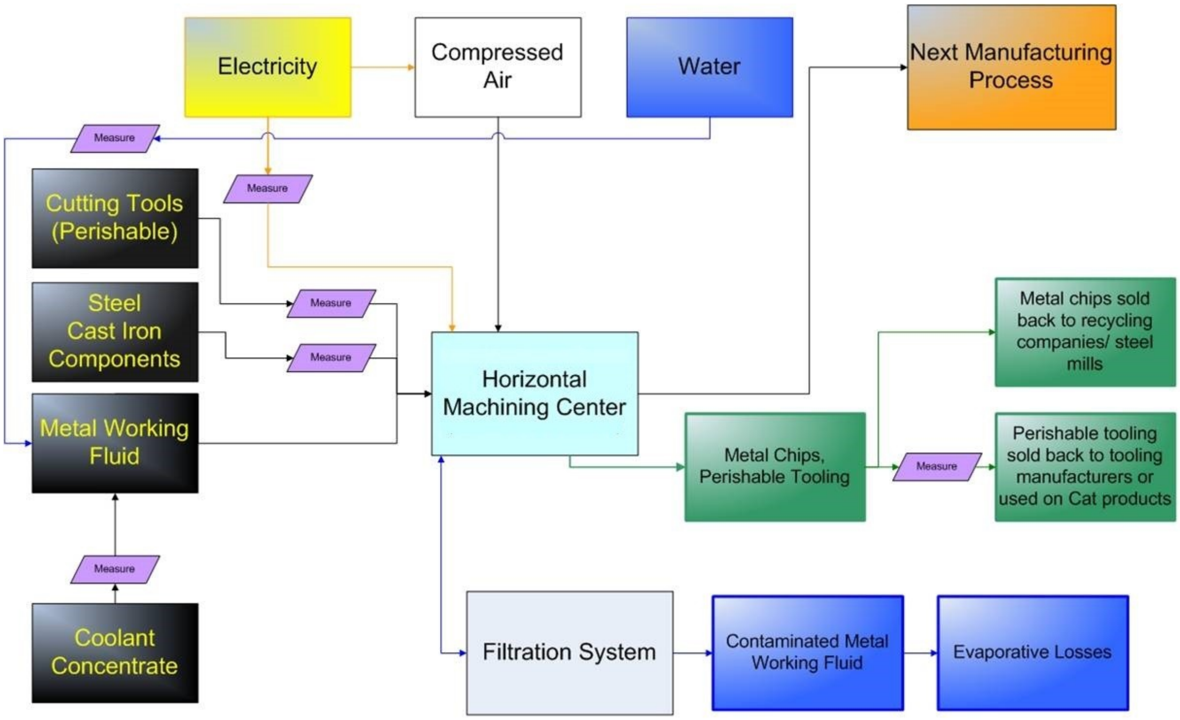


Figure 5.13: A modified version of the resource consumption map based on the scope and boundary of the assessment

2.4 Define operational definitions

This step is based on these principles “You can manage, what you can measure; you can measure, what you can define; you can define, what you can understand” (Discover 6 Sigma, 2013). An operational definition is a clear and concise, detailed definition of a measure in a data collection initiative. Operational definitions are fundamental in collecting data and essential in ensuring that everyone in the system has the same understanding of the measure and collects data in the same way. Key elements that should be defined in the operation definition are (1) metric(s) to be measured; (2) units of measurement; (3) how to measure; and (4) measurement equipment required (if applicable).

Just as the key inputs and outputs are identified in step 2.2, operational definitions should be defined for each of the inputs and outputs to ensure accuracy and consistency in the data collected since the data may be collected by different individuals over a period of time.

In order to assess the performance of the machining center, operational definitions were selected in order to evaluate the key inputs and outputs of the system. An example of the operational definitions can be seen in Table 5.1 below.

Table 5.1: Operational definitions selected to evaluate the key inputs and outputs of the system

	Electricity	**Material**	**Metal Working Fluid (MWF)**	**Perishable Tooling**
Metrics to be measured	- Electrical energy used in machining a part - Electrical energy measured in idle mode - Value added electrical energy consumption = electrical energy measured in machining a part – electrical energy measured in idle mode	- Weight of incoming part - Weight of machined part - Metal chip weight = weight of incoming part – weight of machined part	- Amount of water added to the coolant tank/day - Amount of chemicals added to the coolant tank/day - Amount of MWF = amount of water added to the coolant tank/day + amount of chemicals added to the coolant tank/day	- Inserts required - Inserts used - Inserts recycled
Units of measurement	kW	kg	L	Number of
How to measure	Power meter	Weighing scale on material handling system	Number of containers/pump	Count
Measurement equipment required	Power meter	Weighing scale on material handling system	N/A	N/A

2.5 Collect data during production

With the identification of key inputs and outputs and the operational definition clearly defined, production data associated with the discrete manufacturing process of interest can be gathered. Data should be obtained and averaged over a period of time to ensure that an accurate trend is captured during the process.

5.4 Conclusion

In this chapter, a resource consumption assessment and mapping methodology (showing resources and waste paths) for manufacturing process chains was presented. This systematic methodology was developed to identify and quantify the energy and waste streams for discrete manufacturing processes as part of a process chain. This methodology was then validated by using the methodology in a step-by-step guide to perform an example analysis on a machining operation in a Caterpillar facility. This methodology can also be used to perform a baseline measurement of energy and waste stream generation for discrete manufacturing operations.

Resource consumption mapping can be further replicated across different discrete manufacturing processes at different facilities around the world to further improve the sustainability of manufacturing operations in facilities. This will be a key enabler in achieving the facility operational sustainability goals.

The next chapter will illustrate how these concepts are applied to a manufacturing process chain via a case study with Caterpillar Inc.

Chapter 6

Process Trade-off Analysis – Sustainability Impacts from Discrete Manufacturing Processes

As described in the last chapter, Caterpillar, like many other major corporations, has established a number of sustainability goals to be met by the year 2020 to drive sustainable development achievements. While the facility-level and enterprise-level sustainability impacts from the enterprise are well documented, the process-level impacts are not readily available. To better understand the current gaps and opportunities for meeting sustainability goals, and to document the Life Cycle Analyses (LCAs) of Caterpillar products, requires a better understanding of the sustainability impacts from discrete manufacturing processes and product value streams. Specifically, a methodology and user tool is needed to quantify the sustainability impact of discrete manufacturing processes and value streams at Caterpillar.

This research focuses on the sustainability impacts from fabrication processes, specifically welding (manual and robotic), cutting (plasma arc and laser), and machining (milling) previously described. The general methodology is presented here, along with calculations for these processes. Given current utility costs, the percent of product cost from sustainability impacts is relatively small. However, there is value in understanding these impacts for future needs related to regulatory compliance, increased utility cost, and company reputation with respect to sustainability goal achievement.

Understanding the current gaps and opportunities in discrete manufacturing processes performed in-house is a critical aspect in the journey to meeting the 2020 operational goals. At the facility level, the overall sustainability impact (e.g., energy consumption, water consumption, and waste generation) is generally well quantified. However, information at the process level is not as readily available.

In addition, there is an increased focus on Life Cycle Assessments (LCAs) of Caterpillar products. Many LCA tools focus on materials included in the product and the final disposition of the product, but do not include detailed information on the manufacturing required to construct the product. Sustainability impacts of discrete manufacturing processes and product value streams are needed to complete the LCAs.

CHAPTER 6. PROCESS TRADE-OFF ANALYSIS – SUSTAINABILITY IMPACTS FROM DISCRETE MANUFACTURING PROCESSES

The development of a methodology and user tool to quantify sustainability impacts, leading to the identification of gaps and opportunities, is essential in defining a deployment strategy and the development of tools and technologies necessary to improve sustainability in Caterpillar manufacturing facilities.

Recall that the objective is to quantify the energy consumption, water consumption, and waste quantity impacts, as well as the associated costs, for discrete manufacturing processes and process value streams.

6.1 Historical Information and Background

The need to quantify sustainability impacts from value streams, or process chains, is not unique to Caterpillar. Current LCA models commercially available typically do not include manufacturing processes, or do so with only very limited data. The output may be greenhouse gases (GHG) or a factor developed from a combination of numerous health, safety, or environmental factors. This makes it difficult to analyze all of the sustainability impacts (energy, water, and waste) from individual manufacturing processes and compare value stream differences. In addition, several universities have conducted research in the area of sustainability impact analysis of manufacturing processes. Initial methodologies have been published, but working tools are not readily available.

The premise of the currently ongoing research by Overcash and Twomey states that life cycle analyses, even those of only moderately complex products, have focused on the product material life cycle, while often disregarding the manufacture of the product itself (Overcash & Twomey, 2012). The Unit Process Life Cycle Inventory (UPLCI) project, together with the CO2PE! Project, is developing an approach to represent the processing activities in manufacturing plants. The CO2PE! Project is developing data sets for use in the inventory (D. Kalla, Overcash, & Twomey, 2010). The CO2PE! Project has developed datasets for five processes, with the intent to develop a dataset for 120 processes (CO2PE, 2013). Data for the processes will be useful for evaluation of larger Caterpillar value streams.

In 2006, Michigan Tech—in connection with several companies, including Caterpillar—researched environmentally responsible process selection using a life cycle analysis approach (Haapala, Rivera, & Sutherland, 2006). This work included a LCA comparison of two representative heavy equipment manufacturing processes, taking into account casting, laser cutting, bending, and welding. This study used SimaPro, a commercially available LCA software, to conduct the analyses; additional datasets were created to add information on processes not included in the tool (e.g., laser cutting). Single-score results were weighted using Eco-indicator 99, which resulted in more significant impacts from any factors categorized as ecosystem quality or human health and resources impacts. (When single-score results arise from the use of programs such as SimaPro, it becomes difficult to determine the source of contribution to the total environmental impact.) In addition, the weighting used in Eco-indicator 99 and similar programs is not generally user input, but rather based on a group of expert opinions. It is noted that this approach requires a skilled user with an understanding of LCA approaches and weighting, and that multiple users may interpret different results from the same analysis.

In 2007, Caterpillar worked to create a methodology and tool for quantifying the Life Cycle Management (LCM) approach to welding processes at Caterpillar (K. Mauritzson, personal communication, July 2, 2012). The documented methodology quantifies the economic, performance, and sustainability impact from welding processes, including customization for level of automation (robotic or manual) and level of outsourcing (in house or supplier), as well as process information. This detailed analysis required significant input and exists in a format for use by a skilled user with knowledge of both the manufacturing process and business information.

Many studies focus on energy efficiency, proposing methodologies for identifying the total energy consumption from a value stream. Herrmann, Thiede, Kara, & Hesselbach, 2011 estimate a 10 to 30% improvement is possible by focusing on energy improvements and using current technologies. They also propose a manufacturing system simulation approach, using Plant Simulation discrete event software with energy information added. Weinert et al., 2011 recommend an "EnergyBlocks" methodology, essentially creating a block for each production process and subprocess combined to represent the manufacturing process chain. Both proposals seek to include the energy consumption of both the process equipment and the auxiliary equipment.

The ongoing research indicates the importance of understanding sustainability impacts from manufacturing processes, as well as the challenges in doing so.

6.2 Regulatory Impact and Reporting

Regulations on utilization of resources and their impacts have rapidly evolved in recent years, and will continue to impact Caterpillar products and business practice – in the US and around the world. Most recently, greenhouse gas (GHG) regulation has been a primary focus in the U.S. In many countries in which CAT operates, carbon legislation is in place due to the Kyoto Protocol or internal legislative action. In EAME, carbon trading protocols are actively used. In the United States, the U.S. Environmental Protection Agency (EPA) requires GHG reporting for facilities triggering the reporting threshold, and large, new construction that triggers Prevention of Significant Deterioration (PSD) permitting will require an analysis of GHG emissions. In addition, state regulation may require reporting of GHG emissions for specified facilities or analysis for state-level permitting decisions. Energy sourcing (e.g., renewable sources of energy) is increasingly regulated, requiring an average of 20% renewables for U.S. locations by 2020. In addition to GHG regulation, many other air pollutants are also regulated. In the U.S., this includes criteria for air pollutants (particulate matter, nitrogen oxides, carbon monoxide, sulfur oxides, ozone, and lead), as well as hazardous air pollutants (currently 187 listed pollutants).

Water quality and quantity are increasingly of concern in a number of locations in which CAT operates. Reporting of water discharge quality and quantity is required in many areas. Some Caterpillar facilities are mandated to treat wastewater prior to discharge or to pay for wastewater treatment off-site. While water cost is relatively inexpensive in most locations, the cost of maintenance, additives (chemicals), treatment, pumping, and labor can add considerably to the total expenses. Typically, water consumption is not regulated. However, historical water rights are often in place and may later impact business decisions.

Waste disposal is regulated in most countries, particularly for hazardous waste (as defined by each location). Waste disposal and waste shipping regulation may require recordkeeping and reporting of quantities and final disposal. Inappropriate historical waste handling results in remediation requirements. Accidental spills meeting threshold limits must be reported and remediated according to government mandates.

All of these regulated environmental impacts (air, water, and waste) are also of interest to shareholders, consumers, nonprofits, and other organizations. Caterpillar has participated in voluntary public reporting of environmental impacts through the Caterpillar Sustainability Report, U.S. EPA Climate Leaders program, Dow Jones Sustainability Index (DJSI), Carbon Disclosure Project (CDP), and specific information requests. Increased awareness of and voluntary or regulated reporting of sustainability impacts require increasing scrutiny of the information available at the process and value stream levels.

6.3 Process Maps

Following the validated methodology previously described in Chapter 5, process maps specific to welding (manual and robotic), cutting (plasma arc and laser), and machining (milling) were created. Each process map identifies the material and natural resource input to the process and the part and waste stream outputs from the process. This creates a roadmap for identifying the impacts to be quantified for sustainability considerations. Process maps were created with the intent of modeling the majority of Caterpillar operations. Some facilities may have processes that vary slightly from the pictured flow. In general, these processes are typical of any company manufacturing heavy construction equipment or stationary mechanical equipment.

The process map format is color coded for ease of review and to clearly distinguish the inputs and outputs. Incoming to the process, raw materials and parts are shaded black, electricity streams are yellow, water streams are blue, compressed air is white with black outline, and gases are light green. The manufacturing process is light blue, with subcomponents identified within the process as appropriate. Depending on the level of data typically available, incoming and outgoing streams are directed either from the overall process or from the subprocess level. Outgoing product/piece parts are orange, waste typically sent to a landfill is maroon, waste typically recycled is green, airborne emissions are gray, radiant emissions (heat) are red, and wastewater is blue. An example of the process map format is shown below in Figure 6.1.

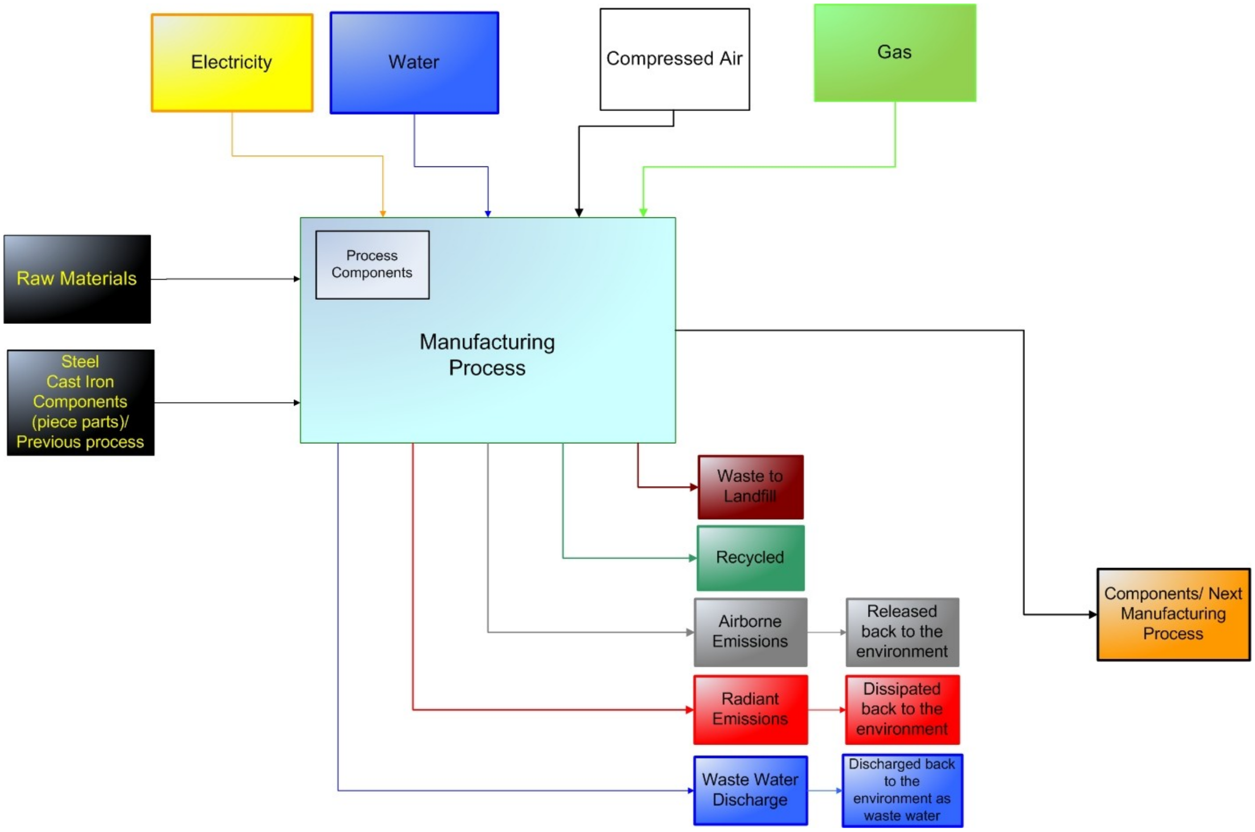


Figure 6.1: Process map format

The specific process maps for the process included in the process chain studied with the relevant input/output streams are shown below in Figures 6.2 – 6.8.

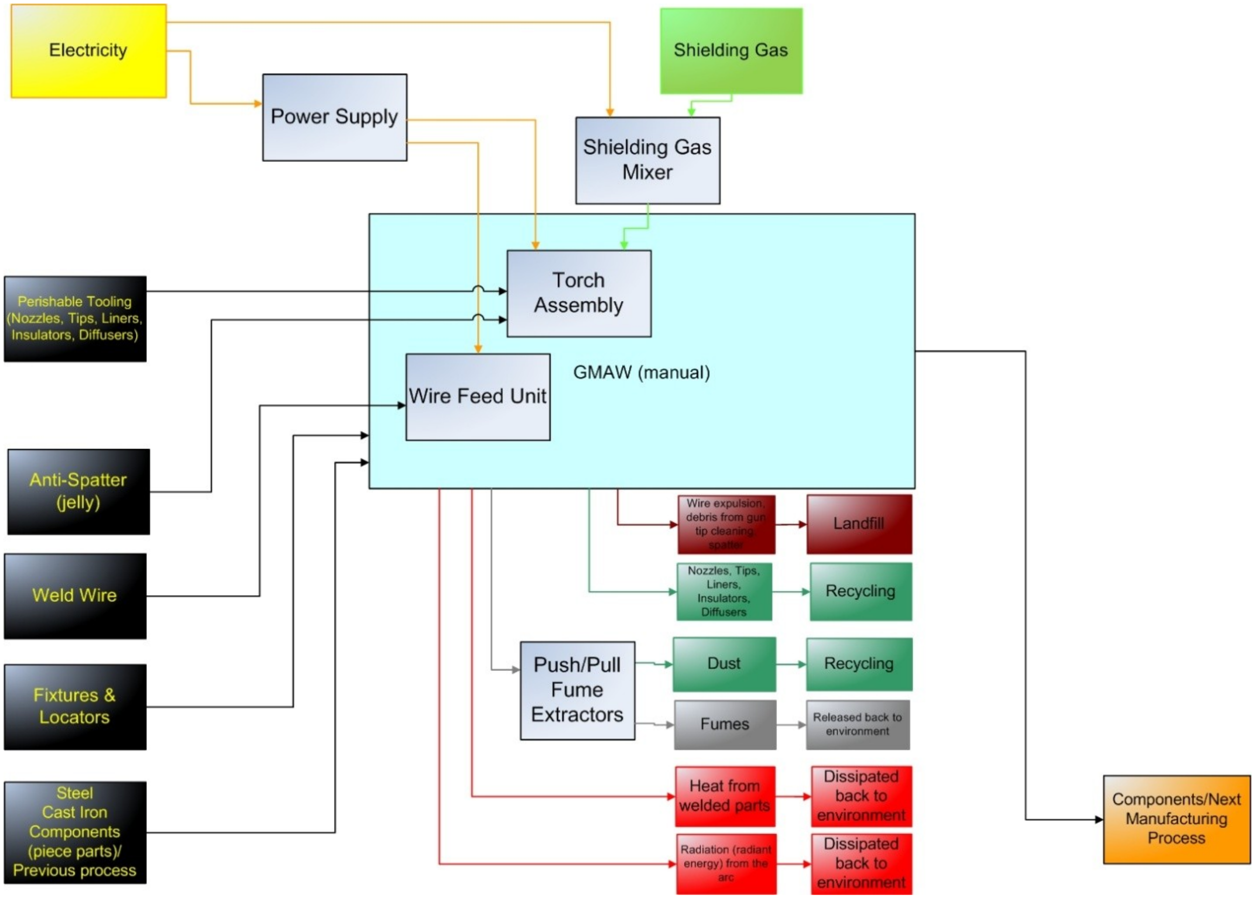


Figure 6.2: Manual gas metal arc welding (GMAW)

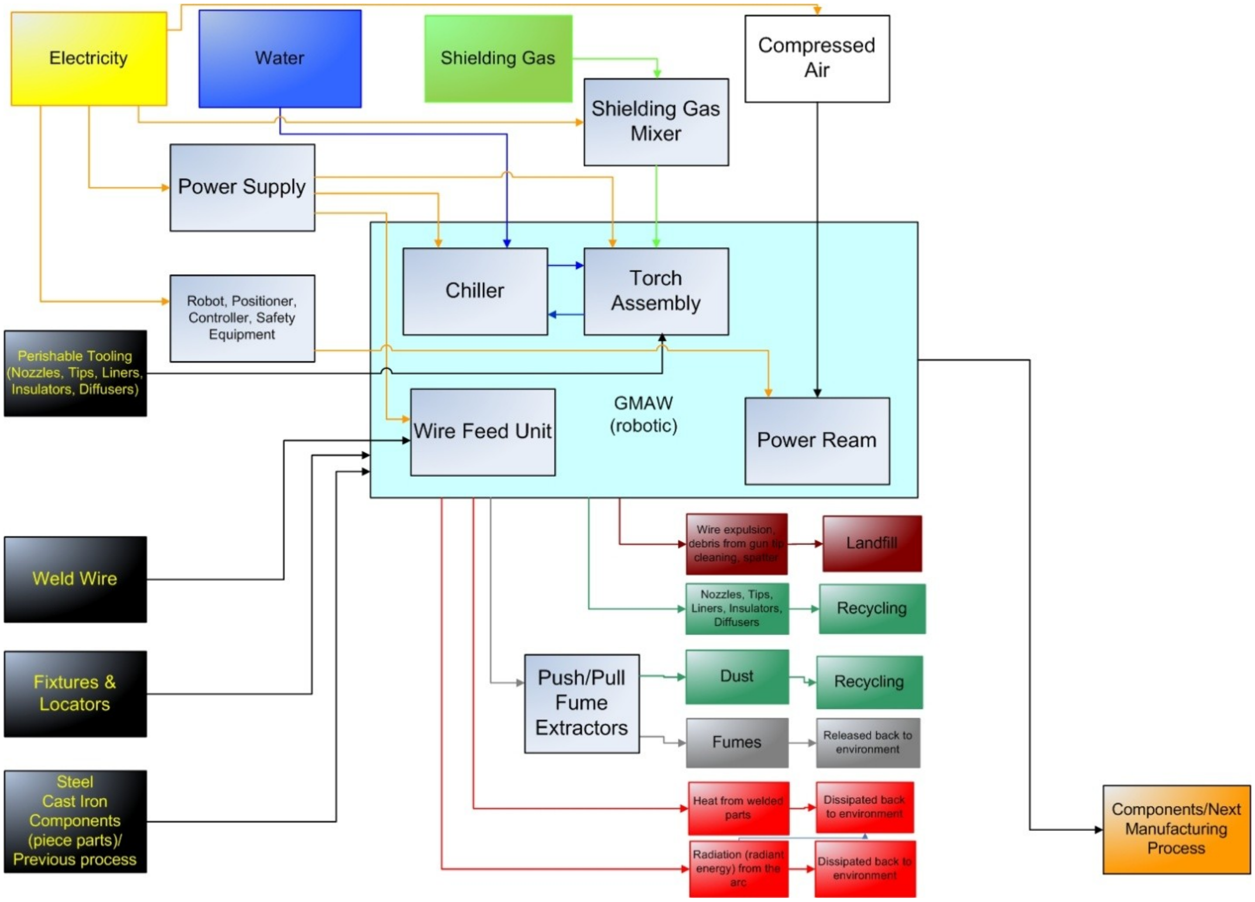


Figure 6.3: Robotic gas metal arc welding (GMAW)

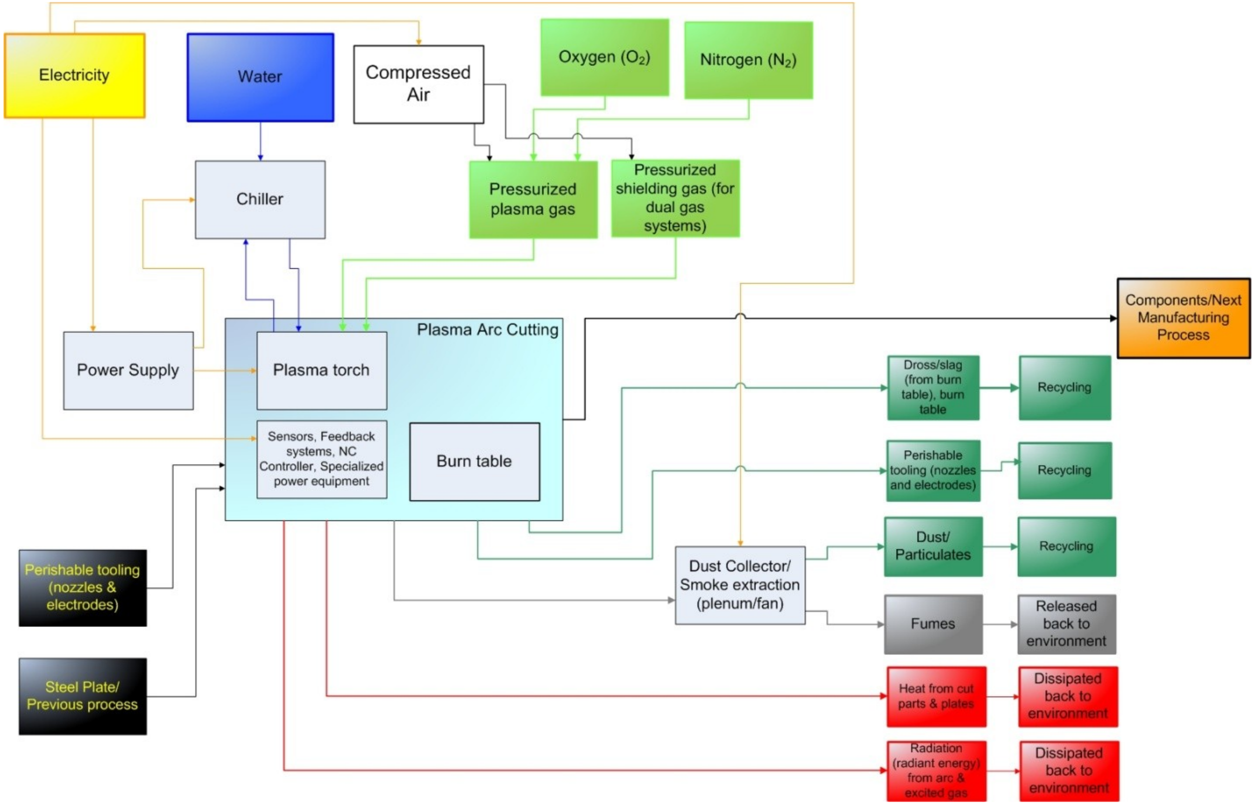


Figure 6.4: Plasma arc cutting

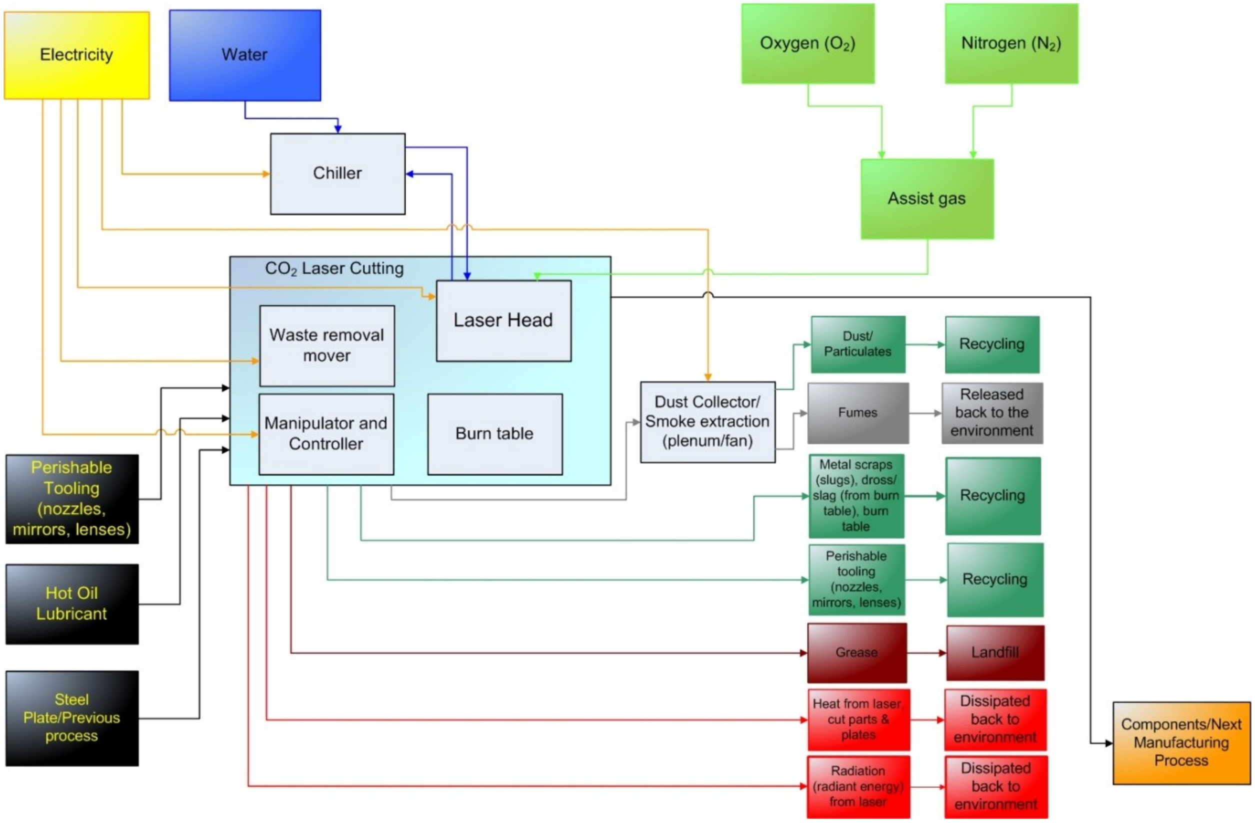


Figure 6.5: CO_2 laser cutting

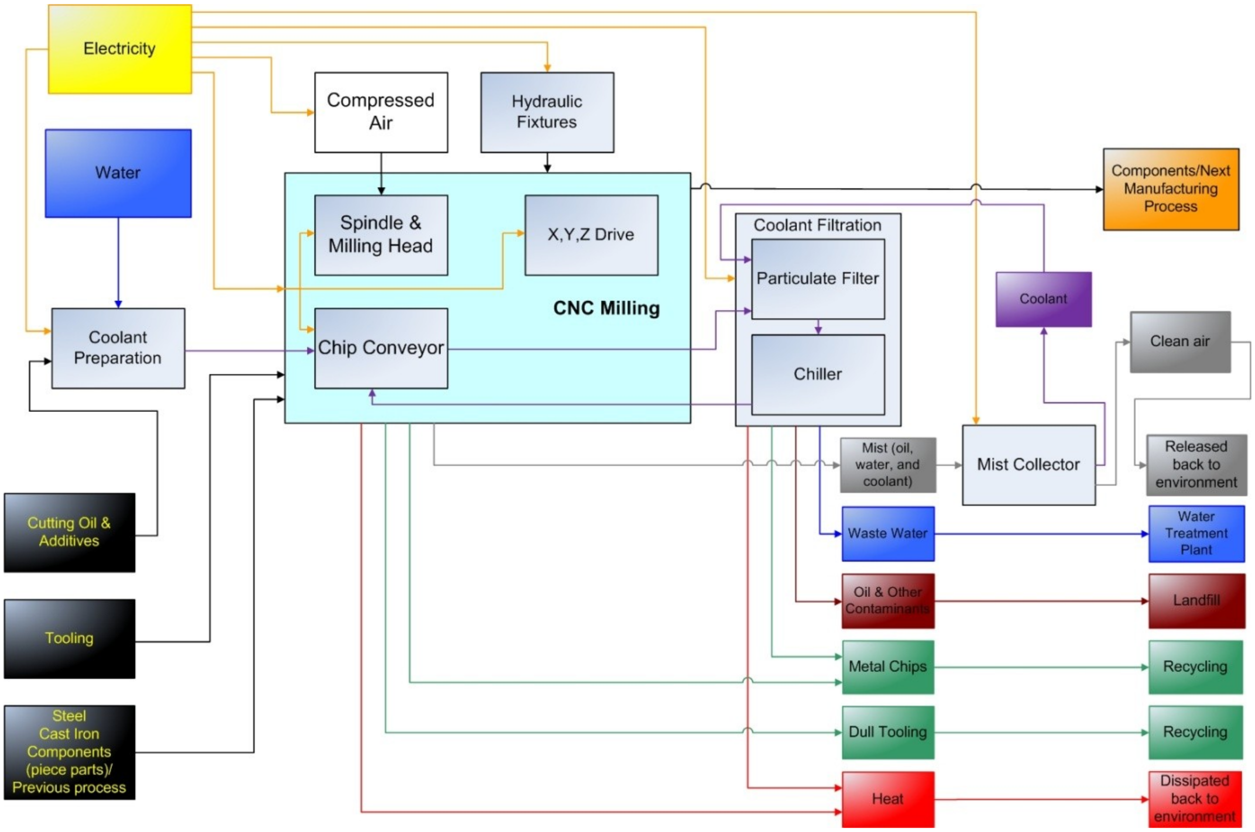


Figure 6.6: Computer Numerical Control (CNC) Milling

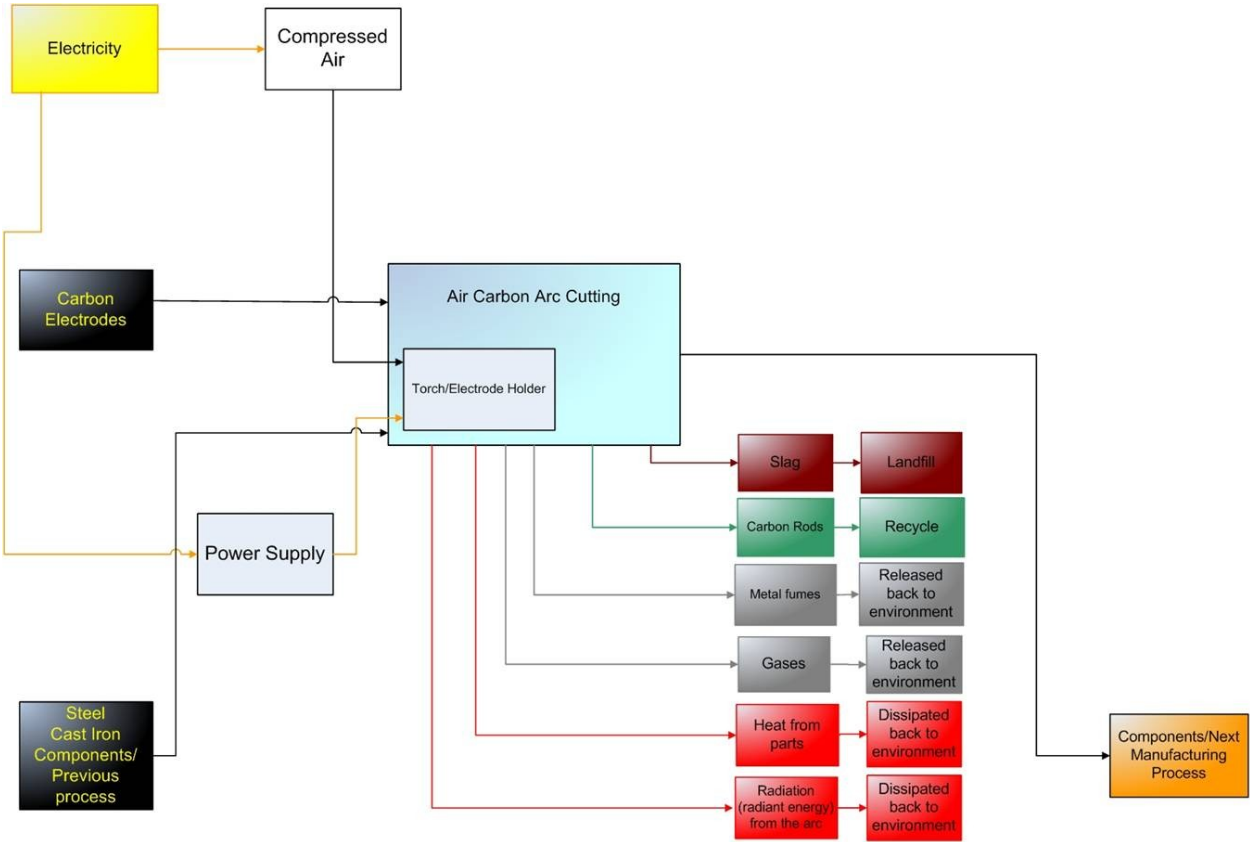


Figure 6.7: Air carbon arc cutting

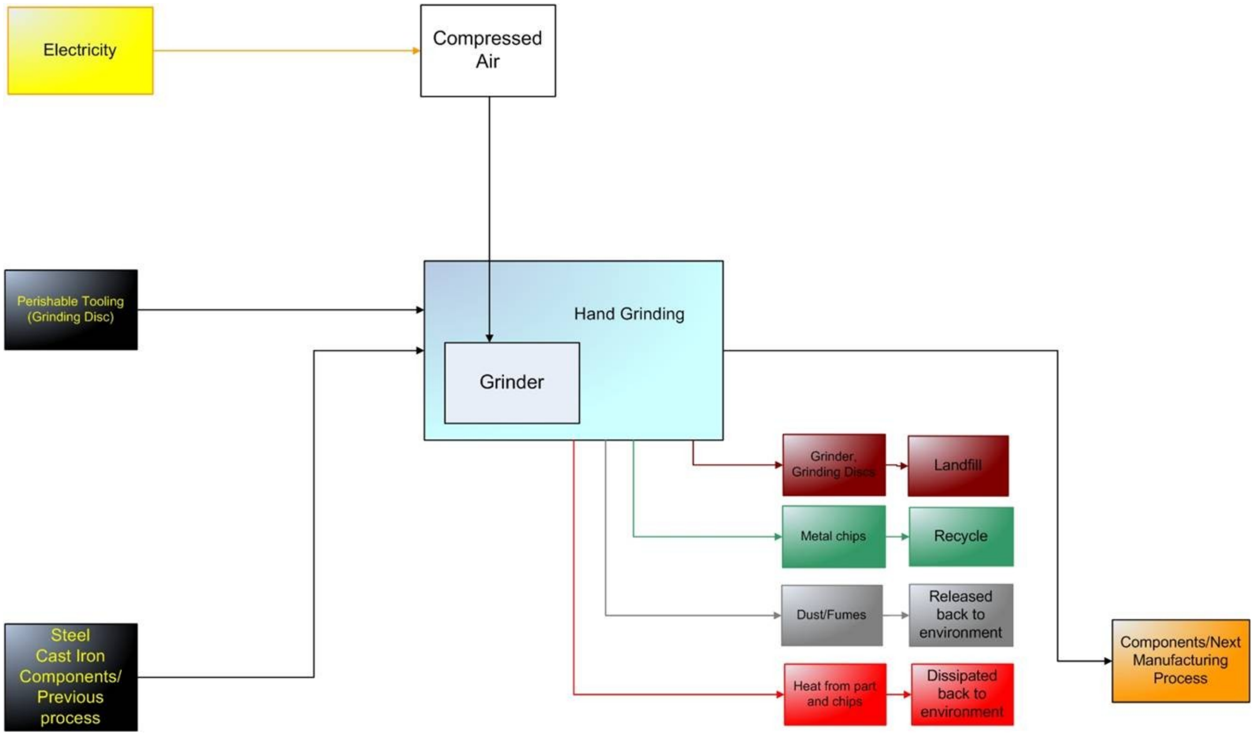


Figure 6.8: Hand grinding

6.4 Model Overview

As described earlier, the sustainability impacts from discrete manufacturing processes are typically not readily available. The data are necessary for facilities to identify the opportunities and estimate the impacts on a production basis of operations. In addition, the data are needed to perform life cycle assessments of products to include manufacturing. This work focuses on the sustainability impacts from fabrication processes, specifically welding (manual and robotic), cutting (plasma arc and laser), and machining (milling).

6.5 Welding Process Building Block

Using the process maps shown above, the inputs and outputs relevant to the sustainability impacts are identified. For manual and robotic welding, the energy consumption includes power to the welding power supply (which then is used to provide power to the chiller, torch assembly, and wire feed unit); the robot/positioner and related safety equipment (for robotic applications only); the compressed air to operate the power ream (robotic applications only); and the shielding gas mixer. Water is re-circulated through the chiller for cooling of the torch assembly. Shielding gas, typically argon and CO_2 at Caterpillar, is plumbed to the shielding gas mixer, where it is mixed prior to use at the torch assembly. Perishable tooling (including nozzles, tips, and diffusers) and weld wire are both consumed by the process. Fixtures are reused numerous times for a given part. Wastes include emissions to the air, excess heat, waste metals, and waste plastics. Basic process details for welding were presented earlier in Chapter 4.

A detailed description of the calculations included in the model is provided in the following sections.

6.5.1 Welding Data

The weld information input into the spreadsheet (all user-entered) is: the weld size; weld type; joint length; and process information (wire diameter, process efficiency, wire feed speed, single pass deposition area, additional tacking time, and production volume). These values are used to determine how long each of the welding processes takes.

For each weld, the following is calculated using the specified inputs:

- Number of passes = ([Weld size (mm)]^2 / 2) / Single pass deposition area (mm^2)
- Total weld length (mm) = Joint length (mm) X Number of passes
- Throat (with penetration) (mm) = Weld size (mm) X cos (45°) + 2.12 (fillet only)
- Deposit area (mm^2) = Throat (mm) / sin (45°)^2 / 2
- Volume (mm^3) = Total weld length (mm) x Deposit area (mm^2)
- WFS/TS ratio = [Deposit area (mm^2) / Number of passes] / Wire area (mm^2) / Process efficiency (%)
- Travel speed (mm/s) = WFS (mm/s) / WFS/TS ratio
- Time (s) = Total weld length (mm) / Travel speed (mm/s)

The welds in a specified assembly are summed together to calculate the impact. The total time for each assembly is calculated as the sum of time calculated for each included weld. Similarly, the total length and total volume of welding for the assembly are the sum of the length and the volume for each included weld.

The total weld time and volume are used for further calculations of the sustainability impacts.

6.5.2 Energy Consumption for the Welding Power Supply

Two common brands of welding power supplies used are Lincoln Electric and Miller. There are two major types of power supplies: transformer-rectifiers and inverters. At Caterpillar, the transformer-rectifiers are more common, although newer installations may include inverters. Transformer-rectifiers take electrical power from the power grid, reduce the voltage through a continuously-loaded transformer to a potential useful for arc welding, and then rectify it to a non-alternating waveform. Because the transformer is always loaded while the machine is on, these machines must be continuously cooled using a fan. Inverter-based arc welding power supplies have a more energy-efficient design, in which electrical power is reduced in a small transformer, rectified and stored in capacitors, and then recovered through solid-state electronic devices (inverters). The user inputs the brand of power supply, type (inverter or transformer-rectifier) and the rated efficiency.

Power data were obtained from various welding power supply manufacturers as well as in-house test data. Data from both of these sources typically contains the current draw, efficiency, power factor, arc-on power, and idle power measured during the test. Empirical data are cross referenced for the user input power supply brand and voltage from the welding specifications, returning the power use during operation and in idle.

Given that test data were not available for the full range of power supplies and voltages used at Caterpillar, a theoretical calculation is also included to compensate for missing data. Lincoln Electric (2013) provides an example of this method.

- V_{out} x I_{out} = Output power (W_{out}) in watts
- $kW_{out} \div Eff$ = Input power in kilowatts (kW_{in})
- Power use during operation = kW_{in}

To account for energy use during idle time for these power supplies, average values of 1.2kW for transformer-rectifiers and 0.3kW for inverter style power supplies are used (C. Ng, personal communication, August 8, 2011).

Energy consumption is calculated as follows:

- Arc-on time (min/assembly) = Arc-on time robotic (min/assembly) + Arc-on time manual (min/assembly) + Arc-on time tacking (min/assembly)
- Energy consumption (kWh) = Arc-on power (kW) X Arc-on time (min/assembly) / 60 + Idle power (kW) X Idle time (hr/assembly)

For some power supplies, both empirical data and calculated energy consumption are available. For these cases, the larger of the total energy consumption values is selected for conservatism.

6.5.3 Energy Consumption for the Welding Robot

A number of commercial welding robots are commonly used throughout the Caterpillar enterprise. In this study, data from Wolf Robotics/ABB, Motoman, and Fanuc were used. Manufacturer data for energy consumption were requested from each of these companies. Manufacturer data on average power consumption were provided by Fanuc based on internal test results. Wolf Robotics provided data for two types of ABB robots: a standard robot and a robot with external axes. Data were estimated from internal knowledge of motor sizes and typical applications, rather than measured power draw. Motoman data were per the datasheets provided for each welding robot. Both Wolf Robotics and Motoman data were provided in units of kVA, requiring a power factor to calculate the energy consumption. Empirical results for power consumption from the robot are determined based on the user input of welding robot brand/type and power factor. Actual consumption will depend on the robot movements during the welding operations.

- Apparent power (kVA) X Power factor = Power (kW) (applies only to Motoman and Wolf Robotics/ABB calculations)

Some Fanuc robots now have power regeneration capability implemented in their controllers, and other brands may be similarly equipped. Literature shows ranges of regeneration capability, some as high as 40% (GE Fanuc, 2008). Regeneration is included in the calculation if applicable.

- Power including regeneration (kW) = Power (kW) X [1 – Regeneration (%)]
- Power consumption (kWh) = Power including regeneration (kW) X Robot arc-on time (min/assembly) / 60

Power use for the robot during idle time was not readily available from any of the manufacturers. The idle-time power consumption is assumed to be negligible for this study. Future studies may consider quantifying the power consumption during idle time for average-sized robots.

6.5.4 Energy Consumption for the Air Compressor

Compressed air is used to operate the power ream for robotic applications. User-entered data include plant air pressure, number of stages on the compressor, and compressor motor efficiency. A default value of 0.014 cubic feet per minute (cfm) is provided for the air flow required for the power ream (Motoman, 2012). Although this is not highlighted as a user input, the user may replace this value if more accurate data are available. In most Caterpillar facilities, the compressed air is supplied to the entire building. Calculations are needed to determine the approximate horsepower (hp) and associated energy (kW) used for the welding operation specifically. Robot arc-on time is used in the power consumption equation because it is assumed that the power ream is constantly drawing power while the robot is in use (welding) and that the amount of power reaming necessary is related to the amount of time that the arc is on.

$HP = [144\ N\ P_1\ V\ k / 33000\ (k - 1)]\ [(P_2 / P_1)^{(k - 1)/N\,k} - 1]$ (The Engineering Toolbox, 2011)

where:
HP = horsepower
N = number of compression stages (user input)
k = 1.41 = adiabatic expansion coefficient
P1 = absolute initial atmospheric pressure (psi) (14.1 psi at sea level)
P2 = absolute final pressure after compression (psi, user input)
V = volume of air at atmospheric pressure (cfm, user input)

- kW = (bhp) x (0.746) / Motor efficiency (U.S. Department of Energy, 2004)

where:
bhp = hp calculated above; motor efficiency = (user input)

- Power consumption (kWh) = Power (kW) X Robot arc-on time (min/assembly) / 60

Actual consumption of compressed air is based on the flow rate of air necessary for the process plus leaks within the lines. The U.S. Department of Energy (2003) estimates leaks from compressed air lines for a facility with a typical maintenance program should expect leak rates of 20%, with variation from 10% for diligent maintenance to 30%+ for less rigorous maintenance programs. A leakage rate of 20% is assumed for compressed air. It is assumed the compressed air is not required during welding idle time periods, so the idle time power consumption for compressed air is therefore negligible.

6.5.5 Energy Consumption for the Shielding Gas Mixer

Data for energy consumption from shielding gas mixers were not readily available. The shielding gas mixer is a centralized system, with power consumption assumed to be much less than the air compressor. Based on literature estimates, the energy for compressed air is 0.02% of the energy for welding power supplies (Motoman, 2012). Given the small expected impact from the energy consumption on the shielding gas mixer, this is assumed to be negligible.

6.5.6 Total Energy Consumption

Total energy consumption is the sum of energy used for each of the power draw sources: welding power supply (which then is used to provide power to the chiller, torch assembly, and wire feed unit); the robot/positioner and related safety equipment (for robotic applications only); the compressed air to operate the power ream (robotic applications only); and the shielding gas mixer (assumed negligible).

- Energy consumed, robotic (kWh) = Power supply (kWh) + Robot (kWh) + Compressed air (kWh)
- Energy consumed, manual (kWh) = Power supply (kWh)

The user-entered cost for electrical power consumption and the calculated total power consumption are used to calculate the total cost for electrical energy. The demand charges and use charges for electricity should both be included in the value entered by the user for total electrical energy costs in units of currency per kilowatt-hour ($/kWh).

- Unit cost ($/kWh) X Units used (kWh) = Total cost ($)

The calculated costs for electrical energy consumption do not include maintenance or other related costs.

6.5.7 Greenhouse Gas (GHG) Emission Calculations

GHG emissions are comprised of emissions from the process operations and emissions resulting from the energy used for the process. For welding, the energy source is electrical energy consumed by the power supply, the robot (if applicable), and the associated equipment. Electrical energy consumption for the building (e.g., lighting and HVAC) is not included in this calculation. GHG emissions from the welding process have not been quantified due to insufficient data. Future studies may quantify the GHG emissions from the process to refine the results.

GHG emissions for electricity are calculated using the quantity of electrical energy consumed and the emission factor appropriate to the location entered by the user. These calculations are shown below:

Total Indirect Emissions from Electricity Purchases [MT $CO_{2\,eq}$] =

$$\left[\sum\left(Total\ CO_2\ from\ electricity + Total\ CO_{2\,eq}\ from\ CH_4 + \ Total\ CO_{2\,eq}\ from\ N_2O\right)\right]$$

Total CO_2 from **Electricity** [MT $CO_{2\,eq}$] = $\dfrac{TEP\ X\ REF}{CF}$

Total $CO_{2\,eq}$ from **Electricity CH_4** [MT $CO_{2\,eq}$] = $\dfrac{TEP\ X\ REF\ X\ 21\ [GWP\ CH_4]}{CF}$

Total $CO_{2\,eq}$ from **Electricity N_2O** [MT $CO_{2\,eq}$] = $\dfrac{TEP\ X\ REF\ X\ 310\ [GWP\ N_2O]}{CF}$

Where:

TEP = Total Electricity Purchases [MWh]

REF = Region/country-specific emission factors $\left[\dfrac{lbs\ CO_{2\,eq}}{MWh}\right]$

$\mathrm{CF} = \mathrm{Conversion\ Factor} = \left(\dfrac{2.205\ lbs}{1\ kg}\right)\left(\dfrac{1000\ kg}{1\ MT}\right)$

Emission factors vary tremendously from country to country and, within a country, by region or state if there are local energy suppliers. Region/country-specific emission factors are based on how carbon intense the energy source is that is used to generate the electricity in that region or country. For example, France's energy mix includes a large portion of nuclear energy which has a lower carbon intensity than a country that generates a large portion of its electricity from coal which is very carbon intense. Therefore, a product made in France would have less GHG emissions than a product made in India (all manufacturing steps being the same).

To further illustrate, if we borrow an example from the automotive industry, a new car's "embodied energy" is approximately 76,000 kWh (Treloar, Love, & Crawford, 2004); depending on where it is manufactured. The embodied energy is the total energy required for manufacturing of the vehicle, from extraction and conversion of ore to building the vehicle including engine, power train, chassis, etc. Using the greenhouse gas conversion factors in Table 6.1 below, we get:

France = 6.30 MTons CO_2 (76 MWh X 0.083 MTon/MWh = 6.30MTons CO_2)
Japan = 36.70 MTons CO_2
USA= 46.60 MTons CO_2
India = 71.76 MTons CO_2

This example shows just how much the result can differ for the same automobile, manufactured with the same process steps, but in a different location with a different energy mix.

Table 6.1: Greenhouse gas conversion factors (carbon intensity of electricity production) (Greenhouse Gas Protocol, 2012; MacKay, 2009)

Country	gCO_2/kWh of electricity (or 0.001 MTon/MWh)
France	83
Canada	220
European Union	353
Japan	483
United Kingdom	580
Germany	601
USA	613
Italy	667
China	778
India	944

Emission factors provided by Caterpillar Global Environmental Health and Safety (EHS), as used in enterprise calculations and updated annually were derived in accordance with guidance from the World Resources Institute. Caterpillar's indirect emission sources for U.S. locations will be converted to CO_2 equivalents utilizing those emissions factors identified in the U.S. EPA's Emissions and Generation Resource Integrated Database (eGRID), 2005 Release, as found on the U.S. EPA's web release (U.S. Environmental Protectional Agency, 2013). This eGRID provides the average emission rates for the 26 subregions that form the North American Electric Reliability Council (NERC) region. Non-U.S. locations are converted using accepted World Resource Institute emissions factors from that country or region. Global warming potential for CH_4 and N_2O are per commonly accepted values from World Resources Institute.

6.5.8 Airborne Emissions

The U.S. EPA provides two primary sources for quantification of airborne emissions from welding operations: AP-42 and South Coast Air Quality Management District (SCAQMD). Emission factors (EFs) from both sources for gas metal arc welding (GMAW) using Electrode E70S (identified as most applicable for GMAW on steel) are provided for particulate matter, nickel, chromium, zinc, lead, manganese, and cobalt, all in terms of quantity of weld wire used (the EF for lead is listed as NA and assumed to be 0 and the EF for cobalt is listed as <0.01 and assumed to be 0.01) (U.S. Environmental Protection Agency, 2000). Additional pollutants not considered by AP-42 but reported in literature as emissions of welding processes include: GHGs (CO_2, CO, NO_x, O_3), antimony, beryllium, cadmium, copper (fume), iron (III) oxide, iron oxide, and molybdenum.

- Emissions for pollutant = Emission factor for pollutant X Weight of wire consumed

Industrial hygiene data collected by Caterpillar were used to estimate emissions not accounted for by U.S. EPA. Results of industrial hygiene monitoring are per department, which include some operations in addition to welding (e.g., machining). Facility sampling includes particulate matter, nickel, chromium, lead, manganese, cobalt, antimony, beryllium, cadmium, copper, iron oxide, molybdenum, and silicon. Air sampling results are provided in concentration (mg/m^3). Samples are typically measured at 2 L/min for 8 hours (U.S. Department of Labor, 2008). For purposes of calculating emissions per part, the results must be converted to a mass basis to create an emission factor.

- Mass emission rate (lb emissions / min) = Concentration (mg/m^3) X Sample flow (2 L/min) X Unit conversion factors

- Emissions per part (lb/assembly) = Mass emission rate (lb/min) X Arc-on time (min/assembly)

In addition, Lincoln Electric has performed some testing of welding operations to estimate the emissions of particulates, iron, manganese, silicon, and copper, using various shielding gases and wire feed speeds. The maximum estimated emissions of each of these pollutants in used in calculations.

- Emissions per part (lb/assembly) = Mass emission rate (lb/min) X Arc-on time (min/assembly)

The resulting emission estimates from these three sources vary significantly and many are based on a small number of sample sizes and generalized data, making a value that is truly representative of a specific operation difficult to identify. In cases where multiple sources are available for a single pollutant, the maximum value is assumed for the total emission calculation.

6.5.9 Water Use

Water is re-circulated in the chiller to cool the torch assembly. Per interviews conducted with machine operators, makeup water is rarely required (Machine Operators, personal communication, July 12, 2011). A small amount of antifreeze is also added to this water when makeup water is included. The total water consumption is assumed to be negligible for the welding process based on this information.

6.5.10 Heat Loss

Although heat loss appears on the process map, previous in-house studies have demonstrated that this heat loss is relatively small and of a quality insufficient for capture and reuse. As a result, heat loss calculations have not been included. Future studies may investigate the potential for capture to further understand the limitations.

- Heat input (joules/inch) = Amps X Volts X 60 / Travel speed (in/min)

One potential impact of heat loss in welding is due to increased air temperature in the facility which would need to be addressed with ventilation systems as part of plant HVAC. This was not considered to be significant in this study.

6.5.11 Shielding Gas Consumption

In Caterpillar facilities, a shielding gas mixture of argon to carbon dioxide (CO_2) is typically used for welding processes. In the U.S., a mix of 90/10 is common. In Europe and Asia, mixes of 85/15, 80/20, and 75/25 are all commonly used. The user inputs the percentage mix.

Shielding gas flow rates are set for each unit. In most facilities, “should” values for the flow rate are defined for manual and for robotic operations, but operators may adjust these values at their own station. Estimates provided by experienced welding engineers varied from minimums of 14 to 19 L/min and maximums of 26 to 33 L/min. An audit in facility #3, revealed that the “should” values of 80 cfh for robotic and 45 cfh for manual were not well controlled, with some manual stations found set over 100 cfh. An evaluation of actual use data from facility #3, assuming 50% manual and 50% robotic operations and 20% leak rate in the lines, correlates well with an average of 39 L/min (37 L/min from robotic and 30 L/min from manual). As a result, the following defaults are assumed for flow rate of shielding gas (see Table 6.2). Although these are not highlighted as user inputs, the user may replace these values, if more accurate data were available.

Table 6.2: Assumed flow rates for welding processes

Process	Max Flow (L/min)	Min Flow (L/min)
Robotic	39.6	35.9
Manual	47.2	14.0

- Max flow rate (L/assembly) = Robot arc-on time (min/assembly) X Robotic maximum flow (L/min) + [Manual arc-on time (min/assembly) + Tacking arc-on time (min/assembly)] X Manual maximum flow rate (L/min)

- Min flow rate (L/assembly) = Robot arc-on time (min/assembly) X Robotic minimum flow (L/min) + [Manual arc-on time (min/assembly) + Tacking arc-on time (min/assembly)] X Manual minimum flow rate (L/min)

- Avg flow rate (L/assembly) = [Min flow rate (L/assembly) + Max flow rate (L/assembly)] / 2

Actual consumption of shielding gas is based on the flow rate of gas necessary for the process plus leaks within the lines. The U.S. Department of Energy (2003) estimates leaks from compressed air lines for a facility with a typical maintenance programs should expect leak rates of 20%, with variation from 10% for diligent maintenance to 30%+ for less rigorous maintenance programs. A leakage rate of 20% is assumed for shielding gas.

- Argon consumption (L/assembly) = Avg flow rate (L/assembly) X Gas mix (argon: CO_2) X 1.20

- CO_2 consumption (L/assembly) = Avg flow fate (L/assembly) X [1- Gas mix (argon: CO_2)] X 1.20

- Shielding gas consumption (L/assembly) = Argon consumption (L/assembly) + CO_2 consumption (L/assembly)

Cost of shielding gas input by user is used to calculate the cost associated with shielding gas consumption.

- Total cost shielding gas ($) = [Unit cost argon ($/L) X Argon units used (L)] + [Unit cost CO_2 ($/L) X CO_2 units used (L)]

The calculated costs for shielding gas consumption do not include maintenance or other related costs.

6.5.12 Weld Wire Consumption

Total weld wire consumption is comprised of the weld wire volume necessary to complete the weld and the weld wire scrap created due to inefficiencies. Wire deposition efficiency is input by the user. Based on expert opinion, a value of 10% was estimated as typical of both manual and automated processes (M. Robinson, personal communication, June 9, 2011). In addition, the efficiency of the process (both robotic and manual) must be considered in the volume of weld wire to be used. Process efficiency is input by the user.

- Wire efficiency = [1+ Wire deposition efficiency (%)] / {Automation (%) X Robotic process efficiency (%) + [1-Automation (%)] X Manual process efficiency (%)}^{2}
- Wire consumption (kg/assembly) = Weld volume / Assembly (mm^3) X Wire density (kg/m^3) / 1000^3 X Wire efficiency (%)

Cost of weld wire input by user is used to calculate the cost associated with weld wire consumption.

- Total cost weld wire ($) = Unit cost ($/kg) X Units used (kg)

The calculated costs for weld wire consumption do not include maintenance or other related costs.

6.5.13 Process Consumables

Consumable tooling for welding processes includes weld wire/electrodes, diffusers, nozzles, tips, and personal protective equipment (PPE) lenses. These materials are all metal, with the exception of lenses, which are plastic. Consumable use data from 2010 and 2011 was collected from various facilities. The specific information from each is provided below (see Tables 6.3 – 6.5).

Table 6.3: Consumable use for facility #1 in 2010

Factors developed from facility #1 data for 2010		
Wire use	28,535	lb
Electrode	2.66	lb/lb wire

Table 6.4: Consumable use for facility #2 in 2010

Factors developed from facility #2 data for 2010	**Total**	**Unit**	**Use per lb wire**	
Electrode (all)	9,318	lb	14.676	lb / lb weld wire
Nozzle/weld	180	each	0.283	each / lb weld wire
Tip	617	each	0.972	each / lb weld wire
Wire	634.9	lb	1.000	lb / lb weld wire
Lens (all)	3,355	each	5.284	each / lb weld wire

Table 6.5: Consumable use for facility #3 in 2011

Factors developed from facility #3 for 2011	**Qty (each)**	**Use per lb wire**	
Diffuser + diffuser/gas	17,100	0.007	each/lb weld wire
Nozzle + nozzle/weld	30,371	0.013	each/lb weld wire
Tip	78,197	0.033	each/lb weld wire
Wire	2,398,443	1.000	each/lb weld wire
Electrode	2,986	0.001	each/lb weld wire

A representative mass for each of the consumables was determined through measurement (weight) of commonly used consumable tooling. The masses used are shown below in Table 6.6.

Table 6.6: Mass of consumables

Consumable	**Mass (lb/each)**
Diffuser	0.073758
Nozzle/weld	0.245597
Tip	0.028252
Lens (all) - plastic	0.03674

From the facility consumable use data, a factor in terms of weight of consumable per weight of weld wire used (lb consumable / lb weld wire) was developed for each consumable. Where multiple data sources were available, the average of all factors is used. In addition, antispatter is used. It is assumed the antispatter stays with the part rather than creating a waste product; therefore, estimates of use are not included. Consumable use is not directly output; rather, this information is used to develop the waste handling information.

6.5.14 Solid Waste

Solid wastes from the welding process shown on the process map can be categorized into four general groups: general waste (wire expulsion, debris from gun tip cleaning, spatter); metal waste (nozzles, tips, liners, insulators, and diffusers); plastic waste (lenses); and waste dust (welding dust). Fixtures are reused numerous times for a given part, and are not considered in this analysis. General waste, metal waste, and waste dust are all metal-based material, while lens waste is plastic. General waste material is typically swept up from the floor. Some facilities may collect this waste in a metals container and recycle it, with varying levels of compliance, while others may dispose of this in landfill containers. Metal waste is typically collected at the welding station in small containers and recycled for metal content. Plastic waste from welding operations is often sent to a landfill, but may be recycled if available in the area. Welding dust may be collected by a fume extractor or similar dust-control equipment, or may be emitted into the air. The user inputs the percent landfilled and recycled of each category.

- General waste landfilled (lb) = Wire deposition efficiency (%) X [Wire use (lb) + Electrode use (lb)] X General waste landfill (%)

- General waste recycled (lb) = Wire deposition efficiency (%) X [Wire use (lb) + Electrode use (lb)] X General waste recycle (%)

- Metal waste landfilled (lb) = [Diffuser use (lb) + Nozzle use (lb) + Tip use (lb)] X Metal waste landfill (%)

- Metal waste recycled (lb) = [Diffuser use (lb) + Nozzle use (lb) + Tip use (lb)] X Metal waste recycle (%)

- Plastic waste landfilled (lb) = Lens use (lb) X Plastic waste landfill (%)

- Plastic waste recycled (lb) = Lens use (lb) X Plastic waste recycle (%)

Data for welding dust collection was obtained to estimate the quantity of welding dust created by welding processes. Using welding dust shipped data from 2010/2011 and the weld wire use for the same time period, a factor of 0.0035 lb dust / lb weld wire was developed. This was accomplished by assuming that approximately half of the wire use was used in the cells with dust collection. The airborne dust waste is added to the total particulate emissions.

- Dust waste landfilled (lb) = Weld wire use (lb) X Dust factor (lb dust / lb wire) X Dust waste landfill (%)

- Dust waste recycled (lb) = Weld wire use (lb) X Dust factor (lb dust / lb wire) X Dust waste recycle (%)

- Dust waste airborne (lb) = Weld wire use (lb) X Dust factor (lb dust / lb wire) X [1 - Dust waste neither landfill (%) - Dust waste recycle (%)]

Cost of landfilling and recycling of solid waste are calculated using the user-input costs for waste handling/hauling. The user inputs the cost per ton of material removed and the cost per haul, as most waste disposal companies charge separately for these items. The total cost of waste hauling is calculated from these two values, assuming an average haul weight of 5,620 pounds (data from 2011, average weight per haul for facility #2). Similarly, recycling costs are entered for each commodity, in this case metals and plastics. A negative value is entered for commodities for which payment is received, rather than made. The haul and mass recycling values are summed, assuming an average haul weight of 5,620 pounds, to calculate a total recycling cost. Although the total cost values are not highlighted as user inputs, the user may replace these values, if more accurate data were available.

- Landfill cost ($) = [Cost of landfill by weight ($/ton) + Cost of landfill per haul ($/haul) / 5,620 (lb/haul) X 2,000 (lb/ton)] X Units landfilled (lb)

- Recycle cost ($) = [Cost of recycle by weight by commodity ($/ton) + Cost of recycle per haul per commodity ($/haul) / 5,620 (lb/haul) X 2,000 (lb/ton)] X Units recycled per commodity (lb)

6.6 Cutting Building Block – Plasma Arc Cutting

Basic process details for plasma arc cutting were presented earlier in Chapter 4. For plasma arc cutting, the energy consumption includes power to the power supply (which then is used to provide power to the chiller and plasma torch head), the NC controller and feedback systems, the compressed air used as plasma and shielding gases, and the dust collector. Water is re-circulated through the chiller for cooling of the plasma torch head. Plasma and shielding gas, typically compressed air, oxygen (O_2), and nitrogen (N_2) at Caterpillar, are run to the plasma torch. Perishable tooling (nozzles and electrodes) is consumed by the process. Wastes include emissions to the air, excess heat, and waste metals.

A detailed description of the calculations included in the model is provided in the following sections.

6.6.1 Cutting Data

The cutting information is input into the spreadsheet. Specifically, the user should input the material type, plate thickness (mm), travel speed (mm/min), and total length of cut (mm). These values are used to determine how long the cutting process takes.

For each cut, arc-on cutting time is calculated using the specified inputs:

- Cutting time, arc-on time (hr/part) = Length of cut (mm/part) ÷ Travel speed (mm/min) ÷ 60

The total cutting time (arc-on time) is used for further calculations of the sustainability impacts.

6.6.2 Energy Consumption for the Cutting Power Supply

The user should input the type of power supply used (inverter or transformer-rectifier), output voltage, output current, and the rated efficiency.

A theoretical calculation is used to estimate the power consumption for the power supply:

- V_{out} x I_{out} = Output power (W_{out}) in watts
- kW_{out} ÷ Rated efficiency = Input power in kilowatts (kW_{in})

- Power use during operation = kW_{in}

To account for energy use during idle time for these power supplies, the plasma arc cutting power supplies are assumed to be similar to welding power supplies. This is because the plasma arc cutting power supplies are very similar to the welding power supplies. As previously described in section 6.5.2, Energy Consumption for the Welding Power Supply, an average of 1.2kW for transformer-rectifiers and 0.3kW for inverter-style power supplies are used.

Energy consumption is calculated as follows:

- Energy consumption (kWh) = Arc-on power (kW) X Arc-on time (min/part) / 60 + Idle power (kW) X Idle time (min/part) / 60

6.6.3 Energy consumption for the NC Controller and Feedback Systems

Data for energy consumption from the NC controller and feedback systems were not readily available. Based on literature estimates for the energy consumption of NC controller and feedback systems for machining operations, this energy was assumed to be negligible (Mori, 2010). This is because the equipment used for the NC controller and feedback systems is very similar for plasma arc cutting and machining operations. For future iterations, this energy consumption might be considered. This data could be obtained by performing real-time monitoring of the plasma arc cutting process or obtaining manufacturer data.

6.6.4 Energy Consumption for the Compressed Air Used as Plasma and Shielding Gases

Compressed air is used as plasma and shielding gases. Compressed-air power consumption is calculated as previously described in section 6.5.4, Energy Consumption for the Air Compressor.

Compressed air used as plasma and shielding gases is not used during idle time, and the idle time power consumption for compressed air is therefore negligible.

6.6.5 Energy Consumption for the Dust Collector

To account for energy use of the dust collector, the plasma arc cutting dust collector was assumed to be similar to the laser cutting dust collector. This is because they both use very similar dust collector equipment. It is also assumed that the dust collector is always running. As a result, average values of 2.9 kW were used for arc-on power and idle power, respectively (Devoldere et al., 2008).

Energy consumption is calculated as previously described above in section 6.6.2, Energy Consumption for the Cutting Power Supply.

6.6.6 Total Energy Consumption

Total energy consumption is the sum of energy used for each of the power draw sources: cutting power supply (which is then used to provide power to the chiller and plasma torch head), the NC controller and feedback systems (assumed negligible), the compressed air used as plasma and shielding gases, and the dust collector.

- Energy consumption (kWh) = Power supply (kWh) + Compressed air (kWh)

The user-entered cost for electrical power consumption and the calculated total power consumption are used to calculate the total cost for electrical energy. The demand charges and use charges for electricity should both be included in the value entered by the user for total electrical energy costs in units of currency per kilowatt-hour ($/kWh).

- Unit cost ($/kWh) X Units used (kWh) = Total cost ($)

The calculated costs for electrical energy consumption do not include maintenance or other related costs.

6.6.7 GHG Emission Calculations

GHG emissions are comprised of emissions from the process operations and emissions resulting from the energy used for the process. For plasma arc cutting, the energy source is electrical energy consumed by the power supply and associated equipment. Electrical energy consumption for the building (e.g., lighting and HVAC) is not included in this calculation. GHG emissions from the plasma arc cutting process have not been quantified due to insufficient data. Future studies may quantify the GHG emissions from the process to refine the results.

GHG emissions for electricity are calculated as previously described in section 6.5.7, Greenhouse Gas Emission Calculations.

6.6.8 Airborne Emissions

Some data are available on the quantification of airborne emissions from plasma arc cutting operations through the U.S. EPA AP-42 document. Emission factors for plasma arc cutting are provided for iron, manganese, copper, chromium, nickel, molybdenum, and nitrous oxide (NO_x), all in terms of arc-on time (U.S. Environmental Protection Agency, 2000).

- Emissions for pollutant (g/part) = Emission factor for pollutant (g/min) X Arc-on time (hr/part) X 60

In instances where range values were given, the maximum value is assumed for the total emission calculation.

6.6.9 Water Use

Water is re-circulated in the chiller to cool the plasma torch head. Per interviews conducted with machine operators, makeup water is rarely required (Machine Operators, personal communication, July 12, 2011). A small amount of antifreeze is also added to this water when makeup water is included. The total water consumption is assumed to be negligible for the plasma arc cutting process based on this information.

6.6.10 Heat Loss

Although heat loss appears on the process map, previous in-house studies have demonstrated that this heat loss is relatively small and of a quality insufficient for capture and reuse. As a result, heat loss calculations have not been included. Future studies may investigate the potential for capture to further understand the limitations.

6.6.11 Plasma and Shielding Gas Consumption

In Caterpillar facilities, dual gas systems utilizing a plasma gas and a shielding gas are typically used during plasma arc cutting. Compressed air, oxygen (O_2), or nitrogen (N_2) is typically used as the plasma gas and compressed air is typically used as the shielding gas (in a dual gas system).

The user should input the required plasma gas type and shielding gas type (if applicable), as well as the required plasma gas flow rate and shielding gas flow rate (if applicable), for the operation.

Actual consumption of plasma and shielding gas is based on the flow rate of gas necessary for the process plus leaks within the lines. Note that leaks are applicable only if compressed air is used (reference sections 6.5.4, Energy Consumption for the Air Compressor and 6.5.11, Shielding Gas Consumption for background). If compressed air is used, assume a leakage rate of 20% for compressed air (U.S. Department of Energy, 2003).

- Plasma gas consumption (L/part) = Plasma gas flow rate (L/min) X Arc-on time (min/part)

- Shielding gas consumption (L/part) = Shielding gas flow rate (L/min) X Arc-on time (min/part)

- Total gas consumption (L/part) = Plasma gas consumption (L/part) + Shielding gas consumption (L/part)

Cost of plasma and shielding gas input by user is used to calculate the cost associated with plasma and shielding gas consumption:

- Total cost plasma and shielding gas ($) = [Unit cost plasma gas ($/L) X Plasma gas units used (L)] + [Unit cost shielding gas ($/L) X Shielding gas units used (L)]

The calculated costs for plasma and shielding gas consumption do not include maintenance or other related costs.

6.6.12 Process Consumables

Consumable tooling for plasma arc cutting includes nozzles and electrodes. Both of these materials are metal. Nozzle and electrode use are calculated using consumption rate factors based on plasma gas type used and estimates of nozzle and electrode wear rates per arc-on time (Cook & Start, 2002).

- # nozzles consumed/part = Consumption rate factor (# nozzles/arc-on time) X Arc-on time (hr/part)

- # electrodes consumed/part = Consumption rate factor (# electrodes/arc-on time) X Arc-on time (hr/part)

The plasma arc cutting nozzle weight is estimated as the weight of a laser cutting nozzle, since it is similar in size to a laser cutting nozzle (refer to section 6.7.13, Process Consumables). For the plasma arc cutting electrode, an estimation factor of four times the weight of the nozzle is used. Note that this estimation factor is an overestimate based on the fact that the nozzle and electrode are of similar sizes, but the nozzle is hollow whereas the electrode is solid.

From the consumable use data that was calculated and the mass values of the consumables, a factor in terms of weight of consumables per part (lb consumable/part) was developed for each consumable.

- Weight of consumables per part (lbs/part) = # consumed/part X Weight of consumable (lb)

Consumable use is not directly output; rather, this information is used to develop the waste-handling information.

6.6.13 Solid Waste

Solid wastes from the plasma arc cutting process shown on the process map can be categorized into three general groups: general waste (dross/slag), metal waste (nozzles, electrodes, and the burn table), and waste dust (cutting dust). General waste, metal waste, and waste dust are all metal-based material. General waste material is typically swept up from the floor. Some facilities may collect this waste in a metals container and recycle it, with varying levels of compliance, while others may dispose of this in landfill containers. Metal waste is typically collected at the plasma arc cutting station in small containers and recycled for metal content. Cutting dust is collected by a dust collector or a similar device. The user inputs the percent landfilled and recycled of each category.

- General waste landfilled (lb) = [Dross/slag produced (lb)] X General waste landfill (%)

- General waste recycled (lb) = [Dross/slag produced (lb)] X General waste recycle (%)

Data were not readily available to calculate the amount of dross/slag produced from plasma arc cutting.

- Metal waste landfilled (lb) = [Nozzle use (lb) + Electrode use (lb) + Burn table use (lb)] X Metal waste landfill (%)

- Metal waste recycled (lb) = [Nozzle use (lb) + Electrode use (lb) + Burn table use (lb)] X Metal waste recycle (%)

Data were not readily available to calculate the consumption of burn tables.

- Dust waste landfilled (lb) = Arc-on time (hrs/part) X Dust factor (lb dust / arc-on time) X Dust waste landfill (%)

- Dust waste recycled (lb) = Arc-on time (hrs/part) X Dust factor (lb dust / arc-on time) X Dust waste recycle (%)

- Dust waste airborne (lb) = Arc-on time (hrs/part) X Dust factor (lb dust / arc-on time) X [1 - Dust waste landfill (%) - Dust waste recycle (%)]

The airborne dust waste is added to the total particulate emissions.

Data were not readily available to calculate the amount of dust produced from plasma arc cutting.

Cost of landfilling and recycling of solid waste are calculated using the user-input costs for waste handling/hauling. The user inputs the cost per ton of material removed and the cost per haul, as most waste disposal companies charge separately for these items. The total cost of waste hauling is calculated from these two values, assuming an average haul weight of 5,620 pounds (data from 2011, average weight per haul for facility #2). Similarly, recycling costs are entered for each commodity, in this case metals. A negative value is entered for commodities where payment is received rather than made. The haul and mass recycling values are summed, assuming an average haul weight of 5,620 pounds, to calculate a total recycling cost. Although the total cost values are not highlighted as user inputs, the user may replace these values if more accurate data were available.

- Landfill cost ($) = [Cost of landfill by weight ($/ton) + Cost of landfill per haul ($/haul) / 5,620 (lb/haul) X 2,000 (lb/ton)] X Units landfilled (lb)

- Recycle cost (\$) = [Cost of recycle by weight by commodity (\$/ton) + Cost of recycle per haul per commodity (\$/haul) / 5,620 (lb/haul) X 2,000 (lb/ton)] X Units recycled per Commodity (lb)

6.7 Cutting Building Block – Laser Cutting

Basic process details for laser cutting were presented earlier in Chapter 4. For laser cutting, the energy consumption includes power to the laser head, the chiller, the manipulator and controller, the waste removal mover, and the dust collector. Water is re-circulated through the chiller for cooling of the laser head. Assist gas, typically oxygen (O_2) or nitrogen (N_2) is run to the laser head. Perishable tooling (nozzles, mirrors, and lenses) is consumed by the process. Wastes include emissions to the air, excess heat, waste metals, waste plastics, and waste glass.

A detailed description of the calculations included in the model is provided in the following sections.

6.7.1 Cutting Data

The cutting information is input into the spreadsheet. Specifically, the user should input the material type, plate thickness (mm), travel speed (mm/min), and total length of cut (mm). These values are used to determine how long the cutting process takes.

For each cut, cutting time is calculated using the specified inputs:

- Cutting time (hr/part) = Length of cut (mm/part) ÷ Travel speed (mm/min) ÷ 60

The total cutting time is used for further calculations of the sustainability impacts.

6.7.2 Energy Consumption for the Laser Head

The user should input the required laser output power setting and the rated efficiency of the laser.

A study by Devoldere, Dewulf, Deprez, & Duflou, 2008 found that the average laser source efficiency was 9%. This is the recommended value to be used for the rated efficiency unless the user has a more accurate value to input.

A theoretical calculation is used to estimate the power consumption for the laser head:

- Output power setting (kW_{out}) ÷ Rated efficiency = Input power in kilowatts (kW_{in})
- Power use during operation = kW_{in}

To account for energy use during idle time, average values of 19.5 kW were used for idle power of the laser head (Devoldere et al., 2008).

Energy consumption is calculated as follows:

- Energy consumption (kWh) = In-cut power (kW) X Cutting time (min/part) / 60 + Idle power (kW) X Idle time (min/part) / 60

6.7.3 Energy Consumption for the Chiller

To account for energy use of the chiller, average values of 12 kW and 7.24 kW were used for in-cut power and idle power, respectively (Devoldere et al., 2008).

Energy consumption is calculated as previously described above in section 6.7.2, Energy Consumption for the Laser Head.

6.7.4 Energy Consumption for the Manipulator and Controller

To account for energy use of the manipulator and controller, average values of 0.99 kW and 0.41 kW were used for in-cut power and idle power, respectively (Devoldere et al., 2008).

Energy consumption is calculated as previously described above in section 6.7.2, Energy Consumption for the Laser Head.

6.7.5 Energy Consumption for the Waste Removal Mover

Data for energy consumption from the waste removal mover were not readily available. It was assumed that the energy consumption for the waste removal mover was on a similar order of magnitude to that of the dust collector. Since this contributes such a small amount to the total energy consumption, this energy consumption was assumed to be negligible. For future iterations, this energy consumption might be considered. This data could be obtained by taking energy measurements of the waste removal mover while running or by obtaining manufacturer information.

6.7.6 Energy Consumption for the Dust Collector

To account for energy use of the dust collector, it is assumed to be always running. As a result, average values of 2.9 kW were used for in-cut power and idle power, respectively (Devoldere et al., 2008).

Energy consumption is calculated as previously described above in section 6.7.2, Energy Consumption for the Laser Head.

6.7.7 Total Energy Consumption

Total energy consumption is the sum of energy used for each of the power draw sources: laser head, chiller, manipulator and controller, waste removal mover (assumed negligible), and the dust collector.

- Energy consumption (kWh) = Laser head (kWh) + Chiller (kWh) + Manipulator and controller (kWh) + Dust collector (kWh)

The user-entered cost for electrical power consumption and the calculated total power consumption are used to calculate the total cost for electrical energy. The demand charges and use charges for electricity should both be included in the value entered by the user for total electrical energy costs in units of currency per kilowatt-hour ($/kWh).

- Unit cost ($/kWh) X Units used (kWh) = Total cost ($)

The calculated costs for electrical energy consumption do not include maintenance or other related costs.

6.7.8 GHG Emission Calculations

GHG emissions are comprised of emissions from the process operations and emissions resulting from the energy used for the process. For laser cutting, the energy source is electrical energy consumed by the laser head and associated equipment. Electrical energy consumption for the building (e.g., lighting and HVAC) is not included in this calculation. GHG emissions from the laser cutting process have not been quantified due to insufficient data. Future studies may quantify the GHG emissions from the process to refine the results.

GHG emissions for electricity are calculated as previously described in section 6.5.7, Greenhouse Gas Emission Calculations.

6.7.9 Airborne Emissions

Airborne emissions from the laser cutting process have not been quantified due to insufficient data. Future studies may quantify the airborne emissions from the process to refine the results.

6.7.10 Water Use

Water is re-circulated in the chiller to cool the laser head. Per interviews conducted with machine operators, makeup water is rarely required (Machine Operators, personal communication, July 12, 2011). A small amount of antifreeze is also added to this water when makeup water is included. The total water consumption is assumed to be negligible for the laser cutting process based on this information.

6.7.11 Heat Loss

Although heat loss appears on the process map, previous in-house studies have demonstrated that this heat loss is relatively small and of a quality insufficient for capture and reuse. As a result, heat loss calculations have not been included. Future studies may investigate the potential for capture to further understand the limitations.

6.7.12 Assist Gas Consumption

In Caterpillar facilities, Oxygen (O_2) or Nitrogen (N_2) is typically used as the assist gas in laser cutting.

The user should input the required assist gas type, as well as the required assist gas flow rate, for the operation.

Actual consumption of assist gas is based on the flow rate of gas necessary for the process:

- Assist gas consumption (L/part) = Assist gas flow rate (L/min) X Laser-on time (min/part)

Cost of assist gas is input by the user and is used to calculate the cost associated with assist gas consumption:

- Total cost assist gas ($) = Unit cost assist gas ($/L) X Assist gas units used (L)

The calculated costs for assist gas consumption do not include maintenance or other related costs.

6.7.13 Process Consumables

Consumable tooling for laser cutting includes nozzles, mirrors, and lenses. The nozzles are metal, the lenses are plastic, and the mirrors are glass. Nozzle, mirror, and lens use are calculated using consumption rate factors based on estimates of nozzle wear rates per cutting time ("Nozzle wear rates.", 2011) and mirror and lens wear rates per machine on time (cutting time + idle time) (K. Mauritzson, personal communication, June 11, 2012; Olexa, 2006).

- # nozzles consumed/part = Consumption rate factor (# nozzles/cutting time) X Cutting time (hr/part)
- # mirrors consumed/part = Consumption rate factor (# mirrors/machine on time) X Machine on time (hr/part)
- # lens consumed/part = Consumption rate factor (# lens/machine on time) X Machine on time (hr/part)

A representative mass for each of the consumables was developed through measurement (weight) of commonly used consumable tooling. The masses used are shown below in Table 6.7.

Table 6.7: Mass of consumables

Consumable	**Mass (lb/each)**
Nozzle	0.19
Lens	0.28
Rear mirror	0.11
Turning mirror	0.11
Output mirror	0.11
Phase shift mirror	0.38
Beam bender mirror	0.38
Molybdenum mirror	1.63

From the consumable use data that was calculated and the mass values of the consumables, a factor in terms of weight of consumables per part (lb consumable/part) was developed for each consumable.

- Weight of consumables per part (lbs/part) = # consumed/part X weight of consumable (lb)

Consumable use is not directly output; rather, this information is used to develop the waste-handling information.

6.7.14 Solid Waste

Solid wastes from the laser cutting process shown on the process map can be categorized into five general groups: general waste (dross/slag), metal waste (nozzles, metal scraps, slugs and skeleton, and the burn table), plastic waste (lenses), glass waste (mirrors), and waste dust (cutting dust). General waste, metal waste, and waste dust are all metal-based material, while the lenses are plastic and the mirrors are glass. General waste material is typically swept up from the floor. Some facilities may collect this waste in a metals container and recycle it, with varying levels of compliance, while others may dispose of this in landfill containers. Metal waste is typically collected at the laser cutting station in small containers and recycled for metal content. Plastic waste and glass waste from cutting operations are often sent to landfill, but may be recycled if available in the area. Cutting dust is collected by a dust collector or a similar device. The user inputs the percent landfilled and recycled of each category.

- General waste landfilled (lb) = [Dross/slag produced (lb)] X General waste landfill (%)

- General waste recycled (lb) = [Dross/slag produced (lb)] X General waste recycle (%)

Data were not readily available to calculate the amount of dross/slag produced from laser cutting.

- Metal waste landfilled (lb) = [Nozzle use (lb) + Metal scraps (slugs and skeleton) produced (lb) + Burn table use (lb)] X Metal waste landfill (%)

- Metal waste recycled (lb) = [Nozzle use (lb) + Metal scraps (slugs and skeleton) produced (lb) + Burn table use (lb)] X Metal waste recycle (%)

Data were not readily available to calculate the metal scraps (slugs and skeleton) produced or the consumption of burn tables.

- Plastic waste landfilled (lb) = Lens use (lb) X Plastic waste landfill (%)

- Plastic waste recycled (lb) = Lens use (lb) X Plastic waste recycle (%)

- Glass waste landfilled (lb) = Mirror use (lb) X Glass waste landfill (%)

- Glass waste recycled (lb) = Mirror use (lb) X Glass waste recycle (%)

- Dust waste landfilled (lb) = Cutting time (hrs/part) X Dust factor (lb dust / cutting time) X Dust waste landfill (%)

- Dust waste recycled (lb) = Cutting time (hrs/part) X Dust factor (lb dust / cutting time) X Dust waste recycle (%)

- Dust waste airborne (lb) = Cutting time (hrs/part) X Dust factor (lb dust / cutting time) X [1 - Dust waste landfill (%) - Dust waste recycle (%)]

The airborne dust waste is added to the total particulate emissions.

Data were not readily available to calculate the amount of dust produced from laser cutting.

Cost of landfilling and recycling of solid waste are calculated using the user-input costs for waste handling/hauling. The user inputs the cost per ton of material removed and the cost per haul, as most waste disposal companies charge separately for these items. The total cost of waste hauling is calculated from these two values, assuming an average haul weight of 5,620 pounds (data from 2011, average weight per haul for facility #2). Similarly, recycling costs are entered for each commodity, in this case metals, plastics, and glass. A negative value is entered for commodities where payment is received rather than made. The haul and mass recycling values are summed, assuming an average haul weight of 5,620 lbs, to calculate a total recycling cost. Although the total cost values are not highlighted as user inputs, the user may replace these values if more accurate data are available.

- Landfill cost ($) = [Cost of landfill by weight ($/ton) + Cost of landfill per haul ($/haul) / 5,620 (lb/haul) X 2,000 (lb/ton)] X Units landfilled (lb)

- Recycle cost ($) = [Cost of recycle by weight by commodity ($/ton) + Cost of recycle per haul per commodity ($/haul) / 5,620 (lb/haul) X 2,000 (lb/ton)] X Units recycled per commodity (lb)

6.8 Milling Building Block

The background on the milling process, including basic process mechanics, was previously presented in Chapter 4. For milling, the energy consumption includes an estimate of aggregate power consumed in the machine envelope (chip conveyer; spindle head; X, Y, Z Drive) and an estimate of the supporting equipment (coolant filtration, hydraulic fixtures, mist collector, compressed air, and coolant preparation). Water is consumed in producing the coolant, which is used with the chip conveyer, and compressed air, which is used to remove chips from the cutting interface. A chiller is used to keep the coolant at the appropriate temperature. Wastes include emissions to the air, heat from the cut, metal chips, dull tooling, water, and coolant additives.

A detailed description of the calculations included in the model is provided in the following sections.

Main Machine Envelope Energy Calculations

6.8.1 Milling Data

The user inputs the workpiece parameters, specifically the cut length, width, depth, and density. These values are used to determine how long each cut will take, as well as the mass of the material removed.

For each cut, the following is calculated using the specified inputs:

- Cut lead-in length (mm) = sqrt [depth (mm) X (Diameter of head (mm) - Depth (mm)]
- Cut time (s) = [Cut lead-in length (mm) + Length (mm)] / Feed rate (mm/s)
- Volume (mm^3) = Length (mm) X Width (mm) X Depth (mm)
- Removal weight (g) = Volume removed (cm^3) X Density (g/cm^3)
- Volume removal rate (cm^3/s) = Removal volume (cm^3) / Milling time (s)

6.8.2 Machine Energy Calculations

Energy consumption in the main envelope of the computer numerical control (CNC) machine is predicted using a methodology from Kalla et al., 2009. Energy consumption of the many components of the larger machine is categorized into basic, idle, and milling energies. Each component of the machine is run for different durations during the cut. By separating these components' energy consumption and measuring the amount of time each category is used per cut, we can find the overall total use. This calculation estimates the power consumption of the

Spindle; Milling Head; X,Y,Z Drive; Chip Conveyer; and any other energy consumption of the main machine envelope. This includes lighting, numerical control, etc.

- Time handling (s) = Air time (s) + Approach time (s) + Over-travel time (s) + Retraction time (s)
- Basic time (s) = Time load/unload (s) + Time handling (s) + Time milling (s)
- Idle time (s) = Time handling (s) + Time milling (s)
- Milling time (s) = Lead in length (mm) + Cut length (mm) / Feed rate (mm/s)
- Milling power = Volume material removal rate (cm^3) X Specific cutting energy [W/ (cm^3 X s)]
- Basic energy (kJ) = Basic power (kW) X Basic time (s)
- Idle energy (kJ) = Idle power (kW) X Idle energy (s)
- Milling energy (kJ) = Milling power (kW) X Milling (s)
- Machine energy/cut (kWh) high = Sum (Basic energy, idle energy, milling energy) (kJ) X (1 hour / 3600 seconds)

Basic energy is the rate at which energy is consumed when the CNC machine is in "standby mode." This would include constantly running equipment, such as numerical control, fans, lighting, unloaded motors, etc. Basic power is estimated at 12.5% and 25%, as suggested by Kalla et al., 2009 as a good estimate that encompasses most machines. The use of these estimated values explains the high and low estimate of energy use that is detailed in the model. However, this value could be experimentally measured and used to replace the estimation in the model to achieve a more accurate value for energy use. *Basic time* is the entire time that the machine is using basic power. This includes not only the loading and unloading of the machine, but also all the time when the machine is cutting and ready to cut, since all the components needed for standby mode also are used when cutting.

Idle power is power that is consumed by additional components when the machine is ready to cut but is not actively removing material. This happens when the cutting head is power up and spinning but is not cutting. This can be because the cutting head might be traveling to a specific location on the workpiece, doubling back on previous cuts, or because of over-travel. The pieces of equipment running during these times include the cutting fluid pump, main spindle, XYZ movement, and the tool changer. The idle power is estimated as 10% of the main spindle's power (Kalla et al., 2009). This value can be experimentally measured to replace the estimate in the model. The user may input this in the inputs tab, and the model will give a more accurate value for the idle power. *Idle time* is the time that is used when the cutting head is being positioned, there is over-travel, and also when the machine is cutting. During these actions, the above equipment is consuming energy.

Finally, *milling power* represents solely the power required when actively removing material, or milling. This is calculated by taking the product of the specific cutting energy, milling time, and the material volume removal rate. *Milling time* is the actual time spent cutting.

6.8.3 Kara Machine Energy Calculations

This is an alternate method of predicting the power of the main machine envelope. As described by Kara & Li, 2011, this method relies on experimentally determined constants C_0 and C_1 that model the specific energy consumption of specific CNC machines. If these are available, they can be entered to create another energy estimate that encompasses the energy consumption of the entire machine envelope. These calculations were found to be 90% accurate in predicting energy consumption of the tested machines.

- Specific energy consumption (kJ/cm^3) = C_0 + [C_1/Material removal rate (cm^3/s)]

Outside Machine Envelope Energy Calculations
The following energy calculations detail the energy consumption of the supporting equipment that is not accounted for in the main machine envelope calculations above. This includes compressed air, coolant preparation, hydraulic fixtures, coolant filtration, and the mist collector.

6.8.4 Compressed Air

Compressed air is used to assist chip movement from the milling area to the chip conveyer. Compressed-air power consumption is calculated as previously described in section 6.5.4, Energy Consumption for the Air Compressor.

Compressed air used to remove chips is not used during standby time, so the standby time power consumption for compressed air is therefore excluded.

6.8.5 Cutting Fluid Preparation

Data for energy consumption for coolant preparation were not readily available. As a result, no calculation was performed. For future iterations, this energy consumption might be considered.

6.8.6 Hydraulic Fixtures

Data for energy consumption of the hydraulic fixtures were not readily available. As a result, no calculation was performed. For future iterations, this energy consumption might be considered. This data could be obtained by taking energy measurements of the hydraulic fixtures while running or by obtaining manufacturer data.

6.8.7 Coolant Filtration (Particle Filtration, Coolant Chiller, Coolant Pump)

Data for energy consumption from Particle Filtration, Coolant Chiller, and Coolant Pump were not readily available. As a result, no calculation was performed. For future iterations, this energy consumption should be considered. This data could be obtained by taking energy measurements of coolant filtration while running or by obtaining manufacturer data.

6.8.8 Mist Collector

The mist collector uses a drum and centrifugal action to coalesce small drops of coolant mist into larger ones. These drops are collected and fed back into coolant filtration. This is driven by a single electric motor. A modified equation from the Office of Industrial Technologies Energy Efficiency and Renewable Energy was used to estimate the energy consumption of the motor (U.S. Department of Energy, 2004). This is assumed to be running during idle time, which is defined above as the sum of time milling and time handling.

- Energy (kWh) = [(HP X 0.746) X (Idle time (hours))] / (Motor efficiency (%))

6.8.9 Total Energy

Total energy consumption is calculated by adding both the energy consumption found within the machine envelope and the secondary supporting equipment. The energy use of each part is then multiplied by the total number of parts to find the overall energy use.

6.8.10 Energy Consumption Cost

The model relies on cost for electrical power consumption entered by the user in the facility inputs tab, and the calculated total power consumption to calculate the total cost for electrical energy. The demand charges and use charges for electricity should both be included in the value entered by the user for total electrical energy costs in units of currency per kilowatt-hour ($/kWh).

- Unit cost ($/kWh) X Units used (kWh) = Total cost ($)

The calculated costs for electrical energy consumption do not include maintenance or other related costs.

6.8.11 GHG Calculations

GHG emissions are comprised of emissions from the process operations and emissions resulting from the energy used for the process. For milling, the energy source is electrical energy consumed by the main machine envelope and supporting equipment. Electrical energy consumption for the building (e.g., lighting and HVAC) is not included in this calculation.

GHG emissions for electricity are calculated as previously described in section 6.5.7, Greenhouse Gas Emission Calculations.

6.8.12 Heat Loss

Although heat loss appears on the process map, the model assumes that this is negligible.

6.8.13 Process Consumables

Tool life predictions are reliant on experimentally derived constants. As a result, no prediction was performed in the model. For future iterations of the model, these constants can be experimentally found and considered. Tool life could also be figured through empirically collected data.

6.8.14 Cutting Fluid Calculation

Cutting fluid use is predicted by dividing the replacement of the entire reservoir over each second. By comparing the time a cut takes, we can estimate its "share" of the use of cutting fluid. This method relies on accounting for all the time that the fluid is being used. This can be estimated by:

- Rate of fluid consumption (ml/s) = Reservoir size (ml) / Replacement time (s)
- Fluid use (ml / s) = Rate of consumption (ml/s) X Time spent cutting (s)
- Replacement time (hours) = Interval between flushing fluid / Daily use (hours) X Number of days operation
- Total fluid Use (L) = Fluid use (ml/s) X (1000ml/L) X [Idle time (s) X # of cuts]

6.8.15 Waste Water and Additive Calculation and Cost

This is simply found by comparing the ratio of water and additives in preparation of the cutting fluid:

- Total water use (L) = % water X Total fluid use (L)
- Total additive use (L) = % additive X Total fluid use (L)

Cost is calculated by finding the product of water cost, found in facility inputs, and the total water used. The same calculation applies for additives:

- Water cost ($) = Total water use (L) X Water cost ($/L)
- Total additive cost ($) = Total additive use (L) X Additive cost ($/L)

6.8.16 Solid Waste

The primary solid waste from the process is the removal volume from cutting the workspace. A secondary consideration that should be examined in the future is dull tooling. Removed mass from the workspace is found simply by the following calculations:

- Volume (mm^3) = Length (mm) X Width (mm) X Depth (mm)
- Removal weight (g) = Volume removed (cm^3) X Density (g/cm^3)
- Total removal weight (g) = Removal weight (g) X Number of parts

6.9 Validation of Welding Building Block

As a verification step to ensure that the model presented in this research was in line with other existing tools, a validation of the tool was performed. Due to the lack of software tools addressing manufacturing process chains (e.g., welding, plasma arc cutting, and laser cutting), only the welding portion of the tool was benchmarked. This basic benchmarking will serve to ensure that the tool presented in this research is in line with other tools at a basic level. To serve as a test case, a part only requiring welding was chosen for the comparison.

The welding building block portion of the tool developed in this research was compared with two existing tools: an internal tool called Manufacturing Line Optimization (MLO) and a commercial tool called Sustainable Minds (SM). The tool developed in this research is referred to as the Process Trade-off Analysis tool (PTA). As previously described, there are many tools that provide a single or a few sustainability impacts from a given process, but none are commercially available that provide air, water, and waste impacts at this time. In this case, MLO calculates the costs associated with new welding processes implemented at Caterpillar, including the quantity and cost of weld wire and shielding gas. Sustainable Minds calculates the greenhouse gas (GHG) emissions and “EcoPoints” score, based on numerous environmental and health impacts, for welding processes per length of weld wire.

A comparison of PTA with both tools is provided below. PTA is closely correlated with MLO and Sustainable Minds, showing variation at a maximum of 24%. PTA results are not very sensitive to the uptime percentages selected, but are sensitive to the percent of automation selected, as shown in the MLO comparison example. The calculated costs of purchased electricity and waste are relatively small compared to the yearly period cost for the operation.

6.9.1 Comparison to Manufacturing Line Optimization

MLO and the PTA welding building block were run using input data from a Building Construction Product (BCP) chain box project (see Table 6.8 and Table 6.9). An optimization using MLO had previously been run with this information. The weld types, lengths, and sizes necessary for the chain box, as well as the planned capacity for the operation, were included per the MLO optimization. In addition, the following assumptions from the MLO optimization were made: 95% automation, 2-arm robot, 43% uptime for manual operations, 54% uptime for robotic operations. The following assumptions were made for PTA based on expected equipment, inverter power supply at 80% efficiency, and Fanuc ArcMate 100iB robot.

Table 6.8: MLO/PTA inputs for test case

Test Case	Chain Box
Year	2013
Production	29,538
Automation ratio	0.95

Table 6.9: MLO/PTA outputs for test case

Category	MLO	PTA	% Difference	% of Period $
Wire cost	$ 303,756	$ 297,664	-2%	14%
Shielding gas cost	$ 40,703	$ 38,080	-6%	2%
Electricity cost	--	$ 8,568		0.4%
Waste cost - landfill	--	$ 2,314		0.1%
Waste cost - recycle	--	$ (12,064)		-0.6%
Yearly period cost	$ 2,125,345	--		

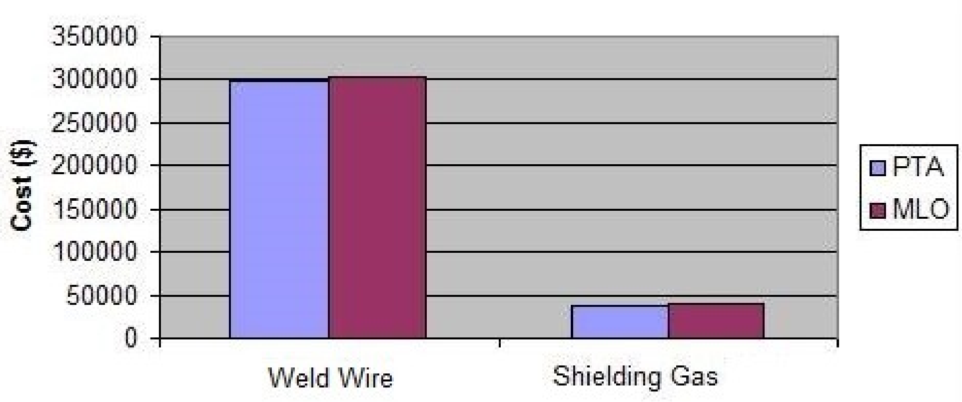


Figure 6.9: Comparison of Process Trade-off Analysis tool and Manufacturing Line Optimization results

As shown in Figure 6.9, the two models resulted in very similar wire costs, with a 2% difference in total values. The shielding gas costs show a slightly larger difference of 6%. These differences could be due to the fact that MLO calculates shielding gas use based on the weld wire use and an assumed ratio of welding wire to shielding gas. On the contrary, PTA calculates shielding gas use based on arc-on time and assumed shielding gas flow rates. The assumed shielding gas flow rates were developed using Caterpillar welding expert opinion and actual use data from facility #3.

The calculated sustainability impacts are relatively small compared to the annual period cost. In this example, purchase cost for electricity and waste (including payments for metal recycled) totals 1.1% of the yearly period cost. The electricity and waste estimates do not include estimates for other regulatory or compliance costs (e.g., employees needed to monitor usage). As utility costs increase, it will be necessary for Caterpillar to have an understanding of the impacts associated with each process.

MLO optimization varies the manual and robot assembly uptime within specified limits to identify an optimized automation ratio. To perform a sensitivity analysis, PTA was run with the same input parameters and assumptions (as MLO) at the lower and upper limits for manual and robotic uptime (Table 6.10) and at 0% and 100% automation to determine the sensitivity of PTA results to the MLO optimization parameters. The range of manual and robot assembly uptimes were run according to the MLO defaults for this case study as shown in Table 6.10.

Table 6.10: Range of manual and robot assembly uptimes used

Assembly Uptime	Lower Limit	Upper Limit
Manual assembly uptime	30.38%	55.63%
Robot assembly uptime	40.46%	68.50%

Assuming an electricity cost of $0.07 per kWh, electricity purchase charges were estimated for the cases.

Table 6.11: PTA sensitivity results

Results for production of 1		**Assembly Uptime Upper Limit**	**Assembly Uptime Lower Limit**	**Assembly Uptime Lower Limit**	**Assembly Uptime Upper Limit**
Percent of production robotic		100%	100%	0%	0%
Time for each assembly (s)		1,193	1,193	1,507	1,507
Additional tacking time (s)		-	-	-	-
Arc-on time (non tacking)	min/assembly	14	14	25	25
Arc-on time (tacking)	min/assembly	-	-	-	-
Total arc-on time	min/assembly	14	14	25	25
Idle time	hr/assembly	0.34	0.11	0.96	0.33
Weight of weld wire consumed	kg/assembly	2.01	2.01	2.06	2.06
Power supply, arc-on power	kW	10.88	10.88	10.88	10.88
Power supply, idle power	kW	0.30	0.30	0.30	0.30
Power supply, total power	kWh	2.63	2.56	4.84	4.65
Robot, total power	kWh	0.23	0.23	-	-
Total Electricity	**kWh**	**2.86**	**2.79**	**4.84**	**4.65**
Total electricity for 1	kWh	2.86	2.79	4.84	4.65
Total electricity for yr prod	kWh	84,406	82,326	142,953	137,412
Electricity purchase cost	$/assembly	$ 0.20	$ 0.20	$ 0.34	$ 0.33
Total Electricity Purchase Cost	**$/yr**	**$5,908.40**	**$5,762.80**	**$10,006.74**	**$ 9,618.82**

PTA results (Table 6.11 above) are not very sensitive to the uptime percentages selected, with a variation of -2 to 4% from the minimum to maximum uptimes. PTA results are sensitive to the percent of automation selected, with differences of 63 to 74% in this example.

6.9.2 Comparison to Sustainable Minds

Sustainable Minds provides a single selection for welding processes, assuming gas metal arc welding of unalloyed steel with 83% argon, 13% CO_2, and 4% O_2 protective gas and a wire consumption factor of 0.0536 kg/m. The CO_2 emission factor developed is 0.045 kg/ft. Sustainable Minds uses the same database as SimaPro, another commercially available tool. Both tools provide relatively little information on the background of this factor. They note the lack of confidence in the information, specifically stating "…only to be used for the technology described or as a rough proxy…Not to be used if welding is of importance in the system considered." Using the user-input weld length, Sustainable Minds calculates the CO_2-equivalents (CO_2-e) emissions from the welding process and the EcoPoints score, which is a proprietary calculation that includes many health and environmental factors to develop an overall ecological impact score for comparison.

Sustainable Minds documentation indicates the welding emission factor is based on 100% automated operations and CO_2 emission factors for U.S. locations (factor used and year represented are not provided) (Meijer, 2013). To closely replicate the Sustainable Minds values, PTA was run assuming 100% robotic operations, transformer-rectifier power supply with 80% efficiency (likely technology in the years of data collection for Sustainable Minds), 1-arm robot (more common), CO_2 emission factors for the Peoria area (near average values for the U.S., current year data used), and 30% tack time added.

Welding data for both doors was obtained from the current production and proposed design drawings and input into both models for the current production and for the proposed design. The current door design requires significant welding of tubes along all sides to a flat plate. The new door design is a stamped door, requiring primarily spot welding of hardware. For the purposes of using the two tools, spot or projection welds were assumed to be similar to gas metal arc welding.

Weld length is input to both models. Results from Sustainable Minds for EcoPoints and CO_2-e and from PTA for energy consumption and CO_2-e are provided below for each door (see Table 6.12 and Table 6.13). As shown, the CO_2-e calculated by the two tools is closely correlated; varying -3 to 14% (see Figure 6.10 below).

Table 6.12: Current design results

	Current Door		
	SM	**PTA**	**% SM to PTA**
Weld length (mm)	17419.40	17419.40	0%
EcoPoints (mPts)	33.40		
Energy consumption (kWh)		2.66	
CO_2-e (kg)	2.57	2.22	14%
CO_2 EF (kg/ft)	0.05	0.04	14%
Weld wire factor (kg/m)	0.05	0.06	-4%

Table 6.13: Proposed design results

	New Door		
	SM	**PTA**	**% SM to PTA**
Weld length (mm)	1757.01	1757.01	0%
EcoPoints (mPts)	3.36		
Energy consumption (kWh)		0.32	
CO_2-e (kg)	0.26	0.27	-3%
CO_2 EF (kg/ft)	0.05	0.05	-3%
Weld wire factor (kg/m)	0.05	0.07	-24%

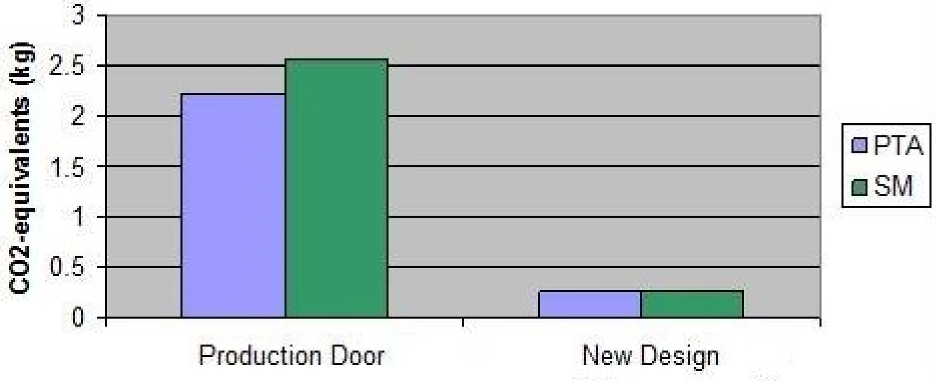


Figure 6.10: Comparison of Process Trade-off Analysis tool and Sustainable Minds

The total length of welding in the current production door design compared to the new door design decreases 90%. Sustainable Minds factors for calculating EcoPoints and CO_2-e from welding processes are based on length of weld. Therefore, the EcoPoints and CO_2-e values calculated also decrease 90% when comparing the two door designs. PTA welding building block calculates the volume of the weld based on the weld type (e.g., fillet), and then calculates the impacts from the total weld volume. PTA calculated a reduction in energy consumption and CO_2-e of 88% for the two door designs (see Table 6.14).

Table 6.14: Comparison of Sustainable Minds and Process Trade-off Analysis tool results

	Compare	
	% Prod to New - SM	**% Prod to New - PTA**
Weld length (mm)	90%	90%
EcoPoints (mPts)	90%	
Energy consumption (kWh)		88%
CO_2-e (kg)	90%	88%

6.9.3 Discussion

In conclusion, the PTA was validated against an in-house tool and a commercially available tool. The PTA performs in line with these two software tools that it was compared against. Again, a very simple part only requiring welding was tested. If a typical part was used, requiring a complex process chain, the results could have varied greatly. This would be due to the fact that the PTA would give much more accurate results than the other software tools. This further confirms that when assessing products that require fabrication processes (e.g., welding, plasma arc cutting, and laser cutting), there is a need for a more sophisticated tool that includes these processes and allows the ability to assess complex manufacturing process chains. In addition to including these processes, process specific data are required versus the broad generalizations and assumptions that can be found in other software tools.

6.10 Application of a Methodology to Map and Address Resource Consumption

As previously discussed in Chapter 5, a methodology to map resource consumption of discrete manufacturing processes was modeled after the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) process. Chapter 5 previously covered steps 1 – 2.5 of the methodology. Those steps are listed below for reference.

1. Define
2. Measure

  - 2.1. Create/review resource consumption map (energy and waste stream map)
  - 2.2. Identify key inputs and outputs that can be measured
  - 2.3. Modify resource consumption map
  - 2.4. Define operational definitions
  - 2.5. Collect data during production

This section will focus on the continuation of the methodology, what happens after you define the system; create the resource consumption maps (energy and waste stream maps), and measure key inputs and outputs. We will continue the discussion with step 2.6, Compile data into an Environmental Value Stream map. A brief description and an example will be provided with each step of the process.

  - 2.6. Compile data into an Environmental Value Stream map
- 3. Analyze
  - 3.1. Perform a Pareto Analysis (optional)
    - 3.1.1. Assign a unit cost ($/x) to each resource category
    - 3.1.2. Identify the biggest opportunity based on total cost ($) of waste generated
  - 3.2. Perform an appropriate root cause analysis
    - 3.2.1. Ishikawa diagram
    - 3.2.2. 5 Whys
  - 3.3. Compile Possible Root Causes Identified
- 4. Improve
- 5. Control

2.6 Compile data into an Environmental Value Stream map

The data collected in Step 2.5 can be compiled into an Environmental Value Stream map. Value stream mapping is a lean process-mapping method for understanding the sequence of activities and information flow used to produce a product or deliver a service. Value stream maps typically examine the time it takes to produce a product and the proportion of that time that is value added, but not the environmental impact of the process. By applying the same concept of value stream mapping to the environmental aspect of the process, the resources consumed and waste generated at each stage in the development of that product can also be integrated into a value stream map.

Figure 6.11 illustrates how an environmental value stream map can be used. Analogous to a value stream mapping process, the top line in the environmental value stream map represents the resources consumed by the process. The bottom line depicts the value added portion of the resources in the process. Hence by taking the difference between the sum of the resources consumed and the value added portion of the resources, the resources wasted in the process can be quantified. In the example shown in Figure 6.11, 135 lbs of material is used by the process, of which only 85 lbs of material is value added. Therefore there is wastage of 50 lbs of material during the manufacturing process that can be reduced to further improve the sustainability impact of this particular manufacturing process.

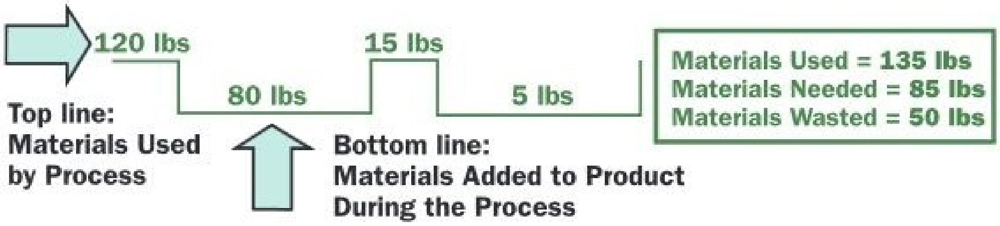


Figure 6.11: Example of an Environmental Value Stream Map (U.S. Environmental Protection Agency, 2007)

The data gathered in Step 2.5 from the study can be presented in an Environmental Value Stream Map, as shown in Figure 6.12.

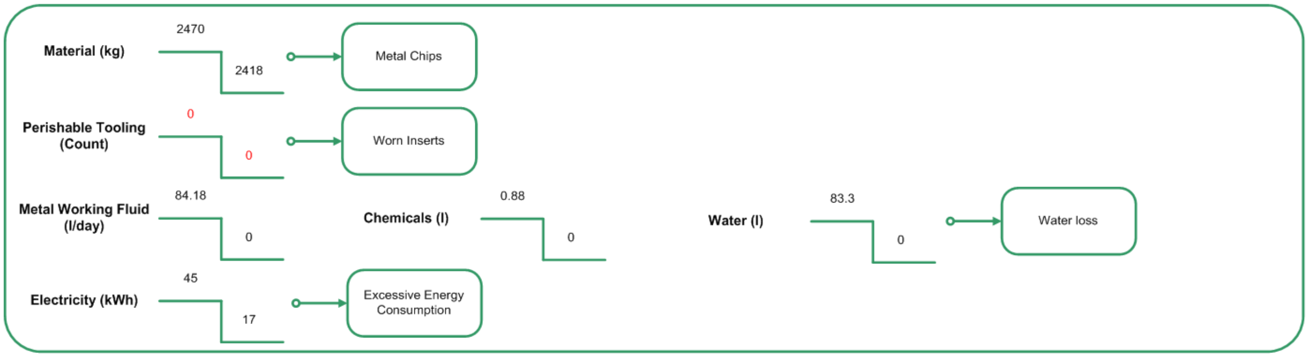


Figure 6.12: Resource consumption data for a horizontal machining center

Figure 6.13 shows the resource consumption map for a horizontal machining center as previously seen in Chapter 5.

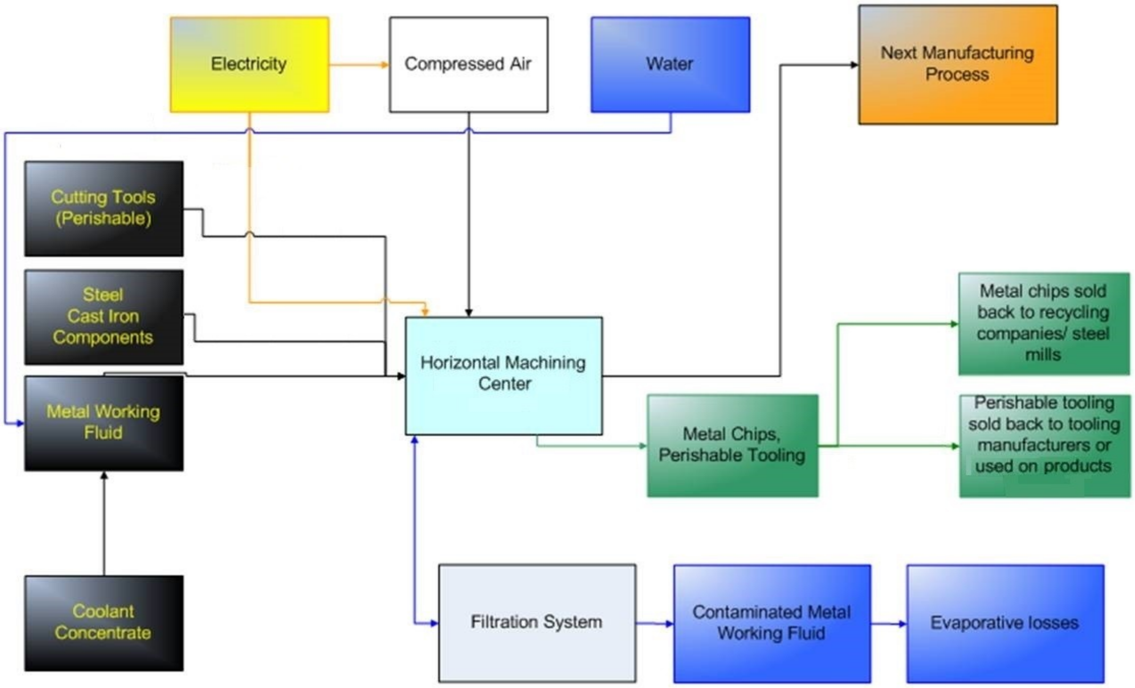


Figure 6.13: Modified resource consumption map for a horizontal machining center

3. Analyze

The purpose of the Analysis phase is to help one better understand cause-and-effect relationships in the process, that is, which of the input factors exert an influence on the output of the process (Shankar, 2009). The analysis can be performed once the resource consumption data for the manufacturing process of interest are appropriately collated. The analysis will provide useful insights to the manufacturing process and assist in determining the possible root causes for waste generation in the manufacturing process. A Pareto analysis can be performed to rank and prioritize the opportunities identified so that the following root cause analysis can be focused on high impact areas. A root cause analysis can be performed after the Pareto analysis to better identify the underlying reasons.

3.1 Perform a Pareto Analysis (optional)

Pareto analysis is a technique in decision making that is used for the selection of a limited number of tasks that produce significant overall effect. Pareto analysis is a formal statistical technique that can be used to estimate and rank the benefit delivered by each action used to address problem root causes. This technique helps to identify the top 20% of causes that need to be addressed to resolve 80% of the problems. The application of the Pareto analysis allows management to focus on the top 20% of the root causes that have the greatest impact on the process. For example, if electricity was a metric of interest, one would rank the consumers of electricity in order of which consumes the most electricity. The assumption here is that to improve performance, one would start with the biggest offender.

3.1.1 Assign a unit cost ($/x) to each resource category

An approach to rank and prioritize the high impact areas is to normalize all the data collected to a common denominator. This can be performed by assigning a unit cost to each of the resources identified.

3.1.2 Identify the biggest opportunity based on total cost ($) of waste generated

The total cost of waste generated for each resource used by the manufacturing process can be determined once the unit cost of resource category has been assigned appropriately. The opportunities to reduce waste generation can be Pareto analyzed according to the total cost and action plans can be initiated for the high impact area. An example of the potential cost associated with each resource category is illustrated in Figure 6.14.

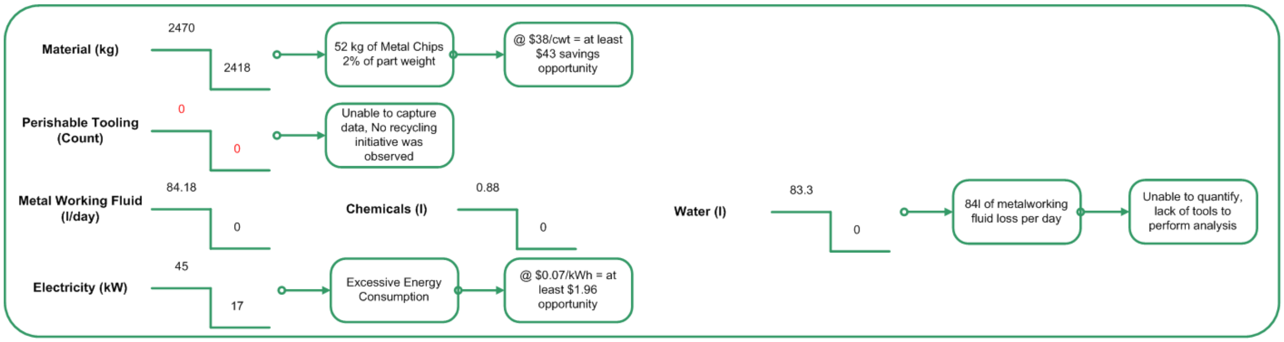


Figure 6.14: Cost associated with resource consumption wastage

3.2 Perform an appropriate root cause analysis

Root cause analysis (RCA) is a problem solving method aimed at identifying the root cause of problems or incidents. The practice of RCA is predicated on the belief that problems are best solved by attempting to correct or eliminate the root cause, as opposed to merely addressing the immediate obvious symptoms. By directing corrective measures at root causes, it is hoped that the likelihood of problem recurrence will be minimized. An example of two RCA tools that can be used will be discussed below.

3.2.1 Ishikawa diagram

Ishikawa diagrams (also called fishbone diagrams or cause-and-effect diagrams) are diagrams that show the causes of a certain event. A common use of the Ishikawa diagram is to identify potential factors causing an overall effect. Each cause or reason for a result is a source of variation. Causes are usually grouped into various categories to help identify the sources of variation. There are many different types of categories that can be used (e.g., 6 Ms, 4 Ps). An example using the 6 Ms is shown below.

- Machines: Any equipment required to accomplish the job
- Methods: How the process is performed and the specific requirements for doing it
- Materials: Raw materials used to produce the final product
- Measurements: Data generated from the process that are used to evaluate its quality

- Mother Nature (environment): The conditions in which the process operates
- Manpower (people): Anyone involved in the process

An overview of an Ishikawa diagram is shown in Figure 6.15.

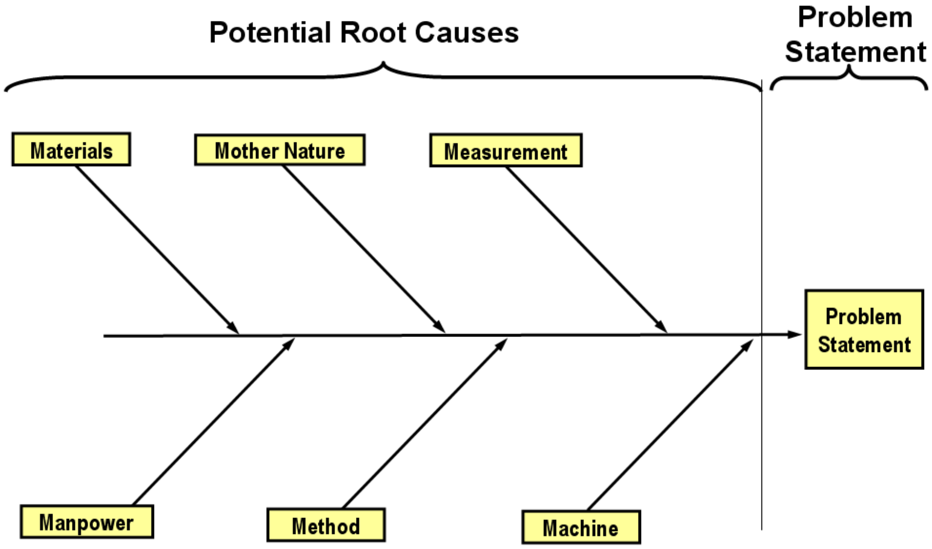


Figure 6.15: Overview of an Ishikawa diagram (adapted from (Loyer, 2012))

As an example, the issue of excessive material removal during machining was analyzed using an Ishikawa diagram. A partially populated Ishikawa diagram is presented in Figure 6.16. By listing and categorizing all the possible root causes to the various categories, project teams can be assigned to review and address the root causes identified. In this example, the method used to fabricate the product is a high impact area that can be addressed to significantly reduce the resource consumption in the manufacturing process as illustrated in Figure 6.16.

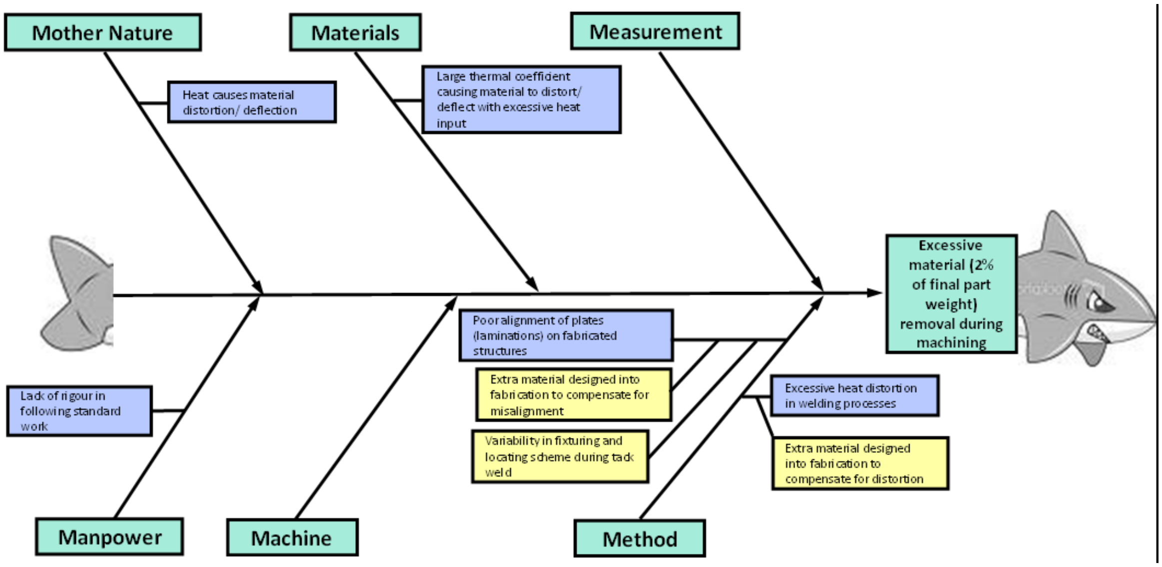


Figure 6.16: Partially populated Ishikawa diagram illustrating possible root causes for excessive material removal during the machining process

3.2.2 "5 Whys"

"5 Whys" is a questions-asking method used to explore the cause/effect relationships underlying a particular problem. The goal of the 5 Whys process is to determine the root cause of a problem. An overview of the 5 Whys method is shown in Figure 6.17.

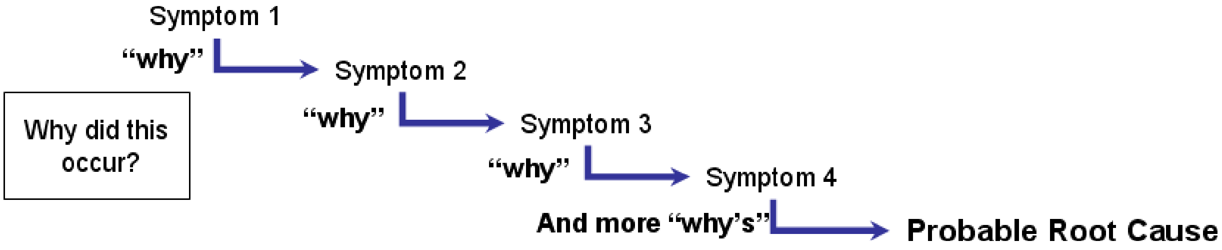


Figure 6.17: Overview of "5 Whys" method

An example 5 Whys analysis was performed to determine the root cause for excessive loss of metalworking fluid during machining. The result of the analysis is presented in Figure 6.18. It is noted from the analysis that the excessive loss in metalworking fluid can be attributed to a poor chip evacuation technique that is employed in the machining center. The important point here is that if you work on the answer to the first "why" question, you will not really solve the problem. By working on the "root" cause, you can fix the problem "permanently".

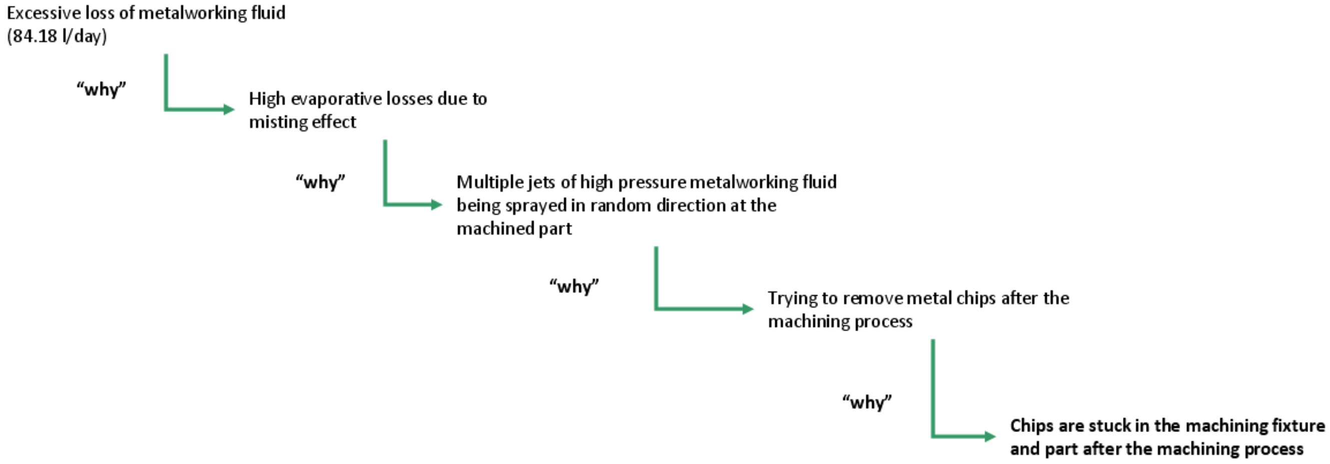


Figure 6.18: 5 Whys analysis illustrating all possible root causes for excessive loss of metalworking fluid during the machining process

3.3 Compile Possible Root Cause Identified

RCA can be performed using either the Ishikawa diagram or the 5 Whys approach for all of the resource consumption wastage categories. This will generate a list of all the possible root causes for each of the resource consumption wastage categories. All the possible root causes can be compiled in a table format as shown in Table 6.15, creating a single document that can be used by the project team to brainstorm for project ideas to eliminate these root causes.

Table 6.15: Possible root cause table for each resource consumption wastage categories

	Possible Root Cause
Excessive generation of metal chips	Excessive weld distortion, fixturing scheme during tackweld, material thermal properties, requires design engineers to add excessive raw material, hoping that the material "cleans up" during the machining process; lack of rigor in following standard work
Lack of perishable tooling recycling	Lack of knowledge on tool performance and tool life; lack of rigor in executing insert recycling program
Excessive water loss	Non-optimal chip removal strategy and technique causing excessive evaporative losses; fixture design causing metal chips to be ledged in fixture and part
Excessive electrical energy consumption	Machine tool construction results in high baseload during idle time

4. Improve

In the Improve phase, the team will brainstorm project ideas to eliminate the root causes identified during the Analyze phase of the project. Project ideas and the business case of each project should be compiled. Action plans can be drafted out for each project idea designed to execute the project ideas to address the root causes and subsequently improve the sustainability of the manufacturing process of interest. An example from the project is presented in Table 6.16.

Table 6.16: Potential topic areas and business case to address root causes identified

	Potential Topic Area for research and development (R&D) projects	**Business Case**
Excessive generation of metal chips	- Reduce thermal distortion in welding processes - More accurate prediction model for thermal distortion in welding processes - Improve robustness of welding processes to minimize and accurately obtain known thermal distortion	- Reduce material usage by at least 2% per part - Reduce energy consumption in manufacturing operations
Lack of perishable tooling recycling	- Development of an application space for optimum tool selection for each material 1E specification (e.g., tool life and performance)	- Improve energy efficiency associated with tooling selection and optimization for machining of fabricated structures and components
Excessive water loss	- Develop dry or near-dry machining techniques - Develop optimal chip evacuation solutions for both part and fixture - Develop process water costing and metering strategies	Based on previous water study at facility #3: - \$1.6M/yr opportunity - Reduction of 71 MMGY
Excessive electrical energy consumption	- Energy efficient machining processes – reduce chip to chip time on machine tools - “green” machine tool development with preferred suppliers - Strategies to improve OEE – virtual validation, etc.	- Manufacturing equipment and process constitute 50% of Caterpillar’s annual spend

5. Control

In the Control phase, the purpose of this step is to sustain the gains. It is very important to monitor the improvements to ensure continued and sustainable success. It is recommended to create a control plan and to update documents and business process and training records as required. In this phase we return to the original work we started with, in collecting the data for each process. One would want to continue to collect these data, using control charts to manage the process within a set of "control limits". If the process were to perform outside the established limits, one would want to investigate or one may wish to shift the control limits which require another round through the DMAIC methodology.

6.11 Summary and Conclusions

In this chapter a model quantifying the sustainability impacts (energy consumption, water consumption, and waste generation) for welding (manual and robotic), cutting (plasma arc and laser), and machining (milling) was presented. This model can be used to evaluate the sustainability impacts from discrete manufacturing processes, or summed to evaluate impacts from manufacturing process chains. Specific outputs from the welding building block of the model have been validated where possible, against output from both internal Caterpillar tools and commercially-available tools. This comparison shows good correlation on the consumption of weld wire and shielding gas as consumables and the greenhouse gas estimates from energy consumption.

Given current utility costs, the percent of product cost from sustainability impacts is relatively small. However, there is value in understanding these impacts for future needs related to regulatory compliance, increased utility cost, and company reputation, with respect to sustainability goal achievement. This information will enable facilities to better define and strategize methods for meeting their sustainability goals. This will also allow increased accuracy of product Life Cycle Assessments (LCAs).

A methodology modeled after the Six Sigma DMAIC process was presented to show how to translate the results from the model to an Environmental Value Stream Map and to translate those results into improvements in manufacturing systems. The methodology enables an analysis to be performed on the resource consumption data and can help identify potential root causes in resource wastages in specific manufacturing processes. The developed methodology was validated on a machining process in a Caterpillar facility. It can be further replicated across different discrete manufacturing processes and process chains at different facilities around the world to further improve the sustainability of manufacturing operations in facilities. This will be a key enabler in achieving facility operational sustainability goals.

Finally, the model developed can be used as a stand-alone assessment tool or combined with other tools in order to gain a holistic view of the manufacturing system. The model created will benefit process planners to a greater degree if implemented with other existing process planning tools (e.g., discrete event simulation). This integration will include sustainability impacts as one of many factors considered in the optimization of equipment selected for new manufacturing processes as well as associated process chains.

Chapter 7

Summary and Outlook on Future Work

This chapter reviews the contents of the dissertation and the research outcomes. Observations on the impact of the work and other considerations are also presented. Finally, an outlook on future work will be given.

7.1 Summary

This dissertation contributes to improving resource consumption efficiency in manufacturing through developing a methodology to assess complex manufacturing process chains. A brief summary of each chapter's contribution is given first.

Chapter 1 introduced resource consumption trends and discussed the idea that as populations increase worldwide, and people strive for a better quality of life (accompanying this with more and better things – automobiles, electronics, shelter, food, health care, and education) more and more energy, water, and other resources are consumed. The consumption of resources in manufacturing was then discussed. Manufacturing today consumes a significant amount of energy, materials, water, and other resources to produce the items consumers demand. Then, the idea of sustainability and how sustainability fits within manufacturing was introduced and the business case for why industry cares about sustainable manufacturing and why they are driven to make changes was presented. Within industry there are several motivators for companies to reduce their energy and resource consumption as they try to build a more sustainable business practice. We concluded by seeing that it is important for industry and particularly manufacturing to do their part in trying to find ways to be more sustainable.

Chapter 2 introduced the necessary background for this research. This included an introduction to manufacturing systems and analysis tools. This provides a background on manufacturing, various ways to view manufacturing with respect to time and space, and ways to identify opportunities for improvement in manufacturing with respect to energy, material, water, and other resource utilization. The chapter then covered some basic terms and definitions of production systems in order to understand how manufacturing system performance is measured. Next, the state of the art was reviewed with respect to methodologies for assessing manufacturing with respect to facility, process chain, and process levels. In addition, a review of existing assessment tools was conducted to assess the capabilities of existing tools. The chapter concluded by observing that there is a need for a tool and assessment methodology to evaluate complex manufacturing process chains.

Chapter 3 introduced research addressing the development of industrial assessment metrics and procedures. Here the necessary background on assessment techniques and resource flows in machining was reviewed. The chapter then developed a large set of metrics to assess industrial systems and looked at three case studies where the metrics and assessment methodology were applied and reviewed the performance of existing systems at each company studied. The work in this chapter focused on a combination of facility level and machine level assessments. From the experiences gained with these studies it was possible to develop the protocol for conducting assessments and testing the validity of these metrics. As a result of this work, a comprehensive list of metrics was developed, different measurement approaches were explored, and different ways of looking at performance indices were discussed.

Chapter 4 laid the background for understanding the analysis of complex manufacturing process chains presented in the Caterpillar case study. Fundamentals of fabrication process chains and decision making as well as the need for a methodology and tools to assess these complex process chains are covered. Next, background on Caterpillar Inc. and the case study conducted in collaboration with them was introduced. The specific production chain assessed and the process level background on the specific manufacturing processes involved was presented. This chapter introduced fabrication process chains as well as the concept of assessing the resource consumption of complex process chains in order to assist in decision making. Background material was given on the Caterpillar process chain case study including the production chain and process details. A detailed background on the individual processes used in the process chains was presented; the details and operating characteristics of the principal processes in the chain were presented.

In Chapter 5, a resource consumption assessment and mapping methodology (showing resources and waste paths) for complex manufacturing process chains was presented. This systematic methodology was developed to identify and quantify the energy and waste streams for discrete manufacturing processes as part of a process chain. This methodology was then validated by using the methodology in a step-by-step approach to perform an example analysis on a machining operation in a Caterpillar facility. This methodology can also be used to perform a baseline measurement of energy and waste stream generation for discrete manufacturing operations.

Finally, in Chapter 6, a model quantifying the sustainability impacts (energy consumption, water consumption, and waste generation) for welding, plasma arc cutting, laser cutting, and milling was presented and applied to a case study with Caterpillar Inc.. A methodology modeled after the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) process was presented to show how to translate the results from the model to an Environmental Value Stream Map and to translate those results into improvements in manufacturing systems.

The next section describes in more detail the research contributions of this work.

7.1.1 Research Contributions

This research has developed and evaluated an approach that effectively allows the analysis of energy, water and other resource use with multiple different processes in a manufacturing process chain. This allows manufacturers to better understand the resource consumption and environmental and economic impacts of fabrication process chains used to make a product.

In summary, the major contributions of this work are:

- Created a list of industrial assessment metrics
    - A database of key metrics to be considered when conducting an industrial assessment was compiled. This database allows users to sort and select from a list of key metrics in order to choose the metrics that are relevant for the performance that they want to measure.
- Developed an industrial assessment methodology
    - This methodology gives users an overview of the key areas to focus on when conducting an industrial assessment. It contains a list of questions to ask and data to collect. This guide allows users to assess the performance of a machining cell as well as capture some facility level aspects specific to that process (e.g., compressed air and noise level). This methodology can be used in combination with the list of metrics mentioned above.
- Created a resource consumption mapping methodology (energy and waste stream mapping)
    - A methodology was developed to map and quantify resource consumption for discrete manufacturing processes including welding (manual and robotic), cutting (plasma arc and laser), rework (air carbon arc cutting and hand grinding), and machining (milling).
- Integrated resource consumption mapping methodology into Six Sigma DMAIC methodology
    - The resource consumption mapping methodology and the research presented in this dissertation was integrated into the Six Sigma DMAIC methodology, allowing manufacturers to use this methodology to assess their manufacturing systems and then integrate the results into the five steps of the DMAIC approach. This approach enables an analysis to be performed on the resource consumption data and can help identify potential root causes in resource wastages in specific manufacturing processes. This methodology was validated on machining process in a Caterpillar facility.
- Developed a model and methodology for process chain assessment
    - A model quantifying the sustainability impacts for welding (manual and robotic), cutting (plasma arc and laser), and machining (milling) has been created. This model (consisting of database modules for each process) allows the characterization of resource consumption and economic and environmental impacts of fabrication process chains using various sources of data. This enables the ability for manufacturing engineers to assess the resource consumption of multiple fabrication process chain configurations.
- Created a process chain assessment tool
    - A process chain assessment tool was created in order to assess various process chain configurations. This tool integrates the database modules created for the

specific process mentioned above and enables manufacturers to assess the relevant resource consumption and emissions patterns to enable a more comprehensive assessment of environmental impact compared to other software tools (as previously discussed in Chapter 2). The specific outputs of the welding model were validated with other internal and commercial tools (i.e., Caterpillar Inc. and Sustainable Minds). The process chain assessment tool developed during this research is currently implemented in industry and is currently in use by Caterpillar Inc.

7.2 Outlook and Observations

7.2.1 Process Variability

In the course of this research, the presence of and importance of variability in the factors controlling the process has been observed. Upon first glance, there are issues that are beyond those simply definable by just measuring certain performance characteristics. These issues involve such factors as manual versus automated labor, interdependencies within the process chain, and the variability in data caused by these issues.

First, there are many different sources of variability that were observed in this research. Although this was not one of the objectives of the work and this variability did not affect the outcome of it, they are important to define and consider, especially in future work.

It is obvious from the research done here that some processes (automated or manual) are less repeatable than others. For example, human or manual processes often show great ranges of performance (both in consumption of energy and resources and in the rate and quality of the output) depending upon process characteristics, required and available skill, tooling, cycle time, etc. For example:

- If a process depends heavily on human skill then how does that affect the resource consumption of the line versus if an automated process was used?

When humans are involved, the process results tend to vary more in terms of throughput or quality or time or energy utilization. Some processes are uniquely dependent on the skill level of the operator:

- For example, in welding, if a low skilled worker is performing the operation versus a high skilled worker, what is the impact on the process?
- For example, does the low skilled worker take more time to weld?
- Or are there quality (and hence yield) differences in the work product with the two different skill levels?
- Are there more mistakes and therefore more rework involved?
- Does this result in more time used to manufacture a product, more energy used, more material used?
- How does this compare to an automated process which is generally much costlier and much more energy intensive, but also much quicker and efficient?

- How do the trade-offs between manual versus automated labor affect the resource consumption of the line?
- Under what circumstance is the process sufficiently under control where the skill level of the operator is not a significant influence for manual labor?

In addition, it was observed that the choice of certain processes combined with other processes have inherent interdependencies that should be measured in order to fully capture the trade-offs associated with selecting one process versus another. Interdependencies are how one process affects another. For example:

- If one chooses process 'A', then how does that decision affect ones options to choose for process B (e.g., does it limit options, does it force the choice of a certain follow on process?).
- If one chooses a particular process 'A', then because that process was chosen, are there certain "extra" next steps that then have to be performed?
- Lastly, another example of how choosing one process affects another is for instance if laser cutting is chosen as a first operation (over say plasma-arc cutting), how does this decision affect the next process (welding)?
- Does it limit the choice of types of welding that can be used?
- Does laser cutting offer a better finished edge such that when joining two parts for welding, is there a better fit up and less joint prep is required, which would result in less steps, less time, less energy, less materials, less labor?
- Does it allow for a smaller gap between the two parts and there for less welding is needed all together which could translate to less time welding, less energy being used, less labor, and less material (weld wire being deposited to fill the gap since the gap is smaller)?

But, do these assumed benefits outweigh the additional cost and energy required of a laser cutting machine versus a plasma-arc cutting machine? It is important to capture these impacts from a resource consumption stand point. These are the types of interdependencies that are critical to capture in order to have a holistic view of the process chain when trying to make trade-offs. It is very important to look at the entire chain and not just focus on one process, as the changes that you make to one process may very well affect (positively or negatively) the performance and resource consumption of the entire line. An additional interdependency briefly discussed above is manual versus automated labor.

In order to have a holistic view of the entire process chain, it is important to look at the interdependencies within the process chain. These interdependencies can cause some variability within the data. It is necessary to assess the variability within the processes because it is essentially important to find out if they are going to affect the decisions that you make. At this point in time, it seems that it will, but more work needs to be done to quantify these impacts in order to see if they do or do not affect the decisions made (e.g., capturing and quantifying the impacts of these interdependencies, conducting a sensitivity analysis to understand how influential the interdependencies are).

7.2.2 The Potential Impact of “Big Data”

Another topic that came in to the discussion in the course of doing this research is “big data.” Big data generally refers to large complex data sets that are difficult or impossible to deal with using the current set of data management tools or analysis techniques. It offers some possibilities with respect to connecting more sources of information and more sources of data that can either help to extract more understanding about how the system operates but also address the interdependencies mentioned above. In order to have a more accurate model and tool and in order to address the variability discussed above, data are needed. Everything about these models and everything about being able to make these different trade-offs is based on data, so big data could actually help – a lot!

One of the possible solutions could be the movement towards big data. In manufacturing those data would come from the development and implementation of sensing systems to monitor process and system details. Big data could offer some opportunities to assist in this area. Big data could greatly help with the variability issue and could help to bound the problem, identify where the opportunities are, and help make more accurate and informed decisions. As mentioned above, the success of this type of analysis is dependent upon the availability of data. Since this research was started, the impact of big data has begun to be discussed. According to General Electric (Evans & Annunziata, 2012), big data are expected to have an impact on many areas such as:

- enterprise/network/system optimization,
- maintenance optimization,
- risk response/system recovery,
- learning,
- advanced sensors, controls, and software applications, and
- advanced analytics.

With respect specifically to sustainable manufacturing, big data are expected to have an impact in the following ways:

- process control and utilization,
- system balancing and availability,
- resource utilization, yield improvement,
- impact assessment,
- technology trade-off assessment,
- machine design,
- feedback to system, machine, process, tooling design, and
- plant operation.

More specifically, the introduction of big data to manufacturing will also allow for:

- data-driven methodologies to characterize manufacturing systems fully and properly

    - select appropriate sensors to capture data needed for manufacturing characterization
    - design process monitoring system with selected sensors based desired analysis
- a comprehensive systems approach that assesses important resource flows across all levels of manufacturing hierarchy
- a holistic analysis of the role of manufacturing in the entire product life cycle.

Having sensors on all critical aspects of the process and systems during the most important parts of the process cycle would allow for a very sophisticated model that could assess the impact of all of the variability inherent in the system. More data would also allow more interactions to be able to be defined. This would also allow for interactions across multiple levels to be addressed (recall the discussion of the "Google Earth" view in Chapter 2). Whether one has the right data or the wrong data is one thing, but the fact that one could now see more interactions would be better. In addition, if the data was on a system that made it more easily available for everybody, that would be a good thing. This would give one the ability to address the interdependencies, which need to be addressed so you have a holistic view, and perhaps give better resolution or improvement in data quality, etc. This also allows one to reduce the variability.

7.2.3 Future Work

Studies like this doctoral research provide a foundation for further research in sustainable manufacturing. Although significant advances could be made in comparison to the current state of this research, there are diverse opportunities for future research, which would extend functionalities of the developed approach and further support integration in industrial business processes. Some of these are delineated below along with comments.

The research reported here focused on a baseline assessment. It would now be beneficial to take this work one step further to assess process chain configurations. A number of opportunities for continuing this work towards the goal of comprehensive assessment of process chains are given below:

Further development of the model to incorporate more data sets

The specific type of data sets needed are directly measured or "in-process data". This can be accomplished by big data as previously discussed in section 7.2.2 above. A continuous data exchange accomplished by embedding the model approach into the company's data environment would yield potential for improvement and would also help to address the process variability as previously discussed above in section 7.2.1. Coupling the model with sensors providing real time energy monitoring and/or production data could provide the model with the latest data and improve the consistency with the actual manufacturing system. Using an interface with enterprise resource planning systems, alternative scenarios for the planning of production capabilities could be automatically evaluated with the model in order to provide decision support. Thinking even further, coupling with machine control might be beneficial from the system perspective as suggestions for ideal modes of operation can be given or even automatically triggered.

Expand the model to include other processes

The model could be expanded to include other processes typical of manufacturing (e.g., forming and casting). The model could also be expanded to include different types of welding, cutting, and machining processes (e.g., shielded metal arc welding, oxy-fuel cutting, turning, and drilling).

Assess interdependencies

In order to assess the interdependencies (as previously discussed above in section 7.2.1 it would be useful to conduct various trade-off analyses and run the model using different process chain configurations. In order to do this, one could see how changing one process affects the other processes and how that affects cost and environmental aspects. This would allow one to assess where various interdependencies exist and to what degree of variability there is based on various process chain combinations.

Integrate the model into other models and tools

The model could be integrated into other models/tools to help provide decision making support for selecting fabrication process chains considering resource consumption and resource consumption cost. The model could be integrated into Life Cycle Assessment software tools in order to assess environmental impacts in addition to global warming potential. The models created will benefit process planners to a greater degree if implemented with other existing process planning tools, in particular discrete event simulation programs such as Autodesk's Process Analysis 360 and Factory Design Suite. This integration would include sustainability impacts as one of many factors considered in the optimization of equipment selected for new manufacturing processes enabling design for sustainable manufacturing. In addition, coupling the model with process simulation software would allow for a detailed analysis on a physical level (e.g., finite element modeling (FEM) simulation in machining or die casting). This is not the focus of the proposed work, but a coupled consideration with those applications is technically possible and might be advantageous in order to consider a holistic view of the system. Currently the model considers the process as a black box with inputs and outputs, whereas with a detailed physical model, the actual impact of certain variables determined on a system level can be realistically assessed and useful information can be generated.

Integration statistical methods

Methods for optimization, multi-criteria decision making (multi-objective optimization) and evaluation under uncertainty are an integral part of assessing the trade-offs in manufacturing systems. Very complex methods are available in this context and can be (manually) applied in context of the data presented in the model. However, in this dissertation, mostly simplified approaches are used in order to facilitate practical application. To improve the quality of decisions, the integration of statistical methods as an inherent part to the model is a promising approach. This would enable the usage of those methods also for users who are not experts in statistical methods.

Include social aspects

Based on the previous work of Hutchins, Robinson, & Dornfeld (2013), in order to achieve a holistic view of manufacturing, it is important to consider the social aspects and impacts of manufacturing when making decisions about the way we manufacture products.

This research has developed and evaluated an effective approach for the analysis of energy, water, and other resource use in multiple processes in a manufacturing process chain. This allows manufacturers to better understand the resource consumption and environmental and economic impacts of fabrication process chains used to make a product. This dissertation helps to provide the technical understanding and tools to enable designers and manufacturing engineers to create manufacturing systems that are truly more sustainable. The implementation of this work can be directly applied to assessing and optimizing manufacturing process chains and the work presented in this dissertation directly contributes to the realization of a sustainable and prosperous manufacturing sector.

Bibliography

Althouse, A. D. (2004). *Modern welding: Complete coverage of the welding field in one easy-to-use volume!*. Tinley Park, Ill.: Goodheart-Willcox Co.

Aviation Metals Inc. (2013). *Laser cutting.* Retrieved November 16, 2013, from http://aviationmetals.net/images/laser-cutting%28unc8f2%29.jpg

Barbaccia, T. G. (2012). *KHL: Construction equipment sales grew 25 percent worldwide in 2011.* Retrieved May 1, 2012, from http://www.aggman.com/khl-construction-equipment-sales-grew-25-percent-worldwide-in-2011-2/

Barber, N. (2009). *U.S. geological survey: Summary of estimated water use in the united states in 2005.* Retrieved from http://pubs.usgs.gov/fs/2009/3098/

Boothroyd Dewhurst Inc. (2012). *DFMA software.* Retrieved February 14, 2012, from http://www.dfma.com/

Caterpillar Inc. (2013). *2012 sustainability report.* Retrieved from http://www.caterpillar.com/cda/files/2674607/7/2012_Caterpillar_Sustainability_Report.pdf

Chen, D., Schudeleit, T., Posselt, G., & Thiede, S. (2013). A state-of-the-art review and evaluation of tools for factory sustainability assessment. *Procedia CIRP: 2nd CIRP Global Web Conference - Beyond Modern Manufacturing: Technology for the Factories of the Future (CIRPe2013), 9*(1), 85-90.

Chien, J., & Dornfeld, D. (2010). *Lam research. presentation.* Berkeley, CA: University of California, Berkeley.

CO2PE. (2013). *Cooperative effort on process emissions in manufacturing.* Retrieved July 23, 2011, from http://www.co2pe.org/

Cook, D., & Start, J. (2002). *Electrode wear in air & oxygen plasma: How to tell good electrode wear from bad and improve system performance.* Retrieved July 2, 2012, from http://www.centricut.com/TA_ElectrodeWear.htm;

Dahmus, J., & Gutowski, T. (2004). An environmental analysis of machining. Paper presented at the *2004 ASME International Mechanical Engineering Congress and RD&D Exposition,* Anaheim, California. pp. 1-10.

Devoldere, T., Dewulf, W., Deprez, W., & Duflou, J. R. (2008). Energy related life cycle impact and cost reduction opportunities in machine design: The laser cutting case. Paper presented at the *15th CIRP International Conference on Life Cycle Engineering,* Sydney, N. S. W. pp. 412-419.

Diaz, N., Helu, M., Jayanathan, S., Chen, Y., Horvath, A., & Dornfeld, D. (2010). Environmental analysis of milling machine tool use in various manufacturing environments. Paper presented at the *2010 IEEE International Symposium on Sustainable Systems and Technology (ISSST),* Arlington, VA. pp. 1-6.

Diaz-Elsayed, N. (2013). Development of energy models for production systems and processes to inform environmentally benign decision-making. (Doctoral dissertation, University of California, Berkeley).

Diaz-Elsayed, N., Jondral, A., Greinacher, S., Dornfeld, D., & Lanza, G. (2013). Assessment of lean and green strategies by simulation of manufacturing systems in discrete production environments. *CIRP Annals-Manufacturing Technology, 62*(1), 475-478.

Dietmair, A., & Verl, A. (2010). Energy consumption assessment and optimisation in the design and use phase of machine tools. Paper presented at the *17th CIRP International Conference on Life Cycle Engineering,* Hefei, China. pp. 116-121.

Discover 6 Sigma. (2013). *Operational definition.* Retrieved November 16, 2013, from http://www.discover6sigma.org/post/2005/11/operational-definition/

Dornfeld, D. (2004). *Future directions. laboratory for manufacturing and sustainability. presentation*. Berkeley, CA: University of California, Berkeley.

Dornfeld, D. (2011). Leveraging manufacturing for a sustainable future. In J. Hesselback, & C. Herrmann (Eds.), *Glocalized solutions for sustainability in manufacturing: Proceedings of the 18th CIRP international conference on life cycle engineering* (pp. 17-21). Technische Universitat Braunschweig, Germany: Springer.

Dornfeld, D. A. (2010). *Sustainable manufacturing - green technology for processes, systems, and products. keynote presentation.* Gifu, Japan: 4th CIRP International Conference on High Performance Cutting.

Dornfeld, D. A. (2013). Concluding remarks and observations about the future. In D. A. Dornfeld (Ed.), *Green manufacturing: Fundamentals and applications* (pp. 269-286). New York: Springer.

Dornfeld, D. A., & Hutchins, M. J. (2013). *ME290I: Sustainable manufacturing. graduate course. presentation.* Berkeley, CA: University of California, Berkeley.

Dornfeld, D., Wright, P., Vijayaraghavan, A., & Helu, M. (2009). Enabling manufacturing research through interoperability. *Transactions of NAMRI/SME, 37*, 443-450.

Dornfeld, D., Yuan, C., Diaz, N., Zhang, T., & Vijayaraghavan, A. (2013). Introduction to green manufacturing. In D. A. Dornfeld (Ed.), *Green manufacturing: Fundamentals and applications* (pp. 1-23). New York: Springer.

Drakopoulos, S., Salonitis, K., Tsoukantas, G., & Chryssolouris, G. (2009). Environmental impact of ship hull repair. *International Journal of Sustainable Manufacturing, 1*(3), 361-374.

Duflou, J. R., Kellens, K., Renaldi, Guo, Y., & Dewulf, W. (2012). Critical comparison of methods to determine the energy input for discrete manufacturing processes. *CIRP Annals - Manufacturing Technology, 61*(1), 63-66.

Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., et al. (2012). Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals-Manufacturing Technology, 61*(2), 587-609.

Duflou, J., Kellens, K., & Dewulf, W. (2011). Unit process impact assessment for discrete part manufacturing: A state of the art. *CIRP Journal of Manufacturing Science and Technology, 4*(2), 129-135.

Ehrlenspiel, K., Kiewert, A., & Lindemann, U. (2007). *Cost-efficient design*. New York: Springer.

EIOLCA sample output. (2011). Retrieved December 2, 2013, from http://blog.metasd.com/2011/05/bigfoot-ii/

Energy Star. (2012). *Energy tracking tool.* Retrieved December 2, 2013, from http://www.energystar.gov/buildings/tools-and-resources/energy-tracking-tool

Engineers Australia. (2013). *Who says 'sustainability' is important and why?.* Retrieved November 10, 2013, from https://www.engineersaustralia.org.au/queensland-division/sustainability-focus

Evans, P. C., & Annunziata, M. (2012). *General electric: Industrial internet: Pushing the boundaries of minds and machines.* Retrieved from http://www.ge.com/docs/chapters/Industrial_Internet.pdf

GE Fanuc. (2008). *The environmental and economic advantages of energy-efficient motors.* Retrieved July 3, 2012, from http://leadwise.mediadroit.com/files/2928energy%20saving_wp_gft688.pdf

Graedel, T. E., & Allenby, B. R. (2003). *Industrial ecology*. Upper Saddle River, N.J.: Prentice Hall.

Graedel, T., & Howard-Grenville, J. (2005). *Greening the industrial facility: Perspectives, approaches, and tools*. New York: Springer.

Granta Design. (2012). *Eco materials adviser.* Retrieved February 14, 2012, from http://inventor.grantadesign.com/en/

Greenhouse Gas Protocol. (2012). *Emissions factors.* Retrieved July 9, 2009, from http://www.ghgprotocol.org/calculation-tools/all-tools

Groover, M. P. (2001). *Automation, production systems, and computer-integrated manufacturing* (2nd ed.). Upper Saddle River, NJ: Prentice Hall.

Groover, M. P. (2013). *Fundamentals of modern manufacturing : Materials, processes, and systems* (5th ed.). Hoboken, NJ: John Wiley & Sons, Inc.

Gruenshpect, H. (2011). *U.S. energy information administration: International energy outlook 2011.* Retrieved from http://www.eia.gov/pressroom/presentations/howard_09192011.pdf

Haapala, K. R., Zhao, F., Camelio, J., Sutherland, J. W., Skerlos, S. J., Dornfeld, D. A., et al. (2013). A review of engineering research in sustainable manufacturing. *Journal of Manufacturing Science and Engineering, 135*(4), 1-16.

Haapala, K., Rivera, J., & Sutherland, J. W. (2006). Environmentally responsible process selection via life cycle analysis. Paper presented at the *2006 International Symposium on Flexible Automation,* Osaka, Japan. pp. 1-8.

Haas Automation Inc. (2013). *Vertical machining centers.* Retrieved November 16, 2013, from http://www.haascnc.com/vmc_intro.asp#gsc.tab=0

Helu, M. (2013). Leveraging manufacturing precision to reduce product life cycle environmental impacts. (Doctoral dissertation, University of California, Berkeley).

Helu, M., & Dornfeld, D. (2013). Principles of green manufacturing. In D. A. Dornfeld (Ed.), *Green manufacturing: Fundamentals and applications* (pp. 107-115). New York: Springer.

Herrmann, C., & Thiede, S. (2009). Process chain simulation to foster energy efficiency in manufacturing. *CIRP Journal of Manufacturing Science and Technology, 1*(4), 221-229.

Herrmann, C., Thiede, S., Kara, S., & Hesselbach, J. (2011). Energy oriented simulation of manufacturing systems–Concept and application. *CIRP Annals-Manufacturing Technology, 60*(1), 45-48.

Herzog, T. (2009). *World resources institute: World greenhouse gas emissions in 2005.* Retrieved from http://pdf.wri.org/working_papers/world_greenhouse_gas_emissions_2005.pdf

Horvath, A. (2009). *CE268E: Life-cycle costing: Models of life-cycle assessment (LCA): Part 1. graduate course. presentation.* Berkeley, CA: University of California, Berkeley.

Hutchins, M. J., Robinson, S. L., & Dornfeld, D. A. (2013). Understanding life cycle social impacts in manufacturing: A processed-based approach. *Journal of Manufacturing Systems, 32*(4), 536-542.

Kalla, D., Overcash, M. & Twomey, J. (2010). *Manufacturing unit process life-cycle inventory heuristics.* Retrieved July 3, 2012, from http://cratel.wichita.edu/uplci

Kalla, D., Twomey, J., & Overcash, M. (2009). *MR 3 milling process - unit process life cycle inventory.* Retrieved from http://cratel.wichita.edu/uplci/wp-content/uploads/2010/03/MR3_Milling_Process_8-19-09Final.doc

Kalpakjian, S. (2006). *Manufacturing engineering and technology* (5th ed.). Upper Saddle River, NJ: Pearson/Prentice Hall.

Kalpakjian, S., & Schmid, S. R. (2001). *Manufacturing engineering and technology* (4th ed.). Upper Saddle River, NJ: Prentice Hall.

Kara, S., & Li, W. (2011). Unit process energy consumption models for material removal processes. *CIRP Annals-Manufacturing Technology, 60*(1), 37-40.

Kazanas, H., & Lerwick, L. P. (2002). Manufacturing processes technology. *Encyclopedia of physical science and technology: Manufacturing processes* (pp. 95-119). San Diego: Academic Press.

Kellens, K., Dewulf, W., Overcash, M., Hauschild, M. Z., & Duflou, J. R. (2012). Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! initiative (cooperative effort on process emissions in manufacturing). part 1: Methodology. *The International Journal of Life Cycle Assessment, 17*(1), 69-78.

Klocke, F. (2011). *Manufacturing processes 1: Cutting*. New York: Springer.

Kong, D., Choi, S., Yasui, Y., Pavanaskar, S., Dornfeld, D., & Wright, P. (2011). Software-based tool path evaluation for environmental sustainability. *Journal of Manufacturing Systems, 30*(4), 241-247.

Kuhrke, B., Schrems, S., Eisele, C., & Abele, E. (2010). Methodology to access the energy consumption of cutting machine tools. Paper presented at the *17th CIRP International Conference on Life Cycle Engineering,* Hefei, China. pp. 76-82.

Lincoln Electric. (2013). *Energy efficiency: Inverter power source.* Retrieved July 20, 2012, from http://www.lincolnelectric.com/en-us/support/process-and-theory/Pages/inverter-power-detail.aspx

Lord kelvin quotations. (2008). Retrieved December 1, 2013, from http://zapatopi.net/kelvin/quotes/

Loyer, C. (2012). *The fishbone diagram and the reverse fishbone diagram concepts.* Retrieved November 14, 2013, from http://www.processexcellencenetwork.com/six-sigma-quality/articles/the-fishbone-diagram-and-the-reverse-fishbone-diag/

Machsources. (2012). *Process chains.* Retrieved November 1, 2013, from http://www.machsources.com/

MacKay, D. (2009). *Sustainable energy-without the hot air*. Cambridge, England: UIT.

Mani, M., Madan, J., Hyun Lee, J., Lyons, K., & Gupta, S. K. (2012). Characterizing sustainability for manufacturing performance assessment. Paper presented at the *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* Chicago, IL. pp. 1-10.

Math! how much CO_2 is released by aeroplane? (2007). Retrieved January 18, 2011, from http://micpohling.wordpress.com/2007/05/08/math-how-much-co2-released-by-aeroplane/

Matos, G. (2009). *U.S. geographical survey: Use of minerals and materials in the united states from 1900 through 2006.* Retrieved from http://pubs.usgs.gov/fs/2009/3008/pdf/FS2009_3008_v1_1.pdf

McKinsey Global Institute. (2007). *Curbing global energy-demand growth: The energy productivity opportunity.* Retrieved from http://www.mckinsey.com/insights/energy_resources_materials/curbing_global_energy_demand_growth

Meijer, J. (2013). *Sustainable minds: SM2013 methodology and database.* Retrieved from http://www.sustainableminds.com/showroom/toto/SM2013-Methodology-Report.pdf

Mihelcic, J. R., Crittenden, J. C., Small, M. J., Shonnard, D. R., Hokanson, D. R., Zhang, Q., et al. (2003). Sustainability science and engineering: The emergence of a new metadiscipline. *Environmental Science & Technology, 37*(23), 5314-5324.

MIT Sloan & The Boston Consulting Group. (2011). *Sustainability: The 'embracers' seize advantage.* Retrieved from http://www.bcg.com/documents/file71538.pdf

Mori, M. (2010). *Power consumption reduction of machine tools. CWG-EREE presentation.* Pisa, Italy: 60th CIRP General Assembly.

Motoman. (2012). *The business case for robots;* Retrieved July 13, 2012, from http://www.churchill-tech.com/images/business-case-for-robots.pdf

National Council for Advanced Manufacturing. (2011). *Sustainability framework model.* Retrieved December 2, 2013, from http://www.nacfam.org/PolicyInitiatives/SustainableManufacturing/NACFAMSustainabilityFrameworkModel/tabid/102/Default.aspx

Nozzle wear rates. (2011). Retrieved July 16, 2012, from http://www.pirate4x4.com/forum/torchmate-cnc-forum/993278-a120-consumable-life.html

OECD. (2011). *Sustainable manufacturing indicators.* Retrieved February 14, 2012, from http://www.oecd.org/innovation/green/toolkit/oecdsustainablemanufacturingindicators.htm

Olexa, R. (2006). *Laser technology: Flexibility adds capability.* Retrieved June 24, 2012, from http://www.ophiropt.com/news_pr/FFjournal_09_2006_2.pdf

OTC. (2012). *Weld spatter.* Retrieved September 7, 2013, from http://www.daihen-usa.com/techtips.php

Overcash, M., & Twomey, J. (2012). Unit process life cycle inventory (UPLCI)–A structured framework to complete product life cycle studies. In D. A. Dornfeld, & B. S. Linke (Eds.), *Leveraging technology for a sustainable world: Proceedings of the 19th CIRP international conference on life cycle engineering* (pp. 1-4). University of California, Berkeley, CA: Springer.

Pacala, S., & Socolow, R. (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science, 305*(5686), 968-972.

PE International. (2013). *GaBi 5 databases.* Retrieved February 14, 2012, from http://www.gabi-software.com/america/databases/gabi-databases/

Pickard, T. (2009). *The insitute of grocery distribution. the increasing demand for water.* Retrieved October 28, 2013, from http://www.igd.com/our-expertise/Sustainability/Water/3750/The-increasing-demand-for-water/

Product Ecology Consultants. (2003). *SimaPro 7, database manual, the USA input output 98 library.* Retrieved from http://www.pre-sustainability.com/download/manuals/DatabaseManualUSAIODatabase98.pdf

Product Ecology Consultants. (2004). *SimaPro 7, database manual, the dutch input output 95 library* Retrieved from http://www.pre-sustainability.com/download/manuals/DatabaseManualDutchIODatabase95.pdf

Product Ecology Consultants. (2006). *SimaPro 7, database manual, japanese input output 2000.* Retrieved from http://www.pre-sustainability.com/download/manuals/DatabaseManualJapaneseIO2000.pdf

Product Ecology Consultants. (2013). *Simapro.* Retrieved February 14, 2012, from http://www.pre-sustainability.com/all-about-simapro

PTC. (2012). *Windchill LCA.* Retrieved February 14, 2012, from http://www.ptc.com/products/windchill/lca

Reich-Weiser, C., Vijayaraghavan, A., & Dornfeld, D. (2010). Appropriate use of green manufacturing frameworks. Paper presented at the *17th CIRP International Conference on Life Cycle Engineering,* Hefei, China.

Reinhart, G., Reinhardt, S., Föckerer, T., & Zäh, M. F. (2011). Comparison of the resource efficiency of alternative process chains for surface hardening. In J. Hesselbach, & C. Herrmann (Eds.), *Glocalized solutions for sustainability in manufacturing: Proceedings of the 18th CIRP international conference on life cycle engineering* (pp. 311-316). Technische Universitat Braunschweig, Germany: Springer.

ReportLinker. (2013). *Global construction equipment & machinery industry.* Retrieved November 13, 2013, from http://www.reportlinker.com/ci02287/Construction-Equipment-and-Machinery.html

Robinson, S., & Dornfeld, D. (2013). *Sustainable manufacturing short course. SMP. presentation.* Berkeley, CA: University of California, Berkeley.

Rogich, D., Cassara, A., Wernick, I., & Miranda, M. (2008). *World resources institute: Material flows in the united states: A physical accounting of the U.S. industrial economy.* Retrieved from http://www.wri.org/sites/default/files/pdf/material_flows_in_the_united_states.pdf

Schabert, A. (2010). *Life cycle assessment of fuel cell components – bipolar plate and membrane electrode assembly.* Unpublished Master's Thesis, Institute for Machine Tools and Industrial Management,Technische Universität München, iwb, Germany.

Schlosser, R., Klocke, F., Döbbeler, B., Riemer, B., Hameyer, K., Herold, T., et al. (2011). Assessment of energy and resource consumption of processes and process chains within the automotive sector. In J. Hesselbach, & C. Herrmann (Eds.), *Glocalized solutions for sustainability in manufacturing: Proceedings of the 18th CIRP international conference on life cycle engineering* (pp. 45-50). Technische Universitat Braunschweig, Germany: Springer.

Schrems, S., Eisele, C., & Abele, E. (2011). Methodology for an energy and resource efficient process chain design. In J. Hesselbach, & C. Herrmann (Eds.), *Glocalized solutions for sustainability in manufacturing: Proceedings of the 18th CIRP international conference on life cycle engineering* (pp. 299-304). Technische Universitat Braunschweig, Germany: Springer.

Shama, M. (2005). Life cycle assessment of ships. In G. Soares, Y. Garbatov & N. Fonseca (Eds.), *Maritime transportation and exploitation of ocean and coastal resources: Proceedings of the 11th international congress of the international maritime association of the mediterranean* (pp. 1751-1758). Lisbon, Portugal: Taylor & Francis Group.

Shankar, R. (2009). *Process improvement using six sigma: A DMAIC guide*. Milwaukee, WI: ASQ Quality Press.

Shiklomanov, I. A. (1999). *UNESCO: World water resources and their use.* Retrieved October 8, 2013, from http://webworld.unesco.org/water/ihp/db/shiklomanov/

Siemens. (2010). *Eco care matrix.* Retrieved October 3, 2013, from http://www.siemens.com/press/pool/de/pressebilder/2010/industry_solutions/300dpi/IIS201005406-01e_300dpi.jpg

Steiner, R., & Frischknecht, R. (2007). *Metals processing and compressed air supply.* Retrieved from http://www.poli.br/~cardim/PEC/Ecoinvent%20LCA/ecoinventReports/23_MechanicalEngineering.pdf

Swiss Centre for Life Cycle Inventories. (2013). *EcoInvent database.* Retrieved June 28, 2011, from http://www.ecoinvent.ch/

The Engineering Toolbox. (2011). *Horsepower required to compress air.* Retrieved June 14, 2012, from http://www.engineeringtoolbox.com/horsepower-compressed-air-d_1363.html

The Whole Weld World. (2011). *Carbon arc cutting.* Retrieved November 16, 2013, from http://www.weldguru.com/CAC.html

Thiede, S., & Herrmann, C. (2011). Energy flow simulation for manufacturing systems. In G. Seliger, M. M. K. Khraisheh & I. S. Jawahir (Eds.), *Advances in sustainable manufacturing: Proceedings of the 8th global conference on sustainable manufacturing* (pp. 275-280). Masdar Institute of Science and Technology and Abu Dhabi University, United Arab Emirates: Springer.

Thompson, D. (1995). *Symposium on research issues in precision manufacturing. presentation.* Berkeley, CA: University of California, Berkeley.

Todd, R. H., Allen, D. K., & Alting, L. (1994). *Manufacturing processes reference guide*. New York: Industrial Press Inc.

Treloar, G. J., Love, P. E. D., & Crawford, R. H. (2004). Hybrid life-cycle inventory for road construction and use. *Journal of Construction Engineering and Management, 130*(1), 43-49.

TWI. (2012). *Cutting processes - plasma arc cutting - process and equipment considerations.* Retrieved November 16, 2013, from http://www.twi.co.uk/technical-knowledge/job-knowledge/cutting-processes-plasma-arc-cutting-process-and-equipment-considerations-051/

U.S. Department of Commerce. (2010). *U.S. carbon dioxide emissions and intensities over time: A detailed accounting of industries, government and households.* Retrieved from http://www.esa.doc.gov/Reports/u.s.-carbon-dioxide

U.S. Department of Commerce. (2012). *How does commerce define sustainable manufacturing?.* Retrieved October 30, 2013, from http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp

U.S. Department of Commerce. (2013). *Gross-domestic-product-(GDP)-by-industry data.* Retrieved June 19, 2012, from http://www.bea.gov/industry/gdpbyind_data.htm

U.S. Department of Energy. (2003). *Improving compressed air system performance: A sourcebook for industry.* Retrieved from http://industrial-energy.lbl.gov/files/industrial-energy/active/0/LBNL-43888.pdf

U.S. Department of Energy. (2004). *Determine the cost of compressed air for your plant.* Retrieved July 1, 2012, from http://www1.eere.energy.gov/industry/bestpractices/pdfs/compressed_air1.pdf

U.S. Department of Labor. (2008). *OSHA technical manual: Personal sampling for air contaminants.* Retrieved December 19, 2011, from https://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_1.html

U.S. Energy Information Administration. (2009). *Manufacturing energy consumption survey: 2006 energy consumption by manufacturers -- data tables.* Retrieved November 1, 2013, from http://www.eia.gov/consumption/manufacturing/index.cfm

U.S. Energy Information Administration. (2012). *Annual energy review 2011.* Retrieved from http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

U.S. Environmental Protection Agency. (2000). *AP 42, 5th edition, volume I, chapter 12: Metallurgical industry, section 19: Electric arc welding* Retrieved from http://www.epa.gov/ttnchie1/ap42/ch12/final/c12s19.pdf

U.S. Environmental Protection Agency. (2003). *Lean manufacturing and the environment.* Retrieved from http://www.epa.gov/lean/environment/pdf/leanreport.pdf

U.S. Environmental Protection Agency. (2007). *The lean and environment toolkit.* Retrieved from http://www.epa.gov/lean/environment/toolkits/environment/resources/LeanEnviroToolkit.pdf

U.S. Environmental Protectional Agency. (2013). *Egrid.* Retrieved July 23, 2011, from http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

UN Water. (2012). *Water use.* Retrieved November 1, 2013, from http://www.unwater.org/statistics_use.html

UNESCO. (2006). *The state of the resource.* Retrieved from http://www.unesco.org/bpi/wwap/press/pdf/wwdr2_chapter_4.pdf

United Nations Environment Programme. (2007). *Global environment outlook 4.* Retrieved from http://www.unep.org/geo/GEO4/report/GEO-4_Report_Full_en.pdf

United Nations. (2005). *World summit outcome, united nations general assembly.* Retrieved from http://www.un.org/womenwatch/ods/A-RES-60-1-E.pdf

Verl, A., Abele, E., Heisel, U., Dietmair, A., Eberspächer, P., Rahäuser, R., et al. (2011). Modular modeling of energy consumption for monitoring and control. In J. Hesselbach, & C. Herrmann (Eds.), *Glocalized solutions for sustainability in manufacturing: Proceedings of the 18th CIRP international conference on life cycle engineering* (pp. 341-346). Technische Universitat Braunschweig, Germany: Springer.

Vijayaraghavan, A., & Helu, M. (2013). Enabling technologies for assuring green manufacturing. In D. A. Dornfeld (Ed.), *Green manufacturing: Fundamentals and applications* (pp. 255-267). New York: Springer.

Wegener, D., Finkbeiner, M., Geiger, D., Olsen, S. I., & Walachowicz, F. (2009). Comprehensive approach to energy and environment in the EcoCare program for design, engineering and operation of siemens industry solutions. Paper presented at the *RISO International Energy Conference,* Copenhagen, Denmark. pp. 45-52.

Weidema, B. P., Nielsen, A. M., Christiansen, K., Norris, G., Notten, P., Suh, S., et al. (2005). *Danish ministry of the environment: Environmental protection agency: Prioritisation within the integrated product policy.* Retrieved from http://www.miljøstyrelsen.dk/udgiv/publications/2005/87-7614-517-4/pdf/87-7614-518-2.pdf

Weinert, N., Chiotellis, S., & Seliger, G. (2011). Methodology for planning and operating energy-efficient production systems. *CIRP Annals-Manufacturing Technology, 60*(1), 41-44.

Wikipedia. (2005). *GDP vs energy efficiency.* Retrieved September 15, 2013, from http://en.wikipedia.org/wiki/File:Gdp-energy-efficiency.jpg

Wikipedia. (2012). *Catapillar D6T.* Retrieved July 24, 2012, from http://en.m.wikipedia.org/wiki/File:Caterpillar_D6T_Mississippi_River_project.JPG

Wikipedia. (2013). *Value stream mapping.* Retrieved October 28, 2013, from http://en.wikipedia.org/wiki/Value_stream_mapping

World Commission on Environment and Development. (1987). *Our common future.* Oxford; New York: Oxford University Press.

World Resources Simulation Center. (2012). *Global water consumption.* Retrieved November 24, 2013, from http://www.wrsc.org/attach_image/global-water-consumption-1900-2025

Yeo, S. H., & Neo, K. G. (1998). Inclusion of environmental performance for decision making of welding processes. *Journal of Materials Processing Technology, 82*(1), 78-88.

Zhang, H., Wang, Y. H., Yue, W. H., Jiang, Z. G., & Zhao, G. (2011). Comprehensive assessment system for resource and environmental attribution in manufacturing process chains. *Advanced Materials Research, 255*, 2909-2913.

Appendix A

Industrial Assessment Metrics

Relevant Variables

Variable	Name	Units	Definition	Source
A_{cell}	Cell footprint	l^2	The footprint of the cell or machine tool being analyzed	On-site measurement or survey
A_{avg}	Average cell footprint	l^2	The average footprint of a cell or machine tool in a facility	On-site measurement and/or survey
A_{total}	Total facility floor space	l^2	The total amount of floor space in a facility	Survey
CA	Compressed air usage	v	The amount of compressed air used by the cell or machine tool being analyzed	Flowmeter or non-invasive approach
D_{comp}	Demand on air compressor	%	The average demand placed on the air compressor (i.e., the amount of time it is functional relative to the operation time)	Observation
E_{HVAC}	HVAC energy	kWh	The amount of energy consumed by HVAC systems in the facility	Historical data and/or calculation
E_{light}	Lighting energy	kWh	The amount of energy consumed by the lighting systems in the facility	Historical data and/or calculation
h_{cell}	Powered cell time	t	The total time that a cell or machine tool is powered on irrespective of productivity	Historical data or observation
$h_{facility}$	Total facility powered time	t	The sum of the powered cell time for each cell or machine tool in a facility	Historical data or observation
$m_{fixutre}$	Total mass of	m	The total mass of each material	Historical data or

	fixture material		type in a fixture for a cell or machine tool	observation or survey
m_{parts}	Total mass of material in all processed parts	m	The total mass of all material processed in a cell or machine tool	Historical data
$m_{replacement}$	Total mass of replacement part material	m	The total mass of each material type in a replacement part for a cell or machine tool	Historical data or observation or survey
n	Noise level	dB	Noise level during production	Microphone
N_I	Injuries per year	injuries	Total number of injuries in a facility per year	Historical data
$N_{process}$	Process loss per cell	m/t	Total mass of chips generated from the processing that occurs in one cell over a specified time period	Historical data or survey
P_i	Idle power	kW	Power demand during idle periods	Wattmeter
P_p	Processing power	kW	Power demand during processing periods	Wattmeter
P_w	Warm-up power	kW	Power demand during warm-up periods	Wattmeter
R_{clean}	Water consumed for cleaning	v/t	The amount of water consumed to clean processed parts	Historical data or measurement
R_{cool}	New coolant oil consumed	v/t	The amount of new coolant oil consumed	Historical data
$R_{cool,r}$	Coolant oil recycled	v/t	The amount of coolant oil that is recycled	Historical data
R_{lube}	Lubricating oil consumed	v/t	The amount of lubricating oil consumed	Historical data
R_{water}	Water consumed for coolant	v/t	The amount of water consumed through the use of coolant	Historical data or calculation from R_{cool}
$S_{savings}$	Lifetime savings	\$	Total amount of savings over the entire lifetime of a technology solution	n/a
$S_{investment}$	Investment cost	\$	Total investment required to implement a technology solution	n/a
SD	Sick days per year	days	Total number of sick days in a facility per year	Historical data
T	Tool life	t, v, or parts	The life of a tool in a cell or machine tool	Historical data
$t_{c,design}$	Cycle time	t	Designed (or ideal) cycle time per part	CAD/CAM or survey

$t_{calendar}$	Calendar time	t	Total calendar days over a specified time period	n/a
$t_{d,planned}$	Planned downtime	t	Total planned downtime during t_s	Historical data or survey
$t_{d,unplanned}$	Unplanned downtime	t	Total unplanned downtime during t_s	Historical data or observation or survey
t_i	Idle time	t	Total elapsed time during idle periods	Historical data or observation or CAD/CAM
t_p	Processing time	t	Total elapsed time during processing periods	Historical data or observation or CAD/CAM
t_s	Operation time	t	Total operation time during a specified time period	Historical data or survey
t_w	Warm-up time	t	Total elapsed time during warm-up periods	Historical data or observation or survey
V_s	Production volume	parts/t	Total processed parts over t_s	Historical data or survey
V_{scrap}	Scrapped volume	parts/t	Total processed parts that are scrapped over t_s	Historical data or survey
V_{rework}	Reworked volume	parts/t	Total processed parts that are reworked over t_s	Historical data or survey
W_{HAZ}	Hazardous waste	v/t	Amount of hazardous waste that must be disposed of over a specified time period	Historical data
W_{solid}	Solid waste	m/t	Amount of solid waste that must be disposed of over a specified time period; this variable does not refer to waste items associated with the completed part or tools (e.g., tools, chips, fixtures) but rather other waste items such as gloves, packaging, etc. that are disposed of through standard garbage disposal	Historical data

Metrics

Power Demand and Energy Consumption

Metric	Variable	Units	Source	Definition
Idle power demand	P_i	kW	Variable	Same as measured variable
Warm-up power demand	P_w	kW	Variable	Same as measured variable
Peak power demand	$P_{p,max}$	kW	Variable	This is the maximum steady-state value during the processing period
Component power demand	$P_{comp,i}$	kW	$P_p - P_{p,w/o\ comp,j}$	Power demand for each identified relevant component, *j*; equation may be used if sub-metering is difficult
Cutting power demand	P_{cut}	kW	$P_p - P_i$	Power demand due to the requirements of the cutting process
Processing energy consumption per year	E_p	kWh/year	$\left(\int_{t_p} P_p dt\right)_{year}$	Total energy consumed during all processing periods over one year
Idle energy consumption per year	E_i	kWh/year	$\left(\int_{t_i} P_i dt\right)_{year}$	Total energy consumed during all idle periods over one year
Warm-up energy consumption per year	E_w	kWh/year	$\left(\int_{t_w} P_w dt\right)_{year}$	Total energy consumed during all warm-up periods over one year

Production Efficiency/Overall Equipment Effectiveness (OEE)

Metric	Variable	Units	Source	Definition
Availability	a	%	$\frac{t_s - t_{d,planned} - t_{d,unplanned}}{t_s - t_{d,planned}}$	A measurement of uptime irrespective of quality, performance, and scheduled downtime
Performance efficiency	$\eta_{performane}$	%	$\frac{t_{c,design} V_s}{t_s - t_{d,planned} - t_{d,unplanned}}$	A measurement of the actual operating speed of machine relative to its designed operating speed irrespective of availability or quality
Process utilization	$u_{process}$	%	$\frac{\left(t_s - t_{d,planned}\right)_{t_{calendar}}}{t_{calendar}}$	A measurement of the schedule effectiveness that compares the

				actual operation time to the total calendar time irrespective of system performance
Quality	q	%	$\frac{V_s - V_{rework} - V_{scrap}}{V_s}$	A measurement of the total number of good to bad parts

Process Consumables and Facility Overhead Charges

Metric	Variable	Units	Source	Definition
Coolant oil consumption	R_{cool}	v/t	Variable	Same as measured variable; this metric refers only to new coolant oil and should not count recycled coolant oil
Recycled coolant	r_{cool}	%	$100*\left(\frac{R_{cool,r}}{R_{cool}}\right)_{cell}$	The proportion of recycled coolant that is used in the cell relative to new coolant
Lubricating oil consumption	R_{lube}	v/t	Variable	Same as measured variable
Water consumption for coolant	R_{water}	v/t	Variable	Same as measured variable
Water consumption for cleaning	R_{clean}	v/t	Variable	Same as measured variable
Tool life	T	t, v, or parts	Variable	Same as measured variable
Fixturing	F	%	$100*\left(\frac{m_{fixture}}{m_{parts}}\right)$	The amount of material used to create a fixture relative to the amount of material it is used to process; each type of material in the fixture should be accounted for separately
Replacement parts	R	%	$100*\left(\frac{m_{replacement}}{m_{parts}}\right)$	The amount of material in the new cell or machine tool parts relative to the amount of material the cell or machine tool processes over the life of the new part; each type of material in the replacement part should be accounted for separately
Compressed air usage	CA	v/t	Variable	Same as measured variable
Effective	$E_{comp,eff}$	kWh	$K*P_{comp}*t_s*D_{comp}$	An estimate of the average energy

compressor energy consumption				consumed by the air compressor for the cell
Effective HVAC energy consumption	$E_{HVAC,eff}$	kWh	$E_{HVAC} * \left(\frac{A_{MT}}{A_{total}} \right)$	An estimate of the average energy consumed by the HVAC system for the cell
Effective lighting energy consumption	$E_{light,eff}$	kWh	$E_{light} * \left(\frac{A_{MT}}{A_{total}} \right)$	An estimate of the average energy consumed by the lighting system for the cell

Process Waste

Metric	Variable	Units	Source	Definition
Rework rate	N_{rework}	%	$100 * \left(\frac{V_{rework}}{V_s} \right)$	The number of parts that are processed through the cell that need to be reworked relative to the total number of parts processed
Scrap rate	N_{scrap}	%	$100 * \left(\frac{V_{scrap}}{V_s} \right)$	The number of parts that are processed through the cell that are scraped relative to the total number of parts processed
Process loss	$N_{process}$	m	Variable	Same as measured variable; each type of material should be specified individually
Hazardous waste	W_{HAZ}	v/t	Variable	Same as measured variable; this metric should include any used coolant and lubricating oil that must be treated as hazardous material as well as any associated contaminated water; each type of hazardous waste should be specified individually
Solid waste	W_{solid}	v/t	Variable	Same as measured variable

Economic

Metric	Variable	Units	Source	Definition
Return on investment	ROI	n/a	$\frac{S_{savings}}{S_{investment}}$	The dollar amount saved by the technology solution relative to the cost of the technology solution

Human Safety

Metric	Variable	Units	Source	Definition
Maximum noise level per cycle	n_{max}	dB/cycle	Variable	Maximum measured noise value over one cycle
Injuries per year	$N_{I,cell}$	injuries	$K*N_I$	Total number of injuries per year in the facility scaled to an individual cell
Sick days per year	SD_{cell}	days	$K*SD$	Total number of sick days per year in the facility scaled to an individual cell

Appendix B

Pre-Assessment Questionnaire

Facility Information & General Energy Usage		
A	**General Information**	
1	Organization Name	
2	Contact Person	
3	Address	
4	Phone Number	
5	Fax	
6	E-mail	
B	**Organizational Information**	
1	Number of Employees	
2	Number of operating hours per day	
3	Number of operating days in a year	
C	**ENERGY**	
1	Have you conducted energy audits?	
2	If C.1. is yes, please mention the year of audit conducted, saving potential identified & copy of the audit report	
3	Have you implemented any energy monitoring system?	
4	If C.3 is yes, please provide the details of the implemented system	
5	At what level is your energy metered	
6	Are you willing to allow energy monitoring to be installed?	
7	If C.6. is yes, please mention if you are willing to install a Long term (using fixed meter) or Short term (using clamp-on meter) system	

8	Have you installed any energy efficient technology/equipment/appliances?			
9	If C.8 is yes, please mention the technology adopted/equipments installed			
D	**Energy Data Plant Level (Year: 2009 - 10)**			
	Type	**Units**	**Annual Consumption (kWh)**	**Annual Cost (USD)**
1	Purchased Power (Grid)			
2	Generated Power			
3	Fuel			
4	Others (Please specify)			
5	Contract Demand (kVA) (The amount of power which a customer agrees to pay to have available at all times)			
6	Peak Demand Registered (kVA) (Maximum demand of the system at point in time)			
7	Diesel/fuel consumption for self generated power (KL/annum)			
8	Are you compliant or seeking compliance with ISO 14001?			
9	Are you compliant or seeking compliance with draft ISO 14040 & 14064?			
10	Are you compliant or seeking compliance with draft ISO 50001?			
E	**Please provide the list of resource conservation (includes energy & material) projects implemented (plant level) (Insert additional rows if required)**			
	Project Name	**Implemented Month & Year**	**Investment (USD)**	**Savings Achieved (USD/annum)**
1				
2				
3				
4				
5				
6				
F	**ENERGY BILL**			
1	Please attach month wise energy consumption/energy bill data for last 12 to 24 Months			
G	**Energy Cost**			

1	Demand Charges (USD/kVA)		
2	Demand Charges for exceeding limits (USD/kVA)		
3	Purchased Electricity Cost (USD Cents/kWh)		
4	Purchased electricity Cost for exceeding limits(USD Cents/kWh)		
5	Generated Electricity Cost (USD Cents/kWh)		
6	Any other Time-of-Use charges		
7	Any other Point-of-use charges		
H	**Utilization of Renewable Energy Sources (plant level) (Insert additional rows if required)**		
	Renewable Energy Source replacing electrical energy	**Energy generated (kWh/year)**	**Savings Achieved (USD/annum)**
1	Wind		
2	Solar Photovoltaic		
3	Small Hydro		
	Renewable Energy Source replacing Thermal energy	**Equivalent Fuel Savings (KL/year)**	**Savings Achieved (USD/annum)**
1	Solar Thermal		
2	Biomass		
3	Others		

Appendix C

Process Level Assessment and Metrics

Process Assessment						
A	**Line-level**					
1	How many machine tools and devices are part of this production line?					
2	Line production capacity/ Day					
3	Please provide Process flow including inspection stages or VSM if available	(attachment)				
B	**Machine-level**					
	Production Management	**CNC 1**	**CNC 2**	**Tooth chamfering**	**Hard turning**	**Final visual**
1	Description of operations					
2	Part Handling Time					
3	Machining Time					
4	Planned Cycle Time					
5	Actual Cycle Time					
6	Volume (production history - part per day or week or month) (preferably per day production)					
7	Number of Manpower					
8	Production capacity					
C	**Utilization Management**					
1	OEE					

2	Average utilization per process station					
3	Major reasons for production time loss					
D	**Rejection Management**					
1	Average rejection quantity (per day)					
2	Average rejection percentage					
3	Major reasons for the rejections					
4	Rework quantity					
5	Rework percentage					
E	**Machine Tool Energy Consumption**					
1	Rated Power (kW)					
2	Number of test cycles					
3	Energy usage during test cycles (kWh)					
4	Total idle duration (seconds)					
5	Energy usage during idle duration (kWh)					
7	Idle power per cycle (KW)					
8	Processing power per cycle (KW)					
9	Total Energy Consumed per day (kWh/day)					
10	Energy consumed during processing per part (kWh)					
11	Energy consumed during rework per part (kWh)					
F	**Processing power - Sub Classification [Based on availability of sub-metering capabilities]**					
1	Overall input power					
2	Hydraulic System Power Consumption					
3	Motion control system (spindle & axes) Power					
4	Coolant circulation system Power					
5	Control System Power					
6	Chip removal system Power					
7	Part Handling systems (like					

	pallets, conveyors) Power					
8	Fume extraction system Power consumption					
9	Miscellaneous Power consumption (additional energy consumers if any like chilled water system, tool cooling system)					
8	Peripheral Equipments					
G	**Material Processing**					
1	Type of material processed [tradename, composition]					
2	Weight of raw material / unfinished workpiece (lbs)					
3	Weight of finished workpiece (lbs)					
H	**Consumables**					
1	Coolant - Trim					
2	Oil (gallons/day) (please insert additional rows to cover all type of coolants used)					
I	**Tooling (Please repeat the set of rows below for each additional tool/insert used)**					
1	Type of cutting tools/insert used					
	Tool life estimated by the manufacturer (number of cycles)					
	Actual tool change frequency (number of cycles)					
2	Type of cutting tools/insert used					
	Tool life estimated by the manufacturer (number of cycles)					
	Actual tool change frequency (number of cycles)					
3	Type of cutting tools/insert used					
	Tool life estimated by the manufacturer (number of cycles)					
	Actual tool change frequency (number of cycles)					
4	Type of cutting tools/insert used					
	Tool life estimated by the manufacturer (number of cycles)					
	Actual tool change frequency					

	(number of cycles)					
5	Type of cutting tools/insert used					
	Tool life estimated by the manufacturer (number of cycles)					
	Actual tool change frequency (number of cycles)					
J	**Utilities (Details required for some common utilities are given below, please follow the similar format for any additional utility equipments)**					
J.a	**Compressors**					
J.a.1	Type of compressed air distribution (Dedicated/Shared)					
J.a.2	Type of Compressor (Reciprocating/Screw/Centrifugal)					
J.a.3	Make & Model of compressor					
J.a.4	Compressed air generation capacity/volume (cfm)					
J.a.5	Total number of compressors present					
J.a.6	Design capacity of compressor (cfm) (For more number of compressors please include additional rows)					
J.a.7	Operating pressure of the compressor (bar)					
J.a.8	Compressor average loading time per day in hours (add rows for more than 1 compressor)					
J.a.9	Compressor average unloading time per day in hours					
J.a.10	Power consumption of compressor during loading (kW)					
J.a.11	Power consumption of compressor during unloading (kW)					
J.a.12	Specific Energy Consumption of Compressor specified by manufacturer (kW/cfm)					
	If dedicated compressor please answer questions below,					
a	Air flow rate for machine tool specified by manufacturer (cfm)					
b	Compressed air Pressure required at machine tool specified by manufacturer (bar)					
c	Measured air flow rate during the test period (cfm)					

	If shared compressor please answer questions below,					
a	Air flow rate for machine tool specified by manufacturer (cfm)					
b	Total air flow rate for other machine tools (cfm) (Design spec)					
c	Compressed air Pressure required at machine tool specified by manufacturer (bar)					
d	Measured air flow rate during the test period (cfm)					
J.b.	**HVAC System**					
J.b.1	Capacity of air conditioning system (Tons of Refrigeration)					
J.b.2	Type of Chiller installed					
J.b.3	Design kW/TR of the system					
J.b.4	Chiller run hours per day					
J.b.5	Air conditioned space (area in Square meters or feet)					
J.b.6	Machine Area (Square meters or feet)					
J.b.7	Operating Power consumption of the chiller system (kW)					
J.c	**Coolant Circulation system**					
J.c.1	Type of coolant circulation system (Dedicated/Shared)					
J.c.2	Design capacity of the coolant circulation pump (liters or gallons per hour)					
J.c.3	Design head/pressure of the coolant circulation pump (bar)					
J.c.4	Rated input power (kW)					
J.c.5	Design efficiency of the pump					
J.c.6	Operating capacity of the coolant circulation pump (liters or gallons per hour)					
J.c.7	Operating head/pressure of the coolant circulation pump (bar)					
J.c.8	Present power consumption (kW)					
	If shared coolant circulation system please answer questions below also,					
a	Coolant flow required for the					

	process (liters/gallons per hour)					
b	Total coolant flow required for all other process shared (liters/gallons per hour)					
K	**Waste Management**					
1	Metal Scrap [lbs]					
2	Coolant Waste [gallons]					
3	Lube oil waste [gallons]					
4	Solid Waste [lbs]					
L	**Maintenance Check Points (Please mention Yes/No against each question)**					
1	Is lubrication oil level checked periodically?					
2	Is hydraulic oil level checked periodically?					
3	Is air/oil/coolant leakage monitored periodically?					
4	Is Machine sound levels monitored at regular intervals?					
5	Is there monitoring system to ensure air pressure at the user end?					
6	Is 3-phase voltage levels are checked for balanced conditions?					
7	All the maintenance related displays, documents around the machine are updated regularly?					
8	Are machine vibration levels monitored at regular intervals?					
9	Is the hydraulic oil condition monitored regularly?					
10	Whether the hydraulic/air filters are monitored for replacement?					
11	Whether the transmission devices like belt, clutch & brake conditions are monitored?					
12	Whether the control panel temperature is monitored regularly?					

Appendix D

Energy Measurement Checklist

Energy Measurement Checklist	
A	**Checklist for Continuous Monitoring (Energy) - Prior to Audit**
1	Ensure the meter is in working condition
2	Check for battery charge
3	Check for the availability of Current & Voltage clamps
B	**Checklist for Continuous Monitoring (Energy) - During Audit**
1	Connect the current & voltage clamps
2	Check for the directionality
3	Ensure the values displayed are positive. Any negative value indicates polarity of clamps needs to be changed
4	Measure energy consumption values of in-process & idle times (Collect data for at least few cycles)
5	Measure the energy consumption values of peripheral systems associated with machine tool including hydraulic system, coolant system, conveyors
6	Get the details of other auxiliaries like air flow, coolant flow if the meters are already provided
C	**Checklist for Continuous Monitoring (Productivity)**
1	Ensure the process flow chart & layout has been collected
2	Collect the cycle time of all the support equipment as well (e.g., loading/unloading robots, conveyors)
3	Identify all inspection stages separately
4	Collect details on types of machines & controller used
5	Collect existing monitoring sheets used
D	**Checklist for Continuous Monitoring (Environment)**

APPENDIX D. ENERGY MEASUREMENT CHECKLIST

1	Collect data on all the types of coolant & hydraulic oils used
2	Collect data on all the types of waste generated
3	Collect the emission factor value of grid electricity consumption
4	Collect the calorific values of fuels (To determine Scope-1 emissions, for example, calorific value of diesel used for diesel generator)
5	Collect details on energy(kWh) saved due to implementation energy saving & alternate energy projects, to determine carbon offset