AN ABSTRACT OF THE THESIS OF

Dane D. Eastlick for the degree of Master of Science in Mechanical Engineering presented on March 15, 2012.

Title: ASSISTING DECISION MAKING IN COMPONENT DESIGN FOR SUSTAINABLE MANUFACTURING

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Karl R. Haapala

Current life cycle assessment tools are often deficient in assisting design for sustainable manufacturing efforts. Integrating an improved assessment method into a decision support framework will provide a means for designers and engineers to better understand the impacts of their decisions. A unit process modeling-based sustainability assessment method is presented to assist design decision making by accounting for and quantifying economic, environmental, and social attributes. A set of these sustainability metrics is defined as a basis for comparison of component design alternatives. The method is demonstrated using two titanium component production alternatives that represent typical design for manufacturing scenarios. The modeling method significantly increases the resolution of sustainable manufacturing metrics over conventional assessment techniques, and is one aspect of the overall decision support framework developed. Additionally, fixed sum importance weighting, weighted sum modeling, and scenario analysis were selected as easily employed and transparent design decision techniques to provide the remaining elements of the framework.

The demonstration of the decision support framework for titanium component manufacturing illustrates that the sequential approach developed can assist engineers in developing more sustainable components and products.

Assisting Decision Making in Component Design for Sustainable Manufacturing

by
Dane D. Eastlick

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Dane D. Eastlick, Author

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CONTRIBUTION OF AUTHORS

Dr. Karl Haapala assisted in the writing and analysis of all manuscripts. Misha Sahakian assisted with the writing and analysis of the first manuscript.

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Assisting Decision Making In Component Design For Sustainable Manufacturing

CHAPTER 1

INTRODUCTION

This chapter provides background and motivation for the research within. A need for improved assessment methods and decision support will be shown, so designers can compare and select component design alternatives on a manufacturing sustainability basis.

MOTIVATION

The manufacturing industry faces the ongoing challenge of reducing environmental impacts, improving the well-being of society, and remaining competitive in the marketplace. A growing population of informed consumers is placing value in environmental and social responsibility and creating demand for sustainable products. Mechanical designers have the opportunity to improve product manufacturing sustainability, but lack the necessary tools for accurate assessment. Current methods of sustainability assessment provide insufficient coverage of sustainability aspects, lack manufacturing process detail, and provide limited means analyze the results and support the decision maker.

To assess the sustainability of a product, one must first define the sustainability metrics of interest, find ways to measure them, and gather the measurement values in each area. This is not a trivial process, due to the breadth of sustainability considerations. Current methods are deficient in the ability to assist design for manufacturing efforts. In some cases, selected sustainability metrics cannot adequately quantify manufacturing sustainability of a single component or product. For example, the Organisation for Economic Co-operation and

Development (OECD) Toolkit (OECD 2004) focuses primarily on the environmental performance of a facility. It does not include social and economic impacts and cannot relate manufacturing impacts to a single product. Although sets of metrics have been devised that are useful across various domains and a spectrum of technical detail, none provide the level of detail required to benefit simultaneous evaluation of product and process designs (Feng et al. 2010). Some design decisions are reflected in product level assessments, such as Ford's PSI (Schmidt & Butt 2006), but can only be used to compare different products or product iterations at a higher level. If an indicator set is to capture more detail, it will need access to more fully developed models of processes from across the product life cycle.

Although recent efforts in sustainable design have improved the information available to decision makers, most assessment methods fail to address all of the critical elements of decision support. In order to fully support product designers, detailed sustainability assessment must be placed into the context of the design decision making process. Although, some methods approach sustainable product design from the decision support perspective, they fail to provide sufficient manufacturing sustainability assessment. For example, Kaebernick explored several methodologies and decision tools in an approach towards product development for sustainable manufacturing, but only looked at important sources of environmental impacts of a product (Kaebernick et al. 2003). Product designers cannot effectively design for manufacturing sustainability if available tools do not include key sustainability metrics, models relating product and process impacts, and supporting methods to compare and choose between multiple design alternatives. Currently, there are no tools that fully address each factor. Ramani reiterates the need for integrated decision support and suggests that a tool which minimizes information-related barriers is likely to significantly enhance the capability, simplicity, and willingness of decision makers to pursue sustainable product design activities (Ramani et al. 2010).

For many products, the manufacturing stage is responsible for the greatest impacts during the product life cycle. Since product design dictates the manufacturing process, decisions made by product designers have the opportunity to significantly reduce these impacts. Thus, the need for a detailed manufacturing sustainability assessment coupled with a suitable decision support system is critical.

BACKGROUND AND PROBLEM DESCRIPTION

Faced with deficiencies in sustainability assessment and limited guidance during decision making, product designers lack the necessary decision support to compare and choose design alternatives on a sustainable manufacturing basis. Component manufacturing sustainability assessment is an area with potential for advancement that can be improved by selecting key sustainability metrics and developing models that capture product and process interactions. Sustainability assessment results can be used in conjunction with common decision analysis methods to more effectively support the decision making process. The following work aims to address these needs.

RESEARCH OBJECTIVES

The objective of the research herein is to assist decision making in component design for sustainable manufacturing. To meet this objective, key sustainability metrics will be identified and selected. Then, as a way to quantify the sustainability metrics, manufacturing process models will be developed. The resulting manufacturing sustainability assessment will be integrated with a design decision making process. Supporting methods will be chosen based on outlined criteria, but sustainability assessment data is compatible with many decision support methods. Finally, these methods will be applied for the case of a titanium component. This will demonstrate the process of component design for sustainable manufacturing and highlight important considerations that arise when designing for product sustainability.

THESIS OUTLINE

The research in this thesis is reported in the form of multiple manuscripts, and begins by identifying the need for improved assessment methods and decision guidance to assist component design for sustainable manufacturing. Chapter 2, the first manuscript, focuses on a method to assess the manufacturing sustainability of titanium components. Key metrics are identified and selected to fully address the economic, environmental, and social aspects of sustainability. Unit manufacturing process models are developed to relate product and process design variables, and then used to quantify the sustainability metrics. The assessment provides an accurate method for quantifying component manufacturing sustainability, but the most sustainable design alternative is still unclear.

Chapter 3, the second manuscript, concentrates on the support required to assist decision makers during component design for sustainable manufacturing. The sustainability assessment method from Chapter 2 is placed into the context of a design decision making process. A six step process is described and supporting methods are chosen to satisfy the requirements of each step. The process is demonstrated on a representative titanium component and the resultant benefit to decision makers is discussed.

In Chapter 4, the research from this thesis is reviewed and summarized. Results of the manufacturing sustainability assessment and its integration into a decision making process are then discussed. Afterwards, contributions from this study are identified and recommendations for future work are outlined. The common theme throughout the thesis is providing methods that assist decision makers in component design for sustainable manufacturing. The goal of the research reported is to demonstrate an approach for assessing manufacturing sustainability and to improve decision making for component design.

CHAPTER 2

SUSTAINABLE MANUFACTURING ANALYSIS FOR TITANIUM COMPONENTS

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ABSTRACT

Product designers are seeking effective ways to meet customer requirements, government policies, and internal business drivers for sustainability. Sustainable products encompass attributes including low, recyclable, and renewable materials use, low energy consumption, cost competitiveness, and consideration of safety and health concerns. Beyond product attributes, however, sustainable products are cognizant of a broader life cycle perspective, which necessitates consideration of manufacturing and supply chain issues during design. Current life cycle assessment tools are often deficient in assisting design for manufacturing efforts due to coarseness of available process data or even a lack of representative process models. In addition, such tools consider only the environmental impacts and do not account for broader sustainability measures. Research with a titanium component manufacturer is addressing these deficiencies. A unit process modeling-based method is described to assist in strategic decision making to balance cradle-to-gate economic, environmental, and social sustainability attributes. A set of sustainability metrics is defined and used as a basis for comparison of design alternatives. The method is demonstrated for analysis of titanium component alternatives resulting from design for manufacturing activities. It is shown that this method can assist engineers in developing more sustainable products.

NOMENCLATURE

C	Feed factor for power constant
d	Depth of cut
E	Machine tool efficiency factor
f	Feed rate
K_p	Power constant, “unit power”
P_m	Power at the motor
Q	Metal removal rate
t	Machine operating time
U	Energy consumed during machining
v	Cutting speed
V	Volume removed
W	Tool wear factor

INTRODUCTION

A changing market and growing list of regulations is forcing the manufacturing industry to simultaneously address all aspects of sustainability, i.e., economic, environmental, and social, in their activities and decision making. Businesses must minimize negative environmental impacts, conserve energy and natural resources, and ensure the well-being of their employees, communities, and consumers, all while remaining competitive in the marketplace.

Although a challenging objective, making sustainability a company priority has the potential of creating positive societal impacts while providing competitive market advantages through win-win scenarios and balancing life cycle costs and benefits. A growing population of informed consumers is placing value in environmental and social responsibility and creating demand for sustainable products. Besides increasing consumer-to-business demand, there is also increasing business-to-business demand for sustainable products (Sweeney 2010). Major retailers recognize that efficient use of materials and waste reduction efforts can result in significant cost savings, and they are demanding it from their suppliers.

Outside of classic economic and market considerations, environmental regulation is another force at play in driving manufacturers to consider impacts of their products more broadly. In some cases, retailers may require documentation from vendors to control waste, cut energy use, and reduce greenhouse gas (GHG) emissions (Sweeney 2010). While this can simply be a means to enhance business reputation in sustainable practices, it can also be the effect of government policy. For example, in the US, a recent executive order requires federal agencies to meet a number of energy, water, and waste reduction targets. One proposed target is for 95% of all applicable contracts to meet a set of sustainability requirements (Obama 2009). Many of these applicable contracts will come from private businesses, who must be aware of the requirements and implement strategies to meet them. Such policies attempt to provide top-down leadership in transforming industry. If a segment of industry has not experienced pressure to change, they soon will experience it as the trend towards increased sustainability policies is likely to continue.

To more adequately measure sustainability, standard and reliable assessment methods must be devised and implemented. While it is widely agreed that the three pillars of sustainability (economic, environmental, and social) must be simultaneously considered in sustainable product, process, and system development, it is not clear how to best quantify and compare among the separate aspects to assist in decision making. To assess the sustainability of a product, one must first define the sustainability metrics of interest, find ways to measure them, and gather the measurement values in each area. This is not a trivial process, due to the breadth of sustainability considerations. Current methods are deficient in the ability to assist design for manufacturing efforts due to the coarseness of available process data or even due to a lack of representative manufacturing process models to provide accurate, quantitative information to engineers and other decision makers. In addition, such decision support tools consider only the environmental impacts and do not account for broader sustainability measures.

The sustainability assessment method being developed under the research reported herein uses concepts of process modeling and environmental life cycle assessment (LCA), while also generating an expanded group of sustainability metrics to assist in design decision making in light of manufacturing-related impacts. In doing so, it is hoped that the uncertainties of environmental and societal impacts will be reduced, while also providing an approach to analyze manufacturing scenarios and improve design decision making. This method aims to assess the sustainability of component design and production and allow designers to make sustainable decisions upfront in the design process.

BACKGROUND

In order to compare sustainability of separate companies and products, standardization is required, and the use of publicly available indicator sets is beneficial. Many indicator sets are for reporting sustainability at a corporate level. Such sets include those specified by the Global Reporting Initiative (GRI) (GRI 2006), Dow Jones Sustainability Index (DJSI) (DJSI 1999), and ISO Guidelines on Environmental Performance Evaluation (ISO 14031) (Kuhre 1997). Only two sets, defined by the Organisation for Economic Co-operation and Development (OECD) Toolkit (OECD 2004) and Ford's Product Sustainability Index (PSI) (Schmidt & Butt 2006), have been identified that devised specifically for evaluating products (Feng et al. 2010).

Although sets of metrics have been devised that are useful across various domains and a spectrum of technical detail, none of provide the level of detail required to benefit simultaneous evaluation of product and process designs (Feng et al. 2010). Some design decisions are reflected in product level assessments, such as Ford’s PSI, but can only be used to compare different products or product iterations at a higher level. If an indicator set is to capture more detail, it will need access to more fully developed models of processes from across the product life cycle. Thus, one goal of this research is to enhance design for manufacturing activities by devising a process model-based approach for sustainability assessment.

Process models form the basis of LCA, which has become a common method for assessing environmental impacts associated with a product, process, or service across their life cycle. Typical impacts include global warming potential (greenhouse gases), acidification (soil and ocean), smog, ozone layer depletion, eutrophication, toxic pollutants, habitat destruction, and depletion of minerals or fossil fuels (Curran 2006). While work is ongoing, LCA currently does not adequately address social concerns, and such impacts must supplement environmental impacts considered by conventional LCA. The four iterative stages of Life Cycle Assessment can be seen in Fig. 1, which have been described by Reap et al (Reap et al. 2008).

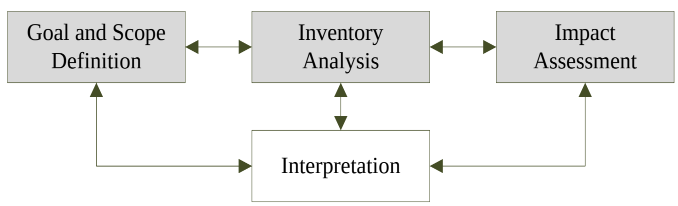

FIGURE 1. Four stages of life cycle analysis.

This representation of a product's life often leads to generalization of the manufacturing processes required. A high level life cycle description often does not incorporate sufficient manufacturing process detail to yield an accurate representation of manufacturing processes in product creation nor allow for concurrent design for sustainability. Further complicating analysis is the fact that similar components can be created using different processes.

Thus, early design choices can have substantial impacts on the resulting product sustainability performance. It has been shown that early stage product design establishes up to 80% of life cycle costs (Ullman 2009). A similar level of dependence on design decisions would be expected for other sustainability metrics across the life cycle, including environmental and social impacts. Thus, to assist in sustainability decision making for the manufacturing stage, measurable indicators must be identified.

Metric Development

When choosing metrics, there are a few key factors to consider. The metrics must provide sufficient coverage to all aspects of sustainability – economic, environmental, and social. The metrics must also provide sufficient detail within those aspects to give meaningful indication of performance. With a few exceptions, most current methods assess sustainability at a high level, targeting countries or organizations, and do not have enough detail to assess single products. Lastly, if the assessment will be used as a tool for comparison against other companies or products, the metrics must be commonly accepted or follow standard guidelines.

Despite the noted shortcomings of current sustainability assessment methods, a review of these methods and their areas of application gives insight into the critical factors that contribute to sustainability. Several indices target a single aspect of sustainability. For example, the Environmental Performance Index (EPI) measures the environmental impacts of entire countries (Emerson et al. 2010). The metrics are thorough and cover many of the subtle details regarding cause and effect of chemicals, ecosystems, the overall health of the earth and its living populations. However, with respect to humans, it only measures effects due to the environment such as air pollution and water availability. There are many environmental impact assessments in use and they provide a good resource for useful, commonly used metrics.

Another high level assessment method is the Dow Jones Sustainability Index (DJSI). Many are familiar with Dow Jones as it relates to financial performance, but given current market demands, it is not surprising that investors are interested in the ways that sustainability performance contributes to the value of a company. Over the years, Dow Jones has developed indices to evaluate performance in areas such as risk management, environmental reporting, labor practices, and many industry-specific concerns. The DJSI combines several of these indices to create one index that covers all three areas of sustainability (DJSI 1999). Understanding the triple bottom line sustainability of a company overall will provide investors with information to make investment decisions. On the other hand, consumers buy products, and must decide if an individual product itself is sustainable. Given the proper tools, manufacturers are in a position to provide this type of information to consumers.

Quantifying a metric requires selection of a measurable indicator for key parameters in a system. Indicators are used to demonstrate the status or performance of a system relative to a particular category (Rachuri et al. 2009). Besides being measurable, a meaningful indicator will be relevant, understandable, manageable, reliable, cost-effective, and flexible (Feng et al. 2010). It is important to note that interpretation must follow indicator quantification. Some metrics may impact multiple indicator values or, conversely, an indicator may require input from multiple system-related metrics (e.g., energy level consumed and energy source profile). Furthermore, an overall sustainability index must weigh separate indicators relative to each other, making compromises and seeking some user-defined balance. From a company perspective, this balance would be defined by company values, e.g., a company may pursue a green image an place higher value on environmental metrics.

Tools that can measure the sustainability of an individual product can help companies add value directly to a marketable item. Ford's Product Sustainability Index (PSI), for example, is used to measure the sustainability of individual vehicles. Indicators include life cycle global warming, life cycle air quality, sustainable materials, substance management, safety, and theoretical life cycle cost (Schmidt & Butt 2006). Issues regarding global warming and air quality are commonly seen in the high level assessments and rely on the same metric, mass of greenhouse gas (GHG) emissions. Other areas of concern common to all companies will be critical to defining sustainability indicators, but the actual metrics may be unique to the application or product being evaluated. Financial performance, for example, is an important indicator of economic sustainability. While a company might measure profits and losses, a product assessment will likely consider the life cycle costs and benefits. A review of current sustainability indicators gives perspective on the important areas to be considered, and is necessary to identify areas of manufacturing requiring different metrics to be accurately evaluated and compared.

The ability of a company to compare itself with market competitors or to known global leaders in sustainability has direct implications for increasing product value and company reputation through targeted improvements. The Global Reporting Initiative (GRI) provides a framework for measuring and reporting sustainability data. The guidelines are developed through a consensus among participants from global business, civil society, labor, academic and professional institutions (GRI 2006). It allows systematic consideration of each aspect related to sustainability and provides suggestions for reporting to facilitate a level of standardization. For areas specific to the manufacturing processes, GRI guidelines provide useful advice for metric selection. To select relevant metrics, one must consider the previously mentioned criteria across each of the aspects of sustainability as discussed below.

Economic Metrics

The capital and operating expenditures required to create a product directly affects economic performance of the manufacturer, but also affects economic systems at local, national, and global levels. Thus, product and process-related sustainability performance metrics should reflect the impact on the company, as well as the financial impacts on the broader economy. Thus, economic metrics are quantified in terms of money value (e.g., dollars). Financial performance is a familiar topic to engineers and other decision makers, being necessary to ensure competitiveness. Moreover, monetary data is straightforward to analyze and communicate to a diverse audience.

Environmental Metrics

The material and energy inputs and outputs connect a process to the external environment. Product performance should reflect the impacts on natural systems and their environmental compartments, including land, air, and water. In general, it is necessary to measure efficient use of inputs (materials, energy, and water) and responsible handling of outputs (emissions, effluents, and solid waste). Thermodynamic metrics account for the mass and energy requirements of industrial activities. They do not normally address the specific environmental consequences of the resource consumption. When thermodynamic outputs are compared to the inputs and reported in terms found in economics, such as return on investment or yield ratio, they take on a familiar form. Environmental metrics focus on chemical changes or hazardous conditions in the environment. They are not easily or reliably converted into quantitative ecological end points such as death, disability, or disease (Seager 2004). Instead, ecological metrics target the effects on living things and the interdependent functions of the natural environment. When the focus of a study is the health or population effects of a pollutant, they may be coupled directly with environmental metric. However, the relationship between a pollutant and an organism becomes critical since not all species react the same way. Additionally, at the ecosystem level, hazardous end points are more difficult to identify than they are in individual organisms (Seager 2004).

Social Metrics

The effects of the product design on the people directly and indirectly involved in production processes must also be considered in manufacturing sustainability assessment. At the very least, product performance should reflect the impacts on social systems due to labor practices, since these are the most closely related to production processes. While the presence of more subtle positive and negative social effects (e.g., community involvement, philanthropic investment, and health effects of air emissions) is evident, it is often unclear how social impacts can be measured or directly related to product attributes and process parameters. The development of such social metrics is a challenging task that must be undertaken in order for designers to be aware of the social implications of their works, and to support engineering decision making for product and process design.

The next section presents an approach that is being developed to assist engineers in the design for manufacturing role in making decisions on the basis of sustainability metrics, rather than simply cost. This work is based on a collaborative industry-university research project, and the initial work is demonstrated using an example from the titanium component manufacturing industry.

DESCRIPTION OF THE APPROACH

A manufacturing process flow is composed of a set of unit processes. To understand the effect of each process on the overall system, it is necessary to decompose the system and analyze the effects of each individual process. This effort can lead to the development of models of the processes to better understand the relationship between material and energy inputs and outputs, and the concomitant effect of changes to process parameters on sustainability metrics. Such process models thus can be used to account for the manufacturing variance due to the physical part design and the resulting process design (Zakarian & Kusiak 2000). In addition, process models can be descriptive and allow prediction of process performance under various scenarios, or facilitate optimization of desired decision variables.

Evaluating unit level effects on sustainability indicators would provide greater certainty regarding the areas that require improvement during manufacturing (Overcash et al. 2009). Predicted process performance can directly generate data and information that would feed into quantification of economic, environmental, and social metrics. In turn, these metrics will facilitate sustainability assessment. This approach is shown schematically in Fig. 2.

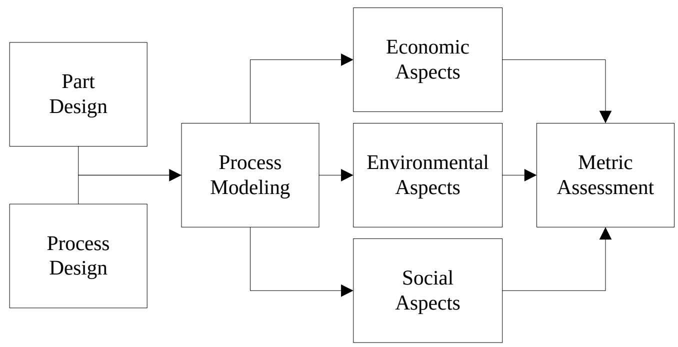

FIGURE 2. Approach to sustainable manufacturing metric quantification and assessment.

Relevant manufacturing variables established in the early design stages that effect sustainability metrics include material type and final product form. In this work, the primary variable introduced is the amount of material removed by the component manufacturer. This value is dependent on the form of input material supplied by the material processor, which is a consideration for design for manufacturing (DFM). Thus, choice of material form will have implications for supply chain sustainability. Relationships underpinning models are provided below for unit processes relevant to titanium component manufacturing using material removal as an input. In order to relate material removal to sustainability metrics values, the material removal rate must first be calculated (Groover 2010) as

$$Q = vfd \tag{1}$$

It should be noted that the model parameters are dependent on material type and are a process design consideration (equation variables are defined in the nomenclature section above). Material removal rate can be used to determine the machine processing time as

$$t = VQ \tag{2}$$

Machining time affects many process-related metrics including energy consumption and cost, labor cost, and use or waste of consumables, such as coolant and tooling bits. In order to calculate the energy consumption during the process, machining power can be calculated (Oberg 2008) as

$$P_m = \frac{K_p CQW}{E} \tag{3}$$

Power consumption and machining time can then be used to calculate the energy consumed during the process as

$$U = P_m t \tag{4}$$

To quantify other metrics for the production of a component, contributions are similarly computed and aggregated for other processes required. The machining energy, for example, is only one component of the total energy consumption for the entire process flow, while operating costs would be the sum of material, shipping, machining (coolant, tool, labor, etc.), and other incremental, unit costs. These relations, in turn, must be linked to assess the overall performance of a design, as well as comparing design variants.

DEMONSTRATION OF THE APPROACH

To demonstrate the approach described above and being developed by the authors, two scenarios for manufacturing of a representative titanium component, shown in Fig. 3, are introduced and compared. The two scenarios consist of different series of manufacturing steps due to changes in DFM strategy from an in-plant material efficiency perspective.

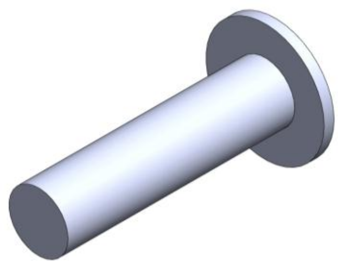

FIGURE 3. Representative titanium component.

The first manufacturing plan (Scenario 1) machines the component from a piece of square titanium billet, while in the second plan (Scenario 2) the raw material for the component is received as a round bar, and then machined to the same final geometry. As a result, primary processing by the supplier also varies. In the Scenario 1, an oversized billet is cut to length. In Scenario 2, the billet is first extruded to form a round bar and then cut to length. Figure 4 illustrates the representative initial billet, intermediate forms, and form of the final component under the two scenarios.

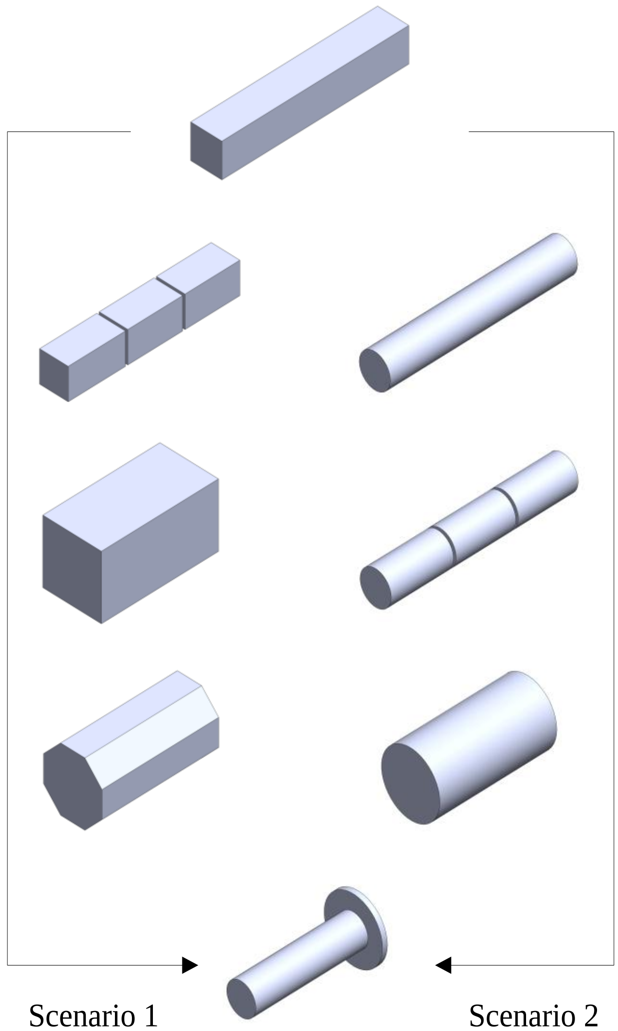

FIGURE 4. Stages of material removal for each manufacturing scenario considered.

While the part design is the same in both cases, the process parameters are quite different for each scenario, and will affect the sustainability performance for the manufacture of each part. Figure 5 shows the assumed process flow and material handling steps for both manufacturing scenarios.

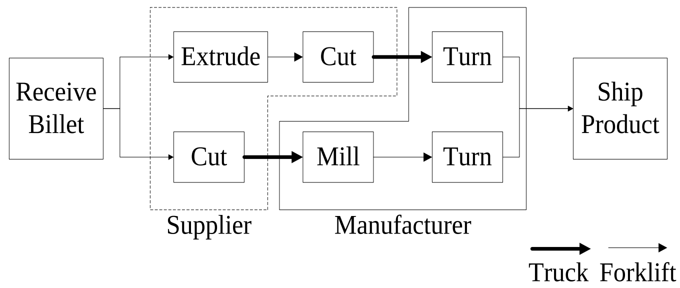

FIGURE 5. Process flow for two scenarios.

To facilitate comparison of the two scenarios using the approach described above, models were created for each of the following unit processes: truck transport, forklift transport, extrusion, band saw cutting, milling, and turning. Differences in flow configuration and material removal requirements were then evaluated using these unit process models. The differences were then compared using a set of selected sustainability metrics introduced below.

Selected Metrics for Sustainability Assessment

A set of sustainability metrics for titanium component manufacturing is being identified based on considerations discussed earlier and involvement of the industry partner. A subset of these metrics are reported in Tab. 1, and will be applied to compare the two scenarios described above.

TABLE 1. Selected sustainability metrics.

Aspect	Metric	Description
Economic	Operating cost	monetary expenses of production
Environmental	Material efficiency	proportion of initial raw material mass in end product
	Energy consumption	amount of energy used from direct and indirect sources
	Greenhouse gas emissions	masses of CO_2, CH_4, N_2O, fluorinated gases generated
	Total waste	total mass of outputs that are not part of the end product
Social	Acute injuries	number of process-related injuries

From the table, it can be seen that the metrics span the economic, environmental, and social aspects of sustainability. The metrics selected are those that are commonly understood, applicable to any manufacturing company, and easily measured and tracked – with the exception of greenhouse gas emissions. All can be directly estimated from a process model except acute injuries. Information is available from sources, such as the U.S. Bureau of Labor Statistics, that relates the type of manufacturing activity performed to injury rates. Knowing the time required for each process and handling step, the overall injuries for each scenario were predicted.

RESULTS AND DISCUSSION

The selected sustainability metrics were quantified for each of the manufacturing, material handling, and transportation processes previously described. For the purposes of comparison, numerical results were normalized and compared on a relative basis, as shown in Figs. 6 and 7. Scenario 2 outperforms Scenario 1 in most categories, including operating cost, material efficiency, total waste, and acute injuries. However, Scenario 1 consumes less energy and so, also emits fewer greenhouse gasses into the atmosphere.

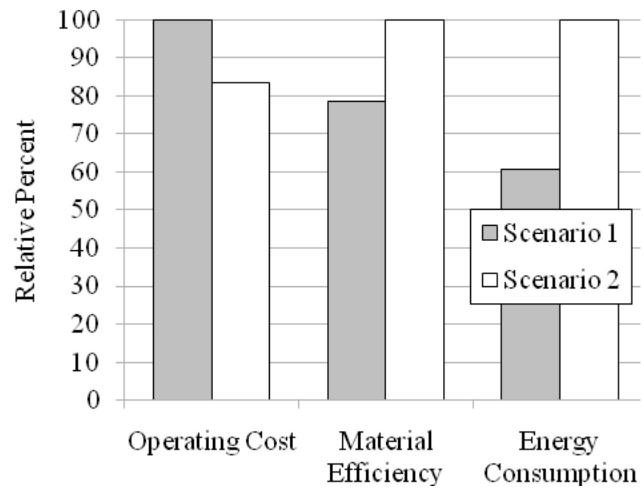

FIGURE 6. Relative comparison of cost, material efficiency, and energy use for each scenario.

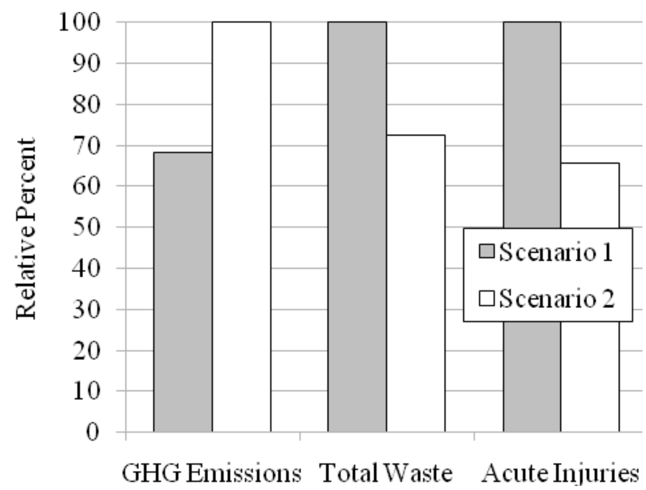

FIGURE 7. Relative comparison of GHG emissions, waste, and injuries for each scenario.

Thus, further analysis is required to determine the better option. Intuition would suggest that Scenario 2 is a better option, since the manufacturing process flow begins with a shape closer to the end product. This approach is much more efficient for the manufacturer. Indeed, the results show that Scenario 2 has better performance in the operating cost, material efficiency, and waste categories. However, the metric results indicate that some of the efficiency is simply displaced upstream in the product life cycle. More overall energy is required for Scenario 2, and the resulting GHG emissions are higher as well. In this case, the extrusion process to form the round bar stock required more energy than the additional machining required for Scenario 1. Thus, the increase in economic performance (lower manufacturing operational cost) is tied to an increase in overall environmental impact, which is externalized by both the material processor and manufacturer.

This example highlights the significance of primary processing variations, and the importance of assessing impacts of a design from a sustainability perspective across the entire supply chain. Moreover, correlations between tradeoffs are not always straightforward. With regard to social impacts, for example, occupational injury rates can vary greatly depending on the working environment throughout the supply chain. The estimated injuries incurred during production are not only dependent on processing time, thus further refinement of unit process models may be necessary in some cases to better reflect the actual situation and provide valid, meaningful results.

CONCLUSION

Individual and business consumers are demanding more sustainable products, while internal and external policies are driving companies toward sustainable manufacturing initiatives. Many factors that contribute to the sustainability of a product, encompassing economic, environmental, and social aspects, as well as a multiplicity of material processing, manufacturing, and transportation processes, among others, across the life cycle. Accurate assessment of sustainability metrics at the design stage to support engineering and business decision making requires detailed consideration of product attributes and process parameters. This type of investigation can be assisted through the development of predictive models of unit manufacturing processes that can estimate variations in energy requirements and material inputs and outputs based on modifications to product and process designs.

In the research presented, it was found that this approach ultimately cannot conclude which design variant is more sustainable from a manufacturing perspective. The approach does, however, increase the resolution of process models compared to common environmental impact assessment techniques. Thus, it allows the designer to investigate tradeoffs that extend beyond the scope of the product's final form, and to consider cradle-to-gate sustainability impacts of similar designs or closely related processing scenarios.

Sustainability performance comparisons are useful for gaining perspective on potential impacts and in considering and formulating a company value structure. Ongoing work aims to further develop the presented approach and create a method to combine metrics into a single sustainability index in a way that provides flexibility for customization of specific performance targets based on company values. This work will form a design decision support framework that can be utilized by manufacturers from across a spectrum of value structures ranging from fiscal to ecological to civic responsibility.

ACKNOWLEDGEMENTS

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CHAPTER 3

INCREASING THE UTILITY OF SUSTAINABILITY ASSESSMENT IN PRODUCT DESIGN

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ABSTRACT

Design engineers are seeking effective ways to make informed decisions regarding product sustainability. Several attempts have been made to identify sustainability metrics, assess sustainability impacts, or support decisions based on sustainability, but none fully support product designers in a way that provides for robust sustainable manufacturing decisions. Sustainability assessments can provide quantitative performance data for design variants, but in many cases, the most sustainable alternative remains uncertain. Adequate support for sustainable manufacturing activities should address each step in the decision making process with enough detail to accurately capture manufacturing impacts. The methods selected throughout the process should consider the specific needs of sustainability related issues and provide transparent, easily understood, efficient solutions. A process is outlined to assist product designers and a demonstration of the process is given for the production of a titanium component to discuss its utility.

NOMENCLATURE

P_m	Power at the motor
Q	Metal removal rate
U	Energy consumed during machining
V	Volume removed
a_n	Alternative number n
w_k	Weight assigned to reflect the importance of criteria k
K	Total number of sustainability indicators
$V(a_n)$	Overall value of alternative a_n
$v_k(a_n)$	Value score reflecting the performance of alternative a_n on criterion k

INTRODUCTION

Businesses are recognizing the value of environmental and social responsibility as various market drivers are creating demands for sustainable products. Thus, product designers are in need of effective methods to evaluate design alternatives on a sustainability basis. It is widely accepted that over 70% of final product costs are determined during early product design (Laperrière & El Maraghy 1992), and some believe it is closer to 80% (Wang Zhenwei & Hui Li 2009). In particular, implementation of design for manufacturing and assembly (DFMA) techniques have been shown to reduce life cycle costs significantly (Boothroyd et al. 1994). A similar dependence on design decisions would be expected for other sustainability metrics across the life cycle, including environmental and social impacts. Since early design choices can have substantial impacts on the resulting product sustainability performance, it essential to support good decision making. While sustainability assessment provides additional information regarding the impacts, it does not help the designer make tradeoffs when the outcome is unclear. Additional support is needed to help organize and analyze the data in a way that improves understanding of alternative performances and the risks associated with the final decision.

Several attempts have been made to identify sustainability metrics, assess sustainability impacts, or support decisions based on sustainability, but there are none that fully support product designers for sustainable manufacturing decisions. Often the metrics and assessments do not address sustainability in entirety or in enough detail to be used for manufacturing impacts. Many of the previous efforts to quantify sustainability metrics are targeted at corporations. Such indicator sets include those specified by the Global Reporting Initiative (GRI) (GRI 2006), Dow Jones Sustainability Index (DJSI) (DJSI 1999), and ISO

Guidelines on Environmental Performance Evaluation (ISO 14031) (Kuhre 1997). Corporate reports do not contain the detail required to assess the sustainability of individual products. In response to this need, efforts have been made to more accurately evaluate specific products. Some examples include the Organisation for Economic Cooperation and Development (OECD) Toolkit (OECD 2004) and Ford's Product Sustainability Index (PSI) (Schmidt & Butt 2006). This trend of increasing detail in sustainability assessment continues as new limitations are discovered and areas for improvement are identified. Another major weakness exists in the ability of assessment to account for the manufacturing variation caused by changes to the product design, as none of the existing methods provide the level of detail required to benefit simultaneous evaluation of product and process designs (Feng et al. 2010). In a previous work, the authors presented a method that supported design for manufacturing activities by using a process model-based approach and included economic, environmental, and the often neglected social component of sustainability (Eastlick et al. 2011). Although the method increased the resolution of metrics compared to common impact assessment techniques, it had limited ability to suggest which design variant was most sustainable. Sustainability metric valuation only accounts for a portion of the decision making process and must be used in combination with other essential elements.

The decision making process is a well-studied area of research, and there are many frameworks available to guide decision makers depending on the industry or domain of concern. Sustainability related decisions have specific needs that should be considered when choosing decision support techniques. The diversity of stakeholders involved in sustainability issues requires clear and effective communication in order to understand the problem and reach a mutual consensus. Azapagic and Perdan (2005a & 2005b) integrated sustainability issues into one of these frameworks and provided structure for those who are facing challenges making decisions related to sustainability. They stressed the importance of providing transparent, easily communicated methods for analysis. Decision makers' preferences should be reflected in the ranking of alternatives. Then, to aggregate preference and assessment data, multi criteria decision analysis (MCDA) can be applied. Sensitivity analysis and uncertainty management are also critical to understanding the results and creating buy in from the decision makers (Triantaphyllou 2000; Azapagic & Perdan 2005b). Employing MCDA and investigating the results thoroughly provide necessary decision support, but in the context of sustainability it is critical that methods are understood by all parties involved. Perspectives, knowledge, and values of sustainability are dynamic and often uncertain or difficult to quantify. This creates additional risk associated with design decisions and requires that the decision support system instills confidence in the user and minimizes the barriers that may exist with new tool adoption.

With that in mind, a process is outlined to assist product designers in component design for sustainable manufacturing. Adequate support for sustainable manufacturing activities should address each step in the decision making process with enough detail to accurately capture manufacturing impacts. The methods selected throughout the process should consider the specific needs of sustainability related issues and provide transparent, easily understood, efficient solutions. A demonstration of the process developed as part of this work is given to discuss the utility of such activities.

BACKGROUND

Although recent efforts in sustainable design have improved the information available to decision makers, most assessment methods fail to address all of the critical needs. In order to fully support product designers, detailed sustainability assessment must be placed into the context of the design decision making process.

Decision Making in Sustainable Product Design

The process of making a decision should be approached carefully in a step by step manner (Hill 1980). During product design, the decision making process includes criteria selection and alternative formation, criteria weighting and alternative assessment, and an overall ranking of alternatives (Otto & Wood 2000; Ullman 2009; Hill 1980). If the goal is to choose the most sustainable design alternative, the process can be expressed as follows:

Step 1. Generate Design Alternatives
Step 2. Select Sustainability Metrics
Step 3. Determine Relative Importance of Metrics
Step 4. Evaluate Alternatives Relative to Metrics
Step 5. Generate Alternative Rankings
Step 6. Analyze Rankings

Despite being a common procedure, the decision making process is not attendant with sufficient detail for current sustainability assessments to be used for sustainable product design. The Environmental Performance Index (EPI) for example, assesses the environmental performance of countries (Emerson et al. 2010). The metrics in this method do not include economic or social aspects of sustainability and lack the detail to capture manufacturing impacts. Similarly, Life Cycle Assessment (LCA) places emphasis on environmental aspects and, though it is product focused, it is not well-suited for manufacturing activities (Curran 2006). In previous work, the authors provided a method to address deficiencies in sustainability metrics and product manufacturing assessment (Eastlick et al. 2011). The method assessed manufacturing sustainability, but provided no support for metric weighting or alternative ranking.

Some methods approach sustainable product design from the decision support perspective, but fail to provide sufficient manufacturing sustainability assessment. For example, Kaebernick explored several methodologies and decision tools in an approach towards product development for sustainable manufacturing, but only looked at important sources of environmental impacts of a product (Kaebernick et al. 2003). Choi incorporated business aspects to LCA and used the Analytic Hierarchy Process (AHP) to evaluate product systems (Choi et al. 2008). Here again, there are deficiencies in both level of model detail and metric coverage. Haapala uses process modeling to provide sufficient assessment detail, but only calculates the waste production and energy consumption (K. Haapala et al. 2004). In this case, the method did not address economic or social considerations and did not provide the support to decide among multiple design alternatives. Howarth and Hadfield took a unique approach to product sustainability assessment. They identified major social, economic, and environmental risks and benefits, which were then scored by the decision maker to assess the product, the manufacturing company, and the manufacturing site (Howarth & Hadfield 2006). All three areas of sustainability were addressed, but the scoring was subjective and product assessment was not based on individual manufacturing impacts. Azapagic and Perdan (2005a & 2005b) provide an integrated decision support framework that fully addresses the decision making process, but leaves the selection of methods to the decision maker. However, the perspective gained from investigation of the framework reminds the decision maker of other important considerations related to the process. After the alternatives have been ranked, the results should be examined to ensure the decision maker understands tradeoffs that have been made. A ranking analysis step should be included to allow the decision maker gain insight from the results. The analysis provides an opportunity to understand the behavior and shortcomings of the model and learn how design decisions affect product sustainability. Azapagic and Perdan (2005a) also suggested that there are other critical factors to be considered when supporting sustainability decisions.

Decision Support for Sustainable Design

Addressing the challenges of sustainable development requires an emphasis on studying and understanding the relationships between parts of the system and the functioning of the whole system (Azapagic & Perdan 2005a). Thus, decision support systems should serve as effective learning tools. In particular, the user should be able to gain a better understanding of the critical model and parameter uncertainties (Basson & Petrie 2007). Sustainability metrics, assessment models, importance values, and decision analysis methods are critical aspects of the performance ranking that the decision maker may choose to explore. A more complete understanding of the model that ranks a design alternative will lead to a better understanding of the risk involved with the decision.

Sustainable development involves a large number of stakeholders with multiple, often conflicting, objectives (Azapagic & Perdan 2005a). Furthermore, improving weaknesses in the model may require expertise in an area with a vastly different technical background. Both of these facts support the notion that selected decision analysis techniques should be easily understood and communicated to a wide audience. The information gained should be used to create discussion that leads to a better understanding of the problem. Many have agreed that factors related to simplicity (e.g., easy to use, quick, easy to understand, and transparent logic) are of high importance to decision making (Ullman 2006; Hill 1980; Sprague & Carlson 1982). Azapagic and Perdan (2005b) reiterate this idea and suggested using the following principles to guide the selection process: ease of use by non-experts, transparency of the method logic, realistic time and human resource requirements for analysis, and ability to provide an audit trail. These qualities may also encourage industry acceptance and usage of such techniques because, despite the increase in customer concerns regarding sustainability, few would argue that it is as big a driver as price and quality (Harris 2012). These uncertainties regarding the value of sustainability make it risky for engineers to spend valuable time on sustainability assessment. If product designers are going to implement a sustainable manufacturing decision making process, it must possess low barriers for adoption. To meet the needs of product designers, approaches toward design for sustainable manufacturing should address each step in the decision making process outlined above, provide a way to analyze the ranking, and employ methods that are transparent and fosters communication throughout a wide range of viewpoints. In addition, to increase the likelihood of industry adoption, the method should be effective, concise, and require minimal effort.

DESCRIPTION OF THE APPROACH

Choosing the alternative that best satisfies the design criteria requires completing the steps outlined in the decision making process presented above, and then carefully examining the results. The six step process outlined previously in the text will be used to rank the alternatives based on their ability to satisfy the manufacturing sustainability criteria. After the alternatives are ranked, they will be examined to fully understand the implications of the results. Since the product designer is responsible for developing the design alternatives and resulting manufacturing process design required for Step 1, the description of the approach will begin at Step 2.

Manufacturing Sustainability Assessment

A manufacturing sustainability assessment method is used to fulfill the needs of Steps 2 and 4. The method uses sustainability metrics that cover economic, environmental, and social aspects of sustainability and that provide enough detail to capture manufacturing impacts. A process modeling approach is used to evaluate alternatives based on their manufacturing process variation (Eastlick et al. 2011). Process modeling is used to relate product and process design variables to selected sustainability indicators and allows for detailed, accurate manufacturing assessment during product design (Kellens et al. 2011a; Kellens et al. 2011b). By decomposing the manufacturing process flow into smaller, unit manufacturing processes as shown in Fig. 8 (NRC 1995), it is possible to develop mathematical expressions that relate input variables to output streams (Bandivadekar et al. 2004).

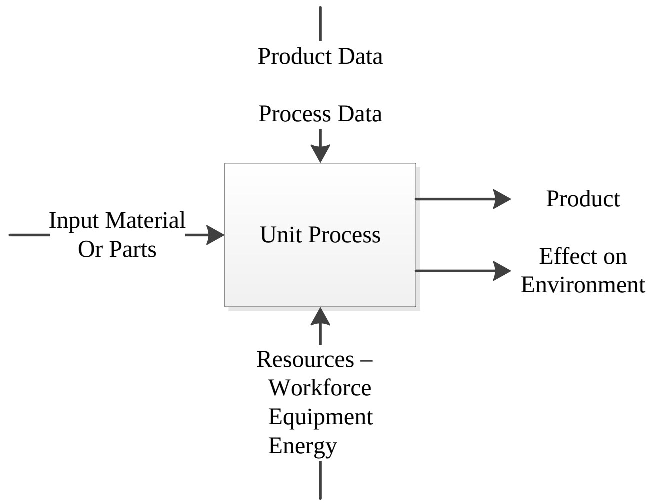


FIGURE 8. Unit process model.

Sustainability metrics must be identified, their presence located within the flows of the process model, then related to design inputs by mathematical equations. In this way, it is possible to relate design choices to sustainability performance. Equation 5 provides an example of how energy used during a machining process can be related to the volume of material removed, which is a design affected input.

$$U = P_m V Q \tag{5}$$

Since the material removal rate is affected by material type, the energy consumption can also be related to material choice, another design affected variable. The previously developed method employs generalized manufacturing process models (Eastlick et al. 2011), but a company may choose to develop and apply empirical models based on direct process measurements when more accurate results are desired. A unit process model contains several functional relationships to quantify the selected sustainability metrics. These unit process models can be linked in accordance with the overall process flow. The modeling results can be used to generate aggregated metric values, but the overall system performance is still unclear. In order to manage sustainability tradeoffs, relative importance of criteria must be specified.

Preference Modeling

Accurately quantifying the relative importance of metrics can be challenging since in many cases, value judgments are incompletely formed or do not exist (Azapagic & Perdan 2005a). There are several ways to elicit the preferences of the decision maker, but a direct weighting method will be used for Step 3 based on the need for a transparency of logic and minimal time requirements. The ability to make quick alterations to the preference model enables the decision maker to experiment with several value schemes and understand how values affect the ranking of design alternatives. Specifically, the fixed sum importance method will be used. Each criterion is given a score that reflects how important it is and the sum of all weights must equal a fixed number. This method has been shown to be an effective way to for a decision maker to consider criteria tradeoffs and relative importance (Ullman 2006). A common technique for organizing the relative importance values of hierarchical criteria like sustainability metrics, is to form a value tree. In this study, a value tree is populated by direct input and serves as a simple model to establish a benchmark. If more advanced methods of preference elicitation are desired, the details to several methods are readily available (Triantaphyllou 2000). After establishing relative importance of criteria, a decision analysis technique can be used to generate alternative rankings.

Decision Analysis

Step 5 requires a method to rank alternatives based on the sustainability assessment and preference model. Decision analysis may be as old as recorded history, and MCDA is one of the most well-known branches of decision making (Triantaphyllou 2000). As a result, there are many analysis techniques to choose from. Recognizing that design alternatives are discrete, the number of criteria to manage is high, and the assessment values are cardinal, guides the search slightly, but there are still many good options available and compatible with the manufacturing sustainability assessment described above. To narrow the list of possibilities for this study, recall the previously outlined needs for sustainability related decisions. To facilitate effective communication and problem understanding from diverse viewpoints, the technique must be transparent and easy to use by non-experts. In addition, to improve the likelihood of industry application, the technique must be quick and easy to implement. Thus, the simplest MCDA methods should be considered first. However, in cases where more sophisticated MCDA methods are advantageous, software packages can be used to satisfy time and human resource requirements (Azapagic & Perdan 2005a; Azapagic & Perdan 2005b). Four MCDA methods will be investigated in this work: one simple method applied using Excel and three advanced methods applied using commercial software packages.

Weighted sum models are commonly used because of their simplicity and transparency to non-expert users (Triantaphyllou 2000; Azapagic & Perdan 2005b; Wang et al. 2009). The general equation for determining the weighted sum can be seen in Equation 6 (Azapagic & Perdan 2005b).

$$V(a_n) = \sum_{k=0}^{K} w_k v_k (a_n) \tag{6}$$

For each design alternative, individual sustainability metric assessment values are multiplied by the corresponding relative importance, and then summed to generate an overall ranking value. Excel is used to perform the calculations and to create charts for communicating results and visualizing data. The three software tools investigated include: OnBalance which uses Multi-Attribute Value Theory (MAVT) (Quartzstar 2010), Logical Decisions which offers MAVT or AHP (Logical Decisions 2012), and Accord™ Manager which uses Bayesian Decision Theory (Robust Decisions 2012).

It is important to remember that MCDA is merely a tool that organizes information in a new way, improves the understanding of the problem, and helps the decision maker arrive at a good decision. Regardless of the method, it is neither the MCDA models nor the decision support frameworks, but the decision makers who make the decision (Azapagic & Perdan 2005b). Thus, exploration of the critical areas is necessary in order to fully understand the ranking results.

Ranking Analysis

As is true with most decisions, and especially those based on sustainability, the amount of benefits, costs, and other outcomes that will be realized is uncertain (Nutt 2002). Step 6 is a stage in the process where sensitivity and uncertainty analysis are commonly applied. Analysis can guide the decision maker to the best alternative or to areas of the model that require improvement. A sensitivity analysis essentially reworks the decision analysis procedure for some extreme preference values (Hill 1980). Scenario analysis is a simple method used for investigating extreme weightings. Although it does not explicitly model the likelihood of different scenarios happening (Azapagic & Perdan 2005b), it does provide a way to investigate sensitivity of the alternative rankings to changes in preference values. Scenario analysis is sometimes criticized for its simplicity and its inability to identify the most critical parameters, but is regularly used in industry to investigate model robustness (Börjeson et al. 2006). It satisfies the criteria of being simple, quick, transparent, and familiar to industry. It has also been shown to be useful for conditions where uncertainty is high, industry has experienced, or is about to experience, significant change, and strong differences in opinion exist (Schoemaker 1991) – all conditions that relate to sustainability. In addition, scenario analysis is independent of the MCDA method and can be applied in the same manner for the four methods described previously. Therefore, scenario analysis will be the method to gain insight on the ranking robustness and the presence of uncertainty. However, it is important to note that other sensitivity analysis methods are compatible with the process outlined above and may be used if desired.

Decision making is not simply a technical process which reduces to the choice of the right MCDA technique. In fact, many MCDA methods are compatible with the manufacturing sustainability assessment described above. The success of the decision making process depends on effective design of social processes within which the technical analysis is structured and conducted (Azapagic & Perdan 2005b). Methods that are well understood, such as those investigated in this study, enable decision makers to look beyond the methodology details and understand the behavior of the system.

DEMONSTRATION OF THE APPROACH

A design for manufacturing (DFM) case of a titanium component is used to demonstrate the six step decision making process described above. The approach aims to provide the necessary detail, breadth, and analysis capability to support component design for sustainable manufacturing.

Step 1. Generate Design Alternatives

Two scenarios for manufacturing of a representative titanium bearing housing, shown in Fig. 9, are introduced and compared.

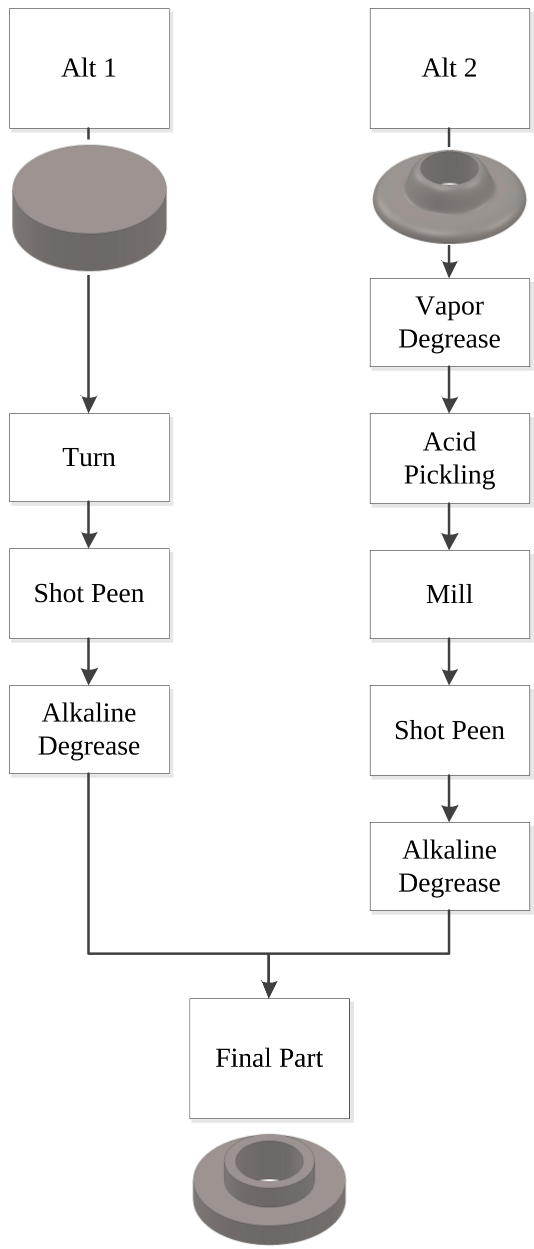


FIGURE 9. Process flow for two design alternatives of a titanium component.

The two design alternatives consist of different manufacturing process flows due to changes in DFM strategy from a sustainability perspective. The first manufacturing plan (Alt 1) machines the component from a piece of round titanium bar stock, treats the surface with a shot peening operation, then cleans the part with a degreaser. The second plan (Alt 2) starts with a near net shape forging, prepares the part for inspection with a degreasing and an acid pickling process, machines the part to the final geometry, and finishes with shot peening and degreasing.

Step 2. Select Sustainability Metrics

A set of sustainability metrics are provided based on previous work by the author and are shown in Tab. 2 (Eastlick et al. 2011).

TABLE 2. Relative importance of selected sustainability metrics.

Category	Weight (%)	Aspect	Weight (%)	Metric	Weight (%)
Economic	40	Economic Performance	40	Operating Cost	40
Environmental	30	Materials	6	Input Material Waste	6
		Energy	6	Energy Consumption	6
		Water	6	Water Use	6
		Emissions	6	Greenhouse Gas Emissions	6
		Waste	6	Total Waste	3
				Hazardous Waste	3
Social	30	Employment	15	Average Wage	15
		Occupational Health And Safety	15	Acute Injuries	5
				Lost Work Days	5
				Chronic Illnesses	5

While additional relevant sustainability metrics have been identified and implemented into the decision making framework in collaboration with an industrial partner, this subset of metrics is selected to account for all three aspects of sustainability in this demonstration.

Step 3. Determine Relative Importance of Metrics

The fixed sum importance method is used to populate a value tree for the baseline scenario. A value tree is used for the hierarchical organization of importance weightings and is expressed as a table (Tab. 2). First, the economic, environmental, and social categories are assigned importance values that sum to 100%. Next, to obtain aspect importance values, the category value is divided by the number of aspects it contains. The metric importance values are obtained in a similar way. The decision maker is able to assign relative importance weightings as appropriate for their judgment or for the values of their organization. In the end, metric values within a category should sum to the category value. The sum metric values across all categories should sum to 100%.

Step 4. Evaluate Alternatives Relative to Metrics

For both alternatives, the selected sustainability metrics are quantified for each process in the process flow. Inputs used for sustainability assessment can be seen in Tab. 3.

TABLE 3. Sustainability assessment inputs.

Scenario	**Alt 1**	**Alt 2**
Initial Weight (lb.)	11.45	5.77
Final Weight (lb.)	5.47	5.47
Enclosed Volume (in.^{3})	91.13	128.00

Initial part shapes are formed using different raw material production processes which are also specified and accounted for in the assessment method presented in previous work by the authors (Eastlick et al. 2011).

Step 5. Generate Alternative Rankings

The raw assessment results (from Step 4) are combined with the relative importance values (from Step 3) in Excel according to the weighted sum method shown in Equation 2. In addition, the assessment and importance values are used as inputs for analysis by three commercial software programs. Free versions of the software, as well as supporting tutorial documents, can be obtained through company websites (Quartzstar 2010; Logical Decisions 2012; Robust Decisions 2012).

Step 6. Analyze Rankings

Three weighting scenarios are used in the ranking analysis. Each scenario places emphasis on a different sustainability category and thus represents an unbalanced set of values. Relative importance values for aspects and metrics are obtained using the fixed sum importance method as described for Step 3. Table 5 contains the category level importance values used for the scenario analysis.

TABLE 4. Relative importance of sustainability metrics for scenario analysis.

Category	**Category Weighting (%)**		
	Scenario 1 (S1)	**Scenario 2 (S2)**	**Scenario 3 (S3)**
Economic	80	10	10
Environmental	10	80	10
Social	10	10	80

Scenario 1 (S1) represents a situation where the importance weighs heavily on economic metrics. The remaining two scenarios (S2 and S3) represent high importance on the environmental or social sustainability categories, respectively.

RESULTS AND DISCUSSION

Two DFM alternatives were evaluated on a sustainability basis by following the six step decision making process previously described. Alternative process flow designs were introduced in Step 1. Steps 2 and 3 resulted in a list of sustainability metrics with baseline relative importance values. In Step 4, metric values were quantified using a process based modeling approach. Figure 10 shows a subset of the selected metrics to provide an example of assessment data.

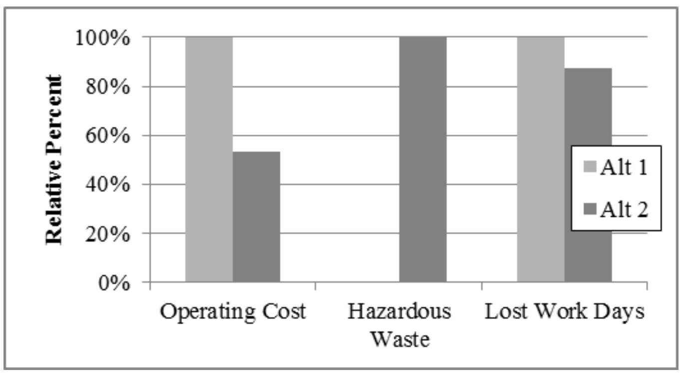


FIGURE 10. Relative comparison of cost, hazardous waste, and lost work days for each scenario.

For ease of comparison in the figure, numerical results for the alternatives were normalized on a relative basis. Alt 2 outperforms Alt 1 in Operating Cost and Lost Work Days, but creates more Hazardous Waste. At this point in the process, it is not clear which alternative is more sustainable, which confirms the need for further analysis to support decision making.

Assessment results were combined with relative importance values using the four software tools previously described (i.e., Excel, OnBalance, Logical Decisions, and Accord™ Manager). Performance rankings from the weighted sum method are shown in Fig. 11.

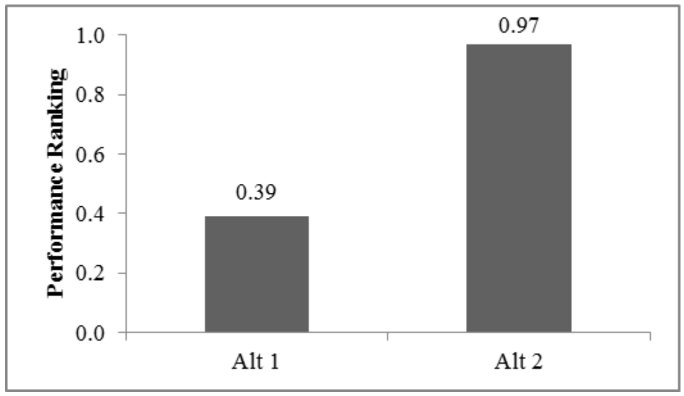


FIGURE 11. Performance ranking using the weighted sum method.

A higher ranking correlates to a more desirable alternative and the results suggest that Alt 2 is a clear winner. However, as mentioned previously, the ranking should not be accepted until the contributing factors are better understood.

The commercial software packages used to apply advanced MCDA methods did not meet the criteria established above for this study. Manual input of sustainability assessment data resulted in substantial time and human resource requirements and was prone to errors. In addition, limited access to ranking calculation data resulted in less transparency and limited ranking analysis. Analysis using Accord™ Manager is shown to demonstrate the limitations encountered when using commercial software tools. A higher satisfaction correlates to a more desirable alternative and again, results favor Alt 2 (Fig. 12).

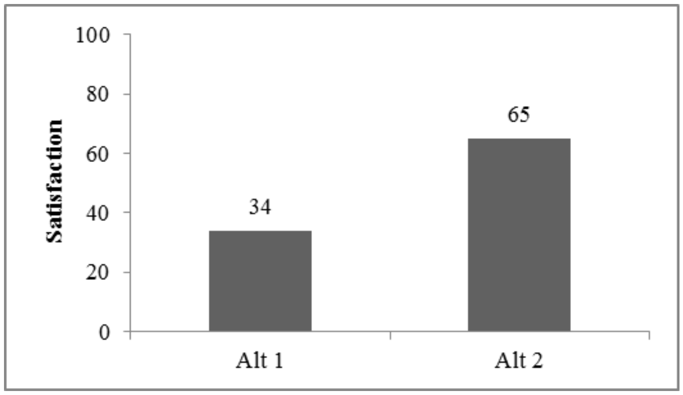


FIGURE 12. Satisfaction ranking using Accord™ Manager.

Ranking results should not be accepted until the contributing factors are better understood. Thus, rankings were inspected in greater detail using the methods in Step 6. Results of the three scenarios using the weighted sum method can be seen in Fig. 13.

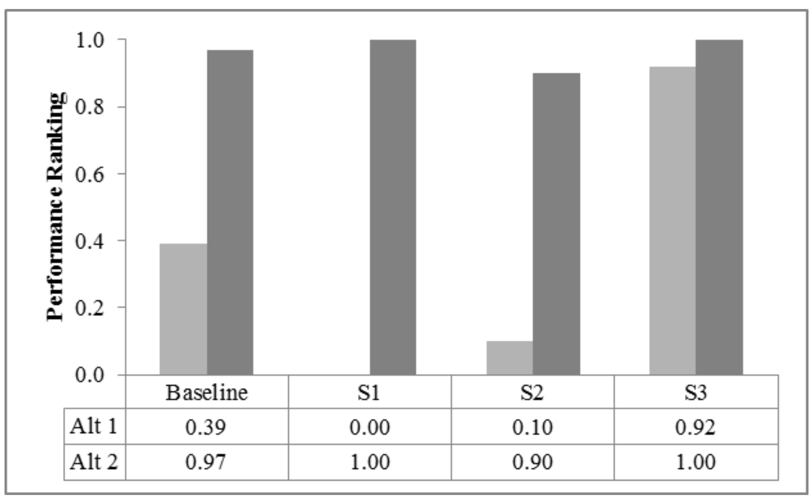
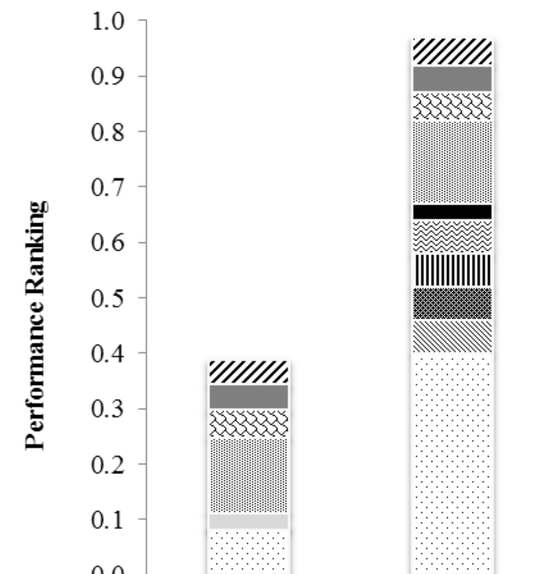


FIGURE 13. Performance ranking for each scenario using the weighted sum method.

The results of the scenario analysis show that Alt 2 outperformed Alt 1 in each case. At this point, deciding that Alt 2 is a more sustainable alternative may be a reasonable conclusion. However, if the decision maker is still in doubt, it is possible to further inspect the data and look at the specific contributions performance score. Figure 14 shows how each metric contributed to the overall performance ranking when using the baseline preference model seen in Fig. 11.



	Alt 1	Alt 2
Chronic Illnesses	0.044	0.050
Lost Work Days	0.047	0.050
Acute Injuries	0.049	0.050
Average Wage	0.135	0.150
Hazardous Waste	0.030	0.000
Waste to Landfill	0.000	0.030
GHG Emissions	0.000	0.060
Water Use	0.000	0.060
Energy Consumption	0.000	0.060
Input Material Waste	0.000	0.060
Operating Cost	0.082	0.400

FIGURE 14. Sustainability metric contributions to the weighted sum performance ranking.

The Operating Cost contribution to Alt 2 is one area that stands out as a primary contributor to its performance. The value of this contribution alone is large enough to outperform Alt 1, suggesting that good performance in the economic category can potentially compensate for poor performance in other areas. Whether compensation is acceptable or not and if so, to what degree, is an ethical question that the decision maker must consider (Azapagic & Perdan 2005b). Thus, it may be necessary to explore the Operating Cost contribution in more detail. The methods used to rank the alternatives (i.e., weighted sum, fixed sum importance, and process model based sustainability assessment) affect the contribution and can be reviewed. For example, closer examination of the sustainability assessment results show that Operating Cost was driven by input material quantities. If the decision maker decides this is a result of modeling inaccuracies, the process model can be revised. In addition, the preference model has one economic metric resulting in all 40% of the category weighting being directly transferred to the Operating Cost metric weighting. The decision maker can consider the appropriateness of the selected metrics. Thus, new metrics may be identified and quantified. These activities can be continued until the decision maker understands and agrees with the performance rankings or finds an area in the model that needs to be refined. Although the most sustainable alternative may initially be in doubt, the process of employing the weighted sum method provides a way to navigate and improve uncertain areas of sustainability the assessment.

Scenario analysis was also conducted using Accord™ Manager using the three scenarios previously described. Results of the three scenarios can be seen in Fig. 15.

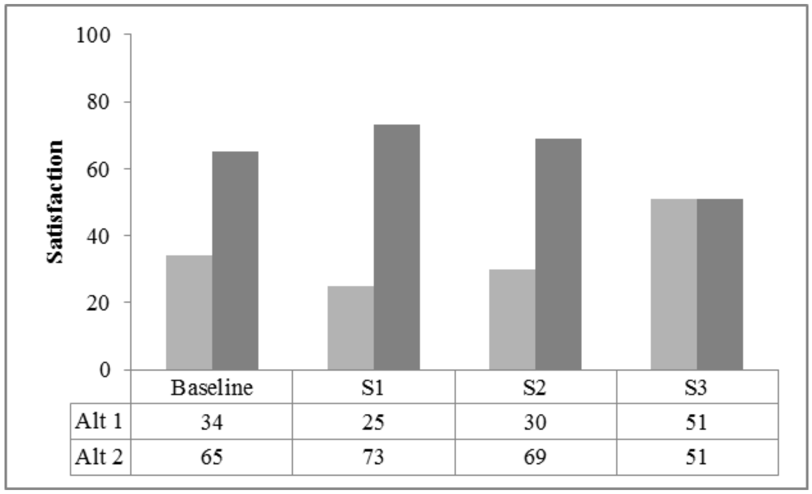


FIGURE 15. Satisfaction ranking for each scenario using Accord™ Manager.

The results show that Alt 2 does not always yield the highest satisfaction. Scenario 3 results in equal satisfaction for both alternatives. In the previous example using the weighted sum method, the decision maker was able to investigate the details of the ranking calculations and work towards making a decision. However, the same type of analysis is not possible using Accord™ Manager. Thus, a similar investigation would begin with the raw assessment data and might lead to identifying model weaknesses, but the opportunity to learn about the impact of preference values on the final decision is lost. The software does have the ability to make suggestions regarding “what to do next.” In this case, it suggests “increasing the knowledge about Operating Cost for Forging” and “developing better and more differentiated alternatives.” This is a useful feature of the tool, since it encourages the user to find a way to further differentiate the alternatives, to avoid a poor decision or indecision, but lack of transparency leaves the decision maker disconnected from the factors that drive the satisfaction ranking.

This example highlights the importance of transparency in methods used to evaluate the sustainability of component manufacturing. It enables the questioning and investigation that must occur for designers to understand how sustainability relates to design decisions. Moreover, it shows that currently available software programs may decrease transparency and inhibit full understanding of the impacts of manufacturing process and metric related influences on the final decision.

CONCLUSION

Product sustainability is difficult to measure, but sustainability assessment can provide useful information to design decision makers. Improvements in manufacturing sustainability assessment provide more detailed quantitative performance data for design variants, but assessment results alone are not enough to support decisions. The entire sustainable design decision process must be addressed in order fully support component design for sustainable manufacturing. A six step process was described and demonstrated for a representative titanium component. A detailed manufacturing assessment based on process modeling was used to quantify the economic, environmental, and social metrics for two DFM alternatives. Simple methods with transparent logic were used to complete the design decision making process. Preferences were determined using a fixed sum method. Decision analysis was conducted and two methods were compared. Finally, scenario analysis was conducted to check for ranking sensitivity and investigate the selected methods for weakness or inaccuracy. Using commercial MCDA software in the process led to longer analysis times and less transparency than a less complex weighted sum method. In this case, the weighted sum method was shown to effectively support the decision making process.

CHAPTER 4

SUMMARY AND CONCLUSIONS

In this chapter, the research presented in this thesis is reviewed. Results of the manufacturing sustainability assessment and its integration into a decision making process are discussed. Lastly, contributions from this work are identified and recommendations for future work are outlined.

SUMMARY OF THESIS

Design engineers have the opportunity to improve product manufacturing sustainability and are seeking effective ways to make informed decisions. Consumers are placing value in environmental and social responsibility, creating demand for sustainable products, but mechanical designers lack the necessary tools for accurate assessment. As discussed in Chapter 1, current methods of sustainability assessment provide insufficient coverage of sustainability aspects, lack manufacturing process detail, and provide limited means analyze the results and support the decision maker. There is evidence of a need for integrated decision support to encourage the practice of sustainable product design activities.

Chapter 2 provided a manufacturing sustainability assessment that captured variation in product manufacturing impacts resulting from DFM decisions. A set of sustainability metrics was defined and used as a basis for comparison of design alternatives. Then, a unit process modeling based method was described to assist decision making by quantifying economic, environmental, and social sustainability metrics. The method was demonstrated for analysis of titanium component alternatives resulting from design for manufacturing decisions.

Chapter 3 supported design for sustainable manufacturing activities by integrating the detailed manufacturing assessment from Chapter 2 into a decision making process. A six step process was described and demonstrated using supporting methods that satisfied the requirements of each step. Preferences were determined using a fixed sum method. Decision analysis was conducted and two methods were compared. Finally, ranking analysis was conducted using scenario analysis. Selected methods were also investigated for weakness or inaccuracy.

CONCLUSIONS

Methods presented in this thesis are used during product design for manufacturability. The goal is to accurately represent product sustainability by including additional performance metrics and critical manufacturing details. In addition, the assessment must be integrated into a decision support framework so component designers can manage the critical tradeoffs that arise during the decision process. In this study, transparent and easily implemented analysis methods were chosen. However, the quantitative assessment method can be used as the basis of any decision analysis method depending on the specific needs of the decision maker.

The sustainability assessment approach taken in Chapter 2 increased the resolution of process models compared to common impact assessment techniques. Thus, it allowed for investigation of tradeoffs that extend beyond the scope of the product's final form. In addition, it allowed for consideration of sustainability impacts of similar designs or closely related processing scenarios. Although the approach provided detailed quantitative sustainability assessment of individual components, it could not conclude which design variant was more sustainable from a manufacturing perspective.

To further assist decision makers when choosing between design variants, the sustainability assessment was integrated with a decision making process as described in Chapter 3. During the demonstration, the most sustainable alternative was unclear after completion of the sustainability assessment in Step 4. However, the additional analysis steps led to a conclusion that Alt 2 was the more sustainable alternative and the integrated decision support process was shown to effectively support the decision maker.

CONTRIBUTIONS

The work carried out in this thesis focused on manufacturing sustainability assessment of titanium components. An assessment method, based on process modeling, was developed to relate product and process variables and then used to quantify key sustainability metrics. A set of standard based metrics were identified and selected to account for the economic, environmental, and social aspects of manufacturing sustainability. To further assist component designers, the manufacturing sustainability assessment method was incorporated with essential elements of the decision making process to provide integrated decision support.

RECOMMENDATIONS FOR FUTURE WORK

The research presented begins to address needs within the product design community to evaluate design variants on a sustainability basis. However, there is still work to be done to allow for widespread use in industry. The present work can be expanded to provide immediate benefits for component designers. Development of an improved user interface would enable the methods to be more easily applied by decision makers. Evaluating multiple components with different manufacturing process scenarios would also be quicker and easier with an enhanced interface. Additionally, the development of standard databases for unit process models and manufacturing sustainability metrics would greatly reduce the time and human resource requirements for component analysis. Designers would have access to more manufacturing process models that support a greater variety of input materials and component designs. Resources would remain focused on component design rather than process model development. Similar benefits would result from the development of standard metric databases along with greater availability of benchmark data and advancement toward sustainability metric validation.

Finally, to assist decision makers in sustainable product design, methods must be expanded to support sustainability assessment for products comprised of multiple components. Development of models that capture variation in sustainability impacts due to component interaction in assemblies is a critical area of work. A multitude of consumer products are comprised of multicomponent assemblies and the effect on product sustainability must be quantified to assist decision makers.

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