2018

Evaluating manufacturing energy consumption for a part using geometry

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Evaluating manufacturing energy consumption for a part using geometry

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
Matthew Charles Frank, Major Professor
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2018

DEDICATION

I would like to dedicate this work to my mother, Alicia M. Gutiérrez Álvarez, my brother, José M. Guzmán Gutiérrez, and Michael S. Libbey for their unconditional love and support throughout my time at Iowa State University.

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ACKNOWLEDGMENTS

First, I would like to thank my mentor and committee chair, Dr. Matt Frank for his support and guidance throughout the course of this work. I would also like to thank my committee members, Dr. Gül Kremer and Dr. Stephen Vardeman, for their support and insights.

Additionally, I would like to thank my family, friends, and the Industrial and Manufacturing Systems Engineering staff for their unconditional support during my time at Iowa State University. Finally, I would like to acknowledge my laboratory group for their help throughout the course of this research.

ABSTRACT

The decisions made during the design process have a significant impact on the manufacturing of a part. Besides technical and functional requirements, designers also weigh in the effects that design geometry, material, and specifications will have on energy consumption. Since most of a part's sustainability impact is defined during the design process, it is important that engineers consider sustainability throughout the design process. Existing tools that assess the sustainability of designs do not consider the geometric complexity of designs and provide little guidance for engineers to improve designs.

Based on the notion that more complex designs will require more resources to manufacture, this thesis proposes a new approach to assess energy consumption at the manufacturing stage. The overarching purpose of this thesis is to propose the framework for a tool that can guide engineers to more sustainable designs. A new sustainability assessment tool should analyze the complexity of design geometries (i.e. CAD files) in order to predict their energy consumption during manufacturing.

Since the first step to develop a tool was to study the major geometric factors that influence a part's manufacturing energy consumption, this thesis presents a paper on the effect that design geometry has on energy consumption during CNC machining. This study found that up to 98% of the variability in energy consumption during the machining of a part can be predicted using its geometric characteristics. In fact, the design's length, reachability score, and bounding volume explain up to 75% of the variability in energy consumption. It was also found that semi-finishing and ball milling operations account for more than three-quarters of the total energy consumption during machining.

The findings from the study can be used to predict the relative manufacturing energy consumption given the geometry of a component. This can be further refined to develop a tool that can guide engineers to more sustainable designs. The model presented in this thesis can be used as a stepping-stone for the development of a tool that can analyze design geometry from a CAD file, provide feedback to design engineers, and guide them to more sustainable designs. Based on the findings of this study, the tool should use an assessment model that takes into account geometric characteristics such as surface area, dimensions, and reachability, in addition to final part volume and volume removed.

CHAPTER 1. INTRODUCTION

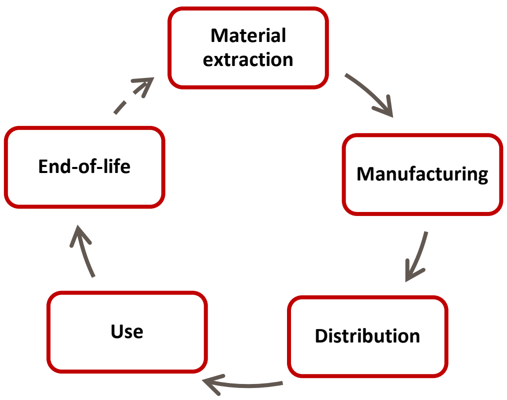

Figure 1.1 Product life-cycle

The choices made during the design process have a significant impact in the life-cycle energy consumption of a part, or component. As shown in Figure 1.1, the life-cycle of a new part begins with the extraction of the material required to make the part, and then it moves on to manufacturing, distribution, use, and end-of-life (Crul, Diehl, & Ryan, 2009). During the design process, a concept is developed into a detailed design that meets the customer needs and wants. The first step of the design phase is to identify the technical and functional requirements of the part and generate a series of sketches that would satisfy those requirements (Dieter & Schmidt, 2013); such sketches are developed into a single *conceptual* design (Figure 1.2). The design is further elaborated by deciding on material, required strength, dimensions, tolerances, and manufacturing specifications (Dieter & Schmidt, 2013); this is often referred to as the *preliminary* design. Multiple iterations of the design are considered during this preliminary phase in order to achieve an optimal design.

Figure 1.2 Engineering design process

The last step of the process is to finalize a *detailed* design through the generation of engineering drawings and computer-aided design (CAD) models. At this phase, prototypes are made and the design is tested to ensure that it meets all requirements. For instance, simulation tools might be used to ensure that the part will meet load and fatigue requirements. Any changes made to the design during or after this step could be costly and the solution space might be significantly constrained.

Besides technical and functional requirements, designers also consider other aspects of the part during the preliminary design process, for example, cost. Since between 70% and 80% of the manufactured costs of a product are fixed during the design process (Dieter & Schmidt, 2013), designers consider how choices might affect the cost of manufacturing, distributing, using, and disposing individual components. Designers are also concerned with the manufacturability of parts or components. That is, the design requirements must be attainable with one or multiple manufacturing processes. Design for Manufacturing (DFM) is among the Design for X (DFX) techniques and tools that aim to guide engineers towards an optimal solution (Dieter & Schmidt, 2013).

Increasingly, design engineers also weigh in the effects that a part's characteristics will have on sustainability when making design decisions. The United Nations Environment Program (UNEP) formally defines sustainability as the consideration of the environmental, economic, and societal impacts of products and processes (Crul et al., 2009). Most of those impacts are defined during the early stages of design and are bound by the design geometry, material, and specifications. In fact, up to 80% of a product's environmental, societal, and economic impacts are fixed during the design and development process (Martin Charter, 2001). Therefore, it is important that design engineers consider sustainability, in addition to technical requirements, cost, and manufacturing constraints, during the design process.

Design for the Environment (DFE) and eco-design tools help the designer develop sustainable products. Research performed by Birch et al. (2012) evaluated 22 different Design for the Environment tools and found that most existing tools require experience in environmental design in order to perform a study and interpret its results. The authors also found that most of the evaluated tools “offer little or no form of assistance” to achieve necessary improvements (Birch, Hon, & Short, 2012).

Several authors agree that life-cycle analysis (LCA), an approach commonly used by such tools, is time consuming, expensive, data intensive, and does not guide design engineers to more sustainable solutions (Birch et al., 2012; Chang, Lee, & Chen, 2014; Lofthouse, 2006; Meng et al., 2015). In fact, most academic and commercial tools require a vast amount of information, not available during the design process. For example, they require material, manufacturing, transportation, use, and end-of-life plans. Although the user does not have to include information about all steps of the product life-cycle, it still requires the user to enter and select information for each part and step within the scope of the analysis. This process is prone to mistakes and might not be intuitive for design engineers without significant experience in sustainability (Lofthouse, 2006).

Recently, work has been done on integrating computer aided design (CAD) and life-cycle analysis (LCA) tools. The idea behind such CAD-LCA integrations is to automatically obtain material, volume, and other information from the CAD models when conducting an LCA analysis. While CAD-LCA integrations reduce the time to conduct an analysis, LCA tools still rely on aggregate values to estimate energy consumption and other metrics of environmental impact. Even though research suggests that optimizing the shape of a component can result in reduced environmental impact during its life-cycle (Gaha, Benamara, & Yannou, 2011), existing tools do not consider the geometric complexity of designs when assessing sustainability.

Research suggests that there is a need in industry for a comprehensive and user-friendly tool that can guide non-expert engineers to an optimal environmentally, economically, and socially conscious design (Gaha, Benamara, & Yannou, 2013). Such tool should be simple and integrated with other design tools to incorporate sustainability in the early stages of design (Rossi, Germani, & Zamagni, 2016). For example, the tool could be integrated with CAD modeling software like SolidWorks or AutoDesk Inventor. Since designers prefer design-specific guidance as opposed to scientific environmental data (Lofthouse, 2006), the tool should provide feedback that leads to re-design ideas. Guidance should be easy to understand, visual, and relevant to the particular project at hand (Lofthouse, 2006). This could be satisfied with a tool that can analyze design geometry and provide geometry-specific feedback to design engineers.

Based on the notion that more complex designs will require more resources to manufacture, this Thesis proposes a new approach to assess energy consumption at the manufacturing stage. Just like there are countless tools to assess how well designs conform to specifications and manufacturing constraints, there should be a tool that can evaluate energy consumption based on design geometry. The overarching purpose of this thesis is to propose a tool that can guide engineers to designs that result in lower environmental impacts during manufacturing.

A new sustainability assessment tool should analyze design geometries (i.e. CAD files) in order to predict their environmental impacts during manufacturing. By providing feedback to engineers during the early stages of design, the tool will help engineers understand how their design choices will influence the part’s manufacturing energy consumption. The influence of geometric characteristics on the societal component of manufacturing remains as an opportunity for future research. Figure 1.3 presents the flowchart of such an ideal manufacturing sustainability assessment tool.

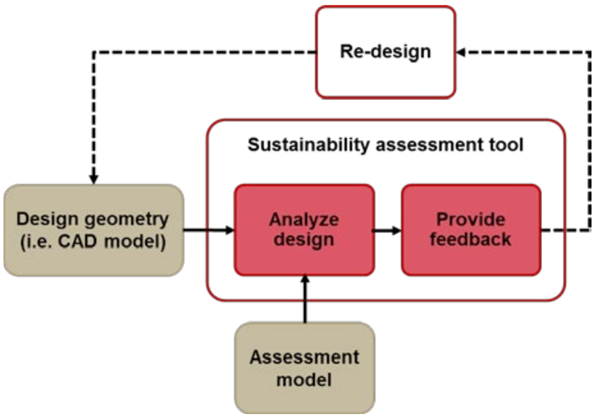

Figure 1.3 Flowchart of proposed sustainability assessment tool

The remainder of this Thesis is organized as follows: Chapter 2 will begin by reviewing literature on the effect that design geometry might have on the energy consumption of the part. Then, it will proceed with a review of existing sustainability assessment methodologies and tools. The first step to develop a tool will be to study the major geometric factors that influence a part's energy consumption during manufacturing. Thus, Chapter 3 will present a methodology to evaluate the effect that design geometry has on energy consumption during the CNC machining of parts. Then, Chapter 4 will present a paper that implements such methodology and proposes a model for the assessment of manufacturing energy consumption given the geometry of a part. Finally, Chapter 5 will present the conclusions of this thesis and opportunities for future work.

CHAPTER 2. LITERATURE REVIEW

Environmental Impacts and Design

As mentioned previously, most of a product's environmental, societal, and economic impacts are defined in the early stages of development and design (Crul et al., 2009). The geometry, material, and specifications of the product's individual components, which are decided during those early stages, play an important role in shaping downstream decisions. In fact, design choices could constrain manufacturing, packaging, transportation, use, and disposal alternatives. For instance, if the design contains internal geometries or undercuts, it will most likely have to be made using a casting process because these features cannot be produced with traditional machining. Likewise, the design dimensions and weight will determine the transportation and packaging requirements. Because of this, there has been increased interest in developing Design for the Environment (DFE) and eco-design techniques (Fiksel & Wapman, 1994; Luttropp & Lagerstedt, 2006; Ostad-Ahmad-Ghorabi, Pamminger, & Huber, 2007; Rossi et al., 2016) that can guide designers to choices that result in reduced environmental impacts. A common practice to reduce the environmental impacts of a component is to reduce the energy required to manufacture, distribute, use, and dispose of it (Fiksel & Wapman, 1994; Luttropp & Lagerstedt, 2006).

Material selection during design can also play a significant role in reducing the life-cycle environmental impacts of a part (Fiksel & Wapman, 1994; Luttropp & Lagerstedt, 2006). For example, choosing a low-density material like Titanium, which will result in lower part weight, can also result in lower fuel consumption during the distribution and use phase. On the other hand, choosing an energy intensity material like aluminum can result in higher environmental impact during the material extraction phase (Crul et al., 2009). DFE and eco-design guidelines suggests that the designer should opt for materials that will result in lower weight, higher recyclability, reduced energy consumption, and longer life (Fiksel & Wapman, 1994; Luttropp & Lagerstedt, 2006).

Research suggests that a reduction in the life-cycle environmental impacts of a part can be achieved by making modifications to its geometry. According to Gaha et al. (2011), the designer should opt for simpler geometries that can be manufactured faster with less steps, thus resulting in a reduction of energy consumption during the manufacturing stage. The authors also point out that "optimization of shapes and volumes" can result in reduced environmental impact for the raw material extraction, manufacturing, and end-of-life phases. In addition, smaller part volumes allow for easier transportation, resulting in lower emissions and energy consumption during this stage (Gaha et al., 2011).

Besides surface area and volume, designs have other characteristics, such as feature dimensions, surface curvature, orthogonality, and intricacy of features, which increase their geometric complexity. While the effect that volume has on the energy consumption of a component is well documented in literature, the effect that geometric complexity has on environmental, societal, and economic impacts is not well understood. Nevertheless, the geometric complexity of a component can have a significant impact on the total energy consumption during manufacturing. In fact, non-cutting energy can be a large component of the total energy required in machining (Dahmus & Gutowski, 2004) and is dependent on the volume of the final part relative to the part's bounding volume as well as on the complexity of the part (Watson & Taminger, 2015).

Sustainability Assessment

Just like engineers evaluate their designs to assess if they are manufacturable or meet technical specifications, designers often evaluate their designs for sustainability. The goal of such sustainability assessment is to determine if the design meets environmental, economic, and societal requirements during the design process. There is a variety of sustainability assessment tools to help the engineer quantify the impacts of the design at each life-cycle stage. These tools often use a select number of metrics to quantify the economic, societal, or environmental impacts.

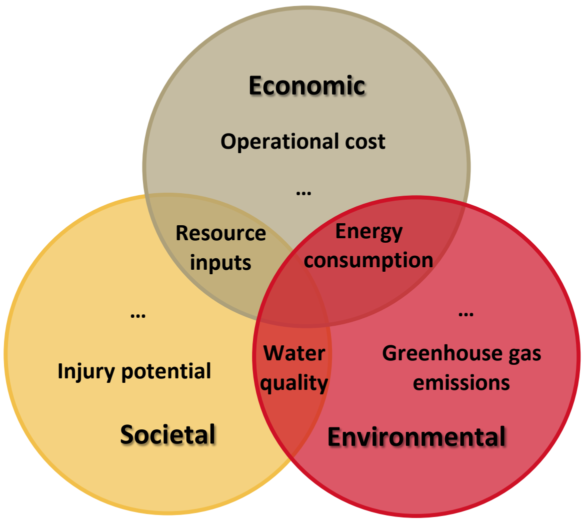

Figure 2.1 Sustainability metrics

Economic metrics include measures of operational cost and capital cost while frequently used environmental metrics include energy consumption and greenhouse gas emissions, to name a few. In contrast, societal impacts are often abstract and difficult to quantify; examples such as injury potential and water quality. As shown in Figure 2.2, societal, economic, and environmental metrics can be related to more than one dimension of sustainability. For instance, energy consumption could result in higher greenhouse gas emissions, fuel depletion, and operational costs during manufacturing; therefore, it is directly related to the environmental and economic dimensions of sustainability.

The most common approach used by sustainability assessment tools is life-cycle analysis (LCA). The next section will begin with an overview of the life-cycle analysis approach, followed by a literature review of LCA tools. Then, it will proceed with a literature review of CAD-LCA integrated tools developed for environmental impact assessment.

Life-cycle Analysis Tools

Life-cycle analysis (LCA) is a common approach used to assess the environmental impact of components and assemblies from material extraction to disposal. The ISO 14040 series dictates a standardized methodology to conduct LCA, which consists of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation of result (International Organization for Standardization, 2006).

The first step in the process is to define the purpose of the study and what component(s) will be studied. At this stage, the person conducting the life-cycle analysis might specify what component he or she wants to evaluate, at what life stages, and to what level of detail. At the second stage, the inventory of inputs and outputs for each component at each step of the life-cycle are specified. Such information can be application-specific or obtained from a life-cycle inventory (LCI) database. LCA dedicated software packages, such as SimaPro (Pré Consultants, n.d.), GaBi (Thinkstep, n.d.), openLCA (Green Delta, n.d.), CMLCA (Institute of Environmental Sciences (Lieden University), 2012), and CCaLC (University of Manchester, n.d.), often include their proprietary LCI databases or provide the user with the option to use their own data.

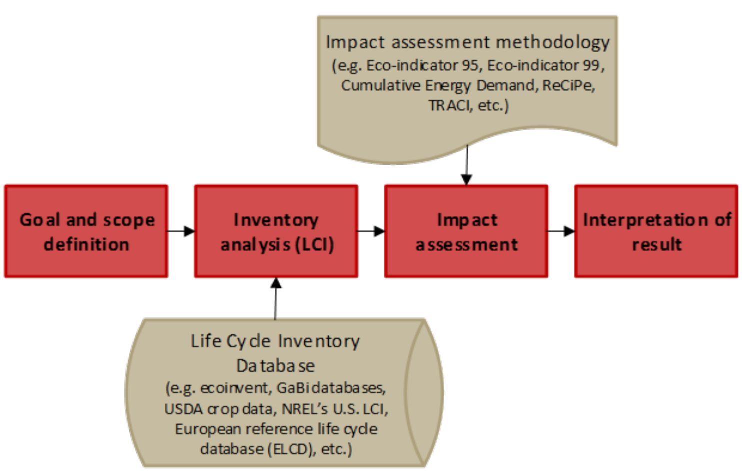

Figure 2.2 Life-cycle analysis flowchart (Green Delta, n.d.; International Organization for Standardization, 2006)

During the third step, the environmental impacts are weighted according to an impact assessment methodology in order to determine the relative sustainability performance throughout the life-cycle. LCA methodologies such as Eco-Indicator 99, provide guidelines for design engineers to assess the environmental impact of components and interpret the results (Pré Consultants, 2000). Finally, the results can be interpreted by the user to make decisions regarding the life-cycle of the component(s) analyzed (International Organization for Standardization, 2006). Figure 2.3 showcases the LCA process, along with the resources used at each step.

Among the benefits of LCA software packages is that they guide the user through the process and provide the necessary tools to conduct the analysis. These packages include comprehensive databases and allow the user to customize the analysis, allowing the user to perform detailed and accurate life-cycle analyses of their product and its parts. However, these packages are often not accessible to designers due to their high costs (Birch et al., 2012). Despite the fact that free of charge LCA software packages have been developed, they still require significant data input and expertise (Birch et al., 2012). For instance, openLCA is an open-source tool to perform LCA studies with a variety of databases available for purchase and free of cost (Green Delta, n.d.). Users have the option to choose from a wide variety of life-cycle inventory (LCI) databases such as Ecoinvent, GaBi, USDA crop data and European reference Life-cycle Database (ELCD), among others. The user also has the option to use one of many impact assessment methodologies, such as Cumulative Energy Demand, Eco-invent 99, or ReCiPe (Green Delta, n.d.). Another free of cost software for LCA is CMLCA developed by the Institute of Environmental Sciences of Lieden University. While CMLCA is also compliant with ISO standards, the user needs to purchase or provide their own data because it is not included with the software (Institute of Environmental Sciences (Lieden University), 2012). Similar to openLCA and CMLCA, CCaLC2 by the University of Manchester includes its own database (CCALC2 database), as well as the

Ecoinvent database (University of Manchester, n.d.). Also, a benefit of CCaLC2 is that it not only calculates environmental impacts, such as greenhouse gas emissions and cumulative energy consumption, but also calculates economic impacts, such as value added (University of Manchester, n.d.).

Although research suggests that results from LCAs can be used to achieve a reduction in environmental impact (Gaha, Benamara, & Yannou, 2013), these analyses require a significant amount of time, information, and experience to perform (Rossi et al., 2016). By using LCA tools during the design of a basin mixer, Gaha et al. (2013) identified material consumption as the main contributor to environmental impacts. Consequently, the authors reduced the weight of the component to achieve a 66% reduction in such impacts. According to the authors, in order to perform accurate and complete life-cycle analyses, the design should be in "advanced stages" and the design choices should be limited (Gaha et al., 2013).

In fact, in order to complete a life-cycle assessment, the user needs to have all the necessary inventory data. This includes knowing the material to be used, the manufacturing steps, use scenarios, end of life plans, and their corresponding flows. This not only requires a vast amount of information, but it also requires a high level of expertise in order to complete. While design engineers are very familiar with component specifications and requirements, they might not be as experienced with the manufacturing process specifics. Hence, they might need to consult other subject matter experts while conducting a life-cycle analysis. This might result in additional costs during the design process (Birch et al., 2012). For these reasons, full LCA approaches are not well suited for the assessment of components during early stages of design (Gaha et al., 2013; Keoleian, 1993; Morbidoni, Favi, & Germani, 2011).

CAD-LCA Integrated Tools

In order to overcome LCA limitations and enable environmental assessments of conceptual designs, several CAD-LCA integrated tools have been developed. The basic concept of most of these CAD-LCA integrations is to extract data from a CAD model to perform a life-cycle analysis. The ultimate goal of CAD-LCA approaches is to integrate LCA to the design process in a way that is familiar, easy to use, and faster for the designer. For instance, SolidWorks Sustainability by Dassault Systems evaluates a CAD model to estimate energy consumption, carbon footprint, air acidification, and water eutrophication at each step of the part's life-cycle (Dassault Systems, 2018). Although SolidWorks Sustainability is widely available, fast, and easy to use, its analysis does not take into account the dimensions of the raw material (billet) and it does not allow the user to specify consecutive processes on the same component (Morbidoni et al., 2011). A similar CAD integrated LCA module, Eco Materials Adviser is included with AutoDesk Inventor (AutoDesk Inc., n.d.).

Umeda et al. (2012) designed a CAD system for the life-cycle design of products, LC-CAD, to serve as a tool for engineers throughout the design of sustainable products (Umeda, Fukushige, Kunii, & Matsuyama, 2012). The model evaluates the sustainability of assemblies at each stage of the product life-cycle but fails to identify the contribution of specific design geometries to the total impacts. Other tools consider individual design features in order to provide a more accurate approximation of environmental impacts. A feature is defined as a district geometric element in a design; examples of features include a hole, protrusion, and groove. Research by Morbidoni et al. (2011) proposes a new approach that obtains "shape and dimensions" as well as "product structure" from the CAD model to estimate the environmental impact. Although this method has proven to be accurate in estimating environmental impacts, it requires companies to have a database with energy consumption, utilization rates, and other machine-specific parameters (Morbidoni et al., 2011).

Eco-OptiCAD by Russo et al. (2014) uses optimization to find the best combination of geometry, material, and manufacturing process given a set of technical constraints (Russo & Rizzi, 2014). The authors successfully implemented the method to reduce the weight of a connecting rod by up to 33% (Russo & Rizzi, 2014). EcologiCAD, developed by Leibrecht in 2005, extracts feature information from a CAD model and allows the user to assign processes to individual features (Leibrecht, 2005). Gaha et al. (2013) proposed an algorithm that uses computer-aided process planning (CAPP) to guide design engineers through feature selection based on environmental impacts and feature technology (Gaha, Benamara, & Yannou, 2013).

Similarly, Tao et al. (2017) propose the extraction of design features from the CAD model then associate each feature to a set of manufacturing operations and parameters obtained from CAPP software (Chen, Tao, & Yu, 2017; Tao, Chen, Yu, & Liu, 2017). A similar tool proposed by Nawata and Aoyaama (2001) proposes the use of computer-aided machining to map individual features to machining parameters (Nawata & Aoyama, 2001).

Other Tools

Meng et al. (2015) developed a Rapid Life-cycle Assessment (RLCA) method with the goal to bridge the gap between the information available during the preliminary design process and the information required to conduct a life-cycle analysis. The RLCA method is based on the idea that design features can be mapped to a database of similar features (with known impacts) when performing an LCA (Meng et al., 2015). While this approach can reduce the time and information required to perform an LCA during the design process, it does require an extensive database of previous solutions for successful implementation.

There has also been work done in developing tools which can predict environmental impact, specifically energy consumption, during manufacturing. One example of this is the work by Kong et al. (2011); in this case, the authors developed a software that can analyze the machining toolpaths in order to estimate the energy consumption and greenhouse gas emissions during machining (Kong et al., 2011). A limitation of this tool is that it requires the design engineer to generate the NC code (machining toolpath) for the part and know the machining parameters in order to compute energy consumption. Given that toolpath generation is often not possible until the design process is complete, this limits the application of this tool until the detailed design phase. Additionally, design engineers seldom have the expertise or experience to plan the manufacturing process; in practice, they might have to consult a manufacturing engineer. In any case, the tool does not provide any insights into how changes in geometry could reduce environmental impact.

Although these approaches can provide feedback to the design engineer about the environmental performance of the design, they do not provide enough guidance to the designer. In fact, these approaches do not consider how the geometric complexity of the design affect environmental impacts of the component during its life-cycle. Given that geometry plays an important role in determining the environmental impact of a component, it is important to understand how it affects the energy consumption during manufacturing.

CHAPTER 3. PROPOSED SOLUTION METHODOLOGY

This Thesis proposes the assessment of energy consumption during the manufacturing of components based on their design geometry. The goal of this assessment is to be able to differentiate between components based on their specific feature topology in order to make inferences about their manufacturing energy consumption. In other words, this Thesis proposes considering a component's geometric complexity in addition to aggregate measures when estimating energy consumption. Take for instance the three parts with the same volume (and mass) illustrated in Figure 3.1. Only considering final part volume to estimate energy consumption would suggest that these components would require the same amount of resources to manufacture. However, the brick (Figure 3.1a) will require significantly less time and resources to machine than the other two parts.

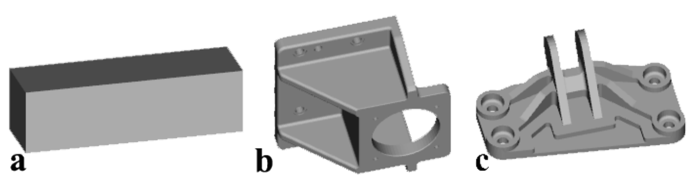

Figure 3.1 Images of three designs with the same part volume

A three-stage approach is proposed in order to study the effect that part geometry has on energy consumption during CNC machining. The first stage is to collect data on the geometric characteristics, machinability, and manufacturing energy consumption of a set of diverse designs. A representative sample of designs with varying geometries is chosen for analysis and their geometric characteristics are recorded. Then, machining toolpaths are generated for all designs considered, assuming that they are all milled in the same machine, with the same stock diameter, material, and finishing strategy. Time and volume removed estimates can then be obtained by simulating each design's manufacturing process. Those simulated values can then be used to estimate the energy consumption during machining. The data collection approach is illustrated in Figure 3.2.

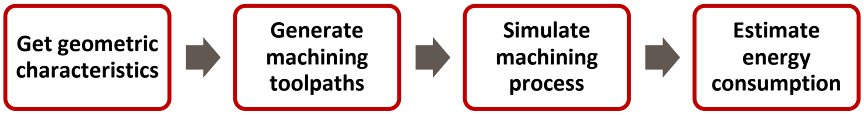

Figure 3.2 Data collection steps

The second stage consists of using penalized linear regression to model energy consumption as a function of component's geometric characteristics. This approach is used, instead of traditional linear regression, because, from the onset of the problem it is not clear which geometric characteristics can explain manufacturing energy consumption. Since penalized linear regression can identify which characteristics are significant predictors of energy consumption, the resulting expression can provide insight into the relationship between design complexity and manufacturing energy consumption. This expression is referred to as the proposed model. Considering that design engineers might not have the tools or time required to obtain all the information required to predict energy consumption with the proposed model, a simplified or abridged model is also presented. This model consists of a linear regression model of energy consumption as a function of the most important geometric characteristics. The most important characteristics are determined by obtaining the standardized coefficients of the proposed model. The goal of both models, the proposed model and the proposed abridged model, is not to obtain an accurate point estimate of manufacturing energy consumption. Instead, the goal is to be able to compare multiple designs (or iterations of the same design) and determine which will have a lower environmental impact during manufacturing.

Lastly, the energy consumption expressions obtained from the statistical analysis are used to estimate manufacturing energy consumption for a different set of components. In order to evaluate how well the proposed models can predict the relative energy consumption during machining, such estimates are compared to energy consumption values and environmental impact metrics obtained with other tools. In addition, the machining process for this second set of components is simulated to obtain “actual” energy consumption values. The energy consumption estimates obtained from the proposed models are also compared to these simulated energy consumption values.

The following chapter presents a paper that follows this proposed solution methodology to determine the relationship between geometric characteristics and energy consumption during manufacturing.

CHAPTER 4. EVALUATING MANUFACTURING ENERGY CONSUMPTION FOR A PART USING GEOMETRY

Abstract

Incorporating manufacturing energy consumption considerations early in the design process can result in a significant reduction of environmental and economic impacts. Existing tools that designs. This paper analyzed the influence that geometric characteristics have on the energy consumption during the manufacturing of components via CNC machining. Thirty-three models from the National Design Repository were analyzed to obtain their geometric and machinability characteristics. Then, time and volume removed estimates were obtained by generating and simulating machining toolpaths for each model. Those values were used to estimate the energy consumption during hog, rough, semi-finish, and ball milling operations. Finally, energy consumption values were modeled as a function of each design's characteristics. This study found that up to 98% of the variability in energy consumption during the machining of a part can be predicted using its geometric characteristics. In fact, the design's length, reachability score, and bounding volume explain up to 75% of the variability in energy consumption. It was also found that semi-finishing and ball milling operations account for more than three-quarters of the total energy consumption during machining. The findings from this study suggest that the relative energy consumption of multiple design iterations can be predicted using geometric characteristics. This work could enable a new DFX tool to provide feedback to a designer about the environmental implications of the design decisions.

Introduction

Sustainability, as defined by the United Nations Environment Program (UNEP), is the consideration of the environmental, economic, and societal impacts caused by the manufacturing, transportation, use, and disposal of products (Crul et al., 2009). Since up to 80% of such sustainability impact is fixed in the early stages of design and development (Martin Charter, 2001), it is important to consider sustainability during the design process. One way to accomplish this is by considering the relationship between the geometric characteristics of a product's components and the energy consumption at each life-cycle stage. Given that energy consumption directly influences the environmental and economic aspects of sustainability, minimizing energy consumption could lead to reduced overall impact. In other words, the first step to reducing environmental impact is to consider the effect that design decisions have on the manufacturing energy consumption of a component.

While research suggests that the shape of a component can result in reduced environmental impact during its life-cycle (Gaha et al., 2011), existing tools do not consider the geometric complexity of designs when assessing sustainability. In fact, most tools estimate environmental impact based on volumetric measures and aggregate values. As a result, design engineers who have a desire to reduce the energy required to manufacture a component might be limited to reducing the design volume or opting for a different material.

This paper proposes a new approach to assess energy consumption at the manufacturing stage. Based on the notion that designs that are more complex will require more resources to machine than simple designs, this paper proposes the assessment of energy consumption based on design geometry. The objective is to evaluate the effect that geometric characteristics have on the energy consumption during manufacturing of components using CNC machining. Hence, this paper presents a model that can predict the relative environmental impact of a component given its design geometry.

The following section will cover relevant literature regarding the role of geometry on the environmental impacts of a component as well as sustainability assessment tools.

Literature Review

Research suggests that a reduction in the life-cycle environmental impacts of a part can be achieved by making modifications to its geometry. According to Gaha et al. (2011), the designer should opt for simpler geometries that can be manufactured faster with less steps, thus resulting in a reduction of energy consumption during the manufacturing stage. The authors also point out that "optimization of shapes and volumes" can result in reduced environmental impact for the raw material extraction, manufacturing, and end-of-life phases. In addition, smaller part volumes allow for easier transportation, resulting in lower emissions and energy consumption during this stage (Gaha et al., 2011). Besides surface area and volume, designs have other characteristics, such as feature dimensions, surface curvature, orthogonality, and intricacy of features, which increase their geometric complexity. While the effect that volume has on the energy consumption of a component is well documented in literature, the effect that geometric complexity has on environmental, societal, and economic impacts is not well understood. Nevertheless, the geometric complexity of a component can have a significant impact on the total energy consumption during manufacturing. In fact, non-cutting energy can be large component of the total energy required in machining (Dahmus & Gutowski, 2004) and it is dependent on the volume of the final part relative to the part's bounding volume as well as on the complexity of the part (Watson & Taminger, 2015).

The process of considering environmental impacts, such as energy consumption, during the design process is commonly referred to as eco-design or Design for the Environment (Dieter & Schmidt, 2013). Most eco-design software use life-cycle analysis

(LCA) to estimate environmental impacts and provide guidance to design engineers. Several tools have been developed to integrate LCA to the eco-design process through CAD-LCA integrations. The idea behind such CAD-LCA integrations is to enable the designer to perform LCA analyses iteratively, based on information from the CAD model features. By doing so, the engineer can compare between designs to select the most environmentally-friendly one. SolidWorks Sustainability by Dassault Systems evaluates a CAD model to estimate energy consumption, carbon footprint, air acidification, and water eutrophication at each step of the part's life-cycle (Dassault Systems, 2018). Although the tool is widely available, fast, and easy to use, its analysis does not take into account the dimensions of the raw material (billet) and it does not allow to specify consecutive processes on the same component (Morbidoni et al., 2011). A similar CAD integrated LCA module, Eco Materials Adviser is included with AutoDesk Inventor (AutoDesk Inc., n.d.). Umeda et al. (2012) designed a CAD system for the life-cycle design of products, LC-CAD, to serve as a tool for engineers throughout the design of sustainable products (Umeda et al., 2012). The model evaluates the sustainability of assemblies at each stage of the product life-cycle but fails to identify the contribution of specific design geometries to the total impact. Other tools consider individual design features in order to provide a more accurate approximation of environmental impact. A feature is defined as a distinct geometric element in a design; examples of features include holes, protrusion, slots, etc.

Research by Morbidoni et al. (2011) proposed a new approach that obtains "shape and dimensions" as well as "product structure" from the CAD model to estimate the environmental impact. Although this method has proven to be accurate, it requires users to have a database with energy consumption, utilization rates, and other machine-specific parameters (Morbidoni et al., 2011). Eco-OptiCAD by Russo et al. (2014) uses optimization to find the best combination of geometry, material, and manufacturing process given a set of technical constraints. The authors successfully implemented the method to reduce the weight of a connecting rod by up to 33% (Russo & Rizzi, 2014).

EcologiCAD, developed by Leibrecht in 2005, extracts feature information from a CAD model and allows the user to assign processes to individual features (Leibrecht, 2005). Gaha et al. (2013) proposed an algorithm that uses computer-aided process planning (CAPP) to guide design engineers through feature selection based on environmental impacts and feature technology (Gaha et al., 2013). Similarly, Tao et al. (2017) propose an LCA method that extracts design features from the CAD model and then associates each feature to a set of manufacturing operations and parameters obtained from a CAPP software (Chen et al., 2017; Tao et al., 2017). A similar tool proposed by Nawata and Aoyama (2001) proposes the use of computer-aided machining to map individual features to machining parameters (Nawata & Aoyama, 2001). Meng et al. (2015) developed a Rapid Life-cycle Assessment (RLCA) method with the goal of bridging the gap between the information available during the preliminary design process and the information required to conduct an LCA. The RLCA method is based on the idea that design features can be mapped to a database of similar features (with known impact) when performing an LCA (Meng et al., 2015). While this approach can reduce the time and information required to perform an LCA during the design process, it does require an extensive database of previous solutions for successful implementation.

There has also been work done in developing tools that can predict energy impact during machining based on NC code after toolpath generation. One example of this is the work by Kong et al. (2011), where the authors developed software that can analyze the toolpaths to generate a part in order to estimate greenhouse gas emission during machining (Kong et al., 2011). A limitation of this tool is that it requires the design engineer to generate the NC code for the part, which is often not possible until the design process is complete. Additionally, design engineers seldom have the expertise or experience to plan the manufacturing process, so in practice, they might have to consult a manufacturing engineer. In any case, the tool does not provide any insights into how changes in geometry could reduce environmental impact.

Although the aforementioned approaches can provide feedback to the design engineer about the environmental performance of the design, they do not provide enough guidance to the designer. In fact, these approaches do not consider how the geometric complexity of the design affect the environmental impacts, specifically energy consumption, of the components during manufacturing.

Methods

The approach followed by this paper consists of three parts: data collection, modeling, and implementation. During the data collection stage, the geometric characteristics and manufacturability of a set of diverse designs were analyzed and recorded. Time and volume removed estimates were obtained by simulating each design’s manufacturing process. These simulated values were then used to estimate the energy consumption during machining. The modeling stage consisted of using statistical methods to model energy consumption in terms of the design's geometric characteristics. Lastly, energy consumption results from the proposed model were compared to results obtained with other tools.

The “Machined Models” from the National Design Repository (Bespalov, Ip, Regli, & Shaffer, 2005) were selected as a representative set of components typically manufactured by CNC machining. All designs were scaled so that the maximum dimension perpendicular to their axis of rotation was 5.5 inches (somewhat arbitrary). Scaling the models ensured that they could be machined from the same diameter stock; this also ensured that the only manufacturing difference between the models were their geometric characteristics. This group was further refined based on each design's visibility; in order for the design to be considered, it only had to require setups along one axis (axis of rotation) and all of its features could be machined with a ¼" diameter tool or larger after scaling (deemed a reasonable commercially available small diameter tool). Additionally, the percent surface visible had to be 100% while the percent surface machinable had to be at least 95%. Thirty-three models met such requirements and were selected for analysis.

A prototype manufacturability analysis software, *ANA*, was used to analyze the machinability of the designs. The machining module of *ANA*, referred to as *MachiningANA*, analyzes designs and scores them in terms of their visibility, reachability, machinability, and setup complexity (M. Hoefer, Chen, & Frank, 2017). The data obtained from the *MachiningANA* analysis includes:

- Height (h), length (l), and width (w)
- % surface machinable
- Machinability Score (S_m)
- % surface visible
- Visibility Score (S_v)
- Reachability Score (S_r)
- Setup Complexity Score (S_{sc})
- Overall Manufacturability Score (S_{total})

The percent surface machinable is the portion of surface area, for facets $j \in 1, \ldots, F$, that can be machined with a ¼" end mill or larger (M. Hoefer et al., 2017). Similarly, the machinability score (S_m) is a normalized measure dependent on the minimum tool diameter required to machine the facets. Designs with small holes or tight corners will have lower machinability scores than parts with features that can be easily machined by any diameter tool. Machinability scores range from 0 to 1 and are unit-less.

The percent surface visible is the portion of total surface area that can be seen by the tool, regardless of orientation. Based on the range of visibility (0 to 180 degrees) about each axis (x, y, and z), a visibility score (between 0 and 540) is assigned to each facet. Then, the overall visibility score for a design (S_v) is a normalized measure of the range of angles from which a facet can be accessed (Frank, 2007). For example, internal geometries or undercuts would be considered non-visible; thus, they would receive a visibility score of zero. High visibility scores correspond to highly visible surfaces or surfaces that can be seen from more than one orientation (visibility score near 1). On the other hand, features that can only be machined from one orientation or that cannot be machined at all will receive low visibility scores (close to 0).

The reachability score (S_r) is a normalized measure of the minimum tool length required to reach a facet. Parts that require long tools to machine pocket features or cavities will have low reachability scores (close to 0). The setup complexity score (S_{sc}) is a normalized measure of the total number of setups required to machine a design. Designs whose features can be fully machined with a small number of setups (< 2) will receive setup complexity scores close to one. The overall manufacturability score (S_{total}) is a weighted mean of the machinability, visibility, reachability, and setup complexity scores.

Additional data recorded for each design includes volume (V_p), surface area (SA), facet count (F), facet normal vectors, and minimum tool diameter for each facet (T_{min_j}). In this case, a facet normal vector is the surface normal vector to any given (triangular) facet. The bounding volume (V_b) for each design is defined as the volume of the minimum box that fully encloses the design and it is calculated as follows:

$$V_b = h \times l \times w$$

where l is the length, h is the height, and w is width. The length corresponds to the maximum dimension of the design, while the height and width correspond to the dimensions perpendicular to the maximum dimension. The diagonal (d) of each design was also calculated as follows:

$$d = \sqrt{h^2 + w^2}$$

The minimum tool diameter for each facet (T_{min_j}) is defined as the diameter of the smallest tool that can machine the entirety of a facet (M. J. D. Hoefer, 2017). These values were then used to determine the diameter of the smallest tool necessary to fully machine the surface of a design (T_{min}):

$$T_{min} = \min(T_{min_j}) \qquad \text{for} \qquad j \in 1, \ldots, F$$

The geometric complexity of each design was assessed by determining the unique number of facet normal vectors (C) obtained from analyzing the STL file for each model. Similarly, using those facet normal vectors, the facets were classified as orthogonal or non-orthogonal, where orthogonal facets are parallel to the XY, YZ, or XZ planes. Using such information, the orthogonal percentage (P) is determined by dividing the sum of surface area for orthogonal facets over the design's total surface area (SA). This percentage could be seen as a measure of how prismatic a component is; perfectly prismatic components, such as a brick, would have an orthogonal percentage of 100%. Finally, two ratios were calculated for each design. First, the surface area to volume ratio (R_{SA,V_p}) is the ratio of the component's surface area (SA) to its volume (V_p). The buy-fly ratio (R_{V_b,V_p}) is the volume of the minimum prismatic box that encloses the design (V_b) divided by the design's volume (V_p).

Machining toolpaths were obtained for each design by running their STEP files through *CNC-RP*, an automated tool path generation software (Mastercam X6 plug-in) for rapid prototyping (Frank, 2007). *CNC-RP* was selected due to its capacity to generate systematic and unbiased tool paths for all the designs. For the purposes of this work, it was assumed that all components were machined out of a 5.5-inch aluminum stock in a HAAS VF-2 CNC machine with a scallop (ball end mill) finishing strategy. Given that the toolpaths generated by *CNC-RP* remove material layer by layer, the machining time estimates are higher than actual machining times for each component (Frank, 2007). Consequently, the energy consumption estimates might be up to one order of magnitude larger than actual values. However, such increase in magnitude will not affect the results of the study; all designs will be equally affected, the relative difference among designs will be the critical measure. *CNC-RP* adds between two and four sacrificial supports to the component model in order to manufacture it in a dual rotary setup; this results in longer stock lengths. To compensate for this increase in material consumption, the component's buy-fly ratio was calculated based on the minimum prismatic box that encloses the design without the supports. Since all the supports are the same length and all the parts are machined from the same stock, the additional energy required to machine the supports will be consistent among all parts. It was also assumed that all the designs were machined from an aluminum stock.

Nevertheless, the specific material is irrelevant for the analysis as long as all the parts considered are assumed to be machined from the same material. As previously explained, the ultimate goal of the model is not to obtain accurate values of energy consumption; rather, the goal is to provide the relative performance of a design when compared to another. For this reason, the increase in energy consumption resulting from the difference in material will not affect the results.

The manufacturing process was simulated in *Vericut* to obtain machining time and volume removed estimates for each design. Based on the tools used, the *Vericut* results for each component were characterized between hogging, roughing, semi-finishing, and ball milling operations. Time (t) and volume removed (V_r) for each design were collected from the text file reports generated by *Vericut*. The material removal rate ($\dot{v}$) for each tool sequence was calculated by dividing the amount of volume removed by the machining time:

$$\dot{v} = V_r / t$$

Then, the material removal rate values were used to determine the machining power for each tool sequence according to the following equation (Oberg, Jones, Horton, & Ryffel, 2012):

$$P_c = (K_p C W \, \dot{v}) / E$$

where P_c is the machining power (kW), K_p is the specific energy consumption for the material (kW/cm^3/s), C is the feed factor (tool-specific), W is the tool wear factor (process-specific), $\dot{v}$ is the material removal rate (cm^3/s), and E is the efficiency factor of the machine. The machine tool efficiency factor, E, is dependent on the efficiency with which the machine converts the electric power input to the driving motor into cutting power (Oberg et al., 2012). Hence, machines with less efficient motors will require higher energy input and will have lower values of E. Since it is assumed that all parts will be milled in the same machine, energy consumption variability will only be affected by differences in the part geometries tested. The values of the parameters K_p, C, W, and E used to calculate the machining power were obtained from the *Machinery's Handbook* (Oberg et al., 2012). It was also assumed that the idle power, P_o, or power consumed by the machine's supporting equipment such as fans, coolant pumps, and computer, was 0.30 kW for the machine. The values of all the parameters used are shown in Table 4.1.

Table 4.1 Constants used for energy calculations

Process	**Tool**	K_p	P_o	C	W	E
Hogging	1" Flat end mill	0.68	0.30	0.96	1.40	0.90
Roughing	0.50" Medium bull end mill	0.68	0.30	1.02	1.30	0.90
	0.50" Short bull end mill	0.68	0.30	0.98	1.30	0.90
	1" Flat end mill	0.68	0.30	0.96	1.30	0.90
Semi-Finishing	0.25" Long bull end mill	0.68	0.30	1.25	1.20	0.90
	0.25" Medium bull end mill	0.68	0.30	1.19	1.20	0.90
	0.25" Short bull end mill	0.68	0.30	1.15	1.20	0.90
Ball	0.25" Long ball end mill	0.68	0.30	1.25	1.10	0.90
	0.25" Medium ball end mill	0.68	0.30	1.19	1.10	0.90
	0.25" Short ball end mill	0.68	0.30	1.15	1.10	0.90

While research suggests that the energy consumption during manufacturing depends on the moving direction of the axes (Kong et al., 2011), this model assumes that the energy will only be proportional to the manufacturing time and volume removed. Thus, the energy consumption for each operation was calculated by adding the idle power (P_o) to the machining power (P_c) and multiplying by the machining time:

$$\text{Energy} = (P_o + P_c) \times t$$

Penalized linear regression was used to analyze the data obtained from simulation in order to generate an equation that can predict the energy required to machine each component. This method was chosen instead of traditional multiple linear regression because, from the onset of the problem, it was not clear which geometric variables could help explain energy consumption. Since it was expected that the effects of design geometry on the energy consumption for each manufacturing stage (hogging, roughing, semi-finishing, and ball milling) were going to be different, they were modeled independently. That is, an equation of energy consumption as a function of geometric characteristics, such as buy-fly ratio, surface area, and orthogonal percentage was obtained for each manufacturing stage. By doing so, it is possible to identify which geometric characteristics could be indicators of energy consumption at each stage of a component's manufacturing process. The predicted energy consumption values obtained from the equations can be added together to obtain an estimate of total energy consumption. Then, those estimates could be used to rank the components (or predict their relative impact) based on the components' expected energy consumption. Based on the results of the statistical analysis, a simpler linear regression model is also proposed to ease the analysis and assessment during the design process.

Results

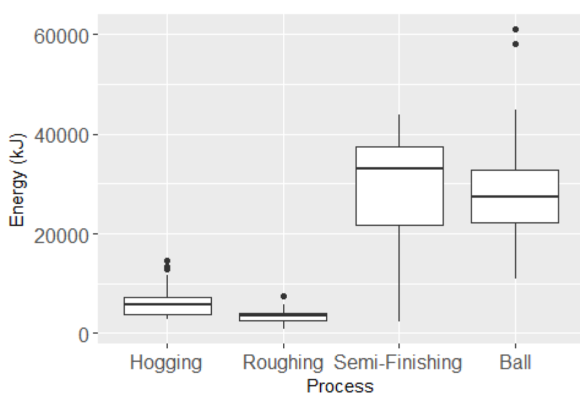

Figure 4.1 Energy data for each machining process

Figure 4.1 shows the boxplots of energy consumption for all 33 designs during hogging, roughing, semi-finishing, and ball milling. As it can be seen in Figure 4.1, the energy consumption for semi-finishing and ball milling operations was higher than the hogging and roughing energy consumption for all designs. It is important to note that *CNC-RP* assumes a bar stock in order to generate toolpaths for a dual rotary setup; this results in longer machining times and material removed for prismatic components. However, this difference in processing time and material removal only affects the energy consumption for hogging. Since hogging only accounts for 9.99% of the total energy consumed during machining (on average), such effect is insignificant.

It should also be noted that the energy consumption for semi-finishing and ball milling operations (43.52% and 41.47%, respectively) account for more than three-quarters of the total energy consumption for all designs. This means that, even if the designs were machined from a near net shape casting, the total energy required to machine them would be sufficiently great when compared to the hogging and roughing energy. Therefore, knowing how to model the energy consumption during these steps is critical to assess manufacturing sustainability.

Proposed Model

As previously explained, penalized regression was used to generate linear regression models for the energy consumed during hogging, roughing, semi-finishing, and ball milling operations. Using these equations, the total energy can be calculated as the sum of the energy for the individual processes:

$$\text{Energy}_{\text{Total}} = \text{Energy}_{\text{Hogging}} + \text{Energy}_{\text{Roughing}} + \text{Energy}_{\text{Semi-Finishing}} + \text{Energy}_{\text{Ball}}$$

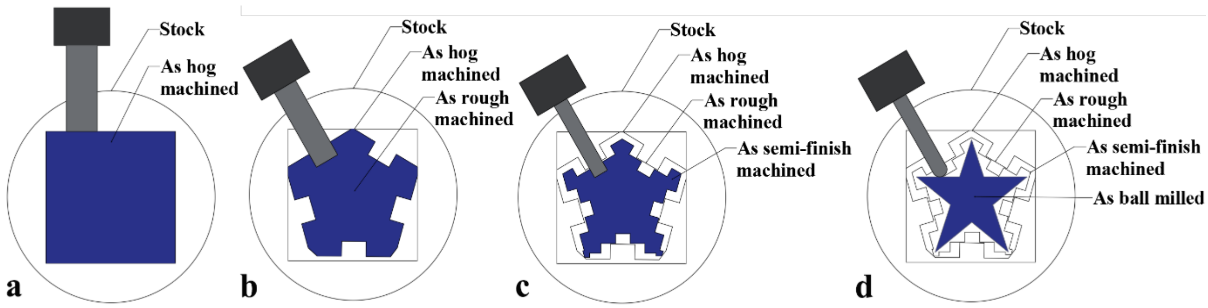

Figure 4.2 Steps in the machining process; (a) hogging, (b) roughing, (c) semi-finishing, and (d) ball milling

During hogging operations, a large amount of material is removed at a fast rate to reduce the stock material to the bounding (nearly) convex hull surrounding the final component, as illustrated in Figure 4.2a. The equation to calculate the energy at the hogging machining stage, $\text{Energy}_{\text{Hogging}}$ is as follows:

$$\text{Energy}_{\text{Hogging}} = -6815.07 - 0.96V_b - 1252.92d + 0.04F + 554.44l - 155.52S_m + 1367.42P + 14471.75S_r + 80.47R_{SA,V_p} - 16.84V_p$$

The percent of variability in energy consumption during hogging explained by the model (R-squared) is 98.16%. The standardized regression coefficients were calculated in order to determine the relative importance of the geometric characteristics; these values can be seen in Table 4.2. The most important characteristics to determine the energy consumption at this stage are part length (l), volume (V_p), reachability score (S_r), and diagonal (d). As the design's maximum dimension (length) is larger, the more energy will be consumed during machining. In other words, as the part becomes longer, the tool will have to travel further distance to machine the desired geometry. Thus, the relationship between length and energy consumption is consistent with the findings by Kong et al.; the authors concluded that energy consumption increases as the length of the machining toolpaths increase (Kong et al., 2011).

Table 4.2 Standardized regression coefficients

Variable	**Hogging**	**Roughing**	**Semi-Finishing**	**Ball**
Bounding Volume	-188	130	1880	243
Buy-fly Ratio	0	78	19	0
Diagonal	-310	244	2438	0
Facet Count	139	-389	0	0
Length	3700	593	7102	5451
Minimum Tool Diameter	0	-246	0	0
Machinability Score	-40	0	1014	0
Orthogonal Percentage	254	-706	-1046	0
Reachability Score	352	-472	-4524	-1573
Setup Complexity Score	0	11	60	0
Surface Area	0	0	0	3558
Surface Area to Volume Ratio	253	0	0	0
Unique Facet Normals	0	379	39	0
Visibility Score	0	164	0	-461
Volume	-731	-129	-5366	0

It can also be observed that designs with larger volume will consume less energy during hogging; this is because there will be less material to be removed. This is also why designs with large diagonals will also require less energy for hogging. Likewise, higher reachability scores correspond with more hogging energy. This is due to the fact that reachability score is inversely proportional to surface depth; the deeper a feature or surface is, the lower its reachability score. Therefore, components that have deep pockets with large surface areas will have low reachability scores; while designs with less deep features will have higher reachability scores. High reachability scores mean that more material can be removed during hogging operations. As seen in Figure 4.2b, roughing operations remove material layer by layer creating a stepped model closer to the final geometry. The formula to calculate the energy at the roughing machining stage, $\text{Energy}_{\text{Roughing}}$, is as follows:

$$\text{Energy}_{\text{Roughing}} = 18210.94 + 0.66V_b + 7.40R_{V_b,V_p} + 985.73d - 0.11F + 88.91l - 880.92T_{min} - 3796.71P - 19401.66S_r + 84.03S_{sc} + 0.86C + 1125.34S_v - 2.98V_p$$

The percent of variability in roughing energy consumption explained by the model (R-squared) is 80.94%. Like for hogging, orthogonal percentage, reachability score, and length are important characteristics to determine the energy consumption at the roughing stage (Table 4.2). For prismatic components with high orthogonal percentages (close to 100) and high reachability scores (close to 1), the hogging operation can remove most of the material; thus, there is less material to be removed during the roughing operations. Consequently, the energy consumption during roughing for such designs is lower than for free-form designs with low orthogonal percentages and reachability scores. As before, longer designs result in longer toolpaths and more energy consumption. Additionally, facet count and unique facet normal also play an important role in determining the energy consumption at this stage. Parts with high curvature will have a high number of unique facet normals, while prismatic designs or designs with orthogonal features will have a smaller number of unique facet normals.

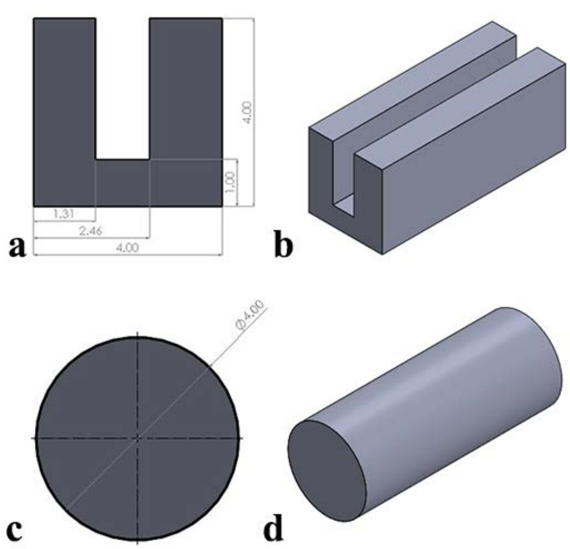

Figure 4.3 Designs with the same volume and length

Take for instance two designs, a slotted bar and a cylinder, with the same volume (V_p), length (l), and diagonal (d) that are machined from the same stock volume. The cross sections of these designs at $l = 5$ inches are shown in Figure 4.3. Since both designs have the same volume and length, the dark gray areas in Figure 4.3a and Figure

4.3c are the same. The bounding volume of the parts (V_b) is also constant between the bar and the cylinder. However, the cylinder has a higher number of unique facet normals than the slotted bar (the bar only has 6 unique facet normals). At the semi-finishing stage, a tool with a smaller diameter is used to further remove material, especially in pockets and features that the roughing tool could not create (Figure 4.2c). The equation to calculate the energy at the semi-finishing stage, $\text{Energy}_{\text{Semi-Finishing}}$, is as follows:

$$\begin{aligned}\text{Energy}_{\text{Semi-Finishing}} = \; & 150842.80 + 9.60V_b + 1.76R_{V_b,V_p} + 9840.64d + \\ & 1064.18l + 3988.51S_m - 5621.99P - 185891.80S_r + \\ & 476.53S_{sc} + 0.09C - 123.62V_p\end{aligned}$$

The percent of variability in energy consumption during semi-finishing explained by the model (R-squared) is 70.63%. Like for the previous processes, length and reachability score play an important role to predict the energy consumption during the semi-finishing step (Table 4.2). Referring back to the slotted bar and cylinder example (Figure 4.3), the slotted bar is expected to consume more energy than the cylinder during the semi-finishing stage. When looking at the bar from the top, the distance between the top surface and the farthest point reachable (3 inches) is longer than the distance between the top of the cylinder and the farthest point reachable (2 inches). Therefore, the pocket in the slotted bar requires a longer tool to machine, longer toolpath, and lower feed rates. This results in a longer machining time and more energy consumption during manufacturing. This fact is reflected in *ANA* since the slotted bar has a lower reachability score than the cylinder. This is a clear example that, as previously explained, the energy consumption depends on the geometry of the part being machined. Finally, a ball end mill tool is used to remove the remaining material and generate the final geometry of the part (see Figure 4.2d). The formula to calculate the energy at the ball milling stage, $\text{Energy}_{\text{Ball}}$, is as follows:

$$\text{Energy}_{\text{Ball}} = 77287.42 + 1.24V_b + 816.75l - 64651.50S_r + 39.54SA - 3162.63S_v$$

The percent of variability in ball milling energy consumption explained by the model (R-squared) is 82.55%. The effect of geometric characteristics on the energy consumption during ball milling is different from the other processes. While the component's length and reachability score are still significant factors, the surface area plays a more significant role than before (Table 4.2). As the surface area of the part increases, so does energy consumption at the ball milling stage. This is because a scallop toolpath for the ball milling operation is surface-based, therefore the toolpath length is proportional to the design's surface area. In a similar fashion, as the design dimensions increase, generally, so does the toolpath length. As previously explained, research has found that longer toolpaths result in higher energy consumption during machining (Kong et al., 2011). It is also interesting to note that the energy consumption during ball milling depends on visibility score. Low visibility scores mean that most of the design's features are undercuts or pockets that cannot be seen from some (or all) orientations. Features with low visibility score have to be machined at an angle or with additional setups, which may result in lower material removal rates, longer machining time, and higher energy consumption.

Referring back to the slotted bar and cylinder example (Figure 4.3), the bar will consume more energy during ball milling than the cylinder. Since the slot can only be machined from one orientation, the bar has a lower visibility score than the cylinder. Given that the bar’s surface area is more than 50% greater than the cylinder's surface area (150.8 in^2 vs. 245.13 in^2), the bar will require significantly more energy consumption at this stage.

Proposed Abridged Model

From the equations above, it can be seen that part length, reachability score, and bounding volume are significant factors for all four milling processes. Therefore, such geometric characteristics play an important role in determining the energy consumption during manufacturing. In fact, 75.49% of the variability in total energy can be explained by modelling total energy in terms of part's length, reachability score, and bounding volume. Furthermore, 72.13% of the variability in total energy among the designs considered can be explained just by considering length and reachability score. On the other hand, just considering volume only explains 14.47% of the variability in total energy. Thus, part volume by itself is not a good indicator of the total energy consumed during manufacturing. Taking into consideration the fact that design engineers might not have the time or expertise required to collect all the data required to calculate the energy consumption with the models previously presented, an abridged model is proposed. Considering the difference in variability that is explained by a linear regression model with and without bounding volume, the latter does not explain significantly more variability than reachability score and length. In fact, it is found that length and reachability score are the two most significant factors to explain the total energy consumption during milling. Thus, the proposed abridged model consists of a linear model of total energy in terms of length and reachability score:

$$\text{Energy}_{\text{Total}} = 397610.30 + 2485.40\, l - 369429.70\, S_r$$

In the absence of a tool that can automatically calculate the values required to determine the energy consumption with the proposed model, design engineers can use the abridged model to easily differentiate among designs. For instance, the design engineer could analyze two designs for machinability using *ANA* and quickly compare their lengths, and reachability scores. Alternatively, the design engineer could consider the depth of pockets and their surface area relative to the part's total surface area in order to compare the designs. Referring again to the simple slotted bar and cylinder presented in Figure 4.3, the design engineer could easily notice that the bracket has a deep pocket and since both designs have the same length, the designer could further infer that the bracket will have a higher energy consumption. Of course, the examples of a slotted bar and cylinder are only for demonstrating the general concept. The following section provides and implementation of the method and use with practical and more complex CAD models of parts.

Implementation

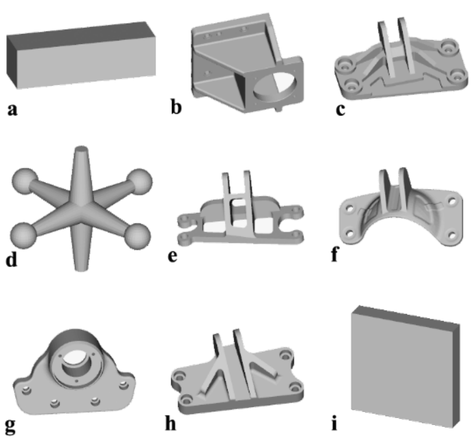

Figure 4.4 Images of implementation models

In order to evaluate how well the proposed models can predict the relative energy consumption during machining, nine additional models (Figure 4.4) were analyzed. A summary of the designs' geometric characteristics can be seen in Table 4.3. These values, along with the proposed model developed for each process, were used to estimate the energy consumption during machining.

Table 4.3 Geometric characteristics for each implementation design

Design	Volume (in^3)	Surface Area (in^2)	Reachability Score	Bounding Volume (in^3)	Length (in)	Diagonal (in)
a	13.13	38.31	1.00	13.13	5.30	2.23
b	13.13	85.55	0.94	55.92	4.72	5.35
c	13.12	84.16	0.93	73.57	7.03	4.92
d	1.50	13.48	0.94	45.94	3.98	4.92
e	6.66	54.94	0.96	62.60	6.62	4.67
f	7.05	60.59	0.94	73.27	7.03	4.92
g	19.78	86.53	0.95	67.25	7.18	5.54
h	28.32	115.39	0.94	107.91	8.23	5.72
i	28.32	77.93	1.00	28.32	5.40	5.34

The energy estimated with the proposed model and proposed abridged model were compared to the energy estimated by SolidWorks Sustainability and ecologiCAD for all designs. For the SolidWorks Sustainability analysis, it was assumed that all three models were milled from a 6061 aluminum alloy in North America. In addition to the comparison to SolidWorks Sustainability results, the proposed model results were compared to the results from ecologiCAD. For the purposes of this analysis, the components were analyzed using the Eco-indicator 99 (EI99) method assuming a functional unit of one aluminum component. In addition, each part had a "Cut" feature that was created by "Milling" the difference between the stock volume ($\pi \times (\text{diagonal})^2 \times \text{length}$) and the component's volume.

Additionally, machining toolpaths were generated and simulated for each design in order to calculate the actual energy consumption. The results are shown in Table 4.4. In general, the energy estimates obtained with the proposed model and proposed abridged model show a relationship with the simulated energy values. In fact, the correlation between the simulated energy values (actual energy) and the results of the proposed model is significantly high, 0.81 (0.31, 0.96). This means that the proposed model is able to rank the designs in terms of energy consumption during manufacturing better than chance (e.g. flipping a coin). That is, the results obtained with the proposed models can be used to make pair-wise comparisons and rank the designs in terms of energy consumption during manufacturing. However, when the actual energy values are very close, the results of the proposed models are not as accurate. This phenomenon can be seen by comparing the results for designs *b*, *c*, and *g* as well as for designs *e* and *f*. In the first case, the actual energy values are between 63 MJ and 67 MJ but the proposed model estimates energy values of up to 71 MJ.

Table 4.4 Energy values obtained with different models

Design	**Simulated Energy (MJ)**	**Proposed Model (MJ)**	**Proposed Abridged Model (MJ)**	**SolidWorks Sustainability (MJ)**	**ecologiCAD (mPts)**
a	5.89	12.18	41.35	2.82	98.21
b	66.92	62.96	60.68	2.82	1222.48
c	63.34	68.01	72.58	2.82	1581.75
d	15.56	59.52	58.83	0.32	973.21
e	78.08	58.54	60.92	1.43	1400.00
f	77.13	91.21	66.60	1.52	1661.59
g	66.06	70.95	62.69	4.26	2009.77
h	82.30	79.71	71.79	6.09	2404.81
i	21.64	41.77	41.60	6.09	1213.57

Likewise, the correlation between the simulated energy values and the results from the proposed abridged model is also 0.81 (0.31, 0.96). On the other hand, the correlation between the simulated energy values and the result from SolidWorks Sustainability is not significant, 0.08 (-0.61, 0.71). While the correlation between the simulated values and the results from ecologiCAD is high, 0.81 (0.31, 0.96), the results from ecologiCAD are dependent on the stock volume selected because its results depend on volume removed during machining. For instance, since the same amount of material is removed to create designs *b* and *i* with a bar stock proportional to the diagonal, ecologiCAD estimates that they will both have the same environmental impact.

It is also interesting to note that three of the designs, *a*, *b*, and *c*, had the same volume but significantly different geometries, as can be seen in Figure 4.4. Designs *b* and *c* have significantly more complex geometry than the brick (design *a*). Thus, it is expected that the machining operation to create designs *b* and *c* will use more resources than the machining operation to create the brick. Nonetheless, SolidWorks Sustainability estimates roughly the same energy consumption for these three parts with the same 13 in^3 volume (Figure 4.5).

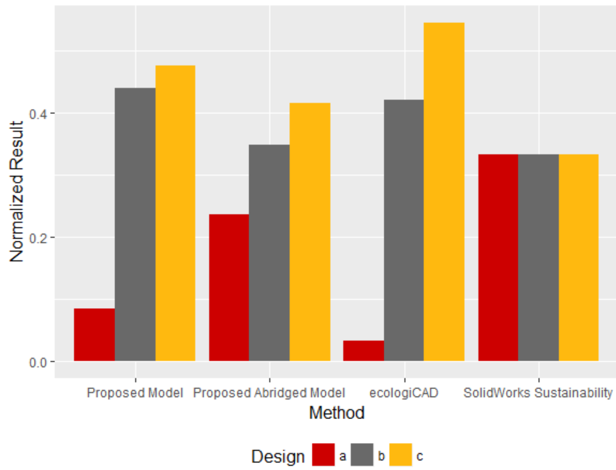

Figure 4.5 Comparison between proposed model and existing models for various designs

Better results can be obtained by analyzing the designs in ecologiCAD. For this analysis, the user needs to specify a stock in order to calculate the amount of material removal during machining. While those values can be obtained readily, the results of the analysis do not provide significant feedback to the designer. In fact, according to ecologiCAD the environmental impact during the production stage is only dependent on the volume of material removed during milling. It is interesting to note that, in this case, the results from the proposed models are in accordance to the results from ecologiCAD. However, the proposed models provide some feedback to the design engineer. The results from these models suggest that by comparing the design lengths and reachability scores, it is possible to differentiate between the three components. We would expect design *c* to require higher energy consumption than the other designs because it is longer and has geometry that is more intricate. Based on these geometric characteristics, we can also expect the brick, design *a*, to have the lowest energy consumption.

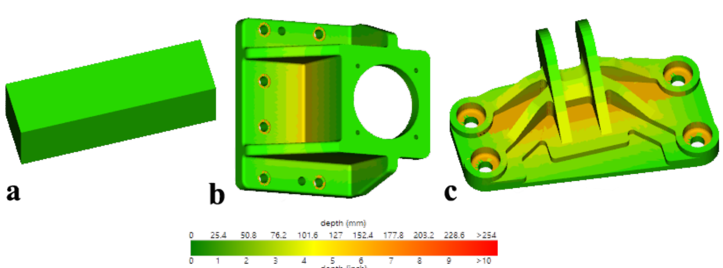

Figure 4.6 Reachability maps for the enlarged model designs

Figure 4.6 shows the reachability maps obtained from *ANA* for all three designs. Given that these designs have relatively large reachability scores (above 0.90), the STEP files were scaled to three times their original size in order to clearly show the differences in reachability. From the image, it can be seen that design *c* has more orange and yellow areas than the other two designs. This means that, among the three designs, design *c* has deeper pockets and cavities. Therefore, if the design engineer wished to reduce the energy consumption during manufacturing, they could consider the reachability maps and determine which cavities and pockets are driving the energy consumption for each design and reduce their depths if possible. Similarly, the design engineer could notice that design *c* is significantly longer than designs *a* and *b.* The results from SolidWorks Sustainability suggest to the designer that by reducing the volume of the design, the energy consumption during machining will also be reduced. Meanwhile, ecologiCAD indicates that high-density (buy-to-fly ratios close to 1) and small volume designs will have lower energy consumption during milling. While this might be true in some cases, ecologiCAD fails to differentiate between designs with the same buy-to-fly ratio and volume. On the other hand, the proposed model is able to identify the effect that specific geometry changes have on the energy consumption during milling.

Since the simulated energy values depend on the machining time estimates obtained from *Vericut*, the machining time estimates were verified by milling one of the designs, *d*. This design was machined out of a 3.0-inch aluminum stock in a HAAS VF-2 CNC machine with a scallop (ball end mill) finishing strategy. The machining times were observed by recording the cycle time for each toolpath operation. As shown in Table 4.5, the machining times obtained from *Vericut* are significantly close to the actual machining times (within 5 minutes).

Table 4.5 Actual and simulated machining times for Design *d*

Process	Seq.	Tool	Actual Machining Times (s)	Simulated Machining Times (s)
Hogging	1	1” Flat end mill	393	334
	2	1” Flat end mill	325	320
	3	1” Flat end mill	336	348
	4	1” Flat end mill	315	312
Roughing	5	0.50” Short bull end mill	1391	1318
	6	0.50” Medium bull end mill	2735	2534
	7	0.50” Short bull end mill	594	583
	8	0.50” Medium bull end mill	1416	1332
	9	0.50” Short bull end mill	1197	1185
	10	0.50” Medium bull end mill	1415	1383
	11	0.50” Short bull end mill	106	139
	12	0.50” Medium bull end mill	444	464
Semi-Finishing	13	0.25” Short bull end mill	528	574
	14	0.25” Medium bull end mill	3491	3736
	15	0.25” Short bull end mill	529	566
	16	0.25” Medium bull end mill	3395	3664
Ball	17	0.25” Short ball end mill	427	459
	18	0.25” Medium ball end mill	2778	2768
	19	0.25” Short ball end mill	424	459
	20	0.25” Medium ball end mill	2803	2850
		Total	25042	25328

Conclusions

This paper focused on the effect that a design's geometric characteristics have on the energy consumption for components manufactured with 4-axes CNC milling machines. Energy consumption directly affects the environmental and economic dimensions of sustainability, since higher energy consumption will result in increased resource use, increased CO_2 emissions, and higher costs. First, the geometric characteristics and machinability of 33 machined models from the National Design Repository were recorded. Then, machining toolpaths for all models were generated and simulated to obtain machining time and volume removed values. Such values were used to estimate the energy consumption during hogging, roughing, semi-finishing, and ball milling operations. It was found that a design's length and reachability score are the characteristics that have the greatest effect on the energy consumption during machining. It was also found that the energy consumption for semi-finishing and ball milling operations account for more than three-quarters of the total energy consumption during manufacturing. The findings from the study can be used to predict relative environmental and economic impact given the geometry of a component. This can be further refined to develop a tool that can guide engineers to more sustainable designs.

Further areas of research include the effect that geometric characteristics have on the energy consumption during other manufacturing processes, such as casting or an additive process like Directed Energy Deposition. With a larger portfolio of processes, it will be possible to make recommendations to design and manufacturing engineers regarding the most sustainable approach to manufacturing given a design's geometry. An important consideration is that, for the purposes of this work, it is assumed that the entire surface of the component requires ball milling. While this might be true in some cases, most parts only require some surfaces to be ball milled depending on the geometric dimensioning and tolerancing (GD&T) specifications. Hence, future work must address this issue by considering the effect of GD&T specifications on energy consumption. This can be accomplished by simulating the toolpaths for a component with different GD&T requirements and modelling the energy consumption during machining as a function of the features to be machined and the required surface finishes specified by the designer.

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

Conclusions

The main contribution of this thesis is a model to assess the energy consumption of components using their geometric characteristics. The basic idea is that sustainability assessments should reflect the fact that complex designs will require more resources to manufacture than simple designs. Without doubt, it is important to understand how a design's geometry influences a component's energy consumption throughout its life-cycle. With that objective in mind, this thesis presented a paper on the effect that geometric characteristics have on the environmental impacts at the manufacturing stage.

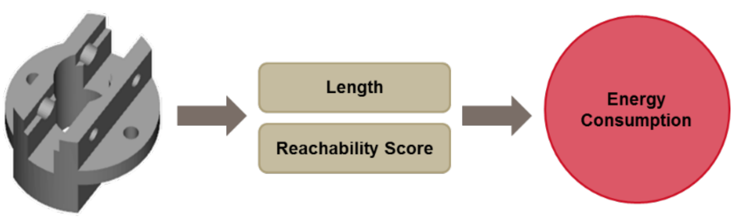

Figure 5.1 Diagram of proposed energy consumption estimation

Specifically, the effect that geometry has on the energy consumption during the machining of parts in a 4-axis CNC machine was studied. The study found that a design's length and reachability score are the characteristics that drive energy consumption during machining. As seen in Figure 5.1, these two geometric characteristics can be used to predict energy consumption during manufacturing. For example, longer parts and parts with deeper cavities and pockets will require more energy consumption to machine. It was also found that the energy consumption for semi-finishing and ball milling operations account for more than three-quarters of the total energy consumption during manufacturing. Hence, it is important to take into consideration the effect that design decisions will have on the sustainability of the finishing steps. The findings from the study can be used to predict relative environmental impact given the geometry of a component. This can be further refined to develop a tool that can guide engineers to more sustainable designs. The model presented in this thesis can be used as a stepping-stone for the development of a tool that can analyze design geometry from a CAD file, provide feedback to design engineers, and guide them to more sustainable designs.

Future Work

Further areas of research include considering the effect that geometric characteristics have on energy consumption during other manufacturing processes. By expanding the process portfolio, it will be possible to make recommendations to design and manufacturing engineers regarding the most sustainable approach to manufacturing given a design's geometry. An important consideration is that, for the purposes of this work, it is assumed that the entire surface of the component requires ball milling. While this might be true in some cases, most parts only require some surfaces to be ball milled depending on the geometric dimensioning and tolerancing (GD&T) specifications. Hence, future work must address this issue by considering the effect of GD&T specifications on the energy consumption. This can be accomplished by simulating the toolpaths for a component with different GD&T requirements and modelling the energy consumption during machining as a function of the features to be machined. Future research should also address tradeoffs between environmental and economic impacts during multiple life-cycle stages. While the results from this work suggest that reducing the depth and amount of pockets could result in higher reachability scores and lower energy consumption, this could also result in higher part weight. In turn, higher part weight can result in more fuel consumption during the use and transportation phases, especially for aerospace applications. For that reason, it is important to assess the sustainability of a component beyond just the manufacturing stage. Likewise, the effect of geometry on the societal aspect of sustainability remains an opportunity for future research.

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