The Pennsylvania State University

The Graduate School

Department of Industrial and Manufacturing Engineering

A QUANTITATIVE ASSESSMENT OF PRODUCT FORM AND ITS IMPACT ON CUSTOMER PERCEPTION AND DESIGN EDUCATION

A Thesis in

Industrial Engineering

by

Nitish Vasudevan

© 2013 Nitish Vasudevan

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2013

The Thesis of Nitish Vasudevan was reviewed and approved* by the following:

Conrad S. Tucker
Assistant Professor
Harold and Inge Marcus Department of
Industrial and Manufacturing Engineering
Thesis Advisor

Gul E. Okudan Kremer
Professor
Harold and Inge Marcus Department of
Industrial and Manufacturing Engineering

M Jeya Chandra
Professor in Charge of Academic Programs and Graduate Program Coordinator
Professor of Industrial Engineering
Harold and Inge Marcus Department of
Industrial and Manufacturing Engineering

*Signatures are on file in the Graduate School

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank everyone who have been instrumental in supporting and guiding me through the course of my master's degree.

Dr. Conrad S. Tucker has been more than an advisor to me. He has guided me through the course of my research providing feedback and suggestions when needed, guidance and the way forward when the going got tough. His continuous presence were all that were necessary for me to proceed through not just a master's program but my overall academic and professional career as well.

A special thanks to my committee reviewer, Dr. Gul E. Okudan Kremer, for her support, guidance and immensely helpful suggestions. Her guidance has served me well and I owe her my heartfelt appreciation for taking out so much of her time on advising me through the process of shaping my thesis.

Members of the Design Analysis Technology Advancement (D.A.T.A.) Lab of the School of Engineering Design, Technology and Professional Programs, all deserve my sincerest thanks - Sung woo Kang, Chinmay Sane, Yixiang Han, Gautam Atulya Manohar, DeRauk Gibble and Andrew Depenbusch. Their friendship and assistance has meant more to me than I could express. Thank you all for your patient and friendly assistance.

It has been a great privilege to be a part of the Harold and Inge Marcus Department of Industrial and Manufacturing Engineering at the Pennsylvania State University at University Park. I sincerely thank Dr. Paul Griffin, the department head, Dr. M. Jeya Chandra, the graduate program coordinator and all other members of the department and the university who contributed to the wonderful experience that was my master's program.

Finally I wish to thank my parents, Vasudevan Kothandaraman and Sudha Vasudevan, and my brother Niraj Vasudevan, for the immense love and support, and for being the driving forces throughout my life. I am what I am because of them.

ABSTRACT

Quantifying the geometric form of a design artifact has vast implications in product design ranging from the ability to foster a better understanding of engineering design concepts to predicting customers' perceptions of aesthetics qualities. In this research, the correlation between geometric product designs and the factors they influence is studied and an understanding of how they are connected is presented. In a company that manages a family of products, determining the design and performance requirements of next generation products is critical to overall market success. The proposed methodology employs design similarity and complexity metrics to help enterprise decision makers evaluate the impact of a product's geometric form on i) customers' aesthetic perception after product launch, and ii) design education. Many engineering students trained in design education, graduate to become world-class engineers and design products for the commercial market. Since a critical dimension that customers evaluate products on, is based on the aesthetics of design, it is paramount for students to understand the impact of their design decisions on the end user. The methodology also aims to refine the assessment of digital designs through an automated similarity evaluation process. A case study consisting of a database of coffee mugs is used to demonstrate the effectiveness of the proposed methodology in assisting next generation product design and development decisions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

The competitive global landscape, where customer satisfaction and retention are critical components of product success, puts pressure on companies to innovate and develop new products so as to meet demands of the increasing market space [1]. Companies are actively involved in pre-sales market research in order to better understand customer requirements, market trends and areas for future innovation. Valuable information from these studies are correlated back to the design phase and in turn, provides designers with feedback required to further update product design portfolios.

"What you see is what you get" – provides insight into human tendencies to attraction based solely on design and outer aesthetics [2]. This has motivated designers and artists to understand and evaluate customers' aesthetic appeal as an important factor during the design phase of a product [2,3]. Product failures relating to a product's geometric form (e.g., such as the sharp edges of the first generation MacBook Pro® or the sleek but slippery Nintendo Wii® controller) highlight the impact of product geometric design on potentially highly successful products [4][5].

The extent of the influence of geometric product design on the market is, however, difficult to measure prior to product launch. Companies simultaneously spend considerable effort in running simulations that attempt to predict customer reception based upon past records of the company and the product family. This, together with the human mentality to buy new and innovative products often result in companies updating the exterior design of products quite frequently [6]. An example of this is the automobile industry which changes exterior design geometry frequently keeping technical specifications at times the same [7]. There is also a need to identify one design amongst many when the possibility of multiple design realizations exists. This can be seen in automobile companies which pursue only one design after considering other possible designs as well [7–9]. Customers eventually evaluate products in the market space based on multiple dimensions (including design aesthetics) and make a purchasing decision.

Design engineers in a company start learning design principles in an academic setting (undergraduate or graduate) prior to working as a designer. In design education, the shift of concept visualization from the drawing board to the digital space has aided in ease of concept development and provided new computerized methods to evaluate designs based on geometry [10]. Traditional methods to assess digitally generated models involve tedious visual inspection that is subject to variations in grading rubrics and perceptions across graders (e.g., multiple teaching assistants assess different students on the same assignment) [11]. This time consuming process becomes overbearing when the number of students to be graded increases, giving rise to an increase in the number of graders required and greater variations across graders. These increases may therefore introduce unintended biases and variations in assessment making it challenging to provide standard quantitative assessments of student performance on digital assignments. The proposed methodology aims to aid product design development through the evaluation of product geometry and better understand customer aesthetic perceptions that influence design. The similarities in the geometric form amongst designs are also evaluated with respect to a benchmarked model to mitigate the challenges faced in assessing product designs. The proposed methodology aims to answer two important questions by employing the complexity and similarity metrics – i) On a direct visual comparison, which product is the most appealing from the view of the end user? ii) How can digital models of designers be assessed more effectively?

The thesis is organized into the following sections; section 2 deals with the literature review pertaining to existing trends in complexity research, product appeal, customer feedback mechanisms and the present engineering education evaluation framework. Section 3 focuses on the proposed methodology for the process of data acquisition, estimation of form complexity and form similarity evaluation. The case study section comprises of an analysis of coffee mugs designed by students to show the impact of product complexity on the proposed methodology. The designs are also evaluated based upon the similarity metric to generate student grades. The last component of section 4 explains the impact of the similarity metric in estimating form similarity that is useful in assessing student designs when benchmarked against a standard design model. The final section showcases the results generated through the complexity and similarity metric and suggests future areas of scope for improvement and research applications.

Chapter 2

LITERATURE REVIEW

This section is classified into three major categories. The first section deals with understanding product geometry and evaluating form based upon physical features. The second section investigates how a product's geometric form is correlated with aesthetic appeal in order to understand customers' perceptions of product form. The final section deals with the impact of product form evaluation on present trends in engineering education that aim to improve the student design grading process.

2.1 Quantifying Product Geometry

Product geometry evaluation consists of understanding the various levels of intricacy present in the geometric features of an artifact. The term complexity evaluates product intricacy based on various factors which contributes to product feature design[12]. The term complexity has many definitions spanning a wide range of disciplines. While there is little consensus on a unified definition, on a general level, the term is used to quantify the level of intricacy of a system. Components, sub-divisions, level of detail, degrees of interactions, hierarchies, incoherence, and randomness have all been used to define complexity across various domains [13–15]. In this work, the term complexity as it relates to the geometry (form) of the product is defined based on the intricacy of physical attributes of the artifact. The form of the product is defined in this work as the physical outer geometry of the product which correlates to the shape and structure [6]. This correlation has been the most suitable to help study influences of visual form complexity [12]. The aim of this research is to isolate the physical characteristics of a product and understand its significance with respect to visual complexity and aesthetic appeal.

Complexity of physical artifacts can be represented in a number of ways. One of the most effective representations of physical artifacts is in the form of digital 3D models [16,17]. These models are useful in conveying concepts of design and reverse engineering capabilities on a digital platform that is readily accessible to all. 3D models are rich in content and to a large extent convey the i) geometry, ii) topology, and iii) subassembly characteristics of the objects they portray [12]. *Crespo-Varela et al.* have undertaken a study of complexity measurement techniques for product design and classified these metrics into software and product based analysis. The metric deals with sub-component interactions and its effective application in the healthcare domain [16]. This research deals with geometric complexity on an individual component level, without their interactions in order to understand the effect of product geometry (form) on engineering design assessments and overall product aesthetic appeal.

Determination of form complexity of 3D models in the stereo lithography (STL) file format represents the wire mesh structure of the surface topologies. This provides a structured method to access coordinate data that is the input for form complexity. This representation of point data visualized in 3-dimensional space is a means of evaluating the complexity of the artifact [18]. This is due to the fact that coordinates along with the direction vectors for the triangles in the wire mesh are stored in a systematic form in the STL file. Interestingness and pleasantness have all been used to quantify the level of visual complexity through qualitative measures defined for a product domain [19]. Other methods of complexity evaluation involve quantitative measures based on the surface topology of a model - crinkliness, structural factors and curvedness [20,21]. Though each technique has its unique way of defining complexity and has varying assumptions, the most efficient process to evaluate complexity is while considering more than one key criterion. This is demonstrated by *Singh et al.* where both density and curvature of the surface are considered to evaluate the design complexity through the evaluation of model detail [22]. Further, design complexity can be obtained through 2D image slices of the object or by considering the 3D object as a whole.

Estimation of form complexity using 2D techniques have been shown to produce results that are not always consistent and rely heavily on multiple image projection techniques which are both hard to store and may not always give the full geometric representation of the 3D artifact [23]. *Saleem et al.* propose a method to evaluate form complexity of 3D objects by considering dissimilarity in 42 2D shadow projections that are generated from different viewpoints positioned along a view sphere [17]. This method while efficient does not capture the full detail of a 3D model, until the number of viewpoints is increased significantly. This becomes time consuming as well as an inaccurate method to estimate form complexity that is dependent on the number of 2D orientations.

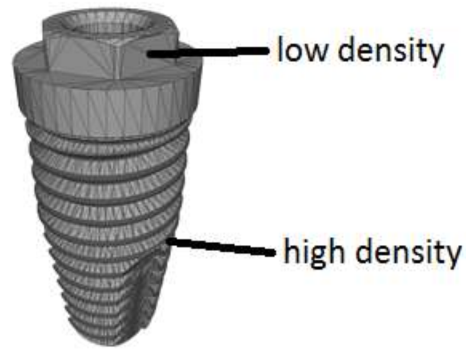

Figure 2-1: Example of 3D artifact in wire mesh representation.

From the wire mesh representation of the 3D model in STL format (figure 2-1), the curvature which represents the surface topology and the density of wire-mesh about a point are considered in calculating the complexity of the artifact. Areas of detail (edges, grooves, curves etc.) carry higher density values where bends are represented by higher curvature values [22]. Other applications of visual complexity determination in 3D include the use of *Bovil's* method for assessment of build environments [24]. *Stickel et al.* have also proposed a *XAOS* metric to evaluate visual complexity based upon usability [25]. Visual complexity measurements have also been used in architecture to assess building plan complexity based on the number of unit boxes present in the structure. This is explained by *Ostwald* and *Vaughan* in *Peter Eisenman's* architecture [26].

In understanding influence of product design complexity on the market, an assessment of the perception and factors which influence customer views is to be undertaken. It is shown that visual impact of product designs influence human perceptions to a great extend when other utilitarian factors remain constant [27–29]. The next section deals with aesthetic appeal and its impact on product design.

2.2 Aesthetic Appeal

Aesthetic appeal is defined as the physical factors of a product (form) that influence the decision to consider a product, as opposed to another visually dissimilar product for purchase, given identical utility and pricing [29]. This research aims to develop a quantitative approach to evaluate product design decisions by helping manufacturers understand the effect of visual form complexity on the overall aesthetic appeal of the product.

Customer perception of a product is as important as the performance of the product [30]. Customers make purchase decisions based upon the aesthetic form and the utilitarian value of a product [31]. Though, performance and costs to a large extent influence customer preferences, visual appeal and product interface interactions also play a role in purchase decisions [3,32]. *Yamamoto* and *Lambert* have shown that in some cases the influence of product design through appeal exceeds the influence due to performance and acts as a major factor while estimating sales of new to market products [33]. Product designs have also been studied using shape grammar techniques where evolving transformations in shapes among similar products determine new designs [34]. Shape grammar analysis used in the design phase is shown to be effective in optimizing the design as well as allowing the designer to change geometric attributes based on manufacturing requirements [35]. *Chau et al.* have used shape grammar analysis based upon non-rational b-spline representations to create models conveying 3D geometry, shape emergence and parametric shape rules, useful in comparing geometry of products [36]. Centrality of Visual Product Aesthetics (CVPA), defined as the significance given to a product – customer interaction based on value, acumen and product response intensity is used to evaluate customer satisfaction. Studies have also been conducted by *Bloch et al.* on high and low CVPA values and their impact on the evaluation of product development [37].

Feedback from customers through surveys and questionnaires in the form of written, oral or electronic data acquisition has always been a hallmark of understanding the impact of new product on the market. Customer feedback forms or questionnaires, aimed at product self-improvement, focus to a large extent on the aesthetic appeal showcased by the product, the utility and pricing as some of the major verticals. It has also been shown that customers prefer to buy products with a high aesthetic appeal, when different brands offer the same utilitarian and relatively similar pricing for their products in today's competitive market [30,38].

The use of a complexity metric to assist as a decision support mechanism to further help evaluate product form as a means to assess the perceived impact of customer feedback is proposed. The results obtained through the analysis of customer perception potentially influence the designer and the design process. Engineering design students who evolve to become designers are exposed to various facets of design influences but the present education framework is incomplete without a proper understanding of how design and customer perception are related. The next section focuses on engineering design education and the impact of the proposed methodology on engineering students and designers. In particular, importance is given in the betterment of student design assessment which is an important factor in design learning.

2.3 Engineering Education

In the context of engineering education, *hands*-on learning experiences are critical to students' understanding of the physical design space. Through activities such as product dissection, students develop an understanding of the interactions between components, the manufacturing process and the assembly sequences that are involved in the product design process [39]. While *digital* and *hands-on* learning experiences are vital to the academic development of students, the manner in which these educational modules are taught fails to connect both in a real-time, dynamic manner. In addition, the techniques employed to assess *digital* design solutions often rely on visual inspection that can vary based on the individuals(s) providing the assessment. The following two sections study in detail digital learning and assessment of student designs.

2.3.1 Digital Learning in Engineering Education

Information as defined by Shapiro and Varian is "essentially, anything that can be digitalized – encoded as a stream of bits" [40]. Furthermore the authors emphasize on the need to digitalize data for the benefit of sharing, editing and transmitting on a common platform, across different users and systems. The competency of millennial workers to utilize digital technologies to accomplish a wide variety of tasks sets the cornerstone for emerging new technologies such as that of the 3D scanner [41]. Studies such as the Kolb's learning cycle have shown that engineering learning can be divided into four stages – "concrete experience, reflective observation, abstract conceptualization and active experimentation" [42]. The integration of multimedia supports and complements hands-on experience through the use of digital tools such as the 3D scanner, livescribe digital pen and the voice to text feature. These devices have accelerated and improved the process of information extraction and storage. Experiments conducted by Stanford University with their bicycle disassembly course have shown that students learn better when multimedia tools are employed as part of the existing teaching methodology [43].

Bernardini *et al* has in detail discussed the various techniques involved in converting physical objects into the digital space, but have failed to include newer tools (3D scanners) in image data acquisition that are both beneficial and upcoming areas in engineering design [44]. High definition 3D image scanners have been around for a while and have a wide range of applications ranging from automobile to art [45][46].

The inclusion of 3D scanners in the existing design engineering framework will be beneficial for students in understanding design based hands-on learning through a digital perspective. This in turn could help students generate novel concepts during their routine exercises with design software. Developments in 3D scanning technology have ensured that low cost, high accuracy digital 3D technology are available to capture physical artifacts better, as a means to understand better the design and construction parameters of an artifact.

2.3.2 Assessing Digital Models in Engineering Design

Classroom designs rendered by students are graded on the sole concept of similarity to the original model (either physical or virtual). The task of grading these individual models is a time consuming process and is generally carried out by more than one person (staff or student) [11]. Typical CAD assessments employ a evaluation rubric where instructors or teaching assistants visually inspect a series of items outlined on the rubric as a means of assessing student performance on digital assignments [47]. This may potentially create evaluation biases. Automated evaluation techniques exist throughout education including scanning-based grading sheets for multiple choice types of assessments [48–50], computer assessment systems for grading essays [51,52], and even computer programs assessing student-computer programming assignments [53,54]. Student assignments primarily based on quantitative evaluations have less controversy surrounding automated grading, compared to textual assessments (such as essays and programming code) that attempt to quantify qualitative data (student responses in the form of text) [47].

The data generated by 3D scanning hardware (or created by 3D modeling software) is at its core, quantitative in nature, which can be represented using mesh diagrams that are simply coordinates in a 3D space. Therefore the 3D similarity metric proposed to evaluate student digital assignments is simply evaluating quantitative data across a wide range of student solutions. The metric employed in this work can help mitigate 3 problems: i) variations in assessment scores across instructors/teaching assistants, ii) comparing student solutions with design artifacts that do not have existing grading rubrics (e.g., artifacts naturally existing in nature) and hence are difficult to replicate in a natural CAD environment, and iii) time needed to evaluate a wide range of digital assignments by students. These advantages help in the betterment of the student design assessment process.

Chapter 3

Methodology

This chapter comprises of the following topics i) Data acquisition – 3D models, ii) Form complexity metric, and iii) Form similarity metric. The first section discusses the type of data collected (digital 3D models) and used in this research and the importance of having auxiliary data collection methods. The next two sections explain the evaluation of form complexity and similarity based upon data acquired in the first section.

3.1 Data Acquisition – 3D Models

The visual data used to represent product designs are typically in the form of 3D renderings created by design software which are readily available. It is for this easy access that data used in this research comprises of 3D models of product assemblies and subassemblies to help estimate product form complexity and similarity. Surface topologies and geometric features of an artifact are easily distinguishable in a 3D model that is considered as a unit as opposed to individual 2D projections or 3D part files. These 3D models are considered in the Stereo lithography (STL) file format, in this work. STL files comprise of triangulated mesh coordinate details (figure 3-1). The file provides information on both position and direction vectors of triangular meshes in coordinate space which makes it easy for design software and simulation codes to map the spatial extents of the product.

Syntax	Example
facet normal n_i n_j n_k	facet normal 9.337524 2.207852 2.817098
outer loop	outer loop
vertex $v1_x$ $v1_y$ $v1_z$	vertex 6.561945 2.555627 5.270489
vertex $v2_x$ $v2_y$ $v2_z$	vertex 6.616785 2.543438 5.184250
vertex $v3_x$ $v3_y$ $v3_z$	vertex 6.692712 2.531525 5.025949
endloop	endloop
endfacet	endfacet

Figure 3-1: Syntax and example for STL file format.

In figure 3-1, n_i, n_j and n_k represent the normal to a triangle in the triangular mesh structure of the 3D model. This is a unit vector in the direction perpendicular to the plane of the triangle pointing outwards from the center of the model. The vertices of the triangle in 3D space are denoted by vn_x, vn_y and vn_z (n=1, 2, 3). Together, these variables provide complete information on the position and direction of an individual triangle in the mesh. The same syntax is used for all triangles in the mesh.

The evaluation of product form complexity and similarity is based on the information extraction from STL file data as seen in the next section. STL files are generated from 3D CAD models of products which have digital representations available. Products which are outdated or which do not have a digital representation can be scanned using a 3D scanner (e.g., Nextengine® portable) to produce a digital representation which can in turn be used to generate STL files. The output of the 3D scanners seamlessly integrates with existing engineering software (such as SolidWorks), thereby enabling designers to edit and manipulate the transformed physical images in a 3D environment. The following section deals with the acquisition of 3D model data of objects for which digital versions are unavailable. This is useful in collating data for cases where the geometry of the artifact may have changed due to degradation caused over the life of use of the product.

3D scanners consist of a camera of varying focal length to capture 2D image projections of artifacts ranging from a few centimeters to a couple of meters in dimension. There is also a set of lasers that measure the relative distance of various points on the artifact to the scanner. These lasers acting as distance measurement devices, is what gives the depth to the digital representation which along with the 2D image enables the 3D capture of the artifact. In some cases visible light is also used as a medium to measure depth [55]. Most portable 3D scanners are accompanied by a turntable controlled by the scanner in order to obtain accurate rotations to cover all angles of projection of the artifact along the scanning plane [55].

The corresponding scan software is loaded and the scanner is synced with the software prior to the scan. The physical artifact to be scanned (in this case, a speaker system, figure 3-2), is placed on the turntable, and the scan software is initiated on the laptop. Scan parameters such as resolution (expressed as points per unit area), quality of scan and number of divisions per 360 degree scan, and region to scan are all specified in the software prior to the scan. The time it takes to create a digital representation of a physical artifact using the 3D scanner is dependent on the complexity and the number of divisions of scans required of the artifact being scanned, the processing power of the machine running the scan software, and time taken for the initial 3D scan setup.

Depending upon the artifact that is scanned, a top and bottom view perspectives may also be scanned and aligned using the software to give a complete 3D representation of the artifact. Once the 3D model is obtained, it can be easily exported to a host of design software. Figure 3-3 shows the results attained after scanning the speaker system seen in Figure 3-2. The scanner used is the Nextengine® portable table top scanner running on ScanStudioHD, the software associated with the scanner.

Figure 3-2: Setup of 3D scanner capturing the digital representation of a physical artifact (speaker system) [56].

Figure 3-3: Different stages of the 3D scanning process [56].

As can be seen from figure 3-3, different perspectives of a physical artifact can be attained in the digital environment ranging from the color view as captured by the scanner (in essence, a 3D visualization of the original physical design artifact), surface view (revealing the contour details of the physical artifact in the digital space) and finally, the mesh view (which is a triangular mesh representation revealing the edges and nodes of the design artifact in the digital space). The surface and the mesh views are generated by the scan software from the original 3D model created by the scanner. The image on the left of figure 3-3 indicates the viewpoint of a customer who sees only the finished geometry whereas the images on the right indicate the viewpoint of a designer.

Figures 3-3 shows visual representations of different design artifacts that have been explored as part of the product dissection activity in class where students are engaged in product dissection and at the same time can seamlessly represent their artifacts in a digital 3D environment (using the 3D scanner). The 3D model data that is generated using the 3D scanner or is obtained from the product database is evaluated for form complexity and is compared for similarities with other products in the database using the techniques discussed in the following sections.

3.2 Form Complexity

Form complexity is calculated for 3D artifacts from their STL files that are coded in ASCII format (figure 3-1). The first line gives the facet normal to the direction of the triangle in the mesh and the three coordinates of the triangle are represented in the loop. Depending upon the number of triangles present in the mesh, the code is repeated with different coordinate values. The calculation of the form complexity of the artifact is divided into two parts. The first step is to calculate the density distribution of the triangulated mesh along the surface of the artifact. Density is defined about a node as ratio of the number of surrounding nodes to the individual edge lengths on the surface of the artifact as seen in equation 3-1. Also, meshes are generated on the surface in such a manner that the regions of high mesh concentration exhibit strong geometric features as opposed to regions of weaker mesh distribution. This is crucial in studying the impact of the form of the artifact alone. The curvature represents the surface topology of the artifact and together with the density provides an insight into the complexity distribution across the surface of the object. Variations in object design can further correlate to changes in the complexity distribution. This is an important factor in understanding regions of influence in the artifact by understanding the difference in customer feedback between the design variations.

Data in the form of triangulated surface meshes are used to determine the density distribution along the area of the mesh. This is generated on a point to point basis. The density equation is shown in equation 3-1 [22].

$$Density(V) = \frac{numNbrs(V)}{\sum_{i=1}^{numNbrs(V)} edgeLength(V, V_i)} \qquad (3\text{-}1)$$

Where,

- numNbrs(V) = Number of neighbors for vertex V
- edgeLength(V,V_i) = Edge length between vertex V and its adjacent vertices V_i

Here, the density at point vertex V is given as the number of adjacent neighbors to V (numNbrs) divided by the total Euclidean edge length distances to and from the vertex to its neighbors. The effective range of density values is from 0 to infinity.

$$cdiff(\vec{x},\vec{y}) = \frac{1}{2}\left[-1\times(\frac{\vec{x}.\vec{y}}{|\vec{x}||\vec{y}|})+1\right] \qquad (3\text{-}2)$$

$$Curvature(V) = \sum_{i=1}^{numNbrs(V)} \frac{cdiff(N(V),N(Vi))}{numNbrs(V)} \qquad (3\text{-}3)$$

Where,

- cdiff(x,y) = cosine difference between normal vectors of vertex V and V_i (x and y are adjacent normal vectors represented by n_i, n_j and n_k from figure 3-2)

The determination of curvature value at a vertex on the wire mesh is done by calculating the cosine difference between the point normal about the vertex and its first ring neighbor. In equation 3-2, x and y are the normal for the vertex points *N(V)* and *N(V*$N(V_i)$ on the wire mesh. The curvature like the density is calculated for each vertex V through the summation of cosine differences for all neighbor points as shown in equation 3-3 [22]. The range for the curvature is fixed from 0 to 1 for all vertices as it is a function of the cosine differences between the two normal. Having generated the density and curvature distribution across all points on the 3D wire mesh, the complexity or level of detail (intricacy) is defined between the two functions as:

$$\text{Complexity} = \text{Density}^{\text{Curvature}} \qquad (3\text{-}4)$$

The density is raised to the power of the curvature function as the values of curvature are bounded in the region of 0 to 1 (equation 3-4). The exponent operator is used as the complexity is already bound within its range. Thus the generated complexity value has a range of 0 to infinity [22]. The complexity values generated pertain to the outer shape of the object and are independent of all other factors. This is a step forward in quantifying the form a component. This can be tied to the customer perception of appeal to understand factors in design which are influential and answers the question of what customers find appealing. A design with complexity value of 2 is thus twice as complex as a design with value 1. This correlation can be better understood when values are correlated to complexities in the manufacturing process, which is beyond the scope of this research. The code used to generate form complexity values is shown in appendix B.

3.3 Form Similarity

To complement the evaluation of form complexity, form similarity is assessed to understand the level of geometric overlay between two models. This helps in evaluating models based on a benchmarked model as an assessment parameter. To understand the *form* of assemblies, it is crucial to consider 3-dimensional representations of components in the form of mesh data and proceed to label the *form* of each combination of subassemblies present in them. This is done by converting mesh data in the form of 3-dimensional models to reeb graphs which provide a graphical representation of the *form* of each model. Reeb graph as a shape retrieval technique has limitations as explained by Bespalov *et al.* and is domain specific to a large extent [57]. The authors in this work have employed a generic reeb graph technique adopted by Doraiswamy *et al.* to evaluate the *form* of the products [58], although the proposed methodology is not limited to Reeb graph techniques to quantify *form* similarity. Other shape geometry retrieval solutions as discussed by Iyer *et al.* can also be employed within domains to evaluate *form* and compare products [59]. Figure 3-4 shows the 3D object on the left and its corresponding Reeb graph on the right. The generation of a Reeb graph represents the connectivity of the various level sets of a 3D model where each level set (represented by lines parallel to the horizontal in Figure 3-4 is the projected 2D section of the model at varying distances from a base reference plane.

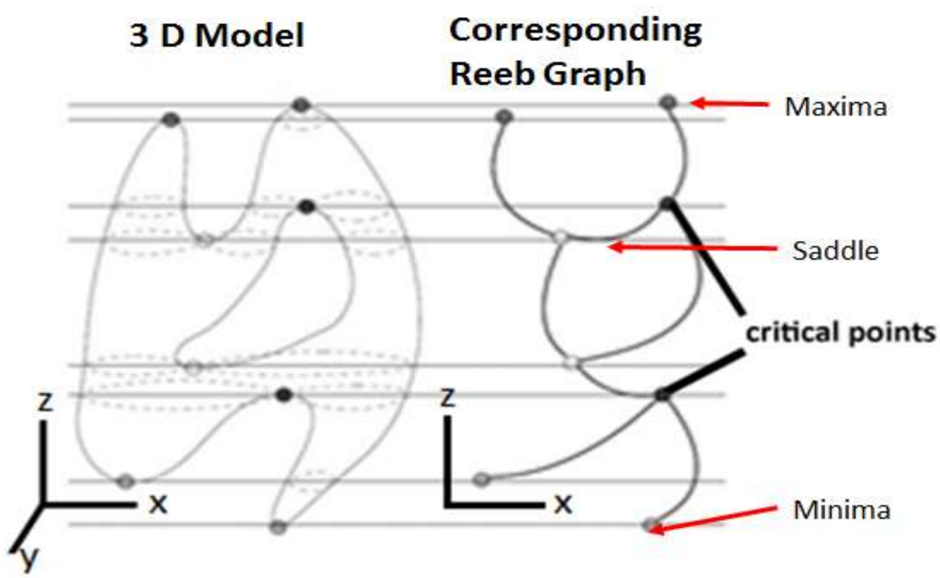

Figure 2-4: Reeb graph sample visualization [60]

The method employed to determine the reeb graph is based on the determination of iso-surface parameters at increasing level set values (along Z axis) through the generated image model [61]. Based on the generated graphs for the various components, graphical similarities which is a representation of the similarities in *form* between graphs is calculated for each possibility. The process to efficiently generate and compare the reeb graph topologies is carried out based on the research done by Doraiswamy *et al.* [61]. Based on *Morse's theory* of surface manifolds, which studies the differential equation of the topology, the reeb graph is computed using a step-wise iteration.

The first step involves the sorting of vertices or coordinate points in the point cloud mesh data that make up the 3D model in increasing order of their function value from a set reference plane (XY plane is considered the reference for explanation). For the purpose of simple validation, we assume that all points in the mesh of the 3D model have equal weights or functional value. The next step involves establishing the Reeb graph function which has an initial value of "NULL" and as the algorithm is iterated, stores the critical point data. The output of the Reeb graph is generated based on this function. The computational step checks the iso-surface parameter at each node and continuously returns the critical values to the Reeb graph function. The final step generates the output of the Reeb graph, a sample of which is shown in Table 3-1.

Table 3-1: Sample output of a Reeb graph

Level set data		
Saddle	Maxima	Minima
1	0	0
2	0	2
3	6	5
.	.	.
1543	1554	1023

The input is represented as a 3D triangular mesh that is generated by rendering the image dataset for a definite number of tetrahedral blocks [58]. The generated Reeb graphs for the various combinations of component subassemblies consist of critical points classified into saddle, maxima or minima based on mesh analysis of each combination [58]. These are determined based on the value of the iso-surface at each point. *Maxima* are points with only lower iso-surface values and minima are those with only higher values. *Saddle points* are either points with multiple higher or lower iso-surface values. An enumerative process which lists all these points is shown in Table 2. The values in the columns indicate the increasing level set values for saddle, maxima and minima for the 3D model. More than one critical point configuration per level set value is possible depending upon the topology of the model. Comparisons are drawn based on the basic evaluation of generated Reeb graphs through critical point similarities which best represent the structure of the components.

Similarity measures between two 3D models are therefore based on the similarities in the level sets and critical point distributions of the Reeb graphs of the models as depicted in Figure 3-5. Point A and point B of the different objects lie on the same level set and are both *maxima* points. This similarity adds to the similarity function value of the two objects, whereas point C which is also a maxima point on a different level set does not add value to the function due to the lack of a corresponding similar nodal value on the other object.

The similarity values that are generated are based on the number of similar nodal level sets that are found between two Reeb graphs of different components. This is done by an iterative process to compare the critical points for each similar level set. The ratio of the similar points to the total points generated (scale of 0 to 1) in the Reeb graph data set gives the similarity ratio for each iterative comparative model. This similarity values generated indicate the level of similarity between configurations. For example, a configuration having 10 different level sets and a similarity value of 0.4 indicate that 4 out of the 10 level sets have similar values. The code used to generate form similarity values is shown in appendix C.

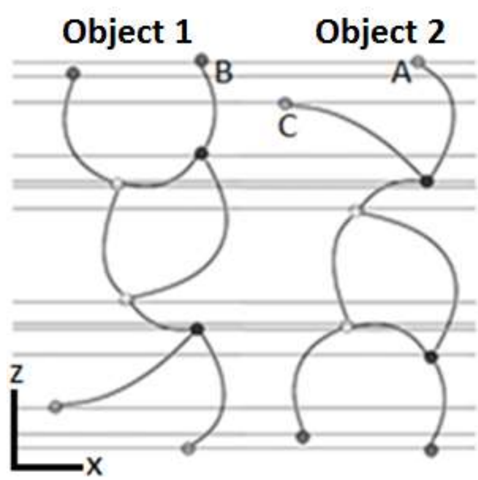

Figure 3-5: Reeb graph comparison on increasing level set values (z-axis) for different configurations [62].

The values that are generated between products, giving the degree of geometric compatibility between the two, indicate similarity in design and the possibility of combination with ease. The impact of this is seen while evaluating student designs with a reference design from the database or one created using a 3D scanner thereby increasing the effectiveness of design education.

Digital 3D scanning technologies along with the form similarity metric have the potential to remove bias during student grading. Figure 3-6 presents an overview of the proposed methodology. This process can be generalized for most scanners with a few modifications.

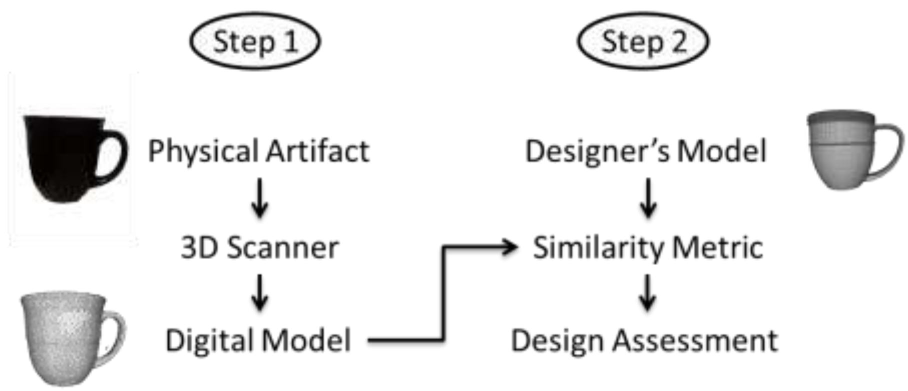

Figure 3-6: Steps involved in the generation of a digital 3D model using a 3D scanner and successive student grade creation.

The setup consisted of a control group consisting of a classroom of 29 freshmen engineering design students who were given the challenge of measuring and modeling the mug using design software within 2 hours and a graduate student creating a model of the mug using the 3D scanner simultaneously. The generated student models are compared to that created by the 3D scanner assuming that a digital model of the mug was unavailable in the database. The results of this proposed methodology is discussed in the next chapter.

The proposed methodology deals with evaluating the geometric form of an artifact through the evaluation of product complexity and similarity. The two metrics are related as they both evaluate the form based upon exterior geometric features. While, the complexity metric evaluates individual levels of detail, the similarity metric highlights the common regions in design amongst two models. The application of these metrics is seen in the next chapter.

Chapter 4

Case Study

This chapter is comprised of a case study involving a coffee mug as the product under investigation. The various sections of this chapter discuss the impact of form evaluation using either the complexity or the similarity metric explained, on aesthetic appeal, engineering education and student design grading. The database of products used for evaluation is shown below (figure 4-1). Factors of design such as color and texture are neutralized to study only the impact of product geometric design. Section 4.1 discusses the case study considered to evaluate complexity values using the proposed metric and aesthetic appeal based on survey results. For the betterment of student design assessment, section 4.2 explains the setup used to grade student designs with a model generated using a 3D scanner as a benchmark.

4.1 Aesthetic Appeal and Complexity – Experimental Setup

To illustrate the concept of complexity evaluation and aesthetic appeal, a case study of coffee mug designs is taken into consideration. The setup consists of various digital mug designs for which complexity values are calculated. A survey to highlight user preference amongst mugs is also created and feedback from a classroom of 40 graduate engineering students is recorded.

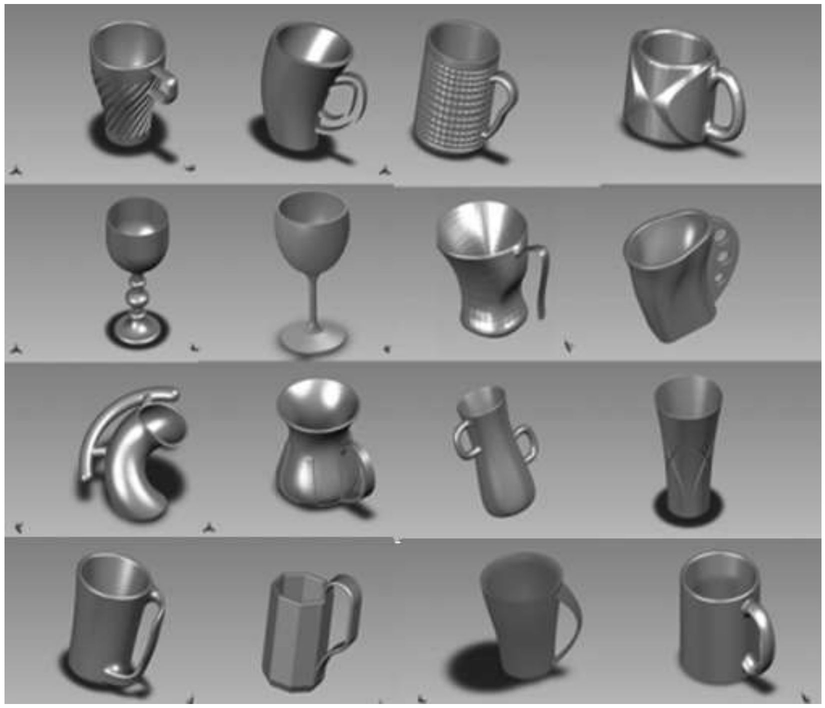

Figure 4-1: Sample of database of coffee mug models used in the survey and to calculate form complexity.

The survey (figure 4-2) consisting of the mug designs required the user to indicate their preference on which they found to be more appealing between the designs shown to them. The users were also asked to eliminate any bias they might have to specific designs while taking the survey. The survey was carried out in the classroom as setup shown in figure 4-3. This is done to understand the influence of customer perception on aesthetic appeal. For simplicity, all mugs were of the same value (cost) and they were asked to indicate what would be their preference for purchase.

Figure 4-2: Sample question from the survey.

Figure 4-3: Schematic of the classroom setup for the survey.

The values of complexity and results from the survey are discussed in the next chapter.

4.2 Student Assessment Through Similarity Evaluation – Experimental Tasks

The impact of the proposed student assessment methodology in chapter 3 on the effect of engineering design education and designers is discussed in this section. To evaluate this effect of 3D scanning and the similarity metric, each student was given a *physical* coffee mug of their own (as part of their *hands-on* experience). They were also provided with basic tools for measurement such as a scale rule and a piece of string to measure curved surfaces. The scanner along with its software interface was setup next to the working students and the scanning process was visually projected on an overhead screen for the students to understand the scan process. To obtain a complete model of the cup, the scanner obtains the 360^{o} scan along with the top and bottom view of the cup. These are then stitched together using the software to create the overall model of the cup.

At the end of the *hands-on* and digital assessment, students were presented with an optional survey regarding their perception of the value of having the 3D scanner integrated into their *hands-on* learning activities and their overall experience with it, with the results and discussion presented in the next section. Of the 29 students, 25 opted to complete the voluntary survey, with results shown in chapter 5.

The generated model of the cup from the 3D scanner is used as the benchmark for comparing similarities with the models created by student. The results generated from the similarity values aid in assessing the quality and performance of student solutions in a quantitative, timely manner. The more similar the student 3D model is to the benchmark solution (as evaluated by the similarity metric), the higher the student grade and vice-versa. The results generated from this process are discussed in detail in the next section. Reeb graphs (for the scan generated using the 3D scanner baseline model) and individual student models (created using design software), are then generated and stored. The similarity metric explained in the previous section compares individual student designs to the design created using the scanner. Furthermore, importance can be given to certain regions in the design. For example, in the case of the coffee mug, the design of the handle, which is more intricate, carries a higher value as opposed to the sweep surface of the mug. This is evident in the similarity distribution of the models and can be analyzed in the reeb graph [63][62].

4.3 Evaluating Product Form Based on Customer Feedback

To effectively evaluate the above mentioned metrics, data from the end user in the form of feedback through surveys is obtained. It is important to note that the survey was designed and carried out following all the guidelines and rules enforced by the Institutional Review Board (IRB) and Office for Research Protections (ORP) for research involving human participants in the survey. The study was approved by the IRB and the ORP at the Pennsylvania State University, University Park campus, under the title "Digital Representation of Physical Artifacts: The Effect of Low Cost, High Accuracy 3D Scanning Technologies on Engineering Education and Student Learning - Survey" and is filed as IRB # 41204. Data from the survey to help understand customer preferences is shown in appendix A. The survey consists of questions with binary responses as well as grading scales where users respond to questions with values from 1 through 5 where each number indicates the level of preference, described in the next chapter. The data from the survey is used to understand trends amongst the control group and translate the results into correlations to support form complexity and similarity.

Chapter 5

Results and Discussions

The results generated in this research are discussed in this chapter. The first section deals with quantifying product form through complexity and estimating customer perceived aesthetic appeal through a survey. The next section deals with product similarity within product entries in a database of digital models created by designers. Assessment of design models are done based upon the level of similarity evaluated based on a single benchmarked model. Coffee mugs are used as the products to generate the results.

5.1 Aesthetic Appeal and Complexity

To investigate the impact of product form on customer perception, the complexity of the artifact is to be calculated. These calculated values are then compared with the survey results to understand customer preferences towards the different models. The generated values for form complexity with density and curvature values are shown in table 5-1 along with the survey scores out of 40 for each mug design and the corresponding question on the survey.

The survey results are an indication of the number of students who voted for m1 as opposed to the other. For example m1 has 34 votes as opposed to 6 for m2. The fourth and fifth column in table 5-1 show the density and curvature values for the corresponding mug designs. For all the comparisons, it is evident that one design is more favorable than the other. In 8 out of the 10 questions, the mug with the higher complexity value dominates the mug with the lower value. However, it cannot be said that more the complexity, higher is the performance on the survey. This correlation is domain specific and requires domain knowledge to quantify. Further, figure 5-1 and 5-2 shows the correlation between density, curvature and complexity from values obtained.

Table 5-1: Results of form complexity for mugs and results from the survey.

Mug	Q. No	Survey Result	Density	Curvature	Complexity
m1	1	34	13.58	0.0045	1.0118079
m2		6	5.364	0.0061	1.0102989
m3	2	22	47.16	0.0042	1.0163166
m4		18	29.059	0.016	1.0553888
m5	3	30	28.89	0.05	1.1831434
m6		10	31.28	0.0036	1.0124719
m7	4	19	30.53	0.014	1.0490258
m8		21	12.29	0.0079	1.0200171
m9	5	24	40.81	0.0061	1.0228823
m10		16	30.89	0.0044	1.0152084
m11	6	22	836.31	0.019	1.1363837
m12		18	16.89	0.0035	1.0099426
m13	7	32	44.68	0.016	1.0626783
m14		8	7.95	0.025	1.0531959
m15	8	28	31.67	0.0036	1.012517
m16		12	109	0.011	1.0529596
m17	9	23	65.42	0.049	1.2273539
m18		17	27.31	0.017	1.0578339
m19	10	10	287.8	0.038	1.2400679
m20		30	31.46	0.0061	1.02126

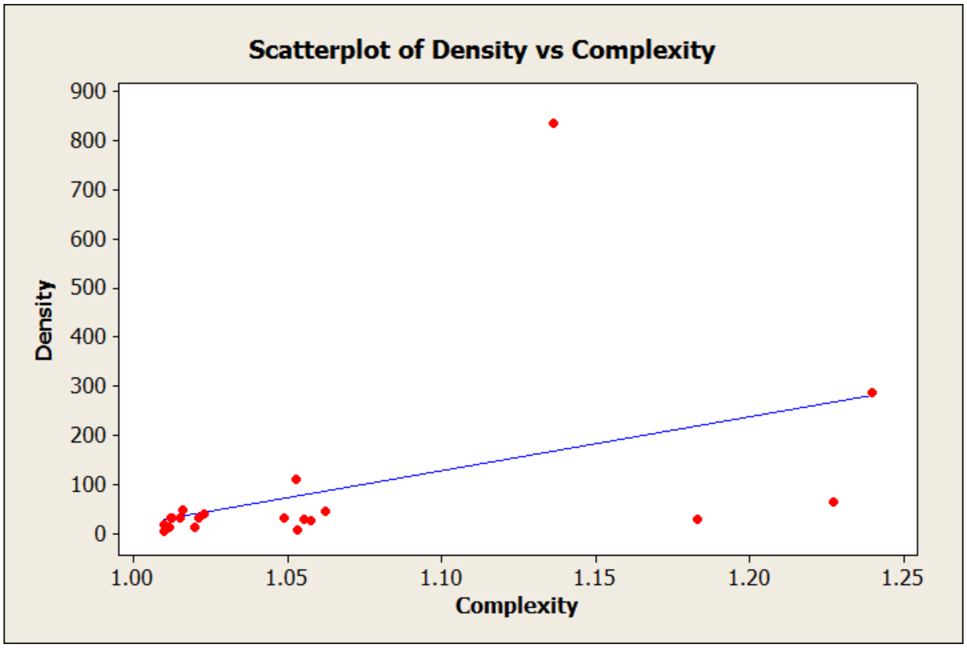

Figure 5-1: Scatterplot for density against complexity.

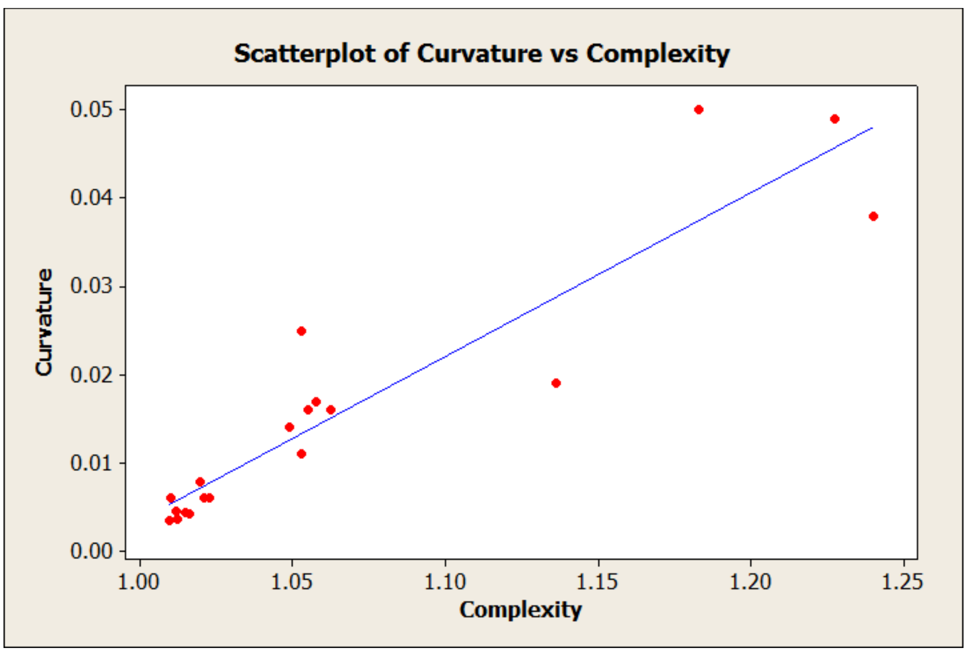

Figure 5-2: Scatterplot for curvature against complexity.

Regression Analysis: Complexity versus Density, Curvature

```
The regression equation is
Complexity = 0.988 + 0.000103 Density + 4.40 Curvature


Predictor         Coef     SE Coef       T      P
Constant      0.987555    0.006755  146.19  0.000
Density     0.00010279  0.00002536    4.05  0.001
Curvature       4.4000      0.3238   13.59  0.000


S = 0.0202745   R-Sq = 93.1%   R-Sq(adj) = 92.3%


Analysis of Variance

Source          DF        SS        MS       F      P
Regression       2  0.094645  0.047323  115.12  0.000
Residual Error  17  0.006988  0.000411
Total           19  0.101633


Source     DF    Seq SS
Density     1  0.018733
Curvature   1  0.075912
```

Figure 5-3: Results from regression analysis of complexity versus density and curvature.

Figure 5-3 shows the output results from regression analysis for complexity response based on density and curvature values from table 5-1 as predictors. It is observed that for a confidence interval of 95%, the generated p values for density and curvature are 0.001 and 0.000 which are less than the limit of 0.05 to prove statistical significance.

Table 5-2 discusses the effect of change in complexity when two mugs are considered. The second column is the difference in complexity values of the mugs considered and the third column gives the percent of people who considered the more favorable mug over the non-favorable one in the survey. The final column displays the percentage effect of unit change in complexity on the percentage of people who had given a favorable option. This indicates the increase in the percentage of the population that would buy the more favorable of the two products given that the company decides to manufacture it over the undesirable product. For example, there are 73% more people who would buy mug2 over mug1 at a change of visual complexity of 0.0015. This is a small change in design that could influence a huge change in market response.

Table 5-2: Analysis of results from form complexity and survey.

Mug	Complexity Difference	% Difference - Survey	% Effect of Change
m1 m2	0.001509	73.68421	488.3121
m3 m4	0.039072	10.52632	2.694065
m5 m6	0.170672	52.63158	3.083794
m7 m8	0.029009	5.263158	1.814338
m9 m10	0.007674	21.05263	27.43393
m11 m12	0.126441	10.52632	0.832508
m13 m14	0.009482	63.1579	66.60573
m15 m16	0.040443	42.10526	10.41113
m17 m18	0.16952	15.78947	0.931422
m19 m20	0.218808	52.63158	2.405379

Further, a plot of difference in complexity and percentage increase in survey responses will suggest the product designs that are to be considered for manufacture due to higher customer responses for minimal increase or decrease in complexity values.

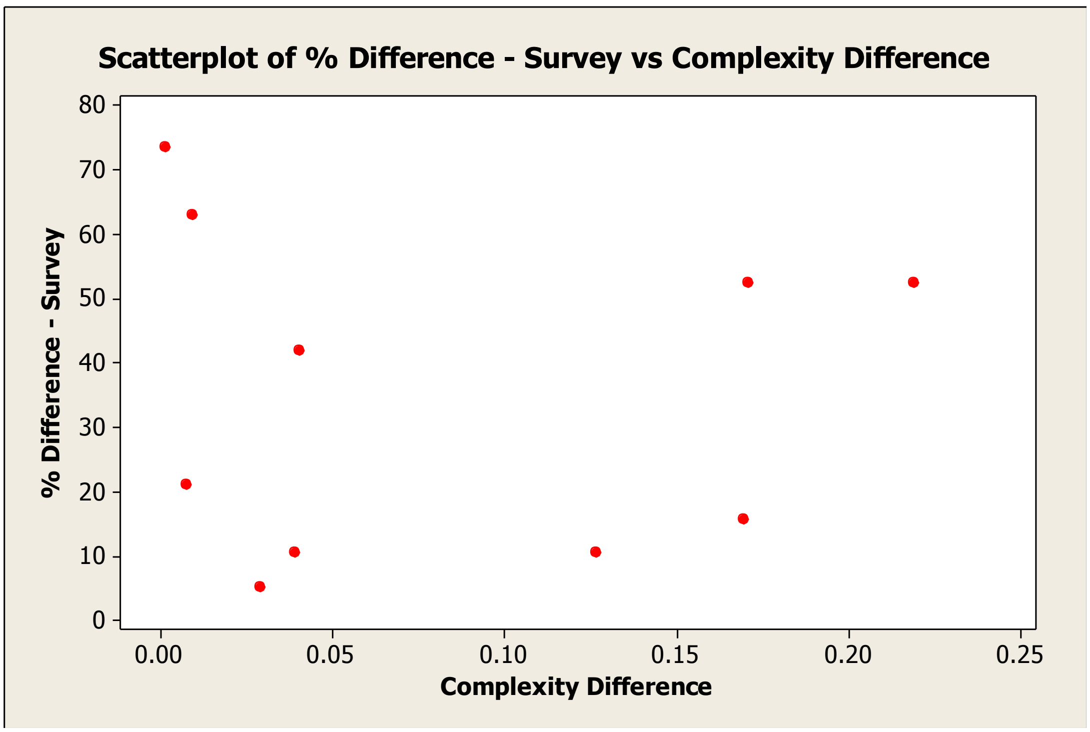

Figure 5-4: Plot of complexity difference and % difference in survey responses.

In figure 5-4, the six mug pairs that have low values of complexity difference, representing minor changes in product design, give vital information and provide an indication as to which product group is to be considered for a design change in order to increase market response. These mugs are highly preferred by customers over the mugs they are compared with. This correlation is also beneficial in understanding design features in these mugs which influence this preference which is left for future work.

5.2 Engineering Education – Product Similarity

The effect of evaluating product similarity and using the results to assess models created by students is discussed in this section, with the end objective to effectively improve the digital design assessment process. It is assumed that no prior digital model of the artifact is present for evaluation. A 3D scanner is used to generate a digital model of the coffee mug while students create individual models using design software. The time taken for the instructor to perform a single complete scan of the artifact using the scanner including set up and post image processing was 55 minutes with the time taken for the actual scan process being 10 minutes. In comparison the time taken by a class of 25 students with 8 females and 17 males (figure 5-5), ranged from 85 to 120 minutes with the majority of them with incomplete models.

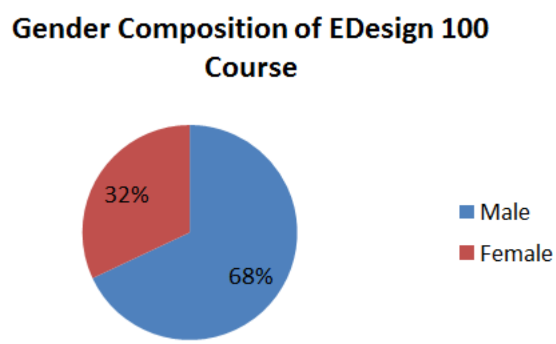

Figure 5-5: Gender Composition of EDesign 100 Course [56].

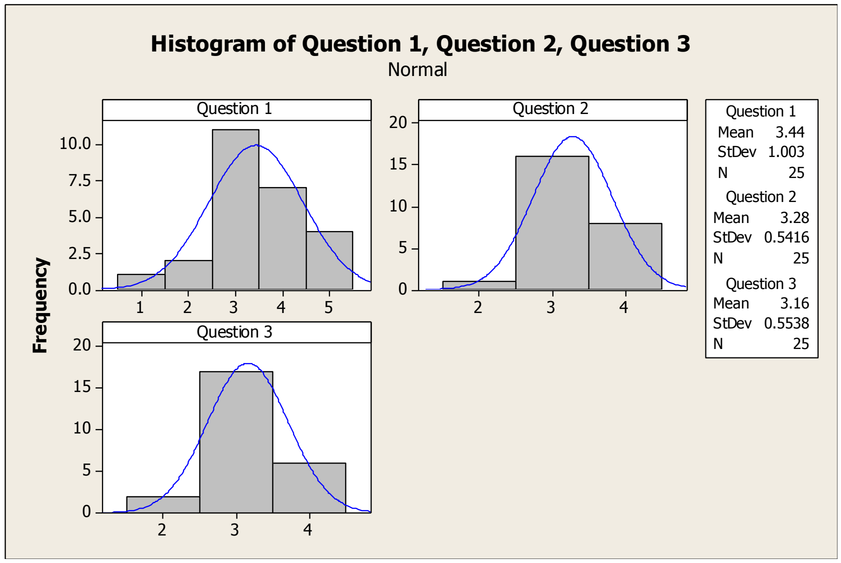

Figure 5-6: Statistical Distribution of Survey Responses [56].

Students were asked a series of questions relating to their experience using the 3D scanner during their design project which included questions such as:

Question 1: On a scale of 5 (5 being the easiest), how much more easily were you able to regenerate a solid part using the scanner as opposed to designing it on design software?

Question 2: On a scale of 5 (5 being the easiest), how easy was it to learn the working of the scanner?

Question 3: On a scale of 5 (5 being the easiest), how easy was it to navigate through the software that is associated with the scanner for scanning?

The results from the questions are shown in figure 5-6. Furthermore based upon Yes / No questions in the survey, 70% of the male and 75% of the female population made up 76% of the students who felt the need to include the 3D scanner as part of future engineering design classes, and 56% of the students also felt that they were able to visualize objects better through the 3D scanner as opposed to using the design software. Also, 68% of the students assert that they had benefitted from using the 3D scanner as part of their team based projects during the external search activities.

Figure 5-7 shows the different perspectives of the mug as produced by the scanner and it also showcases the best and worst designs produced by the students. It is evident that a single artifact is perceived differently by each individual and created using different techniques. This variation in design is not seen in the case of the 3D scanner.

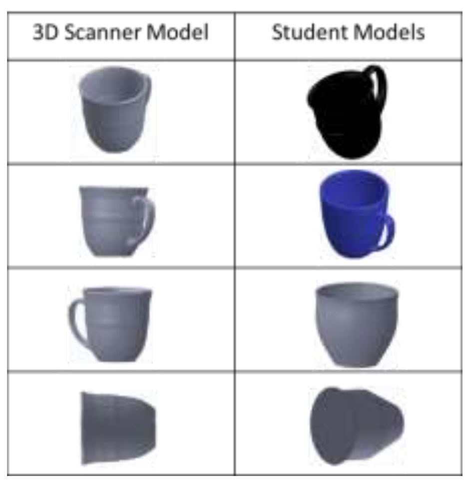

Figure 5-7: 3D model of Coffee Mug rendered by the scanner after editing and those done by students (best and worst).

Figure 5-8 reveals the distribution of assessment scores (Table 5-4) of two teaching assistants (TA1 and TA2) who were assigned the same set of 8 student models to be graded. The figure also shows the scores from the reeb graph similarity metric of the 8 student models as compared to the 3D benchmark model generated. While the assignment given to students was identical, there was significant grading variation between teaching assistants (Figure 5-8), despite the fact that they were given the same rubric to evaluate the 8 student solutions. Figure 5-9 is a box plot visualization of the teaching assistant assessment scores, revealing the inherent variation between teaching assistants and shows that the distribution of scores generated by the reeb graph metric. It is seen that the third quartile score of TA 1 is greater than the first quartile for TA 2. This depicts the degree of variation existing between the two graders. This is of statistical significance and is proved by hypothesis testing at 95% confidence interval.

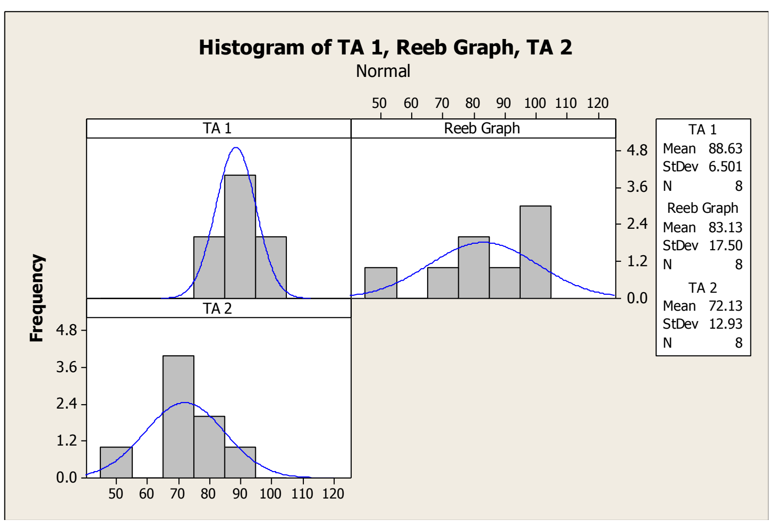

Figure 5-8: Statistical data of student scores based on graders and scores generated from the Reeb graph comparison [56].

Null hypothesis: Mean of the difference between the two TA sample distributions are equal. The results generated from the 2 sample t – tests are shown in table 5-3. A box plot for the generated values is shown in figure 5-9.

Table 5-3: Summary statistics of TA assessment scores [56].

Statistic	TA 1	TA 2
Mean	88.63	72.13
Std. Deviation	6.5	12.93
One sample t at 95% CI	(83.19,94.06)	(61.31,82.94)
Estimate of difference	16.5	
95% CI for difference	(5.0968, 27.9032)	
T – value	3.22	
P – value	0.009	

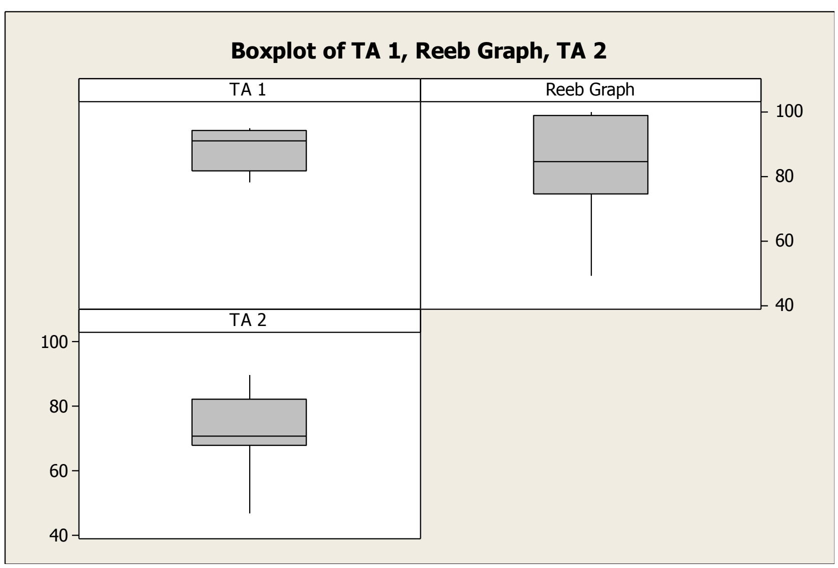

Figure 5-9: Box plot of TA1, Reeb graph comparison and TA 2 assessment scores [56].

Table 5-4: Summary of scores generated by reeb graph comparison and TA 1 and TA 2 [56].

Student	Student Model	TA 1 Score	TA 2 Score	Scores from reeb graph
1		87	69	91
2		78	47	78
3		95	90	100
4		92	73	49
5		95	84	76
6		90	68	74
7		80	68	98
8		92	78	99

It is observed from Table 5-3 that the difference in mean between the grades given by TA 1 and TA 2 are in the confidence interval of (5.0968, 27.9032). A p value of $0.009 < 0.05$, implies that the values generated are statistically significant and that the null hypothesis is rejected and the alternate hypothesis is accepted at a confidence interval of 95%. This confirms the boxplot results, that the mean of the difference between the two TA sample distributions are not equal thereby implying significant statistical variation in the grading of the two TA's.

The summary of scores along with the student models as graded by TA 1 and TA 2 and the scores generated by the reeb graph comparison metric benchmarked against the model created by the 3D scanner are shown in table 5-4. The scores generated by the reeb graph metric are a direct representation of the degree of similarity of the student model with that from the scanner. For example, the student model 1 generated a similarity value of 0.9097 (scale of similarity is from 0 to 1, 1 being identical models) which is rounded off to 0.91. The generated results have a mean of 83.13 and standard deviation of 17.5, thereby covering the extents of both TA 1 and TA 2 grades (maximum of 95 and a minimum of 47) and effectively determining scores that are free of grader toughness. Though the results from the generated metric is subject to variability and the ability to certify with accuracy the credibility, this technique is highly scalable for a large database and reduces time and effort spent in the evaluation process. It also eliminates the variations in results across graders and serves as a single window grader system with uniform toughness to generate un-biased results.

Chapter 6

Conclusions and Path Forward

This thesis proposes a methodology to quantitatively assess a product's geometric form in order to aide in the process of i) understanding customer perceived aesthetic appeal and ii) improving engineering education through better student design assessment techniques. Product form complexity and similarity metrics are used as tools to understand the impact of geometric form on product design and engineering education. While the complexity metric evaluates models individually for intricacy, similarity metric compares the degree of alikeness amongst different models. The data used in this research is of the form of 3D models which depict the outer geometry of an artifact. The form of a product is characterized using complexity as a term used to represent the level of detail of the 3D model of an artifact. The similarity between models generated by designers and a benchmarked model is calculated based upon similarities in generated reeb graphs of the two models.

A case study involving a database of coffee mugs was used to evaluate the impact of the complexity and similarity metrics on customer perception and engineering design assessment. The results reveal the effects of quantifying geometric form of an artifact and aims to help designers better understand customer perception of designs and improve digital design assessments.

This work can further be extended to understand impact of product form and aesthetics on the manufacturing process parameters. Understanding factors in design which affect customer preferences along with these manufacturing parameters will provide a complete justification to product design selection. The major challenge, however, lies in integrating products across different domains using just their form to quantify the design process. This research deals with products that are pure mechanical systems. Future work which can incorporate internal sub-systems (e.g. internal circuits) and their corresponding complexity that will further widen the product database and will also enhance results generated for similarity analysis. The process of improved design assessment can be further extended to other student projects and research domains such as shape grammar. Other forms of student work such as hand-made models can also be assessed using a combination of the 3D scanner and the similarity metric.

REFERENCES

[1] Rust R. T., and Zahorik A. J., 1993, “Customer satisfaction, customer retention, and market share,” J. Retail., **69**(2), pp. 193–215.

[2] Menendez A. R., and Peli E., 1995, Vision Models for Target Detection and Recognition: In Memory of Arthur Menendez, World Scientific.

[3] Dahl D. W., Chattopadhyay A., and Gorn G. J., 1999, “The Use of Visual Mental Imagery in New Product Design,” J. Mark. Res., **36**(1), p. 18.

[4] Baker P., 2009, Design Matters--A Lot: Don’t Develop Products Without It!, Pearson Education.

[5] Verganti R., 2009, Design Driven Innovation: Changing the Rules of Competition by Radically Innovating What Things Mean, Harvard Business Press.

[6] Bloch P. H., 1995, “Seeking the Ideal Form: Product Design and Consumer Response,” J. Mark., **59**(3), p. 16.

[7] Sherman R., and Hoffer G., 1971, “Does Automobile Style Change Payoff?,” Appl. Econ., **3**(3), pp. 153–165.

[8] Boothroyd G., 1994, “Product design for manufacture and assembly,” Comput.-Aided Des., **26**(7), pp. 505–520.

[9] Buller D. J., 1999, Function, Selection, and Design, SUNY Press.

[10] Tovey M., Porter S., and Newman R., 2003, “Sketching, concept development and automotive design,” Des. Stud., **24**(2), pp. 135–153.

[11] Bender D. M., Wood B. J., and Vredevoogd J. D., 2004, “Teaching Time: Distance Education Versus Classroom Instruction,” Am. J. Distance Educ., **18**(2), pp. 103–114.

[12] Rodriguez-Toro C. A., Tate S. J., Jared G. E. M., and Swift K. G., 2003, “Complexity metrics for design (simplicity + simplicity = complexity),” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., **217**(5), pp. 721–725.

[13] Weber C., 2005, “What Is ‘Complexity’?,” Iced 05 15th Int. Conf. Eng. Des. Eng. Des. Glob. Econ., p. 1785.

[14] Adami C., 2002, “What is complexity?,” BioEssays, **24**(12), pp. 1085–1094.

[15] Novak S., and Eppinger S. D., 2001, “Sourcing By Design: Product Complexity and the Supply Chain,” Manag. Sci., **47**(1), pp. 189–204.

[16] Josue C.-V., Kremer G. O., Tucker C., and Medina L., 2012, “An Analysis Of Complexity Measures for Product Design and Development,” Proc. Asme 2012 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.

[17] Saleem W., Belyaev A., Wang D., and Seidel H.-P., 2011, “On visual complexity of 3D shapes,” Comput. Graph., **35**(3), pp. 580–585.

[18] Valentan B B. T., 2008, “Basic solutions on shape complexity evaluation of STL data,” J. Achiev. Mater. Manuf. Eng.

[19] E D., C J., and C L., 1968, “The dimensionality of visual complexity, interestingness, and pleasingness,” Can. J. Psychol. Can. Psychol., **22**(5), pp. 376–387.

[20] Sukumar S., Gribok A., Koschan A., and Abidi M., 2006, “Shape measure for identifying perceptually informative parts of 3d objects,” In 3DPVT, pp. 679–686.

[21] Ichikawa S., 1985, “Quantitative and structural factors in the judgment of pattern complexity,” Percept. Psychophys., **38**(2), pp. 101–109.

[22] Singh I., Rohith B. V., and Naryanan P. J., 2011, “A New Measure of Detail for Triangulated Meshes,” 2011 Third National Conference on Computer Vision, Pattern Recognition, Image Processing and Graphics (NCVPRIPG), pp. 179 –182.

[23] Chen Y., and Wang J. Z., 2002, “A region-based fuzzy feature matching approach to content-based image retrieval,” Ieee Trans. Pattern Anal. Mach. Intell., **24**(9), pp. 1252 – 1267.

[24] Ostwald M. J., and Tucker C., 2007, “Calculating characteristic visual complexity in the built environment: an analysis of Bovill’s Method | NOVA. The University of Newcastle’s Digital Repository, Calculating characteristic visual complexity in the built environment: an analysis of Bovill’s Method.”

[25] Stickel C., Ebner M., and Holzinger A., 2010, “The XAOS Metric – Understanding Visual Complexity as Measure of Usability,” HCI in Work and Learning, Life and Leisure, G. Leitner, M. Hitz, and A. Holzinger, eds., Springer Berlin Heidelberg, pp. 278–290.

[26] Ostwald M. J., and Vaughan J., 2009, “Calculating visual complexity in Peter Eisenman’s architecture: a computational fractal analysis of five houses (1968-1976) | NOVA. The

University of Newcastle's Digital Repository, Calculating visual complexity in Peter Eisenman's architecture: a computational fractal analysis of five houses (1968-1976)."

[27] Bhattacharya S., Sukthankar R., and Shah M., 2010, "A framework for photo-quality assessment and enhancement based on visual aesthetics," Proceedings of the international conference on Multimedia, ACM, New York, NY, USA, pp. 271–280.

[28] Jansen E., Mulkens S., and Jansen A., 2010, "How to promote fruit consumption in children. Visual appeal versus restriction," Appetite, **54**(3), pp. 599–602.

[29] Moorthy A. K., Obrador P., and Oliver N., 2010, "Towards Computational Models of the Visual Aesthetic Appeal of Consumer Videos," Computer Vision – ECCV 2010, K. Daniilidis, P. Maragos, and N. Paragios, eds., Springer Berlin Heidelberg, pp. 1–14.

[30] Khalid H. M., and Helander M. G., 2006, "Customer Emotional Needs in Product Design," Concurr. Eng., **14**(3), pp. 197–206.

[31] Kim T., Okudan G., Okudan G., Ertek G., and Ertek G., 2009, "Innovation in product form and function: customer perception of their value" [Online]. Available: http://research.sabanciuniv.edu/12754/. [Accessed: 13-Jul-2013].

[32] Barnes C., Southee C., and Henson B., 2003, "The impact of affective design of product packaging upon consumer purchase decisions," Proceedings of the 2003 international conference on Designing pleasurable products and interfaces, ACM, New York, NY, USA, pp. 134–135.

[33] Yamamoto M., and Lambert D. R., 1994, "The impact of product aesthetics on the evaluation of industrial products," J. Prod. Innov. Manag., **11**(4), pp. 309–324.

[34] Pugliese M. J., and Cagan J., 2002, "Capturing a rebel: modeling the Harley-Davidson brand through a motorcycle shape grammar," Res. Eng. Des., **13**(3), pp. 139–156.

[35] McCORMACK J. P., and Cagan J., 2002, "Designing inner hood panels through a shape grammar based framework," Ai Edam, **16**(04), pp. 273–290.

[36] Gero J. S., 2004, Design Computing and Cognition '04, Springer.

[37] Bloch P. H., Brunel F. F., and Arnold T. J., 2003, "Individual Differences in the Centrality of Visual Product Aesthetics: Concept and Measurement," J. Consum. Res., **29**(4), pp. 551–565.

[38] Yoshimura M., and Yanagi H., 2001, "Strategies for implementing aesthetic factors in product designs," Int. J. Prod. Res., **39**(5), pp. 1031–1049.

[39] Simpson T., Okudan G., Ashour O., and Lewis K., 2011, "From Product Dissection to Product Archaeology: Exposing Students to Global, Economic, Environmental, and Societal Impact Through Competitve and Collaborative."

[40] Shapiro C., and Varian H. R., 1999, Information Rules: A Strategic Guide to the Network Economy, Harvard Business Press.

[41] Gorman P., Nilson T., and Glassman A., 2004, "The Millennial Generation: A Strategic Opportunity," Organ. Anal., **12**(3), pp. 255 – 270.

[42] Stice J. E., 1987, "Using Kolb's Learning Cycle to Improve Student Learning.," Eng. Educ., **77**(5), pp. 291–96.

[43] Regan M., and Sheppard S., April, "Interactive Multimedia Courseware and the Hands-on Learning Experience: An Assessment Study," J. Eng. Educ., **1996**, pp. 123 – 131.

[44] Bernardini F., and Rushmeier H., 2002, "The 3D Model Acquisition Pipeline," Comput. Graph. Forum, **21**(2), pp. 149–172.

[45] Kusnoto B., and Evans C. A., 2002, "Reliability of a 3D surface laser scanner for orthodontic applications," Am. J. Orthod. Dentofacial Orthop., **122**(4), pp. 342–348.

[46] Taylor J., Beraldin J.-A., Godin G., Cournoyer L., Baribeau R., Blais F., Rioux M., and Domey J., 2003, "NRC 3D imaging technology for museum and heritage applications," J. Vis. Comput. Animat., **14**(3), pp. 121–138.

[47] Elrod D., and Stewart M. D., 2009, "Assessing Student Work in Engineering Graphics and Visualization Course," Eng. Des. Graph. J., **69**(2).

[48] Perry L. D. S., 2002, "The grading system of the real world," Crossroads, **8**(4), pp. 13–17.

[49] Dinan F. J., and Frydrychowski V. A., 1995, "A Team Learning Method for Organic Chemistry," J. Chem. Educ., **72**(5), p. 429.

[50] Zoeckler L. G., 2007, "MORAL ASPECTS OF GRADING: A STUDY OF HIGH SCHOOL ENGLISH TEACHERS' PERCEPTIONS," Am. Second. Educ.

[51] Valenti S., Neri F., and Cucchiarelli R., 2003, "An overview of current research on automated essay grading," J. Inf. Technol. Educ., **2**, p. 2003.

[52] Wang H.-C., Chang C.-Y., and Li T.-Y., 2008, "Assessing creative problem-solving with automated text grading," Comput. Educ., **51**(4), pp. 1450–1466.

[53] Cheang B., Kurnia A., Lim A., and Oon W.-C., 2003, "On automated grading of programming assignments in an academic institution," Comput. Educ., **41**(2), pp. 121–131.

[54] Edwards S. H., 2003, "Rethinking computer science education from a test-first perspective," Companion of the 18th annual ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications, ACM, New York, NY, USA, pp. 148–155.

[55] Rocchini C., Cignoni P., Montani C., Pingi P., and Scopigno R., 2001, "A low cost 3D scanner based on structured light," Comput. Graph. Forum, **20**(3), pp. 299–308.

[56] Vasudevan N., and Tucker C., 2013, "Digital Representation of Physical Artifacts: The Effect of Low Cost, High Accuracy 3D Scanning Technologies on Engineering Education, Student Learning and Design Evaluation," Asme Des. Eng. Tech. Conf.

[57] Bespalov D., Regli W., and Shokoufandeh A., 2003, "Reeb Graph Based Shape Retrieval for CAD," Proc. Detc'03 2003 Asme Des. Eng. Tech. Conf.

[58] Doraiswamy H., and Natarajan V., 2012, "Computing Reeb Graphs as a Union of Contour Trees," Ieee Trans. Vis. Comput. Graph., pp. 1–1.

[59] Iyer N., Jayanti S., Lou K., Kalyanaraman Y., and Ramani K., 2005, "Three-dimensional shape searching: state-of-the-art review and future trends," Comput.-Aided Des., **37**(5), pp. 509–530.

[60] Yan H.-B., Hu S.-M., and Martin R., 2006, "Skeleton-Based shape deformation using simplex transformations," Proceedings of the 24th international conference on Advances in Computer Graphics, Springer-Verlag, Berlin, Heidelberg, pp. 66–77.

[61] Doraiswamy H., and Natarajan V., 2009, "Efficient algorithms for computing Reeb graphs," Comput Geom Theory Appl, **42**(6-7), pp. 606–616.

[62] Tung T., and Schmitt F., 2004, "F.: Augmented Reeb Graphs for Content-Based Retrieval of 3D Mesh Models," In SMI '04: Proceedings of the Shape Modeling International 2004 (SMI'04, pp. 157–166.

[63] Tierny J., Vandeborre J.-P., and Daoudi M., 2009, "Partial 3D Shape Retrieval by Reeb Pattern Unfolding," Comput. Graph. Forum, **28**(1), pp. 41–55.

Appendix A

Survey Results

Respons e ID	Time Started	Date Submitted	IP Address	Regi on	Post al	Which do you find more appealing?									
	1 /14/2013 21:48	1 /14/2013 21:53	1 74.59.223.2 27	A	680 1	19	15	18	13	7	9	11	1	3	5
	1 /15/2013 8:21	1 /15/2013 8:27	1 46.186.218. 51	A	680 2	20	16	18	13	7	9	11	1	4	5
	1 /15/2013 8:22	1 /15/2013 8:25	1 46.186.218. 37	A	680 2	20	15	17	13	8	9	12	1	4	5
	1 /15/2013 8:22	1 /15/2013 8:24	1 46.186.218. 53	A	680 2	20	15	18	14	8	9	12	1	4	6
	1 /15/2013 8:22	1 /15/2013 8:27	1 46.186.218. 50	A	680 2	20	15	18	13	8	9	11	1	4	5
	1 /15/2013 8:22	1 /15/2013 8:25	1 46.186.218. 36	A	680 2	20	15	17	13	7	9	11	1	3	5
0	1 /15/2013 8:21	1 /15/2013 8:25	1 46.186.218. 35	A	680 2	20	15	18	13	7	9	11	1	3	5
1	1 /15/2013 8:23	1 /15/2013 8:25	1 46.186.218. 40	A	680 2	20	15	18	14	8	9	11	1	4	6
3	1 /15/2013 8:23	1 /15/2013 8:27	1 46.186.218. 47	A	680 2	19	16	17	13	7	10	12	1	3	5
4	1 /15/2013 8:22	1 /15/2013 8:27	1 46.186.218. 27	A	680 2	20	16	17	13	8	10	12	1	3	5
5	1 /15/2013 8:22	1 /15/2013 8:27	1 46.186.218. 34	A	680 2	19	16	17	13	8	10	11	1	3	5
6	1 /15/2013 8:21	1 /15/2013 8:28	1 46.186.218. 38	A	680 2	20	16	17	13	7	9	11	1	3	5
7	1 /15/2013 8:22	1 /15/2013 8:26	1 46.186.218. 28	A	680 2	20	15	17	13	7	10	12	1	3	6
9	1 /15/2013 8:22	1 /15/2013 8:27	1 46.186.218. 39	A	680 2	20	15	17	13	8	10	11	1	4	5
0	1 /15/2013 8:22	1 /15/2013 8:26	1 46.186.218. 46	A	680 2	19	15	18	14	7	10	12	2	4	6
1	1 /15/2013 8:23	1 /15/2013 8:28	1 46.186.218. 22	A	680 2	20	15	17	13	7	10	11	1	3	5
2	1 /15/2013 8:23	1 /15/2013 8:28	1 46.186.218. 24	A	680 2	19	15	17	13	7	10	12	1	4	6
3	1 /15/2013 8:23	1 /15/2013 8:27	1 46.186.218. 21	A	680 2	20	15	18	14	8	10	11	1	4	6

4	1 /15/2013 8:23	1 /15/2013 8:27	1 46.186.218. 23	A	680 2	19	16	17	13	7	9	12	1	4	5
6	1 /15/2013 8:24	1 /15/2013 8:27	1 46.186.218. 44	A	680 2	20	15	17	13	8	9	12	1	4	5
8	1 /15/2013 8:24	1 /15/2013 8:27	1 46.186.218. 54	A	680 2	20	15	18	14	7	9	12	2	4	6
9	1 /15/2013 8:24	1 /15/2013 8:27	1 46.186.218. 52	A	680 2	20	15	18	14	8	10	12	1	4	6
0	1 /15/2013 8:24	1 /15/2013 8:26	1 46.186.218. 41	A	680 2	20	15	17	13	7	9	11	2	3	5
1	1 /15/2013 8:24	1 /15/2013 8:27	1 46.186.218. 43	A	680 2	20	16	18	13	7	9	11	1	3	5
2	1 /15/2013 8:25	1 /15/2013 8:28	1 46.186.218. 42	A	680 2	20	16	17	13	7	10	12	2	3	6
3	1 /15/2013 8:28	1 /15/2013 8:30	1 46.186.218. 27	A	680 2	20	16	17	13	8	10	12	1	3	5
4	1 /15/2013 11:46	1 /15/2013 11:52	7 5.102.87.20 5	A	680 1	20	15	17	13	8	9	11	1	4	5
5	1 /15/2013 11:46	1 /15/2013 11:50	7 5.102.97.20 3	A	680 1	19	15	17	13	8	10	11	1	3	5
7	1 /15/2013 11:46	1 /15/2013 11:53	7 5.102.86.24 8	A	680 2	20	15	18	13	7	9	12	1	3	5
8	1 /15/2013 11:46	1 /15/2013 11:50	7 5.102.87.18 8	A	680 1	20	15	17	13	8	9	11	1	3	5
9	1 /15/2013 11:46	1 /15/2013 11:56	7 5.102.96.27	A	680 1	20	15	18	14	8	9	12	1	4	6
0	1 /15/2013 11:47	1 /15/2013 11:53	7 5.102.97.33	A	680 1	19	16	17	13	8	10	11	1	3	5
5	1 /15/2013 11:49	1 /15/2013 11:54	1 30.203.231. 38	A	680 1	20	15	17	13	7	9	11	1	3	5
6	1 /15/2013 11:49	1 /15/2013 11:57	1 98.228.228. 34	N	704 0	20	15	18	13	8	10	11	1	3	5
1	1 /15/2013 11:53	1 /15/2013 11:59	7 5.102.96.62	A	680 1	20	15	18	13	8	9	12	1	4	5
2	1 /15/2013 11:54	1 /15/2013 11:59	7 5.102.87.20 5	A	680 1	20	15	18	14	8	9	11	1	4	5
3	1 /15/2013 12:02	1 /15/2013 12:05	1 46.186.119. 168	A	680 1	20	15	17	13	8	10	11	1	4	5
4	1 /15/2013 12:24	1 /15/2013 12:28	2 16.169.179. 70	A	783 7	20	15	17	13	8	9	12	1	3	5

Appendix B

Java code for Complexity Evaluation

```
package datalab.research.modeldetail;

import java.io.*;
import java.math.*;
import java.util.*;
import java.util.regex.*;

public class NewStlFile {

	private ArrayList<Facet>  facets;
	private ArrayList<Vertex> vertices;
	private double maxLength;
	private double ttlDensity;
	private double ttlCurvature;
	private Map<Integer, Vertex> vertDic;
	public String objectName;

	private static boolean debug = true;

	NewStlFile(File file){
		this.facets = new ArrayList<Facet>();
		this.vertices = new ArrayList<Vertex>();
		this.vertDic = new HashMap<Integer, Vertex>();
		parseStlFile(file);
	}
	/*
	 * Create the file, open it, loop through each line and:
	 * 1. Pull out the object name.
	 * 2. Skip over trash lines such as the first line of the file and the endsolid line
	 * 3. Create a facet block (Just the 7 lines that make up each facet) by
concatenating
	 *		a string.
	 * 4. Send the block to process block
	 */
	public void parseStlFile(File fileName){
		FileReader file;
		try {
			file = new FileReader(fileName);
			Scanner inputFile = new Scanner(file);
			while(inputFile.hasNextLine()){

				if(inputFile.hasNext("facet")){
					String block = "";
```

```
						while(!(inputFile.hasNext("endfacet"))){
							block += inputFile.nextLine();
						}
						processBlock(block);
					}
					else if(inputFile.hasNext("solid")){
						// Skip Solid
						inputFile.next();

						// Grab the solid name
						objectName = inputFile.next();
					}
					else{
						// Otherwise throw out the line, it's not important
						inputFile.nextLine();
					}
				}
			} catch (FileNotFoundException e) {
				System.out.println("Could not find " + fileName + ". Please
make sure the file "
						+ "exists and try again.");
				e.printStackTrace();
				System.exit(1);
			}

			/******************************** Extra Processing
**************************************/
			System.out.println("Getting Max Edge Length");
			maxLength = getMaxEdgeLength();

			System.out.println("Normalizing Edges");
			for(int i = 0; i < vertices.size(); i++){
				vertices.get(i).normalizeEdges(maxLength);
			}
			computeDetail();

	}
		public Double computeDetail(){
			// Initialize detail to the first detail value since initializing to 0 will mess
up the calculation
			BigDecimal first = new BigDecimal(round(vertices.get(0).getDetail()));
			Double dtotal = round(vertices.get(0).getDetail());
			int i = 1;
			for(; i < vertices.size(); i++){
				dtotal += round(vertices.get(i).getDetail());
				try{
					first.add(new
BigDecimal(round(vertices.get(i).getDetail())));
				}
```

```
				catch(NumberFormatException e){
					System.out.println(vertices.get(i));
					System.exit(1);
				}
				if(debug){
					System.out.println("Computing Detail");
					//System.out.println("BigDecimal Total: " + total);
					System.out.println("Decimal Total: " + dtotal);
				}
			}
			if(debug){
				System.out.println(dtotal/vertices.size());
			}
//			return total.divide(new BigDecimal(vertices.size()), 5,
RoundingMode.HALF_UP);
			return dtotal/vertices.size();
		}

		private void processBlock(String block){
			Scanner line = new Scanner(block);
			String pattern = "(-?\\d+\\.\\d+E?e?.\\d+)";
			try{
				line.findInLine(pattern + "\\s*" + pattern + "\\s*" + pattern +
								"\\s*outer\\s*loop\\s*vertex\\s*"
+ pattern + "\\s*" + pattern + "\\s*" + pattern +
								"\\s*vertex\\s*" + pattern +
"\\s*" + pattern + "\\s*" + pattern +
								"\\s*vertex\\s*" + pattern +
"\\s*" + pattern + "\\s*" + pattern);

				MatchResult result = line.match();

				D3Vector norm = new D3Vector(new
BigDecimal(result.group(1)).doubleValue(),
											new
BigDecimal(result.group(2)).doubleValue(),
											new
BigDecimal(result.group(3)).doubleValue());

				D3Vector v1 = new D3Vector(new
BigDecimal(result.group(4)).doubleValue(),
						new
BigDecimal(result.group(5)).doubleValue(),
						new
BigDecimal(result.group(6)).doubleValue());

				D3Vector v2 = new D3Vector(new
BigDecimal(result.group(7)).doubleValue(),
```

```
                                        new
BigDecimal(result.group(8)).doubleValue(),
                                        new
BigDecimal(result.group(9)).doubleValue());

                          D3Vector v3 = new D3Vector(new
BigDecimal(result.group(10)).doubleValue(),
                                        new
BigDecimal(result.group(11)).doubleValue(),
                                        new
BigDecimal(result.group(12)).doubleValue());

                          facets.add(new Facet(norm, v1, v2, v3));

                          Vertex vert1, vert2, vert3;

                          if(!vertices.contains(v1)){
                                vert1 = new Vertex(v1);
                                vertices.add(vert1);
                          }
                          else{
                                vert1 = vertices.get(vertices.indexOf(v1));
                          }

                          if(!vertices.contains(v2)){
                                vert2 = new Vertex(v2);
                                vertices.add(vert2);
                          }
                          else{
                                vert2 = vertices.get(vertices.indexOf(v2));

                          }

                          if(!vertices.contains(v3)){
                                vert3 = new Vertex(v3);
                                vertices.add(vert3);
                          }
                          else{
                                vert3 = vertices.get(vertices.indexOf(v3));

                          }

                          vert1.addNeighbor(vert2);
                          vert1.addNeighbor(vert3);
                          vert1.recomputeNormal(norm);
                          vert1.normalizeEdges(maxLength);

                          vert2.addNeighbor(vert1);
                          vert2.addNeighbor(vert3);
```

```
					vert2.recomputeNormal(norm);
					vert2.normalizeEdges(maxLength);

					vert3.addNeighbor(vert1);
					vert3.addNeighbor(vert2);
					vert3.recomputeNormal(norm);
					vert3.normalizeEdges(maxLength);
				}
				catch(IllegalStateException e){
					System.out.println(e + "\n" + block);
					System.exit(1);
				}

				line.close();
			}

			public int getNumberOfFacets(){
				return facets.size();
			}

			public double getMaxEdgeLength(){
				// Initialize it to the first Max Length
				double maxLength = facets.get(0).getMaxLength();
				for(int i = 1; i < getNumberOfFacets(); i++){
					maxLength = Math.max(maxLength,
facets.get(i).getMaxLength());
				}
				return maxLength;
			}

			public void printVertices(){
				for(int i = 0; i < vertices.size(); i++){
					System.out.println(vertices.get(i));
				};
				System.out.println(vertices.size() + " total vertices.");
				System.out.println(facets.size() + " total facets.");
			}
			public String getSpecifics(){
				String specifics = new String();
				for(int i = 0; i < vertices.size(); i++){
					//System.out.println("Detail: " + detail);
					specifics += "Density for vertice " + i + ": "   +
vertices.get(i).getDensity() + "\n";
					ttlDensity += vertices.get(i).getDensity();
					specifics += "Curvature for vertice " + i + ": " +
vertices.get(i).getCurvature() + "\n";
					ttlCurvature += vertices.get(i).getCurvature();
				}
				return specifics;
```

```
		}
		public String getAverages(){
			return "Average Density: " + ttlDensity/vertices.size() + "\nAverage
Curvature: " + ttlCurvature/vertices.size();
		}
		public static void setDebug(boolean flag){
			debug = flag;
		}
		public static double round(double unrounded){
			BigDecimal bd = new BigDecimal(unrounded);
			BigDecimal rounded = bd.setScale(5, RoundingMode.HALF_UP);
			double r = rounded.doubleValue();
			return r;
		}
	}
```

Appendix C

Java Code for Similarity Evaluation

```
//Similarity_Counter
//Author: Andrew Depenbusch
//Purpose: Take two seperate CSV's as input, compute similarity between points.

import java.io.*;
import java.nio.charset.Charset;
import java.nio.file.Files;
import java.nio.file.Path;
import java.nio.file.Paths;
import java.util.*;

public class Similarity_Counter
{
    public static ArrayList indices1, object1, indices2, object2;
    public static int smallest;
    public static double ratio;
    public static void main(String args[])
    {
        int h=0, i=0, numMatch=0, currentMax=0, current = 0, hMax=100, count=0, saved=0, currenti=0;
        indices1 = new ArrayList();
        indices2 = new ArrayList();
        object1 = new ArrayList();
        object2 = new ArrayList();

        GenerateVectors();
```

```
/*
for(int j =0; j< indices1.size();j++)
{
   //System.out.println(j);
   System.out.println(indices1.get(j));
}*/
currentMax = (int)ratio;
do{
   System.out.println(i);
   System.out.println(h);
   System.out.println(count);
   if(h!=object2.size())
   {
      current = ((Integer)indices2.get(h)).intValue();
   }
   if(current>=hMax)
   {
         if(i<indices1.size()-1)
         {
            while (((Integer)indices1.get(i)).intValue()<currentMax)
            {
               if(i<indices1.size()-1)
               {
                  i++;
               }
               else{
                  break;
               }
```

```
          }
        }
      currentMax+=(int)ratio;
      hMax+=100;
    }
    if(i<object1.size())
    {
      currenti = ((Integer)indices1.get(i)).intValue();
    }
    if(currenti>=currentMax)
    {
      while (((Integer)indices1.get(i)).intValue()<hMax)
      {
        h++;
      }
      currentMax+=(int)ratio;
      hMax+=100;
    }
      System.out.println();
    if(i==0)
    {
if((object1.get(i).toString().equals(object2.get(h).toString()))&&(object1.get(i+1).toString().equals(object2.
get(h+1).toString())))
      {
        numMatch++;
        i++;
        h++;
        saved=h;
        count=0;
```

```
        System.out.println("||||||||||||||||||||||||||||||||||||||||||||||||");
      }
      else
      {
        h++;
        if(h!=object2.size())
        {
          current = ((Integer)indices2.get(h)).intValue();
        }
        if(current>=hMax)
        {
          while (((Integer)indices1.get(i)).intValue()<currentMax)
          {
            if(i<(indices1.size()-2))
            {
            i++;
            }
            else
            {
              h=smallest;
            }
          }
          currentMax+=(int)ratio;
          hMax+=100;
        }
      }
    }
    else if(count>=7)
```

```
{
   h=saved;
   count=0;
   if(i<(indices1.size()-2))
   {
   i++;
   }
   else
   {
      h=smallest;
   }
}
else if(i<indices1.size()-1)
{
if((object1.get(i-1).toString().equals(object2.get(h-1).toString()))&&(object1.get(i).toString().equals(object2.get(h).toString()))&&(object1.get(i+1).toString().equals(object2.get(h+1).toString())))
{
   numMatch++;
   if(i<(indices1.size()-2))
   {
   i++;
   }
   else
   {
      h=smallest;
   }
   h++;
   saved=h;
```

```
            count=0;
            System.out.println("||||||||||||||||||||||||||||||||||||||||||||||||");
        }
        }
        else
        {
            h++;
            count++;
        }
        System.out.println("----------------");
    }while(h<smallest-1);
    System.out.println(numMatch);
}
public static void GenerateVectors()
{
    String[] splitter;
    String line = null;
    double size1=0;
    double size2=0;
    splitter = new String[2];
    Path path = Paths.get("P:\\SungWooResearch\\reconJava\\REEBs\\Coffee Mug_Scanner(REEB).off");
    File file = new File("P:\\SungWooResearch\\reconJava\\REEBs\\Coffee Mug_Scanner(REEB).off");
    if(file.canRead())
    {
            //open the file, read from it
            Charset charset = Charset.forName("US-ASCII");
            try(BufferedReader reader = Files.newBufferedReader(path, charset))
            {
```

```
            while ((line = reader.readLine()) != null)
            {
                splitter= line.split(" ");
                if(splitter.length>=3)
                {
                    indices1.add(Integer.parseInt(splitter[0]));
                    object1.add(splitter[1]);
                }
            }
        }
        catch (IOException x)
        {
            System.err.format("IOException: %s%n", x);
        }
        size1=Integer.valueOf(splitter[0]);
    }
    path = Paths.get("P:\\SungWooResearch\\reconJava\\REEBs\\Student 8(REEB).off");
    file = new File("P:\\SungWooResearch\\reconJava\\REEBs\\Student 8(REEB).off");
    if(file.canRead())
    {
        //open the file, read from it
        Charset charset = Charset.forName("US-ASCII");
        try(BufferedReader reader = Files.newBufferedReader(path, charset))
        {
            while ((line = reader.readLine()) != null)
            {
                splitter= line.split(" ");
                if(splitter.length>=3)
```

```
        {
            indices2.add(Integer.valueOf(splitter[0]));
            object2.add(splitter[1]);
        }
      }
    }
    catch (IOException x)
    {
      System.err.format("IOException: %s%n", x);
    }
    size2=Integer.valueOf(splitter[0]);
}
   if(size1>size2)
{
  smallest=indices2.size();
}
else
{
  smallest=indices1.size();
}
ratio = Math.ceil((size1/size2)*100);
}
```