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A Geometric Design Language and Method of Creating Aesthetic Product Form for Engineering Design

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William Frank Dresselhaus
October 1, 2021

ABSTRACT

The aim of this project is to develop a geometric design language and method of creating aesthetic product form for engineering design, and to empower engineering product designers to create attractive physical products. This should be accomplished by a proposed integrated holistic engineering product design process. This project approach deviates from the traditional industrial design paradigm of product aesthetic form-giving, and embraces architectural design as an inspirational model for total product design. The targeted product category for this project is engineered utilitarian technology products—consumer, industrial, and technical.

Previous geometric product form engineering design courses are addressed first. Geometric based product form design is then validated as a common and viable professional product design approach. Product form principles utilized in this project language and method are then gleaned from existing published sources such as architecture, graphic design, engineering, industrial design, science, and mathematics, as well as from this author's professional product design industrial and educational experience. A systematic and definitive geometric form design language and method are then synthesized and prescribed from these sources for application in engineering product design as an integrated and holistic product design framework. Finally, the resulting product form design language and method are visually simulated with illustrations and demonstrations by application to a number of product designs.

A goal of this project is to empower engineering designers to design attractive, human-centered, utilitarian technology products without a need for industrial designers. The intent is for engineering designers to be trained in the necessary foundation, process, language, method, and tools to do what industrial designers commonly execute in creating aesthetic product forms. The proposed product form design language and method permits engineering designers to integrate aesthetic form-giving appearance, ergonomic, and usability activities as part of a holistic engineering product design process and discipline. This is to be done without the need for extensive, sophisticated, and illustrative product form sketching. The three common simulation and visualization tools of engineering design are utilized in this method: simple orthographic and pictorial line sketching, physical mockups and models, and extensive computer modeling. The developed product form design language and method are exclusively geometric, and use only geometric language, shapes, volumes, elements, and details for aesthetic product form creation.

A rationale for this paradigm shift from the traditional industrial design form-giving approach to a holistic engineering product design approach is presented: a) the traditional two-silo industrial design/engineering design product development scheme, after decades of application, continues to be dysfunctional, and with an ongoing and seemingly unending conflict, b) the human-centered aspects of product design have been neglected by engineering design and its education for some time and inappropriately relegated to industrial design, and c) the natural place of the human-centered aspects of product form design in the holistic design of utilitarian technology products is best integrated within engineering design.

KURZFASSUNG

Ziel dieses Projekts ist es, eine geometrische Designsprache und eine Methodik zur Gestaltung ästhetischer Produktformen für das technische Design zu entwickeln und Produktdesigner zu befähigen, attraktive physische Produkte zu entwerfen. Dies soll durch den vorgeschlagenen integrierten, ganzheitlichen Prozess des technischen Produktdesigns erreicht werden. Dieser Projektansatz weicht vom traditionellen Industriedesign-Paradigma der ästhetischen Formgebung von Produkten ab und bezieht das architektonische Design als inspirierendes Modell für das gesamte Produktdesign mit ein. Die angestrebte Produktkategorie für dieses Projekt sind technische Gebrauchsprodukte - für Verbraucher, Industrie und Technik.

Zunächst werden frühere Kurse zum Design geometrischer Produktformen behandelt. Geometrisch basierte Produktgestaltung wird dann als praktikabler Ansatz für professionelles Produktdesign validiert. Die Gestaltungsprinzipien, die in dieser Projektsprache und -methode verwendet werden, werden dann aus bestehenden, veröffentlichten Quellen wie Architektur, Grafikdesign, Ingenieurwesen, Industriedesign, Wissenschaft und Mathematik sowie aus der Erfahrung des Autors im professionellen Produktdesign in der Industrie und in der Ausbildung entnommen. Aus diesen Quellen werden daraufhin eine systematische und definitive geometrische Formsprache und Methode für die Anwendung im technischen Produktdesign als integrierter und ganzheitlicher Produktdesignrahmen synthetisiert und entwickelt. Schließlich werden die daraus resultierende Produktformsprache und -methode anhand von Illustrationen und Demonstrationen durch Anwendung auf eine Reihe von Produktdesigns visuell simuliert.

Ziel dieses Projekts ist es, Ingenieure in die Lage zu versetzen, attraktive, auf den Menschen ausgerichtete, nutzbringende Technologieprodukte zu entwerfen, ohne dass Industriedesigner benötigt werden. Ingenieure sollen in den notwendigen Grundlagen, Prozessen, Sprachen, Methoden und Werkzeugen geschult werden, um das zu tun, was Industriedesigner üblicherweise bei der Gestaltung ästhetischer Produktformen tun. Die vorgeschlagene Sprache und Methode für die Gestaltung von Produktformen ermöglicht es Ingenieuren, ästhetische Gestalt, Ergonomie und Benutzerfreundlichkeit als Teil eines ganzheitlichen technischen Produktgestaltungsprozesses zu integrieren. Dies soll ohne die Notwendigkeit einer umfangreichen, anspruchsvollen und anschaulichen Skizzierung von Produktformen geschehen. Die drei üblichen Simulations- und Visualisierungstools des technischen Designs werden in dieser Methode verwendet: einfache orthographische und bildliche Linienskizzen, physische Mockups und Modelle und umfangreiche Computermodellierung. Die entwickelte Designsprache und -methode für Produktformen sind ausschließlich geometrisch und verwenden nur geometrische Formen, Volumina, Elemente und Details für die ästhetische Gestaltung von Produktformen.

Es wird eine Begründung für diesen Paradigmenwechsel vom traditionellen formgebenden Ansatz des Industriedesigns hin zu einem ganzheitlichen Ansatz des technischen Produktdesigns vorgestellt: a) Das traditionelle Schema der

Produktentwicklung mit zwei Silos - Industriedesign und Ingenieurdesign - ist nach jahrzehntelanger Anwendung nach wie vor dysfunktional und mit einem andauernden und scheinbar nicht enden wollenden Konflikt behaftet, b) die menschenzentrierten Aspekte des Produktdesigns wurden vom Ingenieurdesign und seiner Ausbildung lange Zeit vernachlässigt und in unangemessener Weise dem Industriedesign zugeordnet, und c) der natürliche Platz der menschenzentrierten Aspekte des Produktformdesigns in der ganzheitlichen Gestaltung nützlicher Technologieprodukte ist am besten im Ingenieurdesign integriert.

ACKNOWLEDGMENTS

First and foremost I thank God for this project—for simply allowing me to do it at all, for giving me the time and abilities to accomplish it, and for the grace and mercy to finish it. It is He who designed and created the great and wonderful universe we live in, with its unbelievable integration and coordination of mathematics and science, and especially the wonderful basis for this project—geometry. It is geometry that has inspired designers and artists over the millennia to develop great works of art, architecture, and design, and it is geometry that has inspired this project. Truly, design is God’s work, and geometry is God’s mathematics. I thank the Lord God of Heaven for everything I have in this world.

Often in these acknowledgments one of the last persons to be thanked is a wife for her wonderful support. But I put my Becky second only to God in my gratitude. She has been a consistent and loving supporter of nearly everything I have ever done, and without her support for this project, and her constant encouragement (especially to just get it done!), it would never have happened. I especially thank her for always patiently listening to my spontaneous "lectures" about geometry, physics, science, mathematics, design, and this project! I love her greatly and thank her dearly.

I am especially grateful to my supervising professor and mentor for this project, Prof. Dr. Manuel Löwer, Director of Mechanical and Safety Engineering at the University of Wuppertal, Germany. Dr. Löwer has not only generously and kindly permitted me—nay, invited me—to even start this project, but has been a great and wonderful supporter and inspiration all along the way. His encouragement, time, and help has been of inestimable value and has been received with much gratitude. Our FaceTime discussions about the project (as well as politics and life as well) have been a joy. I will be forever indebted to him for giving me this wonderful opportunity, and for so patiently tolerating my quite biased and opinionated viewpoints about nearly everything! I sincerely hope that I do not disappoint him with this work.

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I am grateful as well to another faculty member at Hongik University, and that is Prof. Dr. Keun Lee of the HongIk Industrial Design Department—for his wonderful

influence, work, and efforts to create the DongDaeMun Design Plaza exhibit of the Apple and Lisa product design work. I will forever be thankful to him—what a great event and experience!

My teaching time at IDAS (the International Design school for Advanced Studies) at HongIk University was a great joy. I thank Prof. Dr. Ken Nah for his kindness in hiring me there, and for his constant help and encouragement. I am also grateful to Ms. Inja Kim, the Managing Director of IDAS, without whom myself and the entire school would have floundered badly. In addition, I thank the many colleagues at IDAS who were wonderfully encouraging and welcoming to me.

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Jerry Manock was an early graduate “hero” of the Stanford Product Design Program, the first Corporate Manager of Product Design at Apple, a key Stanford mentor of mine, and who also hired me at Apple. He was responsible for the product design of the Apple II, the Apple III, the first Macintosh computers, and much more. I am so thankful to Jerry for the help and incredible opportunities he gave me in those early days, though, again, I was surely a "thorn in his side” with my rude ways.

I thank my colleagues at the Portland State University Department of Engineering and Technology Management (ETM) for their continued support of me and my teaching there. I especially thank Prof. Dr. Tim Anderson, department chair, for the work he has given me in teaching product design in the department and the risk he took in doing that effort. I am also thankful for the dissertation advice he has given me at various points of my confusion. In addition, I am grateful to Prof. Dr. Antonie Jetter of ETM for her valuable doctoral and dissertation advice from a German perspective—and for being a great product design advocate as well.

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I am especially grateful to the authors of the several foundational source books for this project for their seminal principles of design used in this project, some of them long passed away—may they rest in peace. Their monumental works have been incredible sources of inspiration and knowledge of product design, especially for this project. These are authors such as Prof. Tjalve, Prof. Ashford, Prof. Cain, Prof. Coates, Prof. Norman, Prof. Alexander, Prof. Harper, and Prof. Papanek, among many others. Who says that old works are obsolete? These are of lasting and durable value —thank you!

My geometric form analysis research would have been much more difficult had not it been for Prof. Dr. Peter Zec and his outstanding Red Dot Award competition and the four volume set of books and website I used for my visual geometric form analysis. The books and website are filled with exciting and interesting products that were not only a great basis for my research and my form analysis, but also inspiring and motivating. I am very grateful that Red Dot gave me permission to use the images in my dissertation work.

I also thank the outstanding industrial designers I have experienced in my career, either personally or vicariously, such as Jeff Smith (Lunar), Gerard Furbershaw (Lunar), Mike Nuttal (Matrix), Hartmutt Esslinger (Frog), Jony Ive (Apple), Sohrab Vassoughi (Ziba), Bob Brunner (Lunar, Apple), and especially that great man and designer, Dieter Rams (Braun). They have, over the years, and for this project, inspired me by demonstrating their amazing talent in geometric product form design.

And finally, but definitely not least, I thank all of my outstanding engineering students at HongIk MSDE, and my design students at HongIk IDAS, for letting me be their teacher for so many wonderful years—it was pure joy. You helped make it the best job of my life. I especially thank my MSDE engineering students in my product form design courses for proving beyond a doubt that engineers can create beautiful, geometric-based product designs—what a great success you made of those courses! Thank you!

My sincere apologies for anyone I have missed in thanking. I am very grateful to you regardless.

Bill Dresselhaus
October 1, 2021

DEDICATION

This project is dedicated to my father, Harold Dresselhaus, who, dubbed by his many loyal customers as “the gentleman plumber," was a truly great and wonderful man, husband, and father. Given the opportunity, he would have loved to have been a product designer.

KEYWORDS

Product design, form design, geometric form, organic form, product aesthetics, industrial design, engineering design, product form, engineering education, design education, architectural design, geometric design.

Design ist Gottes Werk.
Geometrie ist Gottes Mathematik.

“[Designers] cannot remain at the level of words, reflections, considerations, warnings, accusations, or slogans. They must transpose their insights into concrete, three-dimensional objects.”

Dieter Rams (1984)

“…it is absurd to separate the study of designing from the practice of design.”

Christopher Alexander (1971)

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GLOSSARY AND ABBREVIATIONS

The following are terms, abbreviations, and acronyms used in this dissertation.

3D. The acronym for three dimensional.

AF360. The acronym for Autodesk® Fusion 360® CAD modeling software used for the CAD model designs, visualizations, and demonstrations in this project.

CAD. The acronym for computer aided design.

ED. The acronym for engineering design. Used at times as a brief alternative to the full term.

EDP. The acronym for engineering product design. Used at times as a brief alternative to the full term.

FEA. The acronym for finite element analysis, an analytical process used in engineering design.

GPF. The acronym for geometric product form. This is the form of a physical product and its elemental volumes, parts, details, and composition that are created from one or more combinations of basic geometric elements. These are such as rectangular prisms or right cylinders, straight or radial curves, planar or radial surfaces, right angles and orthogonal relationships, and simple geometric details of edge radii or chamfers. GPF is in contrast to organic product form (OPF).

GUI. The acronym for graphical user interface. This is the visual, and often iconic, graphical interaction mode, typically on a display screen, that permits the user to visually navigate throughout a software program.

ID. The acronym for industrial design. Used at times as a brief alternative to the full term.

OPF. The acronym for organic product form. This is the form of a physical product, and its elemental volumes, parts, details, and composition, that are primarily created from one or more combinations of organic form elements. Organic forms are such as occur in, are derived from, or are imitated from, nature (thus, “organic”). They are often created using bezier-type or T-spline curves rather than radial curves. OPF is in contrast to geometric product form (GPF).

PCD. The acronym for product concept design, the process for developing early ideas and concepts for new products based on human need. It is a human centered design process.

STEM. The acronym for science, technology, engineering, and mathematics—generally related to the education of such topics.

UTP. The acronym for utilitarian technology product. These are products that are relatively complex in nature, have significant technologies as functional components or attributes, accomplish specialized and unique utilitarian tasks, and are often, though not always, used by specialized or trained users. UTPs are also often called “engineering products or engineered products” and can be industrial, consumer, or technology based. The form design of UTPs is the primary product target group for this project.

1. INTRODUCTION

This project concerns the discipline of engineering product design (Cain, 1969; Ulrich et al, 2020). It is specifically about the product form design of engineered utilitarian technology products (UTPs). Product form design, both aesthetic and functional, is an integral and important part of total product design and development (Ulrich et al, 2020; Coates, 2003; Ashford, 1969; Cain, 1969; Dresselhaus, 2016, p. 10). The approach to product aesthetic form design, in collaboration with engineering design, has been traditionally driven by industrial design since the 1920s (Coates, 2003, p. ix). That approach, as will be expanded upon later, has often been a dysfunctional one, and a source of ongoing debate virtually ever since it started (Brezing & Löwer, 2008; Warell, 2001; Evans et al, 2009).

This project proposes to shift that paradigm to one where:

a. architectural design is the inspirational reference model for a total design philosophy,
b. a holistic and integrated engineering product design discipline is possible,
c. organic product form (8.1. Figure) can be completely avoided, and
d. where solely geometric principles and forms (8.2. Figure) are the aesthetic basis for engineering product design.

The primary aim of this project is to develop and prescribe a geometric-based engineering product design form language and method that can be used by engineering product design to create aesthetic forms of technologically sophisticated physical products without a need for industrial designers (Ashford, 1969, pp. xi, 9). This is to be done by properly integrating human-centered activities of product aesthetic form design into an engineering product design discipline of comprehensive and holistic process (Cain, 1969, p. 1). The proposed product form design language and method are unapologetically prescriptive and functionalist (Rams, 1984; Bürdek, 2015, pp. 49-50). They are also solely geometric, based on a long history, theory, and broad application of geometry and proportion in architecture, art, and design, and synthesized from many established areas of design and art (Meisner, 2018; Bass, 2019; Elam, 2011; Droste, 2019; Dondis, 1973).

This Introduction launches the rationale and process for this vision.

1.1. Critical Issues and Questions

Over several decades of an engineering design, product design, and teaching career (9. CURRICULUM VITAE), this author has had increasing concerns regarding the design of physical engineered technology products, especially for their product form language and design. Historically, the traditional two-silo paradigm of industrial design and engineering design collaboration has not always been optimal, to say the least (Papanek, 1970; Packard, 2007 & 2011; Rams, 1984; Brezing & Löwer, 2008; Warell, 2001). The "why" is clear: physical product designs need functionality, ergonomics, usability, and beauty, all properly integrated, that are human-centered and valuable (Coates, 2003, p. 36; Norman, 2013, pp. 8-9; Tjalve, 1979, pp. 6-7; Ashford, 1969, p. 6-7; Cain, 1969, p. 1; Ulrich et al, 2020, p. 2; Rams, 1984).

But key questions remain:

a. Just what is “good” product form language and form design?
b. How should such product form language and design be executed?
c. Can a definitive method for executing such “good” product form language be clearly and logically prescribed?
d. Can such a prescribed and definitive method be more effective and efficient in effort, time, resources, and sustainability than what is done currently?
e. Is there a better model for engineering product design inspiration and process than the traditional industrial design model?
f. Who might be the better design actors to execute a comprehensive and integrated product design method that includes aesthetic product form language and design?

1.2. Toward A Better Way

Too many physical products have been, and still are, designed solely for their superficial styling: for consumer purchase motivation, for corporate brand recognition, or for their business profitability regardless of human value (Papanek, 1970; Packard, 2007 & 2011; Meyer & Norman, 2019; Fitzpatrick, 2011; Evans & Hewitt, 2009). The celebrated German industrial designer, Dieter Rams, has decried this situation (Klemp, 2020, p. 7; Rams, 1984), as well as Norman (1999). This unfortunate scenario will likely continue as long as the traditional cosmetic approach of aesthetic product form creation for promoting sales through a consumer visceral response (Norman, 2013, pp. 50-51) is used for many consumer products.

However, the need for well-designed and sustainably aesthetic utilitarian products remains (Harper, 2018; Ulrich et al, 2020). Such engineered products and systems for consumer, technology, and industrial applications generally do not need superficial and artificial cosmetic form design (Coates’ low “valence” principle, 2003, pp. 243-246). Products in this category are in great need for quality engineering design, appropriate ergonomics, and high usability (Coates, 2003, pp. 34-42), and where those factors best drive a resulting aesthetic product form. This must be product form language that is understandable and discoverable (Norman, 2013, p. 3)—product form design that clearly communicates function and interaction (Coates, 2003, p. 122; Norman, 2013, p. 3; Ashford, 1969, p. 82; Cain, 1969, p. 132; Brezing & Löwer, 2008). A better total design approach is needed over a “styling for purchase” model.

1.3. A Moral Imperative

Any work that purports to be for a “doctor of philosophy," or for a “doctor of engineering," as this project does, cannot conscientiously avoid dealing with its philosophical and moral dimension (Papanek, 1970; Harper, 2018, pp. 2-4; Bürdek, 2015, p. 20). Otherwise, it does not rise to the level of any so-called “doctor” of anything. There are, of course, “philosophies" of many types, but a true philosophy, though perhaps focused in one area, must also relate to everything—a truly comprehensive approach (Trueblood, 1973, p. 7; Bürdek, 2015, p. 77).

Consequently, the philosophical and moral foundations of this project are below. It is sincerely hoped that the results of this project will comply with these.

Need. Physical products are required that meet critical human needs: products that support and promote human flourishing, health, and well-being (Papanek, 1970; Rams, 1984; IDEO.org, 2015).

Sustainability. Physical products are required that endure—with long-lasting, durable, and sustainable viability—designed with care and diligence (Harper, 2018).

Waste. Physical products are required that are designed in such a way that minimizes waste of resources, time, energy, effort, and human creativity (Packard, 2007 & 2011; Papanek, 1970; Rams, 1984; Fitzpatrick, 2011; Su, 2018).

Holistic. Though this project concerns a particular philosophy of product design, and a specific approach to product form design, a holistic and integrated product design model informing engineering design is needed (Rams, 1984; Klemp, 2020; Ashford, 1969; Cain, 1969).

Innovation. Creative innovations, whether aesthetic, technical, or ergonomic, are clearly important to new product design and development. However, these objectives are too often over-emphasized, especially in industrial design, for "creative" visual innovation over against simply good quality product design for functionality, usability, and attractiveness. There are already plenty of poorly designed, and even useless, products in the world, and more being created every day.

This project aims to define a product form design language and method that emphasizes, as Rams (1984) does, designing new, or redesigning existing, products that are fully and completely functional, usable, and attractive (Coates, 2003, pp. 241-244). Products that clearly meet real, human-centered needs, first and foremost, before aesthetic novelty or innovation! Such a language and method clearly should allow for creativity, innovation, and novelty, but only if and when appropriate and essential (Dresselhaus, 2016, p. 44).

1.4. Project Hypotheses

The hypotheses for this project are the following:

a. A functionalist physical product form design language and method, based solely on geometric principles, and based solely on geometric volumes and design elements, can be systematically synthesized, defined, and prescribed.
b. Such a geometric product form (GPF) design language and method is viable, valuable, durable, and sustainable for designing engineered utilitarian technology products (UTPs).
c. Such a GPF design language and method can be developed and synthesized primarily from already existing design knowledge and principles from a variety of disparate sources.
d. A better total design reference and inspirational model for informing holistic and integrated engineering GPF design is architectural design.

e. The better design actors for holistically executing such an integrated GPF design language and method for UTPs are engineering product designers.
f. Such a GPF design language and method for UTPs can be successfully taught, learned, and executed within engineering design.

This project will attempt to demonstrate that a., b., c., and d. are valid. Some of e. and f. has already been accomplished via earlier experimental engineering product form design courses presented in this document. Further work on e. and f. will be suggested in the Recommendations section of this document.

1.5. Research Methodology

This project has the following summarized methodology for its research, development, and resolution of the above hypotheses.

Part 1: Product Design Education Evaluation. The evaluation of the results and insights from previous experimental teaching of college courses in product form design language and method to engineering students at HongIk University (2016) in Seoul, Korea, that were developed and taught by this author—what content worked and what did not, what design language and methods were employed, and what are the key takeaways that affect this project's GPF language and method were analyzed.

Part 2: GPF Common Use Analysis. The analysis and demonstration of the common use of a geometric-based product form design language utilizing a prominent product design global award competition, and a set of specific celebrated designers and firms—which product categories used geometric form and how often, how did certain celebrated design actors and firms use geometric form, and what were the geometric design principles, features, and elements that were used in both these sources were analyzed.

Part 3: Existing Design Form Principles. The finding of foundational form design principles from various extant, though disparate, resources such as architecture, fashion, mathematics, engineering, industrial design, science, and art were researched and discovered—what existing principles, methods, features, and insights already extant that could be used to synthesize a product form design language and method.

Part 4: Product Design Language and Method Synthesis. The synthesizing of a definitive GPF design language and method from combining the results of the educational engineering courses experience (Part 1), key findings of the GPF common use results (Part 2), the findings of existing form design principles (Part 3), and key factors from this author’s personal career experience in product design, management, and engineering—a definitive GPF design language and method prescribed as a holistic engineering product design process.

Part 5: Demonstration of the Form Design Language and Method. A demonstration of the prescribed GPF design language and method (Part 4) via a number of compositions, visualizations, deconstructions, and illustrations—the synthesized GPF design language and method profusely demonstrated using actual and converged physical product designs.

1.6. Dissertation Structure

This project dissertation, after its front matter and this current Introduction, has the following structure:

Background. Various resources and commentary on design history, education, development, practice, theory, applications, and background for this project.

Methodology. The process which the project research, development, and GPF design language and method synthesis were developed and executed in five parts.

Results. The research and development results of findings, principles, and GPF design language and method presented from the Project Methodology work of its five parts.

Discussion and Conclusions. A discussion of the project work, background, methodology, and results, as well as relevant conclusions and comments.

Recommendations. Suggestions for further research in the project area based on the project background, methodology, results, discussion, conclusions, and comments.

References. The list of references and resources used, synthesized, and cited in this project dissertation.

Figures. The numbered figures of the various examples, compositions, demonstrations, illustrations, simulations, principles, and visualizations related to the project content and Results.

Author CV. A brief summary of the author's background.

1.7. Visualizations and Demonstrations

A frustration of this author is that most academic industrial design research publications concerning aesthetic form design are primarily analytical in nature and rarely demonstrate their often declared "methods" to create actual product design forms. Two unusual examples are Tjalve (1979, virtually the entire book!), and Corremans (2008)—there are few others. This project aims to clearly visualize and demonstrate its form design language and method. The quotation from Dieter Rams (1984) used in this dissertation epigraph applies well, "[Designers] cannot remain at the level of words, reflections, considerations, warnings, accusations, or slogans. They must transpose their insights into concrete, three-dimensional objects."

2. PROJECT BACKGROUND

This section reviews pertinent history, literature, theory, and practice relevant to this project.

2.1. Design

2.1.1. Design Definitions

Since there are a multitude of extant definitions of “design,” a relevant one for this project is in order. Alexander (1971, p. 1) states that design is, “The process of inventing things which display new physical order, organization, form, in response to function.” Papanek (1970, p. 3) says design is “the conscious effort to impose meaningful order.” Warell (2001, p. xiv) says that design (the object) is “The result of a design process," and that design (the process) is, “To conceive the idea for some artifact or system and/or to express the idea in an embodiable form.” Krippendorff (2006, p. xiii) says, “Design is making sense of things.” Coates (2003, p. 26) and Norman (2013, p. 47) would agree. Design is a devised “plan or scheme” for something to be realized (Bürdek, 2015, pp. 12-13).

For this project, design is considered the human effort to plan and create order from non-order, or plan and create order from bad order (bad design), or to redesign. As a verb, design is the process of creating order from unordered elements, materials, and components for human value, aesthetics, usability, and utility. As a noun, design is an entity that has been intentionally created and ordered from unordered elements, materials, and components in terms of human value, aesthetics, usability, and utility. There are many kinds of order in design: aesthetic, functional, configuration, ergonomic, etc. Design creates order out of non-order, or it remedies disorder (bad design) with good order (good design).

2.1.2. Design People

Too often, in the world of product design and development, the term “designer" is often used to solely refer to industrial designers—they are simply called “the designers” (Gorman, 2003, pp. 143, 145, 156, 169, 176, & 179). This is unfortunate since, as Tjalve (1979, Preface) says, “the word ‘designer’ [should be] used as a blanket term for people working with design, i.e., engineers, industrial designers, and others, of products."

Papanek (1970, p. 3) affirms that everyone is a designer and everyone designs —design is “basic to all human activity.” Warell (2001, p. 8) agrees. Bürdek (2015, p. 9) affirms that “everything is designed, intentionally or not." Since everything physical has a form by its very nature and existence (Tjalve, 1979, p. 3; Bürdek [on Sullivan], 2015, p. 57), it would follow that engineers, a group that creates a vast quantity of physical objects, would also be designers (Baynes & Pugh, 1986; Ashford, 1969; Cain, 1969; Karsnitz, 2012; Budynas & Nisbett, 2019; Sclater, 2011). However, it is unfortunate that far too often, when speakers or writers are talking about product design and development, usually only the industrial designers are termed as “the designers," and not the engineering designers, nor anyone else who might be executing such as software design, or electronics design, or optical design, among others. It is hypocrisy to define design as a general activity by anyone, and then call only people in a select and so-called “artistic” discipline as “the designers”! However, with the advent of such processes as “user as designer” and “participatory design” (Sanders & Stappers, 2013), where “ordinary” people engage in developing design concepts and parameters, it may be a good thing to designate only certain trained design professionals as “Designers," whatever kind of design they may execute.

2.1.3. Design Value

Good product design and product aesthetic form have long been confirmed as a valuable competitive advantage in the global marketplace of products (Ulrich et al, 2020, pp. 220-223; McKinsey, 2021; Stevens, 2009; Brezing & Löwer, 2008; Bürdek, 2015, p. 8; DMI, 2015; Westcott, 2014). However, more and more new products, from consumer to industrial, are increasingly technologically and functionally complex and sophisticated (Zec, 2019; Norman, 2013, p. 4). There is a global need for new, human-centered, utilitarian products and tools that meet critical human requirements (Bürdek, 2015, p. 91). These are in the areas of medicine, science, engineering, manufacturing, and technology, among others. Zec (2019) confirms this, and categorizes these in his Red Dot Award books of *Working*, *Living*, *Doing*, and *Enjoying*. Even the consumer market requires more technical sophistication in product design (Warren, 2018). Besides these needed new, human-centered product designs, there are multitudes of existing products that may meet human needs functionally, but are extremely hard to use, or are unattractive (Norman, 2013, Chapter 5)—they are poorly designed regarding usability, ergonomics, and/or aesthetics. It is important that these products be redesigned for better human-centered viability as well.

In addition to the commercial, branding, and marketing value of good product design, there is the value of good product design to all the stakeholders of a particular product (Krippendorff, 2006; Dresselhaus, 2016, p. 97). These are all of the people or groups who have a “stake” in the product design. These would include, beyond users, such as: manufacturers, assemblers, repairers, maintainers, shippers, packagers, inspectors, diagnosticians, and more. A product’s holistic design must include accommodation for all of these stakeholders. It is not unusual that the design aspects for any one of these stakeholder areas can make or break a product design success (e.g., difficulty in assembly, difficulty in packaging, difficulty in shipping, difficulty in repair, poor recyclability, unsafe aspects, etc.).

2.2. Product Design

2.2.1. What Is a Product?

Warell (2001, p. xiii) says a product is, “A system, object, or service made to satisfy the needs of a customer.” Ashford (1969, p. 11) says, “All engineering products are articles of utility," and their primary purpose is functionality. Cain (1969, pp. 1 & 8) says that products have a “single overriding functional requirement” above all else, and that “a product may be considered any article or commodity which results from a process." Tjalve (1979, p. 7) declares that, "The most important property of all is the primary function of the product."

Thus, we might define a physical product as a tangible object that has been "productized," or synthesized, and then realized from a set of materials, elements, and components, into a useful and functional entity for human value. In other venues and applications outside of this project, the term "product" may designate less tangible entities such as software, and even service "products" (Deloitte, 2018; DeSID, 2021). However, for this project, when the term "product" is used, it invariably means a physical object.

2.2.2. What Is Product Design?

Warell (2001, p. xiii) defines product design as, "The activities involving the design of products, including the activities of engineering design and industrial design." Given the total approaches to product design of Cain (1969), Ashford (1969), Ulrich et al (2020), and Tjalve (1979), we might define product design as the discipline of comprehensively synthesizing a complete product system from inside out and outside in, especially focusing on function first (Tjalve, 1979, p. 9), and then on such as structure, architecture, usability, ergonomics, electromechanical packaging, safety, repair, upgrade, manufacturability, and a host of other issues, as these authors have identified.

However, such a product design synthesis process need not address the design of the technological components inherent in a product—that work is perhaps better for the engineering specialist. In others words, the specific discipline of engineering product design is an integrating and synthesizing process of composing, assembling, and forming a set of materials, elements, and components into a holistic and comprehensive product system whole, but not necessarily inventing or designing the specific technologies or discreet technical components that are utilized in the product. In this sense, as explained later, the product designer is more like an architectural designer—a 3D geometrist who creates product inside/outside "ensembles" based upon product context (Alexander, 1971, p.16; Dresselhaus, 2016, p. 83-84).

2.2.3. Important Terms

There are several important factors effecting good product design, and understanding what they are, and their differences and similarities, is important to proper functioning of engineering product design.

Organic Form. The term organic form generally refers to shapes, volumes, and forms that are irregular and sculptural in appearance and tend to have a curvilinear aspect to them (Leborg, 2006, p. 28). They are forms that resemble shapes and forms found in nature, and are physical shapes and volumes, and combinations thereof, that are composed of mathematically complex curvilinear lines and surfaces. Organic forms are in contrast to geometric forms. Organic product forms (OPFs) are therefor forms of products, and their elements and compositions, that are created primarily from organic forms: complex, non-geometric curves, surfaces, volumes, shapes, and details that are similar to those found in nature (8.1. Figure).

Geometric Form. The term geometric form means of, or relating to, basic simple geometry—shapes, volumes, details, and forms of objects and elements based on principles that can be expressed with mathematical simplicity (Leborg, 2006, p. 28). This would be such as a straight line, a square or rectangle, a circle or radial arc, a sphere, a cube, a rectangular solid, a cone, a cylinder, and a pyramid. Geometric product forms (GPFs) refer to the physical forms of objects that are composed of mathematically simple geometric elements and combinations thereof (8.2. Figure). For millennia, geometry and geometric forms and proportions have been the basis of architectural design (Meisner, 2018; Ching, 2014; Elam, 2011). Elam (2011, p. 43) says that a geometric form basis brings "compositional cohesiveness” to a project. Organic forms are in contrast to geometric forms, and GPF is in contrast to OPF.

Product Realization. As a noun, this is the physical rendition, or physical mockup, or functional prototype, of a product concept. As a verb, it is the activity of making of such a physical rendition or prototype (Brezing & Löwer, 2008). Product realization and productization (below) are not the same thing. Product realization is a term for making or fabrication of a physical object, whereas productization is a term for synthesis of a concept. The former involves a physical object or prototype fabricated of a product concept, whereas the latter is the concept created from a set of parameters, elements, and context, but is not necessarily a physical (realized) rendition. In a sense, productization is a non-physical, often comprehensive, product concept design, and product realization is the process of taking such a productized concept design and specification, and turning it into a physical mockup or prototype at a certain completion level.

Productization. This is the process of synthesizing, using various principles and processes, a set of elements, materials, components, technologies, and parts, into a coherent, comprehensive, and ordered product design concept (Dresselhaus, 2016, pp. 11-12). It could be said that these elements have been productized into a product design concept from the non-order of these elements to an ordered product system. Productization may take the form of a specification, a set of drawings or sketches, or some other non-physical, but tangible entity set, whereas product realization would result in a productized product design concept turned into a realized physical mockup or prototype at a certain level of completion.

2.2.4. Product Design Quality

Poorly executed product “outsides” regarding usability, ergonomics, and aesthetics can be often worse than no product at all (Norman, 2013, p. 55). Quality product design of new products, and the redesign of existing products, are essential for business viability and human need (Ulrich et al, 2020, Chapter 1). Attention to precision, craftsmanship, performance, service, repair, upgrade, sustainability, reliability, structure, etc., for all of the product stakeholders, is imperative for success (Krippendorff, 2006, p. 60; Dresselhaus, 2016, p. 13). However, contemporary engineering design and education are too often only focused on creating new technical innovations for product "insides" (Brezing & Löwer, 2008; Wilgeroth & Stockton, 2009).

Many of these potential new or redesigned products are physical objects and systems, some with or without enhancing digital devices, interfaces, or software. Many have engineering design content and specialized technological applications. Others are utilitarian consumer products that make human life more enjoyable and sustainable, but are also becoming more and more sophisticated in nature (Zec, 2019, *Enjoying* book). Such product systems require design language and forms that are a logical, human-centered response to a total product context—human factors, functionality, ergonomics, usability, culture, and the environment (Coates, 2003, pp. 30-31). An important and essential part of that human-centered content must be quality product language, product form, and attractive aesthetics (Faste, 1995; Klemp, 2020; Rams, 1984; de Vere, 2009).

There is also the issue of waste—the unbelievable and constant global waste of materials, energy, time, food, land, water, and human effort, among others (Minter, 2013). The waste of consumer packaging alone is staggering (Su, 2018). And sadly, it is both engineering design and industrial design that have significantly contributed to this tragedy. Both disciplines have been responsible in designing wasteful and unsustainable products of questionable value and use (Packard, 2007 & 2011). Papanek (1970) rightly lays most of the blame for this on the consumer advertising industry and industrial design, where both have significantly contributed to a wasteful consumerism and a "style it so they buy it" philosophy (Packard, 2011; Fitzpatrick, 2011). Industrial design research is often focused on enticing consumers to buy products with compelling form and aesthetics (Babapour & Rahe, 2013; Crilly & Clarkson, 2006; Chang & Van, 2003; Gorman, 2003, pp. 181 & 230). But engineering has also been complicit in this by executing the technical design for such products, without which they could not have been produced.

2.2.5. The Legacy Process

The common product design and development legacy process is a combination of industrial design and engineering design as a two-discipline, "collaborative" approach (Brezing & Löwer, 2008; Warell, 2001, p. 5; Ulrich et al, 2020; Dresselhaus, 2016). Unfortunately, this process is often conflicted and dysfunctional, with separate design silos, departments, management, and creators with differing objectives, attitudes, perspectives, motivations, rewards, visions, training, and design criteria (Evans et al, 2009). Industrial design usually develops the external product aesthetic form and language (Esslinger, 2013; Dresselhaus, 2016, p. 37), and then hands this form design intent off to engineering, which then executes the electromechanical engineering design. Granted, some very good industrial design and engineering teams have done this quite well (Dresselhaus, 2016, p. 38), but far too many others simply have created unwarranted problems for product engineering, as well as product development cost, schedule, and product pricing—and, frankly, not always attractive products in the end.

The fundamental root cause (Norman, 2013, p. 42) is that the human-centered aspects of product design within engineering education and practice have been long neglected, and relegated almost exclusively to industrial design (Ashford, 1969, pp. 1-10 & Chapter 1). But product aesthetic form design is the natural and logical result of the design of product function, ergonomics, usability, architecture, technology, and structure, all of which are part of engineering product design (Cain, 1969; Ulrich et al, 2020). The binary legacy approach badly needs to be replaced, especially for engineered UTPs, with a holistic, integrated, and efficient engineering product design process (Bürdek, 2015, p. 109; Dresselhaus, 2016, p. 32). The traditional process is wasteful of time, budget, resources, and human effort (Evans et al, 2009). It is incumbent that the human-centered, aesthetic form-giving, and the electromechanical aspects of product design, are integrated, instructed, and applied in one holistic engineering product design discipline (Wilgeroth & Stockton, 2009).

The problem too often is that a product aesthetic form design is created and prescribed by industrial design too early in the design process, often due to incomplete design and engineering information for the proposed new product. This premature effort, generally represented by dozens of sophisticated and illustration-based industrial design "concept" sketches (Liu, 2013; Eissen & Stuer, 2014, 2019a, & 2019b), hampers a proper holistic design of the product—it represents mainly an outside-in product design rather than an inside-out design approach as well (Warell, 2001). It is clear that industrial design has contributed significantly over the past decades to the design of many functional, useful, and beautiful industrial and consumer product designs (Esslinger, 2013; Klemp, 2020; Zec, 2019). However, compared to the total number of industrial designers graduated in past decades, there are only a few of such top performers. Much historical criticism of industrial design results can be demonstrated as well (Papanek, 1970; Packard, 2007 & 2011; Norman, 1999 & 2013; Alexander, 1971).

A new and valid foundational model is needed to inspire and prepare engineering for such a comprehensive and holistic product design approach. Though the traditional model for aesthetic form-giving activity has been industrial design, this discipline has serious problems with its history, theory, education, and application (Brezing & Löwer, 2008; Alexander, 1971; Papanek, 1970; Burdek, 2015). This project later proposes that it is architectural design that has a far better approach to a total holistic design philosophy, and it can be adapted to engineering product design as an inspirational model.

2.2.6. Product Design Audiences

Coates (2003, pp. 34-35) proposes his three design "audiences" of pre-purchase consumer, post-purchase user, and the observer public. He states that one must properly aesthetically design for the pre-purchase consumer since they only have product appearance to influence their purchase. He claims aesthetic product form, styling, appearance, fashion, culture, and brand for this audience is imperative. This would be the visceral response that Norman (2013, pp. 50-51) describes of the pre-purchase product consumer. The traditional role of industrial design has generally been to create an optimum visceral aesthetic response for products and brands to motivate consumers to buy and consume (Coates, 2003). This apparently remains so, as much industrial design academic research reflects a propensity for aesthetic form design for motivating such pre-purchase consumer sales (Crilly, 2005; Crilly & Clarkson, 2006; Lopes de Castro & Vicente, 2018; Babapour & Rahe, 2013; Blijlevens et al, 2009; Gonzalez et al, 2018; Wood et al, 2011). However, Papanek (1970), Norman (1999 & 2013), Rams (1984), and Klemp (2020), critically eschew this approach and promote a holistic and functionalist attitude.

But, Coates (2003, pp. 40-42) also states that the most important audience of his three to design for is the post-purchase user, since they will make or break a product or brand success by their actual use response to the functionality, ergonomics, usability, and durability of a product. He says the product design form, appearance, and styling is highly important to motivate pre-purchase consumer sales through their immediate visceral response, but the post-purchase user experience, and its response to design for functionality, durability, and beauty, is the main key to long term product and brand success. Norman would agree (2013, pp. 3-5) on such product design responsibility as well: products must be understandable, functional, and usable, or they are not good product design. In addition, it would also seem that a positive post-purchase user satisfaction would also positively effect the Coates' observer public audience as well, most likely more than the pre-purchase consumer visceral response.

The "Amazon Effect." With the emergence of the internet, search engines, and online purchasing, such as Amazon® (amazon.com), these have potentially changed the need for Coates' pre-purchase consumer "style it so they buy it" imperative, often an unfortunate application of aesthetic product form design (Papanek, 1970). Due to the internet search phenomenon, designing for Coates' (2003, p. 44) post-purchase user could now become even more important, and designing the "cosmetic" styling and aesthetic form for the pre-purchase consumer buying motivation less so. This is because it is now possible for pre-purchase consumers to evaluate many important post-purchase issues of understandability, functionality, usability, and durability quite easily (Coates, 2003; Norman, 2013; Harper, 2017). The immediate visceral response to product appearance and styling is still there, but can be significantly preempted, so to speak, by a virtual and vicarious post-purchase virtual usability experience. The post-purchase user audience evaluation can now be done beyond the pre-purchase visceral aesthetic response. Amazon and others are literally doing "product user research" by nature of their business model.

For example:

a. The internet and search engines provide prolific opportunities to view and evaluate the appearance, styling, and form of a myriad of competing products with images and videos—the pre-purchase consumer visceral product appearance response can now be highly comparative, detailed, and broad.

b. Besides product aesthetic form, the internet also provides a plethora of product demonstration and user evaluation videos of post-purchase competing product functionalities and usabilities.
c. Amazon, and many other online product outlets, have profuse, validated-purchase, customer ratings and commentary, with questions and answers, regarding post-purchase user experiences with specific products—good or bad functionality and usability design issues. These are often updated after several months of product use.
d. Many online product purchase outlets offer generous product return policies where products can be purchased and received within days, in most cases tried out for functionality and usability, viewed and tried first hand for aesthetic appearance and styling, and then returned, often without penalty, and with free shipping if the products are not satisfactory. In many cases, products can even be “rented” at a reduced fee for a reasonable period, with an option to purchase.
e. Some product outlets, with slogans such as, “try before you buy," let you rent products to try them first so that the ultimate product purchase is “right” for the consumer (SafeFire, 2021). Outlets such as these have several “test” products that can be rented for a reasonable fee and tried out before purchasing, with no obligation to buy.

A User/Reflective Focus. Because of this so-called “Amazon Effect," more and more pre-purchase consumers can now virtually “see” and “try out” products prior to purchase, and even after buying, physically evaluate the product prior to a permanent commitment. This opportunity also includes a multitude of user information regarding product durability and long term performance, including pricing and material information. In addition, nearly all product user manuals are now available free online for review and download. Most all of this information is about product functionality, usability, and durability, and, interestingly, little about product aesthetic form and appearance, which can be easily seen and evaluated viscerally from a plethora of product images.

Though product aesthetic appearance and beauty remain of high importance to the human experience, this situation shifts the human aesthetic need from a visceral immediate “cosmetics/styling” response, to more of what Norman (2013, pp. 49-55) calls the reflective mode, which he feels is the most important for the designer to design for—product intelligent reflection after the visceral (styling) and behavioral (usability) modes. Thus, it may no longer be as critical to visually “style” and “brand” product appearance for a pre-purchase consumer influence to buy, but to design primarily for product understandability, functionality, usability, and durability in Norman’s reflective mode, and what Harper (2018, pp. 1-4) calls sustainable and durable (and responsible!) product form and aesthetics. This is a long-needed move from what Papanek (1970), Rams (1984; Klemp, 2020), Packard (2007 & 2011), and Norman (1999) have passionately implied as dishonest and irresponsible design.

2.3. Product Design Education

2.3.1. Separate Education Silos

As Brezing and Löwer (2008) indicate, the two-silo paradigm for product design and development is problematic—and on both sides: engineering and industrial design (Warell, 2001, p. 5). Brezing and Löwer (2008) claim that the root of this problem is a common educational lack on both sides, leading to each being unaware of the other's expertise, motivations, and rewards (Wilgeroth & Stockton, 2009). They propose an integrated education system where at least the overlapping subjects that both are involved in would be taught to each. Whether or not this will ever be done is questionable, however. It is still rare for industrial design schools and engineering schools to collaborate, let alone teach common content and skills.

Even at some of the best global schools of both industrial design and engineering design, the approaches taught in their respective curricula significantly add to a dysfunctional scenario (Jiang & Ye, 2013; Norman, 2018). Industrial design students are taught a certain approach that has little or no systematic approach to solution resolution. They are given design briefs that are very open-ended (Brezing and Löwer, 2008). On the engineering side, students have overly defined design briefs that already presuppose a final solution direction and only need specifications to be resolved (Warell, 2001, p. 6; Dieter & Schmidt, 2012). Both of these approaches lead not only to conflict and dysfunction between the two groups, but often bad design in the end as well (Evans et al, 2009).

Ms. Kostellow (Hannah, 2002, p. 26) properly states that design form should be taught in a systematic and organized manner. Elam (2011, p. 5) claims that many design ideas and concepts suffer because the designers did not have an understanding of the visual principles of geometric composition: proportion, golden ratio (Bejan, 2009), and other relationships (Dondis, 1973). As a design teacher, she seems to blame the education of these designers. It is therefore no wonder that there is conflict between industrial design and engineering design in developing new products.

2.3.2. Artistic Limitations

Alexander (1971, pp. 5-11) expresses key insights in his book that highlight the problems of both industrial design and engineering design education. Regarding mathematics and traditional [industrial] design practitioners, he says, “The very frequent failure of individual designers to produce well organized forms suggests strongly that there are limits to the individual designer's [mathematics] capacity." He further states, “The introduction of mathematics into design is likely to make designers nervous," and that designers are “naturally rather skeptical about the possibility of basing design on mathematical methods," though, “modern mathematics deals at least as much with questions of order and relation as with questions of magnitude.” He goes on, “Logic, like mathematics, is regarded by many [industrial] designers with suspicion. Much of it is based on various superstitions about the kind of force logic has in telling us what to do.” He says, “[Industrial] designers turned instead to the authority of resurrected ‘styles’.” Finally he states, “The modern designer relies more and more on his position as an ‘artist,’ on catchwords, personal idiom, and intuition," and “he hides his incompetence in a frenzy of artistic individuality.” Bürdek (2015, p. 121) briefly agrees: “the practice of design could not rely on creative or clever designs.”

2.3.3. Engineering Deficiency

Regarding engineering, Alexander (1971, p. 11) is brief, but devastating: “What is worse, in an era that badly needs designers with a synthetic grasp of the organization of the physical world, the real work has to be done by less gifted engineers, because the designers hide their gift in irresponsible pretension to genius.” (emphasis added).

It is clear that all engineering of physical objects results in forms that have inherent aesthetic qualities regardless of purpose. Therefore, engineering designers must naturally consider aesthetics in their design process. Unfortunately, common current practice is for aesthetic external product form to be separated from engineering design to specialists—generally to industrial designers (Warell, 2001, p. 5). This approach involves product risk. A better way is for engineering designers to execute product designs in a holistic and singular effort themselves. To accomplish this better way of holistic product design, engineering designers must be educated in the principles and methods of aesthetic form-giving (Ashford, 1969, p. 12).

Sadly, engineering schools generally have little or no education or training in product aesthetics and form design (de Vere, 2009; Faste, 1995; Dresselhaus, 2016, p. 71), let alone holistic comprehensive product design. Many engineers are not exposed to, and thus perhaps do not become interested in, these areas due to their engineering “tutors” and due to contemporary engineering education (Ashford, 1969, p. 1). In addition, industrial design schools often “lock out” engineering students from their product design courses due to either not enough class space for such “engineering non-designers," or the excuse that “engineers cannot sketch.” Conversely, industrial design students either do not have adequate STEM training in their curricula (Brezing & Löwer, 2008), or cannot take engineering courses due to their lack of ability or background in mathematics or science. Few industrial designers have had courses in fundamental mathematics, science, physics, or chemistry, often needed for the proper and precise design of UTPs (Bürdek, 2015, p. 7; Evans et al, 2009).

However, many engineers and engineering students have both the desire and the capabilities to learn and apply aesthetic product form design and many industrial design activities quite successfully (Dresselhaus et al, 2018). Such engineers, due to their STEM training and knowledge, are potentially capable of doing at least as well, and even potentially better, at these activities than many industrial design students and practitioners. Properly trained and motivated, such “hybrid engineering product designers” (HongIk University, 2016), would be especially fit to adequately and expertly design entire engineering UTP systems in a holistic manner. To accomplish that vision, a clearly defined form design language and method specifically for engineering design is needed, and should be coupled with an educational program for product aesthetic form design for engineering students and professionals via university courses and/or workshops, books, or seminars (Wilgeroth & Stockton, 2009).

2.4. Industrial Design

This project is primarily about engineers being empowered to carry out the core aesthetic and form-giving activities normally executed by industrial designers—and to do that within a holistic and integrated engineering product design discipline. It is incumbent for this project, then, to raise some of the issues as to why these industrial design activities not only should, but can be, better executed by engineering product design, at least for engineered UTPs.

2.4.1. Emergence

Industrial design first emerged in the USA in the early 1920s, gained momentum in the 1930s, and continues to this day (Coates, 2003, p. ix; IDSA.org, 2021). Bürdek (2015, p. 12) indicates that industrial design as a discipline emerged in Europe in the 1940s. There is a sub-discipline of industrial design that is termed “product design," though is not the same, nor is as comprehensive, as engineering product design. Some authors, such as Bürdek (2015, p. 7), wrongly equate industrial design identically with product design. Product design is actually among other industrial design sub-disciplines designated such as “transportation design” and “entertainment design” (Dresselhaus, 2016, pp. 43 & 45). King and Chang (2016) imply industrial design is now about user experience design, where IntroBooks (2018) states it is only about product design. Some even say that industrial design is dying as a discipline (Ashford, 1969, p. 1; Design News Staff, 2009).

Product design has been around ever since humans started making things (Bürdek, 2015, p. 17). Humans have been designing “products” for millennia—tools, utensils, vehicles, weapons, machines—the list is almost endless. These were designed and created by a variety of actors—craftspeople, engineers, carpenters, masons, farmers, soldiers, ceramicists, warriors, artists, scientists, and many more—by “ordinary” people, by tradespeople, and by various professionals. But a concerning trend is to equate industrial design with product design, as Bürdek does. This is quite unfortunate since it is contrary to actual history and practice. But it does reflect an effort by some industrial design academics, historians (Gorman, 2003), theorists, and some industrial design writers and film makers (Hustwitt, 2009), to attempt to capture the whole of human object making history as “owned" and executed by industrial design. In contrast, product design has been done by many, many different types of practitioners and actors throughout history, whereas industrial design only came on the scene in the early to middle twentieth century (Bürdek, 2015, p. 18; Coates, 2003, p. ix).

2.4.2. Application

Historically, industrial design has generally, and often exclusively, dealt with external aesthetic form-giving and visual “styling” of products, primarily for consumer products (Coates, 2003; Papanek, 1970; Warell, 2001; Bürdek, 2015). Prior to industrial design's emergence, engineers were the primary product form-givers, both physically and aesthetically (Baynes & Pugh, 1986), but have since generally abdicated that role to industrial design (Ashford, 1969, p. 1). In the past, industrial design also dealt with such graphical issues as corporate identity (Bruce, 2007; Bürdek, 2015, pp. 18 & 193), but this has since been generally passed on to graphic, branding, marketing, and media disciplines.

A common use of the term "industrial design" has been to signify that part of product design that deals with external product aesthetic visual form. It is not uncommon to hear comments like "…the industrial design of a product…," to mean the visual aesthetic "styling," or the external form appearance of a product. To assign the term "industrial design" to such a common activity as aesthetic form-giving to objects, quite often executed by a broad-based set of creators, is unfortunate—it seriously biases and inhibits that activity by others who are not "bonafide" industrial designers.

Industrial design practitioners, as part of their professional activities, frequently also claim to address a number of other product design issues such as usability, manufacturing, ergonomics, etc. (IDSA.org, 2021; Cuffaro et al, 2013). Industrial design education commonly trains its adherents in the disciplines and skills of art, aesthetics, design sketching, aesthetic organic form, and some materials and manufacturing, but with little deep STEM education. However, whether or not such "non-aesthetic" design activities happen to be done by industrial designers or not, they are not unique to the industrial design discipline, regardless of any propaganda to the contrary, since many other actors are also capable of, specifically trained in, and routinely execute, such work. These are engineers, architects, technologists, and graphic artists, to name a few. Though some industrial designers at times can and do contribute to product design in these technical ways, these "non-aesthetic" design contributions are often inappropriately claimed by them, or at least implied so, as in design competition credits. Engineers in particular can contribute competently in many non-aesthetic form-giving areas such as technology, usability, ergonomics, manufacturing, and functionality, among others. Likewise, many architects have for generations been excellent technical product designers (Joshi, 2017; Bürdek, 2015).

2.4.3. Form

Industrial design has long focused on the external form of products for the purpose of marketing and sales—to entice consumers to buy and consume (Papanek, 1970; Packard, 2011; Slade, 2007). Too often this design mentality leads to inefficient OPF designs that have little bearing on functionality or usability (Hannah, 2002). Though there have been a number of highly talented industrial designers using GPF based design over the years (e.g., Brunner/Lunar, Rams/Braun, Esslinger/Frog, Moggridge/ID2, Nuttal/Matrix, Vassoughi/Ziba, Sottsass/Olivetti, Ive/Apple, Dyson/Dyson, and others), many of whom are European, they are few compared to the total number of industrial designers graduated from many industrial design schools. Few of these graduates could compare to these industrial design "greats." In contrast to these celebrated industrial designers, who mostly executed GPF designs, industrial design today seems often to prefer an OPF approach (Liu, 2013).

A common mentality of many industrial designers is a requirement for uninhibited "artistic freedom" and a resistance to prescribed or formulaic aesthetic product form-giving methods (Alexander, 1971, p. 11)—there is even resistance to engineering design, often seen by industrial designers as a limiting factor to product design creativity and innovation (Esslinger, 2013, p. 5; Kahney, 2014, p. 149; Hustwitt, 2009). It seems the requirements of engineers, who have a clear design process (Brezing & Löwer, 2008), and the need to "obey" the laws of physics and mathematics, irritates many industrial designers and their "creative freedom."

2.4.4. Education

Industrial design education in America was heavily influenced by the Pratt Institute (2020) program developed by the Kostellows (Hannah, 2002, pp. 16, 20, 24, & 34), and subsequently adopted in most industrial design schools in the USA. This approach was based on Ms. Rowena Reed Kostellow's philosophy of abstract form design. She and her husband created the prototype American industrial design program and philosophy at Pratt, and it became the standard by which most industrial design schools in America followed. This approach tended to move the American version of industrial design education into more abstract organic product styling. For example, Akner-Koler (2007) continues to pursue this approach of abstract organic form development and analysis for industrial design. However, a few American schools followed the Bauhaus approach, as did many European industrial design schools, where a pragmatic "form follows function" philosophy was more predominant (Droste, 2019; Bürdek, 2015, pp. 27-37).

The Kostellow form design philosophy seemed more "form over function," or even abstract "form without function." Ms. Kostellow taught that form could and should be taught and executed irrespective of function. This author's own mentor at the Stanford University Product Design Program in the early 1970s, Robert H. McKim (1980), was educated by Ms. Kostellow at Pratt before he received his mechanical engineering degree at Stanford. He personally told this author that he eschewed the traditional (American) industrial design approach. In Europe, it was the Bauhaus (Droste, 2019) that drove much product design philosophy, and this was primarily based on an architectural form design approach, with an integration of crafts and manufacturing influence. Ms. Kostellow (Hannah, 2002, p. 26-29) tended to discount the "form follows function" principle, whereas the Bauhaus leaned significantly toward a rectilinear architectural and geometric form language.

Ms. Kostellow did rightly feel that design form should be taught in a systematic and orderly manner. Her hierarchy of three form levels is one of the few key principles gleaned from her for this project. Her abstract aesthetic form exploration approach is also valid, but to a limited extent. This project expresses a level of abstract geometric form development as well, but is also coupled directly with a relationship to real world products. Ashford (1969, p. 11) strongly says that a product external form must clearly be driven primarily from its internal anatomical structure and functionality, as do Alexander (1971, p. 15) and Tjalve (1979). Likewise, Alexander (1971, Preface & p. 16) felt separating form study from form context was absurd—design form cannot be divorced from reality of product context.

2.4.5. Process

As Brezing and Löwer (2008) point out, industrial design is a discipline apparently without a clear definitive process, or a clear objective core—this can be verified by simply perusing a number of American industrial design school curricula to see the broad variation (and inconsistency) of courses and requirements between different schools. In addition, it is a discipline with a perception by much of industry as product "appearance stylists" and "making products look pretty" for compelling sales—a discipline that frequently overstates it breadth of competence (IDSA.org, 2021). A better organized, informed, and clear process-based discipline is needed—this project claims that should best be within engineering product design.

Many industrial design papers indicate that a systematic product form design method is possible and needed (Tjalve, 1979; Coates, 1995; Ashford, 1969; Ali, 2014; Bürdek, 2015, p. 109). However, few industrial design academic research papers prescribe a definitive product design form language or execution method with specific elements (Yang et al, 2011). Tjalve (1979, p. 8 & the entire book), Rams (1984), and Coates (2003, Chapter 11) do present such an approach. But they touch only briefly on using a specific geometric-based language and method for product form design. Quite definitive prescriptions of language and method are from architecture (Ching, 2014), graphic design and art (Elam, 2011; Dondis, 1973), drawing (Edwards, 2012), and engineering (Budynas & Nisbett, 2019), among others. Few, if any, prescriptive form methods come from industrial design, apparently due to an apparent aversion to definitive methods that inhibit "creative freedom" (Alexander, 1971, p. 5).

For one example, the Ali & Liem (2014b) paper has numerous analyses and principles described by others, such as the golden ratio (Bejan, 2009), and other mathematical principles. There are many statements in the paper about using geometric principles for design language, but also warning against them as a prescriptive risk. Contrary to the paper title, *The Use of Formal Aesthetic Principles as a Tool for Design Conceptualization and Detailing*, there is not any use of aesthetic principles to create anything, let alone any product concepts or details—it is only analysis. This is a common scenario of many academic industrial design form research papers—lots of analysis of existing products and claims of a form language method that can be applied to form creation, but little or no actual concrete product application (Evans et al, 2009; Crilly & Clarkson, 2006; Eves & Hewitt, 2009; Hsu et al, 1999). In consequence, with some exceptions, few of these academic papers and articles are utilized as foundational for this project.

It seems industrial design research has for some time been struggling to find a "holy grail" of aesthetic product form design language and method (Zhu et al, 2006; Wood et al, 2011; Crilly, 2005; Hall et al, 2018; Lopes de Castro & Vicente, 2018; Akner-Koler, 2007). But much of that work is about ways to analyze mostly existing product design forms, and to determine principles of general form language and terminology. However, perhaps due to a penchant for eschewing anything close to a prescribed design form creation method as being "artistically limiting” (Alexander, 1971, p. 11), few, if any, demonstrate definitive form methods. They primarily have a profusion of text and narration about form applications, references to established form design principles, a plethora of tables of forms and numerical data, many complex process or “method” diagrams and graphs/charts, form analyses of existing products, and sophisticated articulation of aesthetic form theory. But providing practical, clear, real-world application of these is often absent (Eubanks & Schaeffer, 2008; Eves & Hewitt, 2009; Crilly & Clarkson, 2006).

The question also arises whether practicing industrial designers actually apply these academic design research paper results to their product design work. Bürdek (2015, p. 8) claims that academic design research papers have had little or no effect on design practice. In his seminal book, *Keep It Simple: The Early Design Years of Apple* (2013), illustrated profusely with outstanding GPF work, Hartmutt Esslinger rarely, if ever, refers to any academic design research as a basis for his work or its inspiration. He consistently mentions specific companies and designers as his inspiration—e.g., Olivetti and Ettore Sottsass (Morimiya, 2018), Braun and Dieter Rams (Klemp, 2020), and Sony (Kunkel, 1999). In the documentary film on industrial design, *Objectified* (Hustwitt, 2009), rarely do any featured designers cite their inspiration or design basis as any academic design papers or research. In the documentary film, *Rams* (Hustwitt, 2018), about possibly the most influential industrial designer of the twentieth century, Dieter Rams never mentions that the inspiration for his (very geometric) product design work is any academic research, paper, or work. Finally, this author’s personal experience of working with highly capable industrial designers and design firms for many years has been rarely, if ever, included hearing them refer to any design research or academic paper as a design basis or inspiration for their work.

2.4.6. Challenges

Few industrial design form language or method research papers address the design of sophisticated engineered UTPs, or demonstrate how the research results of a paper can be applied to create the forms for such technically complex products. Most academic industrial design research papers are based on relatively simple product systems: hair dryers (Ab Hamid et al, 2013; Ferraris & Gorno, 2013), abstract sculpture (Akner-Koler, 2007), dinnerware (Babapour et al, 2014), fruit bowls (Babapour & Rahe, 2013), toasters (Corremans, 2008), existing running shoes/ cookware/speaker system (Hoegg & Alba, 2011), or already existing technology products that are simply “re-formed,” “re-shaped,” “re-styled,” or analyzed as they currently exist, such as telephone systems (Hsu et al, 1999). One of the few and rare examples of actually creating a new product form from the “ground up," for a highly technical UTP design based on an actual prescribed functional, structural, configurational, and architectural method, is presented by Tjalve (1979, Chapter 5).

2.4.7. Visualization

The book *Presentation Sketching* (Eissen & Steur, 2014) is an example of the questionable nature of much contemporary industrial design education and practice. It is also an example of why engineering product designers are unfortunately intimidated by the profuse sketching approach of industrial design. Though there is much good visual work in this book, there is also a plethora of examples of the intense illustrative style of industrial design sketching and presentation. And that is the concern—the "dramatic" approach presented can be deceptive. It is an approach potentially detrimental to good product design and development that is far too common in industrial design education and practice. It is an approach that places the sophisticated, illustrative, and "realistic" industrial design sketch as too often primary in both defining a design intent and presenting it to clients (Hoftijzer et al, 2018). This approach assumes that two-dimensional, often exotic and dramatic, illustrative, and well-crafted sketches can adequately develop and present a total product design, even to the point of deciding it is the "right" final solution!

This approach assumes that a product's design can (and should?) be primarily, if not solely, developed and presented via sophisticated and dramatic two dimensional visualizations and sketches. This is often done even before adequate engineering analysis and input, and is for the premature validation of the viability of the design and its marketability to clients and stakeholders. This highly questionable approach is promoted and taught in many industrial design schools. Even the best of two dimensional visualizations and sketches cannot possibly adequately convey a product design heft, feel, size, form, tactility, and many other critical physical/sensory factors. Only going to 3D means, such as CAD and physical models can these sensory factors of a product's design be properly validated for their usability, ergonomics, and marketability (Rams, 1984; Ulrich et al, 2020; Ashford, 1969).

There is perhaps a clue to this unfortunate approach, at least for this book. The primary psychological premise that the book is founded upon is a discredited brain theory. The foundational principle of the book is the "three-brain" theory, including the so-called "reptile brain" (Chapter One). This theory has been discredited and is no longer viable in brain science or neurobiology (Thomas, 2012; Toker, 2018; Rozsa, 2020)—yet the basis of much of this book is founded on this false theory.

2.5. Architectural Design

Historically, ever since industrial design first emerged on the scene in the 1920s in the USA, the common paradigm in product design and development has been the collaboration (or lack thereof) between industrial design and engineering design (Brezing & Löwer, 2008; Warell, 2001). The debate about their respective roles and the issues regarding their cooperation has been ongoing to this day. This binary, two-silo system of essentially visual designers versus engineering designers has yet to be resolved (Brezing & Löwer, 2008).

In this project exploration of foundational principles for a potential engineering product design form language and method, significant relevant work has been found in architecture (Ching, 2014, 2019, & 2020; Elam, 2011; Bass, 2019).

Rather than industrial design being a reference model for product design form language and method, it may be that architectural design is a more relevant model. There is a strong case to be made that it is architecture and architectural design, not industrial design, that is the better discipline for an understanding and inspiration for engineering product design, and specifically for product form design. It has historically been architecture that has driven form design for millennia, not industrial design (Bürdek, 2015, pp. 24, 202-216)!

Following are reasons why architectural design may be a better holistic engineering product design reference/inspiration model.

2.5.1. Total Approach

Architectural design must not only deal with the outer form of a building, it must also deal with the interior layout and space issues as well (Ching, 2014 & 2020) —addressing many of the same issues that a holistic engineering product design effort must. For buildings, as product designers do similarly for products, architects deal with:

a. both the inside and outside space and configuration,
b. the overall mechanical structure,
c. the human-centered ergonomics and usability,
d. the inside and outside form and aesthetics, and
e. many material and construction details.

Sullivan's "form (ever) follows function" was derived from his idea that a building's exterior form must be reflective of its interior functions (Sullivan, 1896). Building architects routinely work out the layouts and plans for a building's interior in parallel with its exterior form—they must be mutually complimentary. There is rarely such work done by industrial designers for product design—industrial designers provide the exterior aesthetic form design "intent" (with sketches, renderings, drawings, and/or surface models), and engineers take that intent and attempt to provide both the product final exterior and the interior design and structure to conform to it in engineering CAD modeling (Shih, 2019). Rarely do industrial designers deal with the interior design and details of products.

A product design architectural model is that products are simply like small "buildings," all needing similar issues addressed as architectural buildings do. The biggest difference besides the size factor, is that products don't have people living, working, or engaging inside them—they have components in them. But all of these components require space, order, form, proportion, relationships, access, and technical issues, and more, just as buildings with people in them do.

2.5.2. Education.

Global architectural design curricula generally include, due to a nearly universal educational standard, courses in STEM topics, such as basic physics, mathematics, geometry, and materials. This is so that architecture students may be prepared to apply their knowledge to the technical design issues they are required to work out for a total building design (Ching, 2020). To the contrary, industrial design product design programs rarely have such STEM courses, since they are often in art schools, and are thus not prepared for the technical issues of product engineering.

Architects must also deal with the basic issues of a building, such as heating, lighting, ingress/egress, maintenance, structure, access, construction method, materials, etc. (Ching, 2020). They need to use the STEM knowledge they learned in college to at least address these functional issues at an adequate level to provide to the building and construction engineers and specialists. In contrast, their claims notwithstanding (IDSA, 2020; Cuffaro et al, 2013), industrial designers rarely learn to address such issues in product design, such as internal structure, component configuration, cabling, thermal management, optical systems, interconnection, etc.

Granted, the disciplines of architecture and engineering, though often in the same university, and even in the same colleges together, do not always, and perhaps seldom, work closely together in product design. But in the case of engineering design and industrial design, these two disciplines are generally separated in the university by being in two different schools altogether—the art school and the engineering school. And, due to this, are also often separated by completely different curricula, educational goals, and philosophy—even by physical distance. Not a great scenario for education in collaborative cooperation.

2.5.3. Design Details

Most young graduates in architecture who go into practice will most likely work for a large firm and start by creating detail drawings of buildings and designs, either manually, or via CAD. They generally do not start with overall building form design, which is often done by company principals. They usually must work out the many details of the building construction, both interior and exterior, creating many cross-sectional detail drawings. Thus, architectural design is not just about the overall outside building form delineation—it also is about details of very specific issues of joinery, interaction, intersection, materials, fastening, ornamentation, etc. (Ching, 2014 & 2020). In contrast, it is seldom that product industrial designers deal with the details of the interior spaces, components, and elements of products—these details are generally left to the engineers to deal with. Industrial designers most often only deal with the exterior aesthetic design intent of a product.

2.5.4. Design Drawings

Most architectural design drawings and sketches created for engineering and building construction are in orthographic mode, including many detail designs and cross sections representing a total project design (8.3. Figure). Pictorial renderings, though valuable for client viewing and marketing, are not as useful to the engineers and construction specialists who must build the building. Even many architectural aesthetic form drawings and renderings are also done in orthographic mode since it is the most easily understood and dimensionally accurate for the builders and engineers to understand (Ching, 2020). Architectural design sketching style is also simpler and more geometric than industrial design—much more adaptable to geometric product form design for engineering product design (Drazil, 2020; Ching, 2019). In contrast, much industrial design product form renderings are in pictorial mode, which is beneficial for marketing, branding, and sales, but often useless for product engineering (Liu, 2013).

2.5.5. Practitioners

It should be noted that many trained as architects have also been outstanding product designers in their own right—Rams, Noyes, Eames, Hadid, Graves, Starck, to name a few (Gorman, 2003; Joshi, 2017; Bürdek, 2015). Much of modern product design functionalism was influenced by the German Bauhaus—a school based much on architectural design and founded by architects (Droste, 2019; Bürdek, 2015, pp. 27-37). Its architecture and graphics were strongly geometric in form. Architect Louis Sullivan's (1896) phrase, "form (ever) follows function," is a term that is often applied in product design. It was Sullivan's famous student, the primarily geometric form architect, Frank Lloyd Wright, who said "form and function are one" (Gorman, 2003, p. 190). Dieter Rams (1984), perhaps the most celebrated and influential industrial designer of the twentieth century, was originally educated as an architect—and nearly all of his designs are purely geometric (Klemp, 2020). The famous craftsman architects (with mostly geometric form), Green and Green (Makinson, 2002), not only designed incredibly beautiful homes with many geometric features and elements, also designed products such as furniture and lighting fixtures for those same homes.

2.5.6. System Integration

Architects essentially act as building system integrators. They work out the form, aesthetics, and general design details of a building, and integrate all of these aspects required for a total design. However, the building engineers and construction specialists work out the final execution of the technologies necessary for the completion of the whole integrated system. Likewise, engineering product designers work out the aesthetic form and configuration of components, elements, structure, and technologies for a product (Ulrich et al, 2020; Dresselhaus, 2016, p. 11), but engineering specialists invent and design the specific technologies and components for a product (Budynas & Nisbett, 2019; Dresselhaus, 2016, p. 12).

2.6. Engineering Product Design

All physical objects inherently have a form, regardless if geometric or organic, or whether attractive or not, by simply existing (Tjalve, 1979, p. 3). Long before industrial design came on the scene, it was engineers and architects that were the primary form-givers of physical products and buildings (Baynes & Pugh, 1986; Bass, 2019; Ashford, 1969). Therefore, it would also follow that the ultimate purpose of engineering design is engineering form, and the ultimate purpose of engineering product design is product form. Engineers routinely create many kinds of forms for a variety of physical entities in their work (Ashford, 1969, p. 2). Consequently, Ashford (p. 1) is adamant about the essential role and need of attention to aesthetic form design in engineering. He has a disdain for the reality that engineering has long since relinquished its responsibility for what he calls the inherent human aspects of engineering to the discipline of industrial design. He places the blame for this squarely on engineering educators and professional organizations, and for denying young engineers training and enlightenment in this human-centered area. In the end, he claims, these inadequately trained engineers will continue to create product form aesthetic problems to be cleaned up by [industrial design] specialists.

Ms. Rowena Reed Kostellow (Hannah, 2002, p. 42) says the primary role of the designer is form-giving. Alexander (1971, p. 15) agrees: “The ultimate object of design is form." Form-giving is a fundamental and universal activity of virtually everyone and anyone who creates a physical object—all physical objects have an inherent form simply due to their existence. However, it has been the claim of industrial design as being the unique “aesthetic form-givers” in the world of product design (Hannah, 2002, p. 34). But other design practitioners, such as architects, graphic artists, and engineers, have also provided aesthetic form to products as well (Baynes & Pugh, 1986; Koenig, 2015). Engineers, therefore, due to their prolific creation of physical objects and their inherent forms, are form-givers as well.

In contrast, unfortunately feeding the frequent industrial design bias against engineering (Esslinger, 2013, p. 5), engineering designers are all too often overly concerned with product technical factors, functional performance, and manufacturing issues, to the neglect of product human factors, human needs, and aesthetics (Ashford, 1969, p. 7; Warell, 2001, p. 11; de Vere, 2009). Though engineering product designers generally have the better technical position over industrial designers due to their extensive STEM education, they have relinquished a natural responsibility for the human side of product design—engineering design and its education has allowed industrial designers to control and dominate the aesthetic form-giving aspect of comprehensive product design (Ashford, 1969, p. 1; Warell, 2001, p. 12).

Faste (1995) says that engineers too often think that surface aesthetics can be cosmetically applied after the engineering design is done to make a product look attractive. This must change. He indicates that the world needs to be more integrated and that engineers must realize that if they are applying science to product design, then aesthetics is a natural and required intrinsic consideration (de Vere, 2009).

Since product designs are requiring more technical usability, high technology, and long-term durability in sustainability, function, and aesthetics, engineering product designers, properly trained, can be optimal comprehensive product designers. There are also a multitude of product development scenarios where industrial design is not necessary, not affordable, or not available. In these quite common situations, where engineers are already on a development team, a hybrid engineering product designer should be able to adequately execute a product’s aesthetic form, as well as contribute to the engineering design and technology development of the product—a dual value proposition that industrial design generally cannot provide.

2.6.1. Changing the Paradigm

There are two directions for potentially resolving the conflict between engineering design and industrial design (Brezing & Löwer, 2008):

a. more silos (sadly, they already exist as marketing, sales, manufacturing, purchasing, etc.), or
b. a single discipline to accomplish both product aesthetic form design and product engineering design in an integrated holistic manner.

Considering the latter solution, these are the essential issues for this project: the what, the how, and the who, for a single-discipline, comprehensive engineering product design process and discipline, including a form design language and method that includes integrated product aesthetic form and product engineering.

The issue for this project is not the value of product aesthetic form—this has been well validated (Hannah, 2002; Esslinger, 2013; Bürdek, 2015; Tjalve, 1979; Harper, 2017). The question is when should it be properly and appropriately defined within the total product design and process (Dresselhaus, 2016, p. 10)—and created by what actors? This project proposes a specific framework that identifies both the time and means for creating functional, ergonomic, and attractive product forms by engineering product design.

The overarching aim of this project is to provide a framework of design and education for capable and interested engineering designers to be able to competently execute the key important aspects of traditional industrial design activities by themselves, along with product engineering, as it should be. And perhaps do this even better than industrial design, due to engineering's inherent STEM training. Industrial design may continue its professional path however it desires, but the need for engineering product design to also be able to do much of the same work, without bias, prejudice, or resistance, or even prohibition, is also important to this project outcome and results.

2.6.2. Empowering Engineers

Since the primary task of design is form-giving, and that engineering designers are clearly form-givers, there is an important question to be answered for engineering design: what is, if any, the optimal method to properly and comprehensively design human-centered UTPs, and, especially for this project, their product form design language and aesthetic appearance? This is a not a question for industrial design, which is too often inadequately prepared to deal with the more technical aspects of designing UTPs (Brezing & Löwer, 2008). The issue is about empowering engineering for the task of aesthetic UTP form design without depending upon industrial designers.

But why address this project specifically toward engineering design and not toward industrial design? The best answer to this is from Ashford (1969, pp. 3-4):

> "…the human aspects of engineering design, principally the aesthetic and ergonomic, have somewhat regrettably become more the concern of others than of the engineering designer…," and "[Product] aesthetic and ergonomic quality is inseparable from functional and material decisions," and, "Those aspects which have tended to be lumped under the designation of 'industrial design' are, of course, normal and natural aspects of engineering design, and they have been so since time immemorial."

With the current business emphasis on design as a competitive advantage, even in non-consumer industries where engineers dominate the functional and technological side of product form-giving, it would be expedient to include aesthetic form design language and method education for engineers. In most companies, engineers far outnumber industrial designers, if the industrial designers are there at all. Having aesthetically trained design engineers, even if only a few are specialized in product aesthetic form execution, would be a great asset for a company in both design efficiency and productivity. The common scenario of hiring internal industrial designers to work for only short periods on projects, or engaging outside industrial design services, can be an expensive proposition (Ulrich et al, 2020, pp. 217-218).

2.6.3. The Art of Engineering

To quote Ashford (1969, p. 2), "Engineering is an art, with a history as long as that of any other art and with an equally illustrious roll of practitioners." He goes on to say that, "This is also validated by the history of architecture where the creators of the great cathedrals and ancient edifices were both acting as engineer and architect." The book, *The Art of the Engineer* (Baynes & Pugh, 1986), also validates the incredible artistic talent and training of past mechanical engineers and engineering designers.

Sadly, Alexander (1971, p. 11) says that we must unfortunately often depend on product designs created by less qualified engineers due to the arrogance of industrial designers and their pretense of artistic genius and lack of STEM education. Part of this problem is also identified by Faste (1995) where, on the engineering side, he indicates that engineers often lack confidence in making aesthetic judgements. But he adds that everyone, including engineers, must make aesthetic judgements about the world simply to survive. He also proposes that since everything engineering design does affects product aesthetics, engineers must realize that aesthetics affects the overall quality perception of the products they design.

Therein is the very purpose of this project—to "gift" those so-called "less qualified, educationally deficient, and aesthetically hesitant" engineers with a logical, simple, rational approach to product form design. It is an aim of this project that in some small way it will help in returning a portion of that lost enlightenment, education, and inspiration for the human aspects of engineering design that it properly should be responsible for and execute competently.

2.6.4. "Beautiful" Engineering

Ms. Rowena Reed Kostellow (Hannah, 2002, back cover & p. 16) stated her apparent mantra, "If you can't make it more beautiful, what's the point?" Unfortunately, this attitude drove the industrial design external product "styling" mentality in the USA for decades. However, in a certain but different sense, engineers might relate to this mantra, but on many levels and applications. Quite often, to engineers, something is "beautiful" that is dimensionally precise, or easy to assemble, or easy to repair, or functions flawlessly, or works beyond expectations—a precision mechanism, a "prefect" snap latch, a no-tools/no-fasteners flawless part assembly, a smoothly performing piece of software, and many others.

Even ordinary users rave over easy to use consumer products (Lupton et al, 2014)—to wit, the Apple Macintosh hardware and software systems (Kahney, 2014). Norman (2013, p. 54) describes research in which was found that "beautiful" products that were attractive and easy to use actually were perceived to work better than unattractive products. Thus, quite often, the term "beautiful" is used to describe any product that works well, functions flawlessly, goes beyond expectations, is incredibly easy to use, assembles or repairs easily, lasts a long time, and such attributes. Consequently, it is possible that Jeff Smith (Dresselhaus, 2016, p. 56) is on the right track with his, "form follows everything," in that everything can be, regardless of purpose or function, deemed "beautiful" when designed with care and elegance.

2.6.5. Design Leadership

Faste (1995) expresses the view that engineering designers will be the best to lead in the future. This author's Stanford mentor, McKim (1980), agreed. Faste similarly supports the view that a synthesis of art and engineering is required for optimum product design. Further, he claims that engineers with such an integrated holistic education will be the best technology leaders of the future. On another up side, Faste also makes the case for engineers learning and applying aesthetics in their work as vital to innovating fast-changing, new technological products. He emphasizes that engineering creativity is intrinsically linked to aesthetic sensitivities and capabilities. He claims that part of the reason for a lack of aesthetic awareness and training in engineering is that engineering and its education has become too "scientific"—too much like applied physics, rather than focused on solving human-centered problems as it once did (Sheppard et al, 2008; de Vere, 2009).

2.7. Product Design Form

2.7.1. Product Design Language

Product language is the visual manner in which a product communicates value, usability, function, and aesthetics to a user (Coates, 2003, p. 9; Parmar, 2016; Krippendorff, 2006; Bürdek, 2015, p. 83). A principal contribution of product form design is providing this functional language (Raghubir & Greenleaf, 2006). Leborg (2006, p. 5) says a language for something helps people think differently about it.

Dondis (1973) provides an entire book about visual language and its effects on art, architecture, and design.

Language has great power, and it is so for product form design language. Coates (2003, p. 2) says product forms are essentially vehicles of communication—they exhibit a product language—they are literally media. Norman (2013, p. 14) states that products should visually communicate how a product should be used, or clearly what affordances and functions it offers the user. Di Mari and Yoo (2013, p. 8) state that design language can invoke form, and that a systematic design language framework has an effect on spatial character and essence. Product form communicates a number of discoverable and understandable (Norman, 2013, pp. 67 & 72) things, like function and usability, but also inspires emotion (Esslinger, 2013) and beauty (Coates, 2003, pp. 31-33). All of these are done primarily in a visual manner, though there can also be communication from products to all the senses as well, such as sound, tactile, kinesthetic, etc. (Dresselhaus, 2016, p. 59). However, Bürdek (2015, p. 153) makes a strong case for design's lowly perceived elevation as a discipline due to its lack of "discursive" language, most of which exists as borrowed from other disciplines, and its having little "rigorous discourse."

Brezing and Löwer (2008) state that any integrated design theory "should be simple, immediately comprehensible, and compliant to common knowledge." Consequently, this project avoids using a number of terms that are commonly used in academic design literature language (Eves & Hewitt, 2009; Warell, 2001; Hsu et al, 1999; You & Chen, 2007; Krippendorff, 2006; Bürdek, 2015; Akner-Koler, 2007). They are terms not "…simple, immediately comprehensible, and compliant to common knowledge." For the sake of simplicity and understandability, this project attempts to use terms that are familiar to the engineering student and practitioner.

2.7.2. Working Form Language

In a verbal/written language, such as English or German or Spanish, there are terms such as syntax, grammar, structure, semantics, etc. But these are general descriptive terms in all verbal/written languages. Using these terms, as many industrial design researchers do relative to form design research, helps somewhat to understand product form, but does not help significantly to "speak" actual design "sentences" and product "communication" in actual product design "compositions." This seems a flaw in much industrial design form language research: frequent use of general language terms, descriptions, and analyses, but seldom any specific "speaking," with design language "words," and creating product form design "compositions," to use a verbal/written language analogy.

Common product form language terms are often confusing—esoteric terms that generally have been "borrowed" from other disciplines. These include such as: taxonomy and DNA (biology), typology (archeology), semantics (linguistics), semiotics (communications), consilience (humanities), grammar (linguistics), morphology (biology), syntax (linguistics), and pedagogy (education). However, most all of these terms are seldom referred to or utilized by many practicing designers and engineers outside of design academia. In their writings and publications (Rams, Esslinger, Ive, Moggridge, and others), and this author's personal interactions with many capable industrial designers (Vassoughi, Brunner, Nuttal, Lunar, frogdesign, and others), virtually none of them have used such terms regarding their work, except for the term, “design language." Thus, the question arises whether or not these terms are even relevant to real-world product design practice or work.

Actual speaking and writing of verbal communication and written compositions in a language requires words such as nouns, verbs, adverbs, adjectives, and prepositions. For a product form design language, only after such design “words" are determined, can they then be structured with grammar, syntax, semiotics, and semantics to make a coherent design language communication or composition of product form (Krippendorff, 2006). Actually creating specific new product form communication and compositions via a design method requires these specific design “word” elements, and not only general language structural terminology. Ching (2014) makes this case well in comparing verbal/written language and design language.

2.7.3. Form and Proportion

Besides the two-dimensional and three-dimensional aspects of form, proportion has always been a key element in many forms of design (Hannah, 2002, p. 54; Ashford, 1969, pp. 58-64). Meisner (2018), Bass (2019), and Elam (2011) make extensive explanations and descriptions of proportion and its appearance and value in architecture, art, nature, and product design, especially the Golden Ratio and its derivatives. Proportion has a very significant role to play in GPF language and design.

2.7.4. Cooking Up Product Form

Product form design can be quite analogous to the preparation and cooking of food: there are utensils, ingredients, recipes, seasonings, cuisines, and menus. In any particular cuisine, there is plenty of freedom to create many different and delicious dishes. Such is true for “cooking up” product form design—limitations and constraints only make for a challenging and creative enterprise that does not limit artistic freedom any more than cooking in a particular cuisine does.

Cooking. Food cooking has both general universal tools, methods, and principles, as well as specific cuisine related ones. In the same way, the “cuisine” of GPF design for UTPs also has good, general design processes and principles, but also the specific geometric based product form language and design synthesis process.

Language. As with the specialized language of food cooking, product form design also has its language of visual design principles and various forms and details.

Cuisine. Just as in various food cuisines (e.g., Indian, Japanese, French, Chinese, etc.), there are product “cuisines," such as consumer and industrial, and their sub-categories. Likewise for this project, engineered UTPs are a targeted product design “cuisine” for product form language and method application.

Recipes. Recipes in food cooking contain the ingredients for the recipe as well as the amounts and proportions of them, and the process recommended for cooking.

Likewise, a product form language and method would be similar, with form “ingredients," dimensions, proportions, and a composition process.

Utensils. Just as the many utensils and tools available in food cooking (e.g., knives, pots/pans, heating devices, appliances, etc.), there are a variety of “utensils” and tools for creating product form design. Among many are sketching tools and materials, mockup making and prototyping tools and materials, CAD modeling software and computers, making tools such as 3D printing and CNC machining, etc.

Ingredients. Ingredients in food cooking can be meats and vegetables of many kinds. Similarly for geometric product form design are rectangular prisms, right cylinders, other geometric volumes, and form operations, as well as the manufacturing materials for the product.

Seasonings. These enhance the flavor of a food composition. In the same way, product design edge radii, textures, color, finishes, and details, all enhance the visual “flavor” of a product form composition.

2.7.5. Converged Product Form

Many products that have the same functional aspects often seem to have converged to a specific set of functions, affordances, and signifiers that appear nearly universal across a product category. Due to this apparent function/usability convergence, many such products have also appeared to converge in form. For example, consumer level inkjet printers all have a roughly same gestalt form factor and size, and they all perform pretty much the same functions, roughly in the same manner, and in the same desktop positions: copying, scanning, and printing. The top cover is where the paper to be copied is entered, either flatbed or feeder, and the lower front center is where the copied documents emerge, with paper below. The controls are positioned in a few different places, but usually left top, right top, or center front. A simple tour of an office supplies store printer section would validate this.

The idea of product form convergence can be easily demonstrated. One can perform an Internet image search of any particular kind of product that has been around for some time and that search will generally produce a plethora of similar converged gestalt form images of the product. A search for such as sewing machines, band saws, hand power drills, table saws, drill presses, mobile smart phones, MRI machines, 4-door sedans, mid-size pickup trucks, computer displays, guitar amps, forklifts, game controllers, etc., will generally deliver images of products that have very similar gestalt forms. These images will generally show only variances of aesthetic details such as color, texture, radii, chamfers, and moderate proportional differences. Even in the case of user controls, as with game controllers, the buttons and levers to control the game are all mainly in the same positions on almost all game controllers, indicating a convergence of usability as well as of form.

Mike Nuttal, an award winning industrial designer and founder of Matrix Product Design in Palo Alto, California USA, was formerly with Bill Moggridge’s ID2 design firm. He once said to this author (Nuttal, personal communication, c. 1985), that he felt if a designer knows as much as possible about a new product design context, then there is probably only at most three overall form variations that the product form can logically take. This is why, after his thorough product context research for a new product industrial design, he would only present three product design form options to his client. By this, Mr. Nuttal validates the idea of product form convergence: if a product context is precisely known, its overall form will be "naturally" driven and determined by this context (Alexander, 1971, p. 15; Duranti & Goodwin, 1992). Varied aesthetic details and operations that retain this overall context-determined gestalt form can then be applied by the designer for product form distinction, attractiveness, novelty, or interest.

A form convergence phenomenon is also demonstrated in CAD modeling software programs. Over past years of many CAD software programs emerging with unique and different graphical user interfaces (GUIs), protocols, and formats, there are now a few major "survivors." Most of them have quite similar GUIs, and generally so-called as "contextual." These CAD software GUIs have essentially converged to a few very similar usability paradigms for creating CAD models.

This common phenomenon for product simultaneous form and usability convergence, if true, would indicate that the idea of a product designer's "creative and intuitive artistic freedom" imperative may be a risky approach, especially when taken too far. If product functionality, ergonomics, usability, and gestalt form design converge naturally and logically to only a few basic overall form options due to long usability experience in the marketplace, then designers must be ready and willing to conform to that convergence of new products and not violate it with some arbitrary "artistic license." Products in a particular functional category will tend to converge to common gestalt forms and converge to the most logical human-centered functions, functional surfaces, ergonomics, and usability. For the responsible product form designer, in the end, the job is to conform to these converged norms of form and ergonomics in the best way possible without disrupting them with arbitrary branding and styling novelty.

In the end, all of this tends to indicate that, when a product total context is fully and properly considered, the product, in a significant way, "designs itself."

2.8. Form Follows What?

2.8.1. Form Follows Something!

It is apparent from many sources that form does follow something! There is an ongoing debate about what that "something" might be: function, emotion, everything, context, etc. (Hannah, 2002, p. 34; Esslinger, 2013; Warell, 2001, p. 15; Alexander, 1971, p. 15). Many have dealt, pro and con, with the functionalist term, "form follows function." But, regardless of all the intellectual machinations both for and against the term, the idea that "a product's form should follow [or reflect or communicate] its function and purposes" has endured (Norman, 2013, p. 11). It has a natural, logical, and intellectual appeal of honesty and forthrightness (Rams, 1984). It is important to this project to determine just what does form follow regarding product aesthetic form design and apply that finding to the human-centered work of engineering product design. However, it may well be that many existing product functions are not recognizable, or don't "follow" from their forms, frankly, because they are simply poorly designed and loaded with arbitrary "styling" artifice and novelty (Norman, 2013, p. 292).

2.8.2. Form Follows Function

In 1896 Louis Sullivan (1896) coined the term, "form (ever) follows function" as a basis for architecture: that a building's exterior design should reflect its interior functions and purposes. Walter Gropius adopted the "form follows function" principle as foundational for the work of the Bauhaus in architectural design, industrial (and product) design, and graphic design (Droste, 2019). Ashford (1969, p. 11) also says that a product external form must clearly be driven primarily from its internal anatomical structure and [its] functionality.

A trend in design media (Hustwit, 2013) repudiates "form follows function" as obsolete and untenable since many of today's products, due to new digital technologies driving product functions, are unrecognizable as to their observable (visible form) function and purpose. Early in the industrial design movie, *Objectified* (Hustwit, 2013), the narrator states that simple legacy objects, such as spoons and chairs, are easily identified as to their function and purpose by their form, but not so with contemporary technology-driven product forms such as mobile phones and data drives. The narrator declares that if aliens from outer space arrived and saw spoons and chairs they would clearly know what they were for simply from their forms.

This, however, is erroneous logic and assumes that the aliens would be anthropomorphic, with human body characteristics. But if not, without posteriors to sit on, or mouths to eat with, they might well be completely confused about the function of spoons and chairs! It is also quite probable that the first time many unenlightened Westerners encountered chopsticks (8.4. Figure), without knowing of their eating context, the purpose might not have been clear for these quite common objects from Asia.

The reason why we immediately recognize the function of many objects is from a long legacy of their observed and experienced form, use, and cultural familiarity. There are many objects in many cultures that may not be recognized as to their function by those from another culture—the noise-making "scissors" of the Korean cart vendor come to mind (8.4. Figure). Besides, form follows function can be quite valid regardless if the form immediately communicates the object's function or not. Norman (2013, p. 14) says that a product's function and usability may not be immediately apparent upon first encounter, but a well-designed product should need only one initial description or demonstration of its function and use to be necessary—its form-function clarity should be clearly established from then on.

Consider the modern mobile phone. At first encounter its functions may not be clearly apparent—just what is this small, thin rectangle with radiused corners and edges with a black front surface and round bumps on its back? But with one demonstration of its use it is clear from there on. Millions use one all over the world without trouble. Why? Because a modern mobile phone is a form follows function device. A speaker near the human ear, a receiver near the human mouth, a rectangular shape for an interactive screen, a round camera lens (or more) on the back side, a physical size that fits the human hand and face, and side actuator buttons where the device is gripped and fingers placed—all forms, controls, features, and locations based on logical and ergonomic human functionality and usability. Distinctive product branding is in the design details, such as colors, finishes, textures, logos, radii, and materials.

One approach to see that form follows function is valid is to look at its opposite extreme—what are the alternatives? These might be: “form need not follow function," or “form over function," or “function follows form." One can see that applying these opposites could lead to ridiculous product designs where function and performance would be seriously hampered or even useless, aesthetics could be horrible, and usability might be non-existent. Visualize mobile phones arbitrarily shaped like apples, bananas, or fish, created at the whim of designers enamored by biomimicry. Or a phone as a spherical ball or cube by pure geometrists, without considering human factors.

2.8.3. Form Is Function

Sullivan’s student, Frank Lloyd Wright (Gorman, 2003, p. 190), further expanded the term to “form and function are one," again primarily applied to architecture. Wright essentially said form is function. Thus, product form, more than just being a pleasing and attractive visual attribute, must also communicate what the product is and how it functions as well (Coates, 2003, Chapter 6; Norman, 2013, p. 3).

2.8.4. Form Follows Emotion

In his book, *Keep It Simple*, Hartmutt Esslinger (2013) presents his own version: “form follows emotion." The visceral and psychological responses of consumers of a product form are critical to its market success (Norman, 2013, p. 223). Often, however, poorly designed, or poorly functional products, can evoke an extreme anger (emotional) response if the product does not work well, or is unsafe (Norman, 2013, p. 212). In contrast, well-designed products that work well, are attractive, or are easy to use, invoke positive user emotional responses. Norman (2013, p. 54) cites research that indicates that “beautiful” products actually “work” better!

There may well be many “emotions” associated with a product and its many attributes. A user can be very angry if a product is difficult to use—should form follow that emotion? An assembler can get very frustrated that a product is very difficult to assemble—should form follow that emotion? A repairer can get angry and frustrated if a product is very difficult to repair—should form follow that emotion? One can see that form may well follow many different, but very real, human emotions not associated with only an aesthetic visceral response, and from a broad variety of a product’s stakeholders, besides its users or consumers. So, Esslinger may be quite correct, though perhaps not as he intended.

2.8.5. Form Follows Everything

Jeff Smith, co-founder of Lunar Design (Dresselhaus, 2016, p. 56), in response to many “form follows X” proclamations by various design competitors, declared that “form follows everything” in an effort to be innovative with a unique brand statement. This version is most likely quite true. Design does follow many things in its total context, but “everything” is a very broad and nondescript category, and possibly not very helpful for design application or method. Philosophically, when something is everything, it becomes nothing. Perhaps a better word than “everything” could be used—such as “context” (Alexander, 1971, pp. 15-16).

2.8.6. Form as Media

Coates (2003, Chapter 5) emphasizes that products are communicators—they have a language that tells a story and conveys information. Norman (2013, p. 71) states that products must communicate understanding and discoverability to the user: understanding what the product does, and discovering the product functionality, usability, and interactions needed to successfully operate it. Without these, the product is near useless. Bürdek (2015, pp. 139-142, 144) talks about “the information function of a product," product language, “the meaning of things," and “products as messages." Krippendorff (2006) has written an entire book on this topic of product form as semantic language.

2.8.7. Form as Curtain

A product external form also relates to the service design principles (Deloitte, 2018; DeSID, 2021) of back stage and front stage activities, and is related to the line of visibility, or “curtain," between them (Polaine, 2013). A product external form is like a separating visual “curtain” between the product interior “back stage” technology, components, structure, and elements, and the product “front stage” user functionality, usability, ergonomics, and aesthetics. Product internal components such as circuit boards, motors, fans, power supplies, batteries, and cables, are not generally for product user interaction—they are simply the technological transformation means to its affordances and functions (Norman, 2013, p. 10). These need not necessarily be seen or interacted with by the user, but, as in the back stage operations in a service, they are behind the external product enclosure form “curtain." A product’s form design should provide the means for its user’s understandability and discoverability, and its affordances, signifiers, information, and ergonomics. But it should properly “hide” those areas, elements, and components that would be confusing, irrelevant, or unattractive. A product form is a control mechanism of what the user can encounter, engage, understand, discover, use, and interact with, but also what the user need not know, see, or encounter that might confuse or distract.

In contrast, some have found that this internal technical element visibility, properly done, can also create emotional and aesthetic product attractiveness, such as Apple’s first iMac enclosure translucency showing interior technical components (Kahney, 2014, p. 123), or Dyson’s vacuum chamber clarity to see the accumulated debris (Dyson, 2005).

2.8.8. Form Follows Context

For this project, the most valid term is “[product] form follows context” (Alexander, 1971; Bürdek [on Alexander], 2015, p. 110)—a product’s complete and full context. The GPF design method prescribed in this project attempts to abide by that principle, where a product form is not determined until after a complete context for the product is determined first. In his seminal book, *Notes on the Synthesis of Form*, Alexander (1971, p. 21) states that form and context are complimentary and must coincide. He is essentially saying that form follows context, where context is more than simple function, but a totality of a product’s environment, interactions, and purposes. This concept that form follows context implies that a product form is more than just a communicator of functionality, or attractiveness and visual appeal, or emotion, but of much more. This is similar to Jeff Smith’s “form follows everything," but perhaps more definitive.

Abstract Form Design. Alexander (1971, Preface) also states, “It is absurd to separate the study of designing from the practice of design” and, “the study of method by itself is always barren” (Preface). These claims rightly contradict the Kostellow approach (Hannah, 2002, p. 34) of isolating and studying abstract aesthetic form as a discipline in itself with little or no consideration of product function, context, ergonomics, or application. A product must be an “ensemble comprising the form and its context.” (Alexander, 1971, p. 16). Good product fit is where product form essentially follows product context—in essence, “form follows context," though Alexander does not explicitly state it in these terms. Alexander’s position is that product form cannot ultimately be divorced from product context. Design practice is better informed by a product’s contextual attributes and should drive a product’s final form, which cannot be done purely abstractly, contrary to Kostellow’s approach.

This project affirms that the phrase, form follows context, is a more comprehensive and valid construct. Product function is only part of a product's total features and characteristics, whereas a product’s context includes such as aesthetics, ergonomics, usability, function, controls, environment, and manufacture/assembly. It also includes Norman’s (2013, p. 56) visceral, behavioral, and reflective responses, and his discoverability and understandability as well.

Artistic Freedom. Creating purely “artistically free” product designs is not product design at all—it is art for art’s sake, of interest only to design critics, competitions, and museums! Functionalist constraints on product design heighten the creative challenge. Constraints on any creative effort inspire innovation (Coates, 2003, pp. 42-46). Product requirements of meeting human need, useful functionality, usability, ergonomics, and reliable technology alone would drive product form design. Based on those alone, a prescribed method would be logical and appropriate.

Unfortunately, it is often the case in industrial design that there is a penchant for so-called “pure artistic freedom," especially for product form design, and a fear of it being “limited” through some prescribed constraints. Additionally, there is also often a resistance to any form of prescribed “method” or form design process, claiming this would also “limit the creativity” of the designer inappropriately

(Alexander, 1971). This is a very unfortunate mentality, and frankly dangerous to good product design. It may well be that the "artistic freedom" argument of industrial design against prescriptive and definitive form language and method is simply a distracting narrative and smokescreen to hide behind due to a dislike of, or even an inability for, dealing with the realities of physics, chemistry, and mathematics!

Functionalism (Bürdek, 2015, pp. 49-50; Rams, 1984) is unapologetically the basis of this project—to develop a definitive and prescribed GPF design language and method that takes into account the full constraints and requirements of product context. The absurd idea of an opposite non-functionalist design approach, where usability is not understandable, ergonomics in not human, functionality is poor, detailing is terrible, harmony is absent, complexity is rampant, intelligence and innovation are unaddressed, and aesthetics are unattractive, is ridiculous and absolute nonsense—but it seems as though some imply this can be reasonable for the sake of "beautiful" form (Hannah, 2002, back cover)!

2.9. Product Design Simulation

Simulation. This term is often interpreted as meaning "engineering simulation in the form of FEA (finite element analysis)," or some similar engineering analysis technology (English, 2019; Digital Engineering Editors, 2019). However, the generic meaning this term used in this project is anything that simulates, represents, or imitates something else, such as an object, process, or system. Consequently, design sketches, mockups, prototypes, and CAD models are simulations, whether they are engineering based or not (Dresselhaus, 2016, p. 40).

2.9.1. A Visual Enterprise

Physical product design is very much a visual enterprise (McKim, 1980; Hanks, 1977; Arnheim, 2004a & 2004b; Ferraris & Ferraro, 2013; Hanks & Belliston, 1992 & 2008). The triad combination of idea- and concept-sketching (Hoftijzer et al, 2018), making of concept mockups and prototypes (Brown, 2019; Hallgrimsson, 2019; Tjalve, 1979, pp. 89-92), and creating 3D CAD models (Coates, 1988, 1989, 1993, 1994, 1995, & 2003) is indispensable to responsible product design process (Dresselhaus, 2016, pp. 57-60). For this project's GPF design language and method, each has its proper place, importance, and level for engineering product design—and for properly "seeing" the design results.

2.9.2. Design Sketching

The value of sketching for creative thinking in general, and for product design specifically, has been well-established (Baskinger & Bardel, 2013, p. 8; Dresselhaus, 2016, p. 72; Hanks & Belliston, 2008, p. 2; Edwards, 2012, p. XVI-XVII; Hanks & Belliston, 1992, pp. 5-7; Olofsson & Sjolen, 2005). Design sketching has been a core medium for architects (Drazil, 2020; Ching, 2014 & 2019), engineers (Baynes & Pugh, 1986; Tjalve et al, 1979), and industrial designers (Eissen & Steur, 2014, 2019a, & 2019b; Robertson & Bertling, 2013). Drawing has been the basis for art (sculpture, painting, etc.) itself (Edwards, 2012; Arnheim, 2004a & 2004b). Sketching and drawing have been foundational tools for artists, engineers, and architects for millennia (Edwards, 2012). Unfortunately, today most engineers have little or no training in any type of art, aesthetic form, or design sketching, let alone sophisticated design visualization training. The question relevant for this project, and specifically for engineering product design, is what kind and level of sketching is really necessary for proper GPF design of UTPs?

Industrial design generally trains its adherents in a sophisticated and illustrative design sketching style as an essential and required skill. Much time is spent developing and practicing line quality, shading, shadows, perspective, viewpoints, highlights, etc. The books on this are many (Eissen & Steur, 2014; Robertson & Bertling, 2013; Mead, 2017; Henry, 2012). Such sophisticated illustrative sketching is often portrayed as the quintessential capability of industrial design aesthetic form creation.

Some have tried to tone down this traditional industrial design sketching style to a more learnable skill level (Hanks & Belliston, 2008; Baskinger & Bardel, 2013), but these still require significant practice that most engineers have no time or inclination for. Some sketch advocates have promoted an even simpler style that almost anyone can learn (Roam, 2009, 2011, 2013, 2016a, & 2016b). Others have promoted a mid-level approach in engineering product design that encompasses simple line idea and concept sketching to formal detail drawings (Tjalve et al, 1979; Tjalve, 1979; Hanks & Belliston, 1992), though modern CAD software now can “automatically” create formal detail drawings from CAD models (Willis & Dogra, 2020). Due to this common industrial design mentality, and its implied sketch sophistication “requirement” to be an aesthetic form designer, engineering designers are often intimidated into feeling they are visually incompetent for, and incapable of, product aesthetic form design.

However, sophisticated illustrative product form sketching is simply not essential for designing most UTP aesthetic product forms. This can be demonstrated easily by comparing the work in sophisticated product design sketching books such as by Liu (2013), or Robertson & Bertling, (2013), or Mead (2017), and the simple line sketching of celebrated designers such as Dieter Rams (2014) and Hartmutt Esslinger (2013). The plethora of design sketching books mostly shows sketching examples of existing products whose forms are already known and the sketches are mainly of stylistic variations. These are such as toasters, computers and mice, household items, kitchen appliances, PDAs, mobile phones, common furniture, backpacks, etc. (Eissen & Steur, 2014, 2019a, & 2019b; Liu, 2013), and rarely of totally new and complex UTPs (Tjalve, 1979, Chapter 5). Entertainment sketch artists, like Robertson & Bertling (2013) and Mead (2017), sketch new concepts, but few, if any, have any real world constraints—they are entertainment fantasy sketches often for sci-fi films. However, if one examines the sketches of Dieter Rams (Klemp, 2020; Hustwitt, 2018; Lovell, 2011), Hartmutt Esslinger (2013) and Frog Design, and Olivetti designers (Shapira, 1979), their sketches are generally simple line drawings of basic form—nothing close to sophisticated illustration.

Prior to contemporary CAD modeling software prevalence, engineers mainly utilized geometric orthographic sketches and precision layouts for their complete designs (Baynes & Pugh, 1986), or simple line drawings and sketches (Tjalve et al, 1979; Tjalve, 1979; Ashford, 1969; Cain, 1969). Besides that, early engineers were quite good at rendering their designs in realistic and artistic renditions (Baynes & Pugh, 1986), and were so trained as well. Since contemporary CAD modeling is capable of creating production drawings, precision layouts, and photo-realistic renderings, simple orthographic and pictorial form concept line drawings and sketches profusely used by such as Tjalve (1979; Tjalve et al, 1979) are quite adequate for this project's GPF design language and method work. Engineering product designers can sketch basic form line sketches in orthographic mode, on gridded engineering paper or using grid underlays if needed, or pictorial sketches, with or without using perspective underlays (Dresselhaus et al, 2018). The point is that sophisticated illustrative style sketching and manual or digital two-dimensional rendering are simply not generally required for engineering form concept work by engineering product designers. They can go directly to CAD modeling as a familiar form-giving and visualization tool utilizing all of these features quite easily (Dresselhaus et al, 2018). What is especially no longer necessary is sophisticated and tedious two-dimensional perspective pictorial constructions (Tjalve et al, 1979, pp. 75-83; Robertson & Bertling, 2013) for visual accuracy—CAD now does that easily.

2.9.3. CAD Modeling

CAD modeling is now well-established as indispensable for product design as well as for the engineering of a final product (Vukašinović & Duhovnik, 2019; Coates, 1994 & 2003; Shih, 2019). This design tool allows for a host of advantageous and beneficial visualization, analysis, and manufacturing applications (Dresselhaus, 2016, p. 29). For this project’s GPF design language and method, CAD modeling is likewise indispensable. It provides engineering product designers with a very familiar, flexible, and powerful creative tool and design means for product aesthetic form concept development. Engineering product designers using CAD, properly trained in product aesthetics and form design, are able to competently and comprehensively design both a product’s aesthetic form and its product engineering, starting with only simple orthographic or pictorial manual sketching (Dresselhaus et al, 2018).

Coates (1993 & 1994) emphasizes the powerful use of CAD in product design and aesthetic form. CAD modeling of complete physical product designs and systems is now nearly always required for manufacturing and production (Vukašinović & Duhovnik, 2019; Shih, 2019). Much more can be done with CAD modeling than simply design—there is engineering analysis, rendering, assembly, exploded views, technical drawings and details, and more . All of this is especially important for engineering product design, where sophisticated, illustration style sketching capability and skill are rare. Except for early simple idea-sketching, most all GPF design work can be done by engineering product designers almost exclusively in CAD modeling (Dresselhaus et al, 2018).

In most product design and development projects in industry, engineering designers take initial product aesthetic form sketches and renderings, and often CAD surface models (Tutorial Books, 2020b), of new product concepts created by industrial design and convert them to final engineering CAD models for eventual manufacturing and production. These engineer-generated CAD models that include aesthetic product form design intent must be more refined, precise, and complete, with many engineering details, than the original industrial design renditions. Often, the initial industrial design CAD surface models are not “perfect” in continuity, and may need rework by engineering (Dresselhaus, 2016, p. 38).

However, engineering product designers that are trained and capable of holistically creating GPF designs for UTPs can accomplish this process more efficiently using initial simple idea-sketching, and going directly into CAD modeling for design intent precision without a so-called “surface to solid” transfer. These single-discipline, engineering product design sourced models can then be immediately ready for engineering refinement for manufacturing and production.

There are a number of advantages in CAD modeling for a holistic and integrated CAD-based engineering product design approach.

Solid GPF Design. For this project’s GPF design language and method for engineers, surface, or so-called “sculptural," modeling is not required, nor is it encouraged. All the tools and features needed for full GPF modeling are present in the “Solid” side of CAD software programs, such as AF360 utilized in this project.

Visual Immediacy. Modern CAD modeling programs provide the ability to immediately see changes and variations in aesthetic product form concepts in real time as a CAD model is being created. Precise dimensions may be entered and explored “on the fly," or simple “push-pull” type operations can be executed while seeing their immediate form effects. This is far more efficient and effective for engineering product designers creating GPF designs than with profuse and laborious manual sketching or digital sketching.

Minimal Sketching. CAD modeling provides engineers who are not adept at sophisticated manual sketching an avenue to easily create product form concepts starting with simple line concept sketches, either orthographic or simple pictorials (Tjalve et al, 1979; Tjalve, 1979; Dresselhaus et al, 2018), and then go to digital “sketching” directly in the CAD software.

Sketch to CAD. Simple conceptual line drawings and idea-sketches can be integrated into CAD modeling quickly. Only simple line concept sketches in orthographic mode need be drawn roughly and then precisely reproduced in CAD. Orthographic rough or precise sketches can be imported into a CAD program and then modeling done “around” or over the sketch. In many cases, one can bypass manual form idea-sketching altogether and start immediately in a CAD modeling “sketch” directly.

Simplicity. According to Dresselhaus et al (2018), engineering students do much better at product form development by starting with only simple orthographic or pictorial line idea-sketches, and then moving directly to CAD modeling for further ideation, completely bypassing the profuse and sophisticated concept sketching typical of industrial designers as unnecessary. Simple, straightforward, preliminary configurational line drawings, such as those throughout the Tjalve book (1979), are highly recommended.

Parametric Modeling. Parametric modeling in a CAD program is advantageous for the form variation and form division methods of Tjalve (1979), also integrated in this project's GPF design language and method. Predetermined dimensional proportions (such as Phi and its root variations), and variations in product form details can be quickly, easily, and precisely applied and visually evaluated immediately. Preset ratios and detail dimensions can also be created for standard designs of new GPF compositions conforming to a branded “product family look and feel," such as edge radii and form proportions, or for standard part and component dimensions and forms. Not only is a CAD-based parametric approach more realistic and visually accurate than sketching such variations, it is faster and more precise (Shih, 2019).

Photo-Realistic Rendering. CAD modeling software allows for the rendering of models into photo-realistic renditions for visual evaluation quickly and easily. Colors, textures, lighting, positioning, viewpoints, environments, and other visual attributes can be explored with virtual realism, making tedious, and often unrealistic, manual rendering unnecessary, as well as the skills to create them.

Animation and Analysis. CAD modeling software also allows for various methods of dynamic animation of models as well as their physical analysis with realistic physics. None of this is possible with manual sketching techniques.

CAD to Physical Rendition. Finally, as explained below, physical renditions of product form designs are important for a number of reasons. CAD models can be easily turned into physical models and prototypes through processes such as 3D printing and CNC machining. Such physical models can range from rough product concept renditions all the way to completely functional product prototypes. These can be only aesthetic form “appearance” models, to models that only have partial features or functionality for demonstration or testing.

2.9.4. Physical Modeling

A CAD model (without extremely sophisticated and expensive interactive virtual reality software) cannot be kinesthetically manipulated for heft, “feel," touch, or physical space orientation (Dresselhaus, 2016, p. 60). Only physical mockups and prototypes can accommodate this. Precisely made product form mockups, whether preliminary or refined, are critical for human perception (Goldstein, 2010), especially by those who may not be trained visually (e.g., marketing, management, sales, manufacturing, etc.). Such mockups help a designer to think and create—the “build to think” concept (Brown, 2019, Chapter 4). Some designers barely sketch, but use “soft” mockups as three-dimensional “idea-sketching." Also, presenting design concepts to non-designers for evaluation or approval often requires more “realistic” renditions beyond two-dimensional sketches and even rendered CAD models on screens. Many non-designers often cannot translate two-dimensional images into three-dimensions easily.

The parallel use of physical mockups and prototypes along with various CAD modeling renditions throughout the product design process is an important process (Dresselhaus, 2016, pp. 75 & 105). In the early stages of GPF development these mockups can be simple geometric forms. As the design process proceeds, these mockups should have more refinement and detail. Hartmutt Esslinger, in his seminal book, *Keep It Simple: The Early Design Years of Apple* (2013), shows that he and his team first did simple, rough line sketches of form concepts, then went immediately to CAD modeling, and finally made precision CNC machined physical mockups for Steve Jobs' evaluation. This was the most effective visualization method for design form review and approval for top corporate executives and clients.

2.10. Project Caveats

These are caveats regarding the aims, claims, and objectives of this project.

2.10.1. References

A major portion of this project's references used for background, analysis, and synthesis of the proposed GPF design language and method are relatively "old"—from far past historical periods to several decades previous to today. Some contemporary dissertation guides advise having references within the past six years, while others say "older" references are quite valid if appropriate to the work (Hallas, 2016; Wolf, 2019). This project is interested in the truth of how to best execute human-centered product design, and truth is where one finds it. Whether that truth is found in older or recent publications, the age of the publication, or of its references, is irrelevant to this project. Far too often it was found that many recent industrial design academic papers and publications were of inadequate value.

2.10.2. Exclusivity

It is not a claim of this project that its resulting GPF design language and method are necessarily the best or exclusive. It simply purports that a geometric product form language and method are able to be synthesized, and are quite adaptable and viable in engineering product design for creating attractive aesthetic forms of UTPs. It is a viable functionalist framework and approach that is amenable for engineering product design in executing human-centered form-giving activities in a comprehensive and holistic manner (Ashford, 1969, p. 1).

2.10.3. Creative Freedom

It is not an intention of this project's GPF design language and method to limit creative freedom when designing product form compositions in engineering product design for UTPs. On the contrary, this project's GPF language and method provide for significant aesthetic design license within its functionalist and geometric basis. Engineering designers already use geometric form to invent and design new and innovative solutions to a broad spectrum of problems (Budynas & Nisbett, 2019).

This project's language and method simply expand that natural capability to aesthetic product form design and provide a broad palette of aesthetic visual options.

2.10.4. Organic Form

It is not a claim of this project that attractive OPF design should be eliminated, but only that it should be avoided for most UTP design by engineering product designers. The relevant issue is the execution difficulty between the two form approaches of OPF and GPF. The best of OPFs are generally quite difficult to create well and can generally be executed by only a few highly talented form designers. A straightforward GPF design language and method for engineering product design is quite adequate and viable for most UTPs.

2.10.5. Geometric Difficulty

It is not a claim of this project that creating attractive GPF compositions is inherently easy—the claim is that it is simpler and less difficult than creating high quality OPF compositions. Creating quality GPF compositions will definitely take visual sensitivity and appropriate aesthetic and form-giving training. It will also require design craftsmanship, with well thought-out product context, language, and communication (Ashford, 1969; Rams, 1984).

2.10.6. Curved Surfaces

It is not a claim of this project that curvilinear shapes, surfaces, and forms should not be used to create attractive GPF compositions. Radial, cylindrical, and spherical surfaces and forms are quite acceptable when and where appropriate and viable. Curved geometric shapes, surfaces, and forms can be defined by simple dimensioned radii and tangencies. In many situations, main extant OPF curves, surfaces, and forms can also often be geometrically imitated using radial curves, surfaces, and forms without reducing visual quality.

2.10.7. Optimum Actors

It is not a claim of this project that engineering product designers are necessarily the universally optimum aesthetic form designers for all physical products. However, when properly trained in aesthetics and GPF design for UTPs, they are proposed in this project as the optimum design actors to execute a single-discipline, holistic, integrated, and comprehensive UTP form design process (Ashford, 1969, Chapter 1; Bürdek, 2015, p. 113).

2.10.8. Industrial Design

It is not a claim of this project that certain talented, competent, and well-trained industrial designers cannot execute attractive product aesthetic form, whether OPF or GPF, or cannot work well with product engineers (Dresselhaus, 2016; Ulrich et al, 2020). However, for the product design of technologically sophisticated UTPs, it is questionable whether the majority of industrial design graduates of many industrial design schools throughout the world are properly trained, educated, or competent to do such. Their education, skills, mentality, abilities, methods, and approach to product design and aesthetic form design, and their STEM education and capabilities, are often inadequate and/or inappropriate in most cases (Ashford, 1969; Alexander, 1971; Brezing & Löwer, 2008). It often seems that, as with many creative endeavors, there are but a few highly talented actors, including in industrial design, who can create very well-designed and attractive product aesthetic forms, and who may or may not have acquired that capability from their formal design education.

2.10.9. Architectural Design

It is not a claim of this project that there should be a new two-silo paradigm of architects and engineers working together on product design and development, where architects replace the industrial design function. Architects may not have the least interest, or have the proper engineering technical knowledge, for doing that, though there have been, and will be, many exceptions (e.g., Dieter Rams, Eliot Noyes, Charles Eames, Michael Graves, and others), all trained as architects, but who have designed many products (Joshi, 2017; Karisa, 2013; Bürdek, 2015). The paradigm proposed in this project is that architectural design is a better holistic, integrated, and inspirational model for engineering product design in theory, education, process, and practice than is industrial design.

3. PROJECT METHODOLOGY

This section describes the Project Methodology used for the research and development of creating a GPF design language and method for engineering product design.

This methodology was executed in five parts.

Part 1: Identification of key findings and learnings from the previous engineering design experimental courses in product design form that were created and delivered by this author at HongIk University (2016) in Seoul, Korea.

Part 2: Research that indicates GPF design is a common and successful form language by an analysis and demonstration of products in an international design awards competition and of selected celebrated product designers/firms, including demonstrating by deconstruction the apparent GPF design forms used.

Part 3: The discovery and organization of existing foundational design form and aesthetic principles and methods from multiple existing published sources.

Part 4: The synthesis of a definitive, functionalist, and prescriptive GPF design language and method based on the engineering product form course findings (Part 1), the GPF common use analysis and design language (Part 2), the discovered existing foundational published form principles and methods (Part 3), and this author's professional experience in product design (9. CURRICULUM VITAE).

Part 5: Demonstration of the synthesized GPF design language and method via CAD visualizations and simulations of existing products and converged products.

3.1. Part 1: GPF Design Education Evaluation (Methodology)

3.1.1. Part 1 Objective (Methodology)

The objective of this part of the Project Methodology was to identify key learnings, principles, and insights gained from the outcomes of the experimental product form design courses in engineering design taught at HongIk University (2016) that are applicable to this project.

3.1.2. GPF Education Courses Background

In roughly the period of 2010 to 2017, experimental engineering product design college courses in GPF design were developed and taught by this author. These were delivered over several semesters to engineering design students in the Mechanical and System Design Engineering (MSDE) Department of the College of Engineering at HongIk University in Seoul, Korea. Jee (2012) and Dresselhaus et al (2018) present general descriptions of these experimental education efforts and their partial results. The 8.5. Figure provides the entire Dresselhaus et al (2018) paper, and the 8.6. Figure provides visual GPF design results of some of the final student work output of several of these courses. The courses content and teaching was exploratory, with evolving content and instructional development aspects. The goal was to discover if aesthetic product form design, specifically geometric based, could be successfully taught to engineering students.

3.1.3. GPF Education Success and Inspiration

These exploratory courses and general teaching results indicated that GPF design could be taught successfully to engineering students with good results. However, the design language and method utilized in these courses was still unrefined and underdeveloped in terms of definition, synthesis, process, and organization. More work was necessary in design language, process refinement, and method definition. These courses, and their results and initial successes, were the inspiration for this current project—to synthesize a definitive, functionalist, and prescribed GPF design language and method that would empower engineering product designers to create attractive and sustainable aesthetic product forms.

3.2. Part 2: GPF Common Use Analysis (Methodology)

Before developing any kind of work on a definitive, functionalist, and prescribed GPF design language and method, a significant (and ideally common) presence of GPF design in the real world of physical products should first be verified. Otherwise, it would be an irrelevant and useless exercise to develop such a design language and method for something that was not shown to be generally important.

3.2.1. Part 2 Objective (Methodology)

The objective of this part of the Project Methodology was to validate and demonstrate a common and successful GPF design language and its use in consumer, industrial, and technology products. This research was broken into four segments.

Product Design Award Competition. This segment objective was to validate that GPF design is a common, viable, and successful method used for creating attractive product forms by analyzing a global award-winning product design competition. The chosen product design award competition represented well-respected global product designers and design firms for their outstanding product design work.

Celebrated Designers/Firms. This segment objective was to validate that GPF design is a viable and successful method used for creating attractive product forms by analyzing the work of celebrated designers and design firms. Selected published works of celebrated product designers and firms were utilized.

GPF Language Demonstration. This segment objective was to validate and demonstrate the GPF language of several product designs from the award competition via visual deconstruction and simulation. These selected products were unpacked into their composite geometric forms showing their GPF language use and forms.

GPF Language Elements Used. This segment objective was to compile the apparent key GPF principles, elements, and details utilized in the award competition products and by the celebrated designers/firms. This was for use later in the GPF design language and method synthesis.

3.2.2. GPF Use Analysis—Design Competition

For this segment, overall total award products and GPF award products were counted, tabulated, and analyzed.

Product Designs Source. All award competition product design counts, whether for all products, or for only those of GPF, were taken from the four Red Dot Award 2019-2020 Product Design books of *Doing, Working, Living,* and *Enjoying* (Zec, 2019). However, the Materials and surfaces category in the Red Dot Award book *Working* was not counted in any totals due to the nature of these entries as not being relevant to GPF product analysis.

Criteria for Product Counts. The following criteria were used to count and compare the total award products and GPF award products.

> *total product count.* All product award designs in each Red Dot Award book, in each book category, and in the entire four-book set, at all award levels, were counted, and the results logged in a spreadsheet.
>
> *GPF product count.* All qualifying GPF award product designs in each book, in each book category, and in the entire four-book set, at all award levels, were counted, and the results logged in a spreadsheet. Each selected and counted GPF award product was identified in each award book by placing a round dark sticker by the selected and counted product photograph and its description for future reference and research analysis purposes.

Criteria for GPF Product Selection. The following criteria were used to determine the selection and counting of the GPF product award designs in the four Red Dot Award books.

> *geometric form.* Products in the Red Dot Award books were deemed a GPF product, and counted and logged as such, if and only if they could, by visual observation of their Red Dot Award book photograph(s), be seen as clearly composed of purely geometric composition. No award products were deemed a GPF product, nor counted and logged as such, if they were composed completely or partially of an OPF. If a product photograph did not clearly and visually indicate that it was a GPF composition, it was not counted as a GPF product. As such, GPF selection counts were "conservative"—if in doubt, did not count.
>
> *organic form.* No award products in any of the Red Dot Award books were counted as a GPF product if they were designed with an overall organic form. This rejection included award competition products that were designed for any close human body contact (e.g., chairs, sofas, vehicle seating, baby car seats, etc.), designed for human wearing apparel or clothing, or similarly designed for any ergonomic contour requirements for human body conformability (e.g., backpacks, helmets, clothing, etc.). This rejection also included award products that had aerodynamic requirements (e.g., airplane, rocket, propellor, or flying devices), that had any fluid dynamic requirements

(e.g., boats or water craft), or that had any other similar organic contouring requirement (e.g., automobiles or ground transportation).

3.2.3. GPF Use Analysis—Celebrated Designers/Firms

For this segment, overall total products and GPF products in each designated publication were counted, tabulated, and analyzed.

Product Designs Sources. All celebrated designers/firms product design counts, whether for all products, or for only those of GPF, were taken from the book by Hartmutt Esslinger (Frog Design), *Keep It Simple: The Early Design Years of Apple* (2013), from the book by Klaus Klemp (2020, mostly Braun work), *Dieter Rams: The Complete Works* (2020), and from the book by Yuji Morimiya (2018, multiple designers), O*livetti Product Design 1963-1980* (2018). All of these sources represent globally recognized and celebrated designers and their product design work.

Criteria for Product Counts. The following criteria were used to count and compare the total products and GPF products in each selected celebrated designers/firms publication.

total product count. All discreet product designs in each publication were counted and the results logged in a spreadsheet.

GPF product count. All qualifying GPF product designs in each publication were counted and the results logged in a spreadsheet.

Criteria for GPF Selection. The criteria for GPF selection in the celebrated designers/firms publications were essentially the same as for the Red Dot Award books GPF selection criteria previously described.

3.2.4. GPF Language Demonstration.

For this segment, to demonstrate the GPF design language used for evaluating these works, several product designs from the Red Dot Award competition were analyzed and deconstructed into their composite GPFs and visualized and simulated via CAD modeling.

3.2.5. GPF Language Utilized

For this segment, a compilation of the GPF design language principles and elements apparently used in the GPF product selections of the award competition and of the celebrated designers/firms was made for use in the synthesis of the project's GPF design language and method developed later.

3.3. Part 3: Existing Design Form Principles (Methodology)

3.3.1. Part 3 Objective (Methodology)

The objective of this part of the Project Methodology was to discover and identify any already existing design language, methods, processes, or principles, from relevant published sources, that were pertinent to this project synthesis of a GPF design language and method. Demonstration images were also created illustrating many of the various principles and design language that were found.

3.3.2. Research Sources

The sources researched for this part of the Project Methodology were both books and academic research papers and publications, as well as published articles and websites. The primary categories of such sources investigated were: architecture, graphic design, art, aesthetics, product design, industrial design, engineering design, science, and mathematics. Each of the primary foundational sources were listed and the main principles and methods identified and documented for each.

3.3.3. Visualization of Principles

Many of the key findings of existing form design principles, elements, methods, and features in this Project Methodology were visualized and demonstrated in various images for visual clarity and understanding.

3.4. Part 4: GPF Language and Method Synthesis (Methodology)

3.4.1. Part 4 Objective (Methodology)

The objective of this part of the Project Methodology was to develop and prescribe a definitive, systematic, functionalist, and ordered GPF design language and method for the creation of attractive aesthetic product compositions by engineering product designers without the need for industrial designers. This was to be done by synthesizing the educational course learning results from Part 1, the design language discovery results from Part 2, the existing foundational principles results from Part 3, and the product design career experience of this author.

3.4.2. GPF Target Products

The intended application of this project's GPF design language and method was primarily for engineering UTPs—products that have significant technology and engineering design content, and that are highly utilitarian. These could be consumer, industrial, or technology products. They especially should be products and systems that meet human needs and increase human well-being and flourishing. The aim is to focus on a GPF design language and method that optimizes efficient process and minimizes wasteful effort in creating products and systems by engineering product designers in a holistic and integrated process.

Industrial Products. Industrial UTP applications would be products such as laboratory instruments and devices, test instruments and devices, medical devices and products, industrial and manufacturing tools, construction equipment and vehicles, wood and metal shop tools and equipment, restaurant and food industry equipment and devices, military equipment and devices, security and protection equipment and products, sports and recreation equipment and products, and for any array of UTPs that have significant technology and engineering design requirements that are used in commercial, military, or industrial applications.

Consumer Products. Consumer UTP applications would be products such as espresso machines, refrigerators, mobile phones, microwave ovens, laptop and desktop computers, navigation devices, exercise and health equipment and devices, gaming and interaction products and devices, photographic products and equipment, kitchen and gardening products and equipment, and the like—products designed primarily for the consumer market, but that have significant engineering design and technology content.

Technology Products. Technology UTP applications would be products such as internal product components having significant engineering design content such as hard drives, cabling, interconnection, mechanical components and mechanisms, brackets, fasteners and fastening systems, air movers, optical components and devices, sensors and control devices, internet of things products and components, and other such UTPs.

3.4.3. GPF Target Creators

The target creators of this project's GPF design language and method are students and practitioners within the field of engineering design, and more appropriately within mechanical engineering and mechanical design. In addition, others who have a STEM knowledge and background should also be able to learn and execute this GPF language and method as well. Ideally, this GPF design form language and method would be utilized within specific engineering product design educational programs as well as many industry applications.

3.5. Part 5: GPF Language and Method Demonstration (Methodology)

Once a synthesized GPF design language and method was created, it was essential that it be validated by actual design demonstrations of UTPs.

3.5.1. Part 5 Objective (Methodology)

The objective of this part of the Project Methodology was to validate and demonstrate the GPF design language and method developed in Part 4 by applying it to several existing product designs and to several so-called common “converged” product designs. This application demonstration was visualized and presented in various simulations and images.

3.5.2. GPF Language and Method Visualization

A number of demonstrations of the GPF design language and method were created to provide a visual demonstration of the approach. These were presented for clarity and understanding of the language and method. These demonstrations were presented in visual imagery that show the product compositional forms and how they were arranged.

4. PROJECT RESULTS

This section presents the results of executing the Project Methodology used for research, development, synthesis, definition, prescription, and demonstration of a GPF design language and method for engineering product design. These results are documented here per the five parts of the Project Methodology.

4.1. Part 1: GPF Design Education Evaluation (Results)

4.1.1. Part 1 Objective (Results)

The objective of this part of the Project Results was to summarize the boundary conditions for the experimental courses, and present the identified key learnings, principles, and insights gained from the outcomes of these experimental product design courses (Dresselhaus et al, 2018; Jee, 2012) presented in the Project Methodology (8.5. & 8.6. Figures).

4.1.2. GPF Courses Boundary Conditions

There were a number of boundary conditions for these experimental product design form courses. These are summarized below. Only one initial boundary condition was changed, almost immediately, and this was the sketching versus CAD modeling approach to concept design. A sketching based approach was abandoned for a CAD modeling based approach.

The course name would be “Form & Esthetics for Engineering Design." The course name was meant to briefly and clearly describe what the course was about and for whom. The abbreviation/acronym for this course was “FEED."

External product aesthetic form design was to be taught to engineering students in a single semester course. The challenge here was both time and audience —facilitating a successful outcome in only one semester of 15 weeks, and engineering students grasping the method to create attractive product form designs, ideally as good as industrial design students. The intent was to teach engineering students what industrial design students commonly learned and executed for external product aesthetic form design, though often within a far more extensive form education.

The course was to be taught exclusively to third and fourth year college level engineering students. More advanced engineering students were enrolled due to their supposed maturity in experience, attitude, desire, and technical knowledge. Students who took the course were already generally interested in learning product design and industrial design due to a general culture of design at HongIk University. Most students in the course were in mechanical engineering, but some were in computer engineering and industrial engineering as well.

The student audience for the course would be primarily Korean engineering students. This was due to the course being first taught in Korea at a Korean engineering school that was within a prominent design university. However, at times a few were also college exchange students from other countries (e.g., Germany).

The assumption was made that the developed teaching method could be adapted to other student audiences within many college engineering schools.

The teaching language for the course was to be American English. This was due to the instructor's native language and his lack of Korean language skills, but also because of the University's emphasis on student learning in English. Though there was, of course, an understandable language barrier for some, the course was taught in a highly visual manner, using simple English terms and expressions, and many visuals and demonstrations.

The teaching method was to use only geometric forms for product aesthetic form design. The goal was to focus on a simple, clear form approach, and, since engineers were generally quite familiar with basic geometric forms, this was the exclusive form method taught. The instructor also felt that there were many, many successful products designed partially, or only, with geometric forms, and these were presented in the course. There was also the specific exclusion of using any so-called organic or surface modeled forms to reduce confusion and complexity. These latter form types were forbidden to be used.

The teaching method was to be highly visual, with many visualized examples of forms and methods. Due to the language issue, new terminology and principles, and the course being about a visual design method, the course was to use a plethora of images and visual examples of principles, forms, and methods.

The teaching method was to begin using a traditional approach of manual sketching and rendering of product forms. It was first assumed, incorrectly, that engineering students could first be taught basic manual geometric product aesthetic form sketching with simple rendering, as is often done with industrial design students. It was very quickly found that this was not possible—the manual sketching skills of most engineering students were not even close to being able to adequately represent simple geometric forms, let alone full product designs! The concept sketching approach was abandoned very early during the first rendition of the course.

The final teaching method was to use CAD modeling as the primary visualization approach. This was decided when the sketching approach failed miserably early on. CAD modeling, like basic geometric forms, was a very familiar expression tool for engineering students and it was utilized as a successful primary method of product aesthetic form visualization. Manual and digital sketching were encouraged for initial ideation, but not required, and product form concepts could be soon started in CAD models. In the end, CAD models were then rendered digitally for final quality results. This was perhaps one of the greatest discoveries in the course development—to use the students' most familiar and practiced tool for generating their product form concepts (and it was NOT sketching!).

The final outcome objective for the course was for the students to be able to design attractive external aesthetic product forms. This type of course was generally unknown in engineering schools globally, and was quite new for this university. For an engineering student to be able to take a course like this they generally had to enroll in an industrial design course, if it was even available to them. These were often very difficult to get into, and even if enrolled, engineers had to compete with already very practiced industrial design students.

The products that the students would be challenged to create were common technology-based products. The category of products for the students to design used a middle level of technology, where electronic, chemical, and/or optical methods were used for functionality. These were such as espresso machines, optical microscopes, digital projectors, and the like. The all too common industrial design form exercises such as for computer mice, simple kitchen appliances, home dinnerware, and such, were avoided.

All work in the course was to be individual and not team-based. The goal of the course was to develop individual capability and skill in designing attractive product forms independently and without peer support.

A method for the course teaching was defined and developed. This course was both new to the students, but also to the instructor—both were starting from a basic level for the first time. This meant that the teaching method and steps of application would have to evolve during multiple sequential renditions of the course over several semesters.

Basic visual engineering parameters for the course products were defined. To be certain that the engineering students were also applying their engineering knowledge to product aesthetic form design, certain key parameters for the products to be designed were prescribed. These were such as being aware of visual design for such as air flow and venting, controls and interconnection, manufacturing and assembly issues, human usability and ergonomics, safety concerns, and general practical issues of physics and engineering.

There were no aesthetic, art, sketching, or form prerequisites for the course. Except for being an engineering student of third or fourth year, with basic geometry and CAD modeling skills, no student was expected to have any sketching, aesthetics, or art training prior to the course.

The course outcomes were to be visual and presented to the class in an exhibit. At the end of the course, students were required to present their product form design results in visual posters showing their product aesthetic form designs and renderings, and displayed in a class exhibition.

Basic teaching on aesthetics, geometry, and form principles was to be presented in the course. The course teaching was to first present the basics of aesthetic principles and geometric form applicable to product design. Most all relevant and basic principles needed would be taught during the course.

4.1.3. GPF Design Language

Based on the teaching efforts, boundary conditions, and student results of the experimental product form design course, given for several semesters, are the main learnings gleaned and evaluated from this educational experience listed below.

General Design Language Terminology. Design form language terms such as grammar, syntax, typology, semantics, morphology, syntactics, semiotics, etc. (You & Chen, 2007; Krippendorff, 2006; Bürdek, 2015; Warell, 2001), were not taught as part of the course instruction in GPF design language. This was partly due to the course being taught in English as a second, and often difficult, language for the students—such terms would have added an unnecessary difficulty level for the course. Though these terms were not used in the instruction of the course, the students were still quite successful in GPF design understanding and creation without them by using only simple terminology. These rather sophisticated and esoteric terms may thus not be needed for teaching an engineering product design GPF language and method. They are, for this project, seemingly quite superfluous and unnecessary.

Design Language "Words." In this experimental product form design course, a clear and simple form language approach was needed to help the engineering students create new product forms and aesthetic compositions—a more practical lexicon of design "words" was needed besides the above cited sophisticated general language terms. A simple design language appropriate to the creation of product design communication (Coates, 2003, pp. 104-108; Bürdek, 2015, pp. 144, 148-151) through visual compositions was needed. Just as with verbal communication, without "words" there is no product form design possible, and no real design language. Consequently, only relatively ordinary, and generally familiar (at least to engineers) product language terms were used in this project. These were such terms as: configuration, architecture, orientation, alignment, and attractive, as well as well-established visual language words such as in Dondis (1973).

General Design Process. Two key learnings came from this teaching experience regarding overall engineering GPF design process.

First, since engineers generally have little or no sophisticated sketching training or skills compared to that of industrial designers, it was found that engineers need only be required to draw simple graphic diagrams and create basic orthographic (and pictorial, if possible) line sketches for initial rough form concept development. Then they could move to CAD "sketching" and modeling (Tutorial Books, 2020a, pp. 14 &15) relatively quickly based on their preliminary manual sketches for further conceptual work. This allows them to work in a medium (CAD) that they are quite familiar and skilled with, instead of the traditional industrial design sophisticated and illustrative style sketching that they are not generally capable of. If some engineers can sketch well and create good pictorial sketches, then all the better.

Second, engineers should use only the "solid" mode of CAD modeling software (Tutorial Books, 2020a, p. 5), and not the "surface" mode (Tutorial Books, 2020b, p. 1). It was found in this teaching experience that far too often, if engineers use the "surface" mode of CAD software, it can lead to a disaster of non-geometric, contorted organic forms. Doing all of the GPF design work in the CAD "solid" mode would be the most successful process—from a CAD precision sketch to photo-realistic rendering. An additional advantage to this method is the actual physics present in the "solid" CAD mode that often prohibits incorrect design features.

Models created in this mode are often then directly ready for design drawing documentation and manufacturing.

4.1.4. GPF Key Language Learnings.

Following are the GPF design language and method key principles, terms, and design "words" gleaned and learned from the experimental design education course outcomes. These were appropriately incorporated into the synthesis of the resulting GPF design language and method of this project.

a. use simple, orthographic multi-view line sketching to begin form concepts;
b. move soon to CAD "sketch mode" for product form concept design;
c. move then to CAD solid modeling for product component form design;
d. execute most product form concept work in CAD modeling, not in refined sketches;
e. use only simple geometric forms: rectangular prism and right cylinder;
f. create primarily rectilinear and planar forms for product compositions;
g. compose product form compositions mainly of the two geometric forms;
h. create total product form compositions with a three-level form hierarchy;
i. apply appropriate visual design principles throughout the creation process;
j. appropriately apply form edge radius and chamfer details last;
k. incorporate usability, interaction areas, restricted volumes, and controls;
l. apply surface texture, color, and value where appropriate, and at the end;
m. apply manufacturing-based parting gaps, or their simulations; and
n. finalize product form designs in CAD modeling/rendering, not in sketches.

4.2. Part 2: GPF Common Use Analysis (Results)

4.2.1. Part 2 Objectives (Results)

The objectives of this part of the Project Results were three. First, was presentation of the GPF data collection, tabulation, and visual evaluation of the Red Dot Award product designs analysis (8.7. & 8.8. Figures). Second, was the analysis and presentation of the results of the GPF designs by celebrated designers/firms (8.9. & 8.10. Figures). Third, was the GPF common use analysis by product geometric deconstruction using CAD modeling visualization (8.11. Figure).

4.2.2. GPF Analysis of Red Dot Competition

The data for this part of the project research is gleaned from the four books of the Red Dot Awards for 2019-2020: *Doing, Living, Working,* and *Enjoying* (Zec, 2019). Though these are primarily only a recent one-year source for this analysis, the Red Dot Award competition is globally international, with contributions across a wide spectrum of product design categories and areas, and from many countries, designers, and design firms. This data is presented in the 8.7. & 8.8. Figures. All count data is presented in both spreadsheet and bar graph form for each Red Dot Award book, for each book category, and for the entire four-book set, at all award levels, including relative percentages of GPF award products versus total award products.

4.2.3. GPF Analysis of Celebrated Designers/Firms

The data for this part of the project research was taken from three books of the work of celebrated designers/firms: the book by Hartmutt Esslinger (Frog Design), *Keep It Simple: The Early Design Years of Apple* (2013), the book by Klaus Klemp, *Dieter Rams: The Complete Works* (2020, mostly Braun work), and from the book by Yuji Morimiya, O*livetti: Product Design 1963-1980* (2018, multiple designers). The three designers/firms selected are also quite globally celebrated as either individual designers (Rams and Esslinger), or firms (Frog Design and Olivetti). All resulting celebrated designers/firms count data is presented in a spreadsheet and in bar graphs of the results for each designer/firm, including relative percentages of GPF products versus total products. These results are presented in the 8.9. & 8.10. Figures.

4.2.4. GPF Prevalence

It should be noted that though this particular Project analysis is limited to a small segment of global product publications and designers/firms, GPF products are present frequently everywhere around us. One need only observe one's surroundings to see many, many physical products and designs that are geometric. One can also simply search the internet for UTPs such as desktop printers, woodworking tools, device controls, office equipment, firearms, audio equipment, photographic equipment, medical products, and many other UTP categories, to find a plethora of GPF designs.

4.2.5. GPF Language Demonstration

This segment validates GPF design by deconstructing several products from the Red Dot Award competition into their component geometric forms. These are presented in the 8.11. Figure. These deconstructions are visual only and are approximate dimensional and proportional representations based on the Red Dot photos of the products.

4.2.6. GPF Language Utilized

The following are the GPF design language and features apparent from the photographs of the GPF product designs in the Red Dot Award competition books and the celebrated designers/firms publications. These were used in the synthesis of the project's GPF design language and method.

a. use of primarily rectilinear geometric forms and shapes;
b. use of rectangles, squares, and circles, and parts thereof, for surface shapes;
c. use of primarily rectangular prisms and right cylinders as major forms;
d. use of intersections of rectangular prisms, right cylinders, and parts thereof;
e. use of edge radii on virtually all edges, with ball corners;
f. use of small edge radii for many size products: ~1, ~2, or ~3 mm radii;
g. use of larger edge radii for human contact “softness”: ~10 to ~15 mm radii;
h. use of larger edge radii for safety or cleaning issues: ~10 to ~15 mm radii;
i. moderate use of varied or multiple edge radii on different surfaces or forms;

j. infrequent use of edge chamfers, and only in appropriate locations;
k. use of feature and element alignments, and orthogonal relationships;
l. infrequent use of large radial (cylindrical) surfaces;
m. rare use of spherical surfaces;
n. moderate use of angled plane and beveled surfaces;
o. use of rectilinear or cylindrical geometric forms for signifiers and controls;
p. general use and application of basic common visual principles; and
q. use of surface textures, color, value, and finish for distinction and contrast.

4.3. Part 3: Existing Design Form Principles (Results)

4.3.1. Part 3 Objective (Results)

The objective of this part of the Project Results was to present the discovery of existing form and design principle findings already extant and described by others. These are intended to provide the foundational basis, along with the earlier educational course experience results, the results of the Red Dot Award books and celebrated designers/firms analyses and principles, and this author's own personal product design experience, for synthesizing a functionalist, definitive, and prescribed GPF design language and methodology for use in a holistic engineering product design discipline.

4.3.2. Research Discovery Basis

The existing design and form principles for this project have been predominantly found in books rather than in academic papers or articles, since authors tend to more comprehensively elucidate their principles and processes in books than they do in narrowly defined academic research papers or articles (Meyer, 2009, p. 6). In addition, as mentioned earlier, many sources for said principles have been found in what may be considered “older" references. These principles are presented after significant discovery research and analysis. The essential nature and primary contribution of the project's GPF design language and method is an integration and synthesis of these principles into a systematic framework that can be used by engineering product designers in product form design and development. The following sections identify these foundational design principle findings, their sources, and their application to this project's GPF language and design approach.

4.3.3. Major Foundational Sources

The following sources were found to contain the key foundational principles upon which this project's GPF design language and method are based. It should be noted that these findings are primarily for application to the GPF design of UTPs, where utility, usability, and functionality take precedence over novelty of form and “styling” for promoting consumer sales (Coates, 2003, p. 241; Bürdek, 2015, p. 18).

The Aesthetics of Engineering Design **(Ashford, 1969)**

The general foundational basis of this book is that it well elucidates the argument and rationale for a holistic engineering product design discipline and approach that includes and embraces the human-centered aspects of engineering product design and development. It encourages engineering product design without industrial designers needed as the product aesthetic form creators. It emphasizes the need for engineers to "take back" these human factors of product design and return them to engineering product design as a holistic system and discipline. Though this book generally deals with engineering form and aesthetics, a rarely published topic, it also has a valuable contribution in its inspiration and philosophy of reestablishing, in both engineering design education and its practice, the human aspects of design and product aesthetic form design. Ashford's attitude toward replacing industrial design practice with an inherent responsibility of engineering product design is highly relevant to this project.

Its specific value is that it also has excellent content that covers product aesthetic form creation and development, and a host of solid basic design principles of form, proportion, surface treatment, and human perception. Published in the same year as the Cain (1969) book, these two books go hand-in-hand together with the Tjalve (1979) book for the creation process of aesthetic product form in engineering product design and development.

Engineering Product Design **(Cain, 1969)**

The general foundational basis of this book for this project is that it represents the concept that engineering and product design are fully compatible, and together are a bonafide and distinct discipline. Engineers are presented as creators of products, and not just of technologies or simply of machines or parts of machines, but complete products that are for industry, commerce, and consumers.

Its specific value for this project is that, just as Ashford (1969), it presents excellent expanded content, process, and methods of engineering product design beyond aesthetic form design. However, it does present industrial design as the aesthetic form creators for product design (p. 25) in contrast to Ashford.

A Short Course in Industrial Design **(Tjalve, 1979)**

The general foundational basis of this book for this project is that it is a unique and seminal treatment of total product form design and its process. It is primarily based on a whole product system configuration approach leading to a comprehensive product form design. The overall product design process in the book is nearly identical to what this author has practiced in his product design career. The process Tjalve presents is used extensively in this project as the primary overall foundational basis for general product form design, principles, terminology, and methods.

For its specific value for this project, there is little in this book that is problematic—many, many principles are applicable to this project's process synthesis. However, due to its age, the products represented are relatively out of date. The title is also an unfortunate misnomer by indicating it is about the narrow activity of industrial design. But the book also covers the creation of design form in several areas of mechanical and engineering design in addition to aesthetic product form design. There are applications to the form-giving of mechanical brackets, structures, frames, devices, component assemblies, and other mechanical and engineering physical elements. This book validates that form-giving is not the exclusive domain of industrial design, but also of engineering and mechanical design as well.

Tjalve (p. 147) also uses a geometric approach to his product form development process and examples, though this geometric language is not detailed, but only generally described and applied. This project utilizes this source's overall product form design process to synthesize, define, and prescribe a specific GPF design language and method in detail. It should be noted that this is one of the few, if any, publications that actually describes in detail a complete product form design process from human need to a new and unique total product form design of a sophisticated UTP (Chapter 5).

Watches Tell More Than Time: Product Design, Information, and the Quest for Elegance **(Coates, 2003)**

The general foundational basis of this book for this project is that it is one of only a few product form design books, besides Tjalve (1979) and Ashford (1969), that gives both broad and specific principles for aesthetic product form design. The book is generally focused more toward industrial design of consumer products, and often vehicles, than toward engineering product design. Unfortunately, some of the book is rather esoteric and not very clear, such as the topics of subjective concinnity, daimons, stereotypes, zeitgeists, and ideals—all a bit hard to follow, and not always practical for direct design application.

For its specific value for this project, this comes primarily from its last summarizing chapter of key aesthetic product form design principles (Chapter 11). However, in numerous places elsewhere, other specific form design principles, processes, and methods are very valuable, e.g., objective concinnity, constraints, valence, product communication and language, proportions, “creative" CAD modeling, and many others utilized in this project.

The Design of Everyday Things: Revised and Expanded Edition **(Norman, 2013)**

The general foundational basis of this book for this project, frequently recognized as one of the best books on product design and product usability, is its broad coverage of primarily two main areas:

a. human cognition and response as it relates to products, and
b. product usability related to discoverability and understandability.

Norman elucidates an outstanding general philosophy of product usability design in this book.

For its specific value for this project, it is an outstanding product design usability resource, and serves as a foundational basis for many design principles in this project's GPF design language and method. However, it has little on specific product design form language or creation method, though it clearly states that research has shown that “beautiful” products work “better” (p. 54).

Architecture: Form, Space & Order **(Ching, 2014)**

The general foundational basis of this book for this project is that it exemplifies what this project presents as an important model: an alternate to industrial design for a holistic total design model for engineering product design. A traditional industrial design model is based primarily on the exterior of a product form design, and too often for consumer visceral sales attraction. An architectural approach deals with both exterior and interior form design—inside and outside. The book supports the idea that product design is more like product "architecture" design.

For its specific value for this project, the book deals with foundational human needs, as well as order, space, accessibility, heat and cold, construction detail, and a myriad of other basic issues of building design, where all are applicable and adaptable to engineering product design, and specifically to a geometric form approach.

***Operative Design: A Catalog of Spatial Verbs* (di Mari & Yoo, 2013)**

The general foundational basis of this book on architectural spatial design for this project is that it presents a comprehensive philosophy for the use of "form operations," termed "spatial verbs," on overall visual forms. These can be generally applied to product form designs quite well.

For its specific value for this project, it presents a number of these operations visually, and how they can be performed on geometric form volumes as design "actions" or "operations." These visual operations are integrated into, and used extensively, in this project's GPF design language and method. These operational "verbs" provide excellent visual language for geometric physical product form design based in architecture and geometry.

***A Primer of Visual Literacy* (Dondis, 1973)**

The general foundational basis of this book for this project is its overall philosophy, value, and presentation of a quite comprehensive visual language for art, architecture, and design, and ideally applicable to product form design.

Its specific value for this project is that it contains many terms and visual relationships that make for a visual design language and its application that can be used for both describing and creating aesthetic physical product forms.

***The Geometry of Design: Revised and Updated* (Elam, 2011)**

The general foundational basis of this book for this project is that it is one of several books that cogently present the argument, with compelling demonstrations, that geometry is the historical and foundational basis, and has been for millennia, of order, logic, and proportion in art, architecture, design, and nature.

Its specific value for this project is that it presents numerous delineated examples of a common geometric visual foundation and proportional system regarding painting, sculpture, architecture, graphics, and product design. It also provides a number of geometric and proportion principles and ratios, including the golden ratio, phi, and its root derivatives, applicable to product form design.

***Aesthetic Sustainability: Product Design and Sustainable Usage* (Harper, 2017)**

The general foundational basis of this unique book for this project is that it elucidates an intellectual background, logical rationale, and general creation guide for designing products with sustainable and durable aesthetics. Though the author's background is primarily from the fashion industry, the prescribed Aesthetic Strategy Model is ideally suited for general GPF design application.

The specific value for this project are the dark gray left side design guidelines for "The Beautiful" that were utilized in this project (pp. 134 & 145).

Notes on the Synthesis of Form **(Alexander, 1971)**

The general foundational basis of this book for this project is primarily in its many philosophical statements about the flaws of practicing visual designers: their technical knowledge limitations, their skewed psychological perceptions of form and aesthetics, their design fears and failings in terms of logic, mathematics, and method, and their "hiding" of their incompetencies behind a pretense of artistic freedom, license, and elitism.

The specific value for this project is its elucidation and clarity of the relationships of product form and context, of product ensemble and good fit, and of product form and functional forces.

NOTE: The following two books have been cited frequently in this dissertation and were partially foundational for many good product form design principles utilized in this project, as well as insights regarding product design history, theory, and principles. However, they also both have flaws in their content that are here presented for each. Since they are seminal design books, they are here cited for their potential negative effect they may have had on product design theory, education, and practice.

Elements of Design: Rowena Reed Kostellow and the Structure of Visual Relationships **(Hannah, 2002)**

The general foundational basis of this book for this project is its philosophical approach to teaching design form in a systematic and ordered program, as well as certain various positive insights into design form development. Sadly, however, the Kostellow form design philosophy was one of essentially form development and creation only in the abstract, rather than based on any specific product, functional, contextual, ergonomic, or other real-world requirements. This form approach was also mostly organic based, though some geometric form is addressed. Unfortunately, this unrealistic method negatively affected industrial design and product form development teaching and practice in the United States for decades.

The specific value of this book for this project, on the positive side, is the hierarchy principle of three form levels, one of the few principles gleaned from this book and utilized for this project.

Design: History, Theory, and Practice of Product Design **(Bürdek, 2015)**

Both the general and specific foundational bases of this book for this project are its comprehensive treatment of many key product design historical, theoretical, and philosophical issues, as well as a number of related design insights and principles. However, this book's content is unfortunately biased almost exclusively toward European and German content, and the Ulm School of Design. It has limited content, often negative in nature, regarding American design aspects. In addition, either negatively portrayed, completely left out, or too briefly presented, are many key aspects of design history, theory, and philosophy, primarily American, such as the Stanford d.school, design thinking, the IDEO contributions, Steve Jobs and Apple Computer, and the Kostellow educational history, to name just a few.

4.3.4. Project Philosophical Bases

Based on the previous foundational sources, the following are key general philosophical principles and bases for this project and for holistic engineering product design.

a. Engineering product design as a distinct design discipline (Cain, 1969).
b. Architectural design as a better inspirational process model (Ching, 2015).
c. Product form design follows its environmental context (Alexander, 1971).
d. Academic design research rarely affects design practice (Bürdek, 2015).
e. Objective concinnity as an optimized product design goal (Coates, 2003).
f. An applied holistic total product form development process (Tjalve, 1979).
g. Geometric form can achieve optimal product design (Tjalve, 1979).
h. Geometric form and proportion as a product design basis (Elam, 2011).
i. Applying visual form operations to GPF products (di Mari & Yoo, 2013).
j. Usability as second most important product design factor (Norman, 2013).
k. Product design for durable aesthetic sustainability (Harper, 2017).
l. Visual design principles applied as standard process (Dondis, 1973).
m. A systematic approach to product design form education (Hannah, 2002).

4.3.5. GPF Design Language Lexicon

In the following two divisions of general and specific findings of existing form design principles and concepts, a lexicon of product form design language "words" and terms for a GPF design language and method (Dondis, 1973) is presented. These can be generically categorized as follows.

Nouns. These are the basic geometric forms of GPF design.

Verbs. These are the visual form operations extracted from di Mari and Yoo (2013), such as bend, fracture, intersect, etc., that are applied to the GPF design language "nouns" to create design "compositions."

Adjectives/Adverbs. These are the various aesthetic modifying GPF features, such as edge radii and chamfers, surface textures and colors, parting gaps, and others, that visually modify the design language nouns and verbs.

Prepositions. These are the various visual design elements and features, such as alignment, proportion, contrast, orthogonality, shape, etc., that visually connect various "language" elements in a GPF design composition.

Composition. This is the final assembly and ensemble of design language words and elements (nouns, verbs, adverbs, adjectives, prepositions, etc.) that culminates in an attractive and functional total product design.

4.3.6. GPF Language and Method General Findings

The following findings are general product design and aesthetic form principles from the previously cited sources that have been synthesized into a GPF design language and method. These principles are broadly applied in this project's GPF design in a holistic manner. This list can be used as a general form, appearance, function, and usability CHECK list.

product context (Alexander, 1971, p. 15). A product's context is the complete set of factors—ergonomic, functional, aesthetic, environmental, manufacturing, stakeholders, etc.—from which the product's final form should flow.

CHECK: Has the total product context been evaluated fully and completely?

unity (Tjalve, 1979, p. 144). The product design and its GPF should be perceived as a unified and integrated whole.

CHECK: Do the product forms and appearance seem to be as an integrated and unified whole?

order (Tjalve, 1979, p. 144). Gestalt visual order is what humans immediately look for and attempt to perceive from any object (Bürdek, 2015, p. 151).

CHECK: Do the product forms and appearance seem orderly and a whole?

simplicity (Norman, 2013, p. 177). Products should be created that have a visual appearance, functional perception, and ease of usability of simplicity, even though they may actually be quite complex in their technology and performance. This fits with the perceptions of unity and order (Tjalve, 1979), and with objective concinnity (Coates, 2003, Chapter 9).

CHECK: Do the product forms and appearance imply simplicity and ease of use, and are not intimidating?

product factors (Coates, 2003, pp. 241-243). The three main factors are:

a. function (performance),
b. ergonomics (including usability), and
c. beauty (aesthetic attractiveness).

Coates says ergonomics is the primary consideration, but Tjalve (1979) says function is first. This project agrees with Tjalve—without a function, ergonomics and beauty are irrelevant.

CHECK: Have these three factors been addressed properly and are they in the proper order for the product forms and appearance?

three key properties (Tjalve, 1979, p. 143-144). Aesthetics (beauty), unity (wholeness), and order (logic). Coates (2003) would combine unity and order as concinnity, add ergonomics, and with both before beauty.

CHECK: Do the product forms and appearance give an impression and perception of order, logic, and attractiveness?

five basic aesthetic properties (Tjalve, 1979, pp. 7 & 143). "The appearance of a product is the consequence of choice of configuration (renamed from Tjalve's "structure"), form, material, dimension, and surface (including color [and texture])."

CHECK: Have all five of these properties been properly addressed in detail for the product forms and appearance?

understandability (Norman, 2013, p. 3). Good product design requires that product functionality and usability be understandable and not confusing, and ideally directly from the product itself, or at least easily from its documentation, one time.

CHECK: Do the product forms and appearance seem clearly understandable regarding its function, purpose, and usability?

discoverability (Norman, 2013, p. 3). To use a product successfully, its (understandable) information must also be easily discoverable.

CHECK: Are the product usability and functional characteristics easily discoverable by the user?

aesthetic durability/sustainability (Harper, 2017, p. 2-6). Products should have a character of long lasting, enduring, and stable aesthetic attractiveness and beauty.

CHECK: Do the product forms and appearance seem to be enduring and sustainable, and not overly novel, trendy, stylistic, or artificial?

instant payoff (Harper, 2017, p. 134). Product designs should have an immediate positive user perception. This supports Norman's (2013) understandability and discoverability, and Coates' (2003) inherent form communication.

CHECK: Are the product form and appearance immediately positive and inviting per Harper's criteria?

pattern booster (Harper, 2017, p. 134). Product designs should have a positive reinforcement of user patterns. This supports Alexander (1971) in his requirement that a product design must reflect its environmental and user context.

CHECK: Do the product form ensemble and appearance "fit" into the use environment and contextual patterns?

comfort booster (Harper, 2017, p. 135). Product designs should be "comfortable" to the user. This reinforces Norman's (2013) claim that "beautiful" products "work better" than unattractive ones. It also supports Coates (2003) in his ergonomics and usability as being very important product design factors.

CHECK: Do the product form and appearance seem comfortable and friendly to the user?

blending in (Harper, 2017, p. 135). Product designs should reflect normal community quality. This supports a "family look" style for general system appearance and a "community" of products (Tjalve, 1979, p. 100). It also supports Coates (2003, p. 244) in that UTPs should have a neutral or slightly positive valence where utility and usability take precedence over novel form and style.

CHECK: Do the product form and appearance have a family look with its "relatives" in the product line, if any?

reflective response (Norman, 2013, p. 53). A designer should focus primarily on the user reflective response, which is driven initially by the visceral aesthetic response, and then the behavioral usability response. The reflective response will have the longest lasting effect on the product brand and image. This correlates with Coates' (2003) post-purchase user as the most important to design for.

CHECK: After purchasing and then using the product does the user feel a positive and lasting response and reflection?

design ingredients (Coates, 2003, p. 242). These are four: contrast, novelty, objective concinnity, and subjective concinnity. For this project, in the design of UTPs, novelty and subjective concinnity should be minimized, contrast should generally be moderate, and objective concinnity should be maximized.

CHECK: Are the product forms and appearance low in novelty and subjectivity, moderate in contrast, and high in objective concinnity?

aesthetic factors (Coates, 2003, p. 242). The two essential aesthetic factors of product form are:

a. information, and
b. making sense.

These coincide with Norman's (2013) discoverability and understandability. Harper (2017) would agree based on her "The Beautiful" guidelines.

CHECK: Is the product information and communication clear, and do the product forms and appearance make good sense and meaning to the user?

ergonomic objectives (Coates, 2003, p. 37). These are three:

a. minimize nonessential work,
b. optimize essential work, and
c. minimize user danger.

These are commensurate with Rams (1984).

CHECK: Are the product essential functional value optimized and the product nonessential work minimized, and is the product safe for all stakeholders?

objective concinnity (Coates, 2003, Chapter 9). This is product design elegance, beauty, balance, coherence, and harmony, which are key to product success. Objective concinnity should be the primary goal of the product designer, and should be optimized for UTPs for aesthetic durability and longevity (Harper, 2017). Tjalve (1979) might call this principle "order." To Harper (2017), this might mean all of her "The Beautiful" guidelines.

CHECK: Are the product forms and appearance high in objective concinnity?

subjective concinnity (Coates, 2003, Chapter 10). This may be ethnic, national, cultural, gender, age, language, or legacy related, and should be dealt with in the appropriate context for each product design, generally minimized as much as possible toward a universal and global product appeal.

CHECK: Are the product forms and appearance low in subjective concinnity and highly universal and inclusive?

product audiences (Coates, 2003, pp. 119-121). The most important of these three (pre-purchase consumer, post-purchase user, and the public) to design for is the post-purchase user for optimum brand success.

CHECK: Has the post-purchase user been the most considered for the product design functions, forms, usability, and appearance?

novelty (Coates, 2003, p. 137). Product novelty tends to decline over time since its perception becomes more common, and thus less novel. Novelty should be minimized for durable and aesthetically sustainable UTP designs where clarity of product language, function, ergonomics, communication, and usability are foremost. Novelty, if used, should be innovative and informative, with functional or usability value to the user or stakeholder, and as visually sustainable as possible.

CHECK: Are the product forms and appearance novelty low, interesting, and informative, and if properly novel, will they remain sustainable?

valence (Coates, 2003, pp. 243-246). This is the intrinsic attractiveness or "good"-ness (positive valence), or averseness or "bad"-ness (negative valence), of an object or product. This factor should be either neutral or slightly positive for UTPs, since the usability, understandability, and discoverability factors (Norman, 2013) must be at a high utilitarian level. UTPs are not meant to be novel styling paragons of consumerism, but to be utilized comfortably and easily by users, and accessed efficiently by their stakeholders.

CHECK: Is the product form and appearance valence neutral or somewhat positive (low novelty, moderate information, high objective concinnity)?

function (Tjalve, 1979, p. 9). A product must accomplish something useful for the user and is the primary product design consideration. A function is essentially a transformation where input is transformed into output. A function and its means are not the same thing.

CHECK: Does the product have a clear functional and valuable transformational purpose, and do the product forms and appearance convey that clear function and purpose?

sub-function (Tjalve, 1979, p. 9). These contribute additional functional transformation support to the product main function.

CHECK: Are the product sub-functions useful, clear, and supporting the main function?

functional means (Tjalve, 1979, p. 9). These are the various technologies by which a given function or sub-function can be realized for the required functional transformation.

CHECK: Are the product functions and sub-functions, and their required transformations, properly realized by optimized technology means?

geometric form elements (Tjalve, 1979, p. 147). These are geometric volumes and parts thereof for the product forms and appearance design. The GPF design language and method in this project is based solely on such geometric forms.

CHECK: Are the product forms and details geometric at all levels?

4.3.7. GPF Language and Method Specific Findings

The following findings are specifically and directly applicable design form method principles from the cited resources that are synthesized into a GPF design language and method. These principles are directly applied in the GPF synthesized process stepped sequence provided later.

Since product design form creation, and especially GPF design, is a visual activity, it is important that there is not only textual descriptions of these principles and applications, but also visual clarity and understanding. To realize this, many of the following discovered design form language and method principles are visualized in images and the related figures cited.

total product development process (Tjalve, 1979, p. 8). A comprehensive product design and development process must be synthesized that starts with finding human need, addresses human-centered features and characteristics, covers all parameters of a product context, and prepares the product for production (8.12. Figure).

human need and root cause (Norman, 2013, p. 43). Products must be designed to resolve human need and their root cause, and these must be determined at the very first with the PCD process (8.12-1. & 8.13. Figure) before any product design concept or development work is done—if no human need is resolved, then there is no product value!

context parameters (Tjalve, 1979, pp. 3-7). This follows the human need analysis and the PCD process by looking at all the context surrounding a product concept (8.12-2. & 8.14. Figure). This should evaluate all user and stakeholder areas and issues that would affect the overall product design, and a list made of these as a checklist throughout the product form design and product development process.

constraints (Coates, 2003, pp. 42-46). A broad and/or specific set of design limitations and requirements within the context parameters of a product, represented in the product relational configuration(s), specified configuration(s), functional means, interaction areas, restricted volumes, and Tjalve's (1979) material, dimension, and surface issues (8.12-2. & 8.14. Figure).

main function and sub-functions (Tjalve, 1979, p. 9). The main function is the primary product functional purpose and transformation offered by a product to the appropriate and qualified users. This is the most important product property after human need, and must be determined next. Sub-functions are auxiliary functions and transformations that support the main function and are determined after the main function (8.12-3. Figure).

functional means (Tjalve, 1979, p. 9). A method "…by which a specific function can be realized." A functional means is the technology by which a function is made possible. A particular function may have several functional means available to it for accomplishing its purpose. All of these means must be determined before relational configurations, specified configurations, interaction areas, or restricted volumes can be determined (8.12-3. Figure).

geometric composition forms (Tjalve, 1979, p. 147). This project's GPF design language and method utilizes the two basic geometric forms for GPF compositions: the rectangular prism and the right cylinder (8.15. Figure). These two geometric forms are recommended as the only two forms to start a GPF design. Only one or two of these basic GPF volumes, or portions thereof, need to be used to visually make up an attractive GPF composition. These can be used singularly or in varied combinations of either or both, and of different dimensions and scale for each form. A starting point for a GPF can simply be a cube form, and then apply different proportions and operations appropriately.

form hierarchy (Hannah, 2002, pp. 48-57). These are three main forms in order of decreasing relative size and renamed: primary (dominant), secondary (subdominant), and tertiary (subordinate). A GPF composition may have less than the three main forms, but it is not recommended to have more (8.16. Figure). These may be one, two, or three of the two basic forms of cuboid and/or right cylinder for an overall GPF composition.

geometric form ratios (Elam, 2011, pp. 6-7). These are ratios of, surrounding, and derived from, the so-called “golden proportion” phi (1.618…). These proportions are generally preferred by humans. Also included are the so-called “root proportions.” Coates (2003), Meisner (2018), Elam (2011), and Bass (2019) validate and demonstrate these. These proportional ratios can be used in parametric CAD modeling of GPF (8.17. Figure).

visual language principles (Dondis, 1973, Chapter 3). These are basic visual relationships to be considered and applied while composing a GPF design (8.18. Figure). Also gleaned from Leborg (2006), Hannah (2002), Harper (2017), Elam (2011), Tjalve (1979), Norman (2013), Ashford (1969), and Coates (2003).

geometric lines and planes (Tjalve, 1979, p. 147). Product lines and planes should generally be made orthogonal to one another (8.18. Figure). If not, such as with the rotate or shear operations, the angle of difference should be appropriate and reasonable.

visual operations (di Mari & Yoo, 2013). These describe various product visual form modifications made on a product form volume. These can be singular or in multiple applications. A variety of modifying visual form operations may be applied to the individual or combined GPF volumes in a GPF composition to add visual interest, attractiveness, various visual effects, or other advantageous or attractive features. Selected visual form operations can be applied to the GPF compositional volumes or to the overall integrated GPF composition. These should be minimized to one, two, or three per GPF overall composition to avoid an overly complex and “busy” GPF composition. The specific operations are as follows.

shift. Shifting of one GPF volume relative to another (8.19. & 8.20. Figures). If there is more than one basic form in a GPF composition, these should generally be intersected and positioned so that one is shifted relative to the other in at least one plane to create visual contrast and interest, rather than in less interesting planar coincidences. If said forms are intersected with planar alignment, it is best that they are separated visually and appropriately by real or simulated parting gaps and/or by appropriate colors or textures.

intersect. Intersection of two GPF volumes (8.19. Figure); the shift operation may also be additionally required for visual clarity.

rotate. Rotation of one GPF volume relative to another form volume (8.20. Figure); the shift operation may also be additionally required for visual clarity.

bend. Bending of a portion of a GPF volume (8.21. Figure).

shear. Shearing of one face of a GPF volume (8.22. Figure).

radial surface. Creation of a large radial, or cylindrical, surface area on a GPF volume (8.23. Figure).

fracture. Separation into two parts of a GPF volume with a relatively large gap between them (8.24. Figure).

interaction areas (Tjalve, 1979, p. 48). Renamed from the original Tjalve “functional surface," where these are user or other interaction spaces, and are a key basis of a product's form. External interaction areas relate to surroundings, and internal interaction areas relate to product internal elements (8.25. Figure). These must be identified and dimensioned early on and assigned within each possible specified configuration of a product. Different possible product specified configurations may have different interaction areas due to different functional means that are applied.

restricted volume (Tjalve, 1979, p. 60). Renamed from the original Tjalve “banned area." A product restricted volume is a volume in space within the overall product design where various physical elements, functional devices or movements, or operator actions must not be hampered during product use (8.26. Figure). These must also be identified and dimensioned early on and assigned with each possible specified configuration of a product. Different possible product specified configurations may have different restricted volumes due to different functional means applied.

relational configuration (Tjalve, 1979, p. 9). Renamed from the original Tjalve “basic structure." It is visualized as a schematic diagram that contains the functional means of a product concept that shows their relationships to one another based on an input/transformation/output diagram. It does not specify any specific physical dimensions, or any structural, spacial, or layout construct. A particular product relational configuration may depend on particular functional means employed for any of the functions and sub-functions of the product. A product concept generally has only one input/transformation/output diagram, but may have more than one relational configuration based on different functional means (8.27. Figure). If a product function has multiple possible functional means, this could significantly affect the product relational configuration and resulting specified configurations.

specified configuration (Tjalve, 1979, p. 12). Renamed from the original Tjalve “quantified structure." A product specified configuration is derived from the product relational configuration by adding specific functional and sub-functional technological means via actual physical components and elements with key relationship factors and dimensions. These are all configured in optimized physical spacial (3D) arrangement(s) in physical mockups and CAD models. When combined with product interaction areas, restricted volumes, and controls, displays, and other signifiers and quaternary forms, the total GPF can be designed (8.28. Figure). If a product function has multiple possible functional means, this could significantly effect the product relational configuration and resulting specified configurations.

configuration variation method (Tjalve, 1979, pp. 21-22). Renamed from the original Tjalve “structure variation method." This is first identifying and specifying the product interaction areas and restricted volumes, creating the schematic gross dimensional electromechanical forms of the product elements and components, and then variably arranging them into potentially viable 3D specific configurations for application of the form variation method (8.28. Figure).

form variation method (Tjalve, 1979, pp. 48 & 74). This is first creating the 3D specified configuration(s) based on the relational configuration, the interaction areas, and the restricted volumes, and then enclosing these with aesthetic GPF options for the total gross product form (8.29., 8.30., & 8.31. Figures).

form division method (Tjalve, 1979, p. 74). Visually dividing up the main forms of a GPF gross composition after using the form variation method. Applied to an overall GPF of the 1-3 main hierarchical forms (8.32. Figure).

visual perception (Tjalve, 1979, p. 166). Renamed from the original Tjalve “means of expression." These are methods to be applied to a product form that modify the visual perception regarding weight, size, center of gravity, balance, stability, movement, etc. (8.33. Figure).

quaternary forms (Norman, 2013, p. 14). Quaternary forms are such as controls, venting, displays, connector banks, and various signifiers added after the main gestalt forms and operational features are applied. Proper application of a variety of these product elements can be applied to a GPF composition in a geometrically attractive aesthetic manner (8.34. Figure).

signifiers and controls (Norman, 2013, pp. 13-14). Signifiers is the general term designating indicators, displays, and controls of a product design, and though they are quaternary forms, they should be added at the appropriate time in the product form-giving process. They are generally added after the 1-3 main hierarchy forms of the GPF composition (8.35. Figure).

4.4. Part 4: GPF Language and Method Synthesis (Results)

4.4.1. Part 4 Objective (Results)

The objective of this part of the Project Results was to synthesize and prescribe a coherent, logical, and systematic GPF design language and method for engineering product design from the findings of the previous three parts of this Project Methodology and Results. It is intended to be integrated with product aesthetic, functional, architectural, ergonomic, usability, and structural design within the discipline of engineering product design. This GPF design framework follows an initial assessment of product context parameters for human need, functionality, ergonomics, and aesthetics. A sequence of steps for GPF composition design and creation was developed and documented. It aims to be a systematic framework for creating functional, ergonomic, usable, and attractive GPF compositions in an effective and efficient manner when designing and developing engineered UTPs that meet human needs.

4.4.2. GPF Design Method Features and Principles

The following are the fundamental features and principles for this project's GPF design language and method.

GPF Design Synthesis Process. A full GPF design synthesis process, as presented in the 8.12. Figure, and described in the stepped sequence following, is necessary since the aesthetic form design of any product must not only conform to preliminary key context considerations, but also to component and element configurations that will drive the GPF design (Tjalve, 1979). This project's GPF method avoids excessive and premature form design concept sketching prior to essential first steps, as is common with industrial design legacy process.

Product Design Checklist. Though generally and partially dealt with in this project in a previous section, and recommended as further research in the Recommendations section of this document, a comprehensive product design and development checklist and process should be followed. Product context factors and parameters lists should be carefully and thoroughly utilized for application to the whole product design as well as its GPF. Such partial guides are available, as those by Ulrich et al (2020).

Target Product Attributes. The target products for this method are primarily engineered UTPs, designed for their durability, ergonomics, usability, and functionality, and with a neutral or slightly positive valence (Coates, 2003, pp. 40 & 246). Their GPFs are not necessarily to be designed for their fashionable styling or consumer novelty. The end post-purchase user is the most important target for such products. A GPF design language and method are quite appropriate for engineered UTP design, and for utilitarian consumer products as well, where the goal for these products is to simply accomplish essential or critical work and activities. Since humans first try to perceive order and logic in viewing a product (Tjalve, 1979, p. 144), and for these products to accomplish useful, critical, or often dangerous work, GPF design should do this quite well. For such products, arbitrary OPF "styling" can be simply unnecessary, if not wastefully superficial.

meaning. A more important aspect of UTPs than their styling for consumer purchase motivation is their "meaning" (Krippendorff, 2006, p. 58; Coates, 2003, pp. 62-63)—that they convey to the user or stakeholder the "essence" of what they are as a product. The product communicates, via its specific forms, their arrangement, and its details, something about what the product is and does—what it "means" to the user or stakeholder (8.36. Figure).

family look. If there is more than one product in a product "line" that should look like they come from the same company and brand, then the visual features of the line of products should have some similarities as a “house style” (Tjalve, 1979, p. 100). Such similarities should not compromise the product human need, root cause, or functionality and ergonomic usability for the sake of “marketing." However, such integrating “family” features can be such as color, texture, edge radii, forms, and other visual features and details (8.37. Figure).

UTP Size Levels. Most all UTPs will fall within three general product size levels. Application of aesthetic principles should therefore be proportional and properly scaled to the relative size of the overall product and GPF. These three general levels are as follows.

small. This size level is for small, or often so-called hand-held level, products such as a mobile phone, electric toothbrush, digital camera, handgun or pistol, staple driver, power drill, etc.

medium. This size level is for medium, or often so-called desktop/tabletop level, products such as an inkjet printer, desktop computer, display screen, desk lamp, food processor, microwave oven, electric guitar, drone, toaster, etc.

large. This size level is for large, or often floor-standing level, products such as a refrigerator, lounge chair, electric stove, clothes washer or dryer, machine tool, riding mower, fork lift, etc.

extreme. This size level is especially large, and may not even be called a “product” by some due to the large size. Such would be vehicles, large construction equipment, military tanks, shipping containers, etc.

4.4.3. GPF Design Method Execution

Concept Sketching. Prior to CAD modeling of GPF, it is recommended that a certain preliminary level of manual sketching, either analog or digital, take place to roughly conceptualize preliminary product concept form directions. These can be simple, orthographic or pictorial, rough product form idea-sketches in simple line work (8.38. Figure). Celebrated designers such as Dieter Rams (1984), Hartmutt Esslinger (2013), and Olivetti designers (Bellini, 2018), used such simple form sketches, and then moved to three dimensions as quickly as possible. These may also include rough orthographic and/or pictorial line sketch layouts of any specific configurations of components and elements. Once these are done adequately as an initial effort, one can move to precision, and even parametric, CAD “sketching” and modeling in CAD software. Often, however, going directly to CAD modeling can be done as well.

CAD Modeling. Designs, compositions, visualizations, and demonstrations for this project's GPF design language and method are to be eventually executed using CAD modeling, generally essential to final manufacturing (8.39. Figure). Though physical mockups are also to be used in parallel for kinesthetic feel and spacial/dimensional perception, much of the GPF design work is done with this medium that engineers are generally most familiar with. During the GPF overall creation steps, the form design should be executed in CAD based on the final product specified configuration and context issues.

The following CAD modeling protocols should be generally applied for general CAD modeling of GPF designs using this project method. Though AF360 is specified and used in this project, many other first-rate CAD software programs will have similar attributes and features.

> *workspace.* One should only create aesthetic GPF models in the SOLID modeling Design Workspace mode of AF360 that has geometric, solid, and mechanical modeling features. One should not create in the SURFACE mode for creating GPFs (8.39. Figure), as this mode is generally for OPF creation and can easily result in unreasonable forms. Everything needed to fully create GPF compositions is in the SOLID Design Workspace mode.
>
> *sketching.* Generally, the first step in modeling in AF360 (and generally in most quality CAD software) is creating CAD "sketches" prior to solid modeling. This initial process is very critical to successful and quality GPF composition creation, especially if using parametric modeling. It should be carefully understood and thoughtfully carried out first. Parametric GPF design generally starts within this CAD "sketching" process.
>
> *components.* When creating any new GPF compositions in AF360, one should generally create separate Components (8.39. Figure) for each distinct and discreet GPF composition or element, especially for the basic primary, secondary, tertiary, and quaternary hierarchical level forms. This especially goes for all discreet technical structures, frames, components, fasteners, and design elements. By doing this, each discreet GPF element may be modified and refined separately, as well as visualized, exploded, animated, and viewed in a composite GPF assembly. This approach also permits viewing each GPF discreet element/component form displayed in different distinct identifying colors, either separately, or in assembly, using the AF360 "Component Color Cycling Toggle" under the "Inspect" menu (8.39. Figure).
>
> *large to small.* GPF composition design in CAD modeling should generally be from larger to smaller forms, operations, features, components, and details. Adding smaller forms, features, elements, or details too early can cause modeling problems if larger forms are modified later before the composition is stable or near completion. The following sequential creation order is recommended:
>
> a. main forms—create the main, hierarchical level forms for the initial GPF composition first: primary, secondary, and tertiary;
> b. visual operations—apply desired and appropriate visual operations for further gross modification of the initial GPF composition hierarchical forms using the form variation and form division methods of Tjalve (1979);
> c. controls and signifiers—add control and signifier quaternary forms where appropriate and required;

d. visual details—lastly, add details such as edge radii, fillets, chamfers, colors, parting gaps, textures, venting, etc., appropriately as desired.

Physical Modeling. Though it is possible to create an entire GPF composition with purely digital means (digital sketching and CAD modeling), this is a somewhat risky approach since CAD models cannot be physically and kinesthetically handled, nor can they always be fully understood by others. Utilizing physical mockups, models, and prototypes is highly recommended for optimal product design results (8.40. Figure). The project synthesis method steps include physical modeling of product elements and components, at least for the relational configurations and the specified configurations of the product. After total product form is determined, a physical appearance model and functional prototype should be created for both visual and electromechanical evaluation. CAD models can generally be transformed via 3D printing or CNC machining into such physical models and prototypes.

4.4.4. GPF Design Method Detailing

The application of visual details is a critical activity for GPF language and design. The phrases, “God is in the details!” and “The Devil is in the details!” are appropriate here—applying proper form details can be a challenging effort, and often can “make or break” a final overall total product form design (8.41. Figure).

Edge Radii. Appropriate detailing of a GPF composition includes adding edge radii to all form and element edges (8.42. Figure). Nothing in the real world has a true “zero” radius edge. At the very smallest level, edges have a “radius” determined by the size of the particles making up the “edge." Nearly all product manufacturing processes inherently result in some radius on all edges, however small. It behooves the product designer to consciously apply an edge radius to virtually all GPF composition edges during the CAD modeling phase except for those that would be considered “sharp” (less than ~0.25mm) due to manufacturing or material forming processes (e.g., plastic injection tooling parting line edges and sheared metal edges).

The following are recommended principles for applying edge radii to aesthetic GPF compositions.

timing. During CAD modeling of GPF compositions the application of edge radii should best be done only towards the latter or end phases of the modeling process as a semi-final modeling step. This is because adding such edge radius details too early can be problematic if larger gross form changes are made before the GPF composition is fully completed. Such larger GPF changes can adversely effect the modeling integrity if too many edge radii have been already added.

dimensional range. For most manufactured products, common edge radii vary generally between 1 to 5 mm. This is the case with most all consumer products, furniture, instruments, and devices, among many others. Unless an edge radius is required particularly to be very small (as for a knife or blade edge), or very large (as with a safety or “softness” comfort requirement as in a child's toy or a device for arthritic users), this range of edge radii can be quite adequate. The relative size of a product and of its GPF components may also effect the choice of edge radii size. For example, a relatively small handheld product may best have smaller edge radii in the range of 0.5 to 1.5mm, whereas a desktop inkjet printer my allow for edge radii in the range of 2-5 mm. In addition, the type or application of a product may effect edge radii choices. For example, a toy of any relative size may best have relatively larger edge radii all around simply for the safety of the child user—perhaps in the range of 5-10mm or larger depending on the relative size of the toy (8.43 Figure). Other products that also may have ergonomic safety requirements may best have larger edge radii for "softness" at appropriate edges where there would be human interaction. For this project, edge radii larger than 5-10mm may be considered as radial or cylindrical surfaces.

dimensional variation. Regardless of how many main GPF elements are extant in a product form composition, using a single edge radius for all appropriate edges is the simplest and most easily executed. This approach of one edge radius for all edges has the risk of being less interesting or novel, but has the advantage of uniformity across a product family and brand. Selecting one edge radius such as 0.5-1mm for primarily handheld products and 2-3 mm for primarily desktop products can be quite adequate for such purposes. For reasons of interest, novelty, or visual variation and interest, the application of more than one edge radius to different edges of GPF compositions may be desired. However, using more than two or three edge radii is discouraged as being too visually confusing. Applying only one edge radius to any one distinct GPF volume is also encouraged—varying edge radii on different edges of the same compositional form may create visual "clutter" or unwarranted visual complexity.

corners. There are certain choices the GPF designer must make when executing edge radii that converge at a three- or multi-surface corner. For edge radii these are:

a. all three edges converging at the corner have the same edge radius dimension—this is the visually and aesthetically "safest" approach, though perhaps not as interesting or novel as other variations, and
b. when executing two or three different edge radii for the edges coming into a three-surface corner, the dimensional difference between the edge radii should be balanced between either not too close in radial dimension(s), or not too far apart in radius dimension(s)—both too close and too far apart in radial dimensions may cause a visually unattractive corner (8.42. Figure).

sophistication. There are certain edge radii variations possible when modeling GPF with AF360, and with many other CAD software programs. When GPF modeling a corner in AF360, there are two options:

a. the "rolling ball" corner, and

b. the “setback” corner.

These are aesthetic discretionary choices of the designer (8.42. Figure).

variability. Variable or “tapered” edge radii may be implemented on a GPF. However, this is not recommended in general unless there is some specific product ergonomic or functional requirement to justify it—variable edge radii can be unattractive (8.42. Figure).

large radii. There may be a case where it is expedient for ergonomic safety, visual interest, or functional form reasons, to add a large radius to an edge (and therefore create a large radial or cylindrical surface) that is in the range of 15-20 mm or larger. This radial dimension will depend on the relative size of the GPF, and would be identified more as a radial surface operation. Larger cylindrical radii tend to be form surfaces rather than edge radii (8.23. Figure). Such major large radius operations should be executed earlier in the CAD modeling process.

Edge Chamfers. The application of chamfers to GPF composition edges is only somewhat similar to applying GPF edge radii, but has more limitations and is less common (8.44. Figure). Edge chamfers, unlike edge radii, are rarely “required” in a GPF.

discretion. The application of edge chamfers to GPF compositions requires aesthetic sensitivity and judgement. The misapplication of edge chamfers can risk creating unattractive product aesthetics—they are aesthetically risky. Edge chamfers, by their inherent nature, also have two relatively “sharp” edges that are not always conducive to situations where ergonomic “softness” is required for safety or comfort purposes. If in doubt, use an edge radius instead of an edge chamfer (8.42. Figure).

timing. During CAD modeling of GPF compositions the application of edge chamfers should best be done only towards the latter phases of the modeling process as a semi-final modeling step. This is because adding such edge chamfer details too early can be problematic if larger gross form changes are made before the GPF composition is fully completed. Such larger GPF changes can adversely effect the modeling integrity if too many edge chamfers have been already added. In addition, if edge chamfers are applied to a GPF where edge radii will also be applied (this is almost certain), the order of application of chamfers versus radii must be considered—sometimes it is best to do one before the other for specific edge and corner treatments. This is often a case of edge radii applied first.

dimensional ranges. For most manufactured products, common edge chamfers can vary generally between 1 to 5 mm. This is the case with most all consumer products, furniture, instruments, and devices, among many others. Unless an edge chamfer is required particularly to be very small or very large, this range of edge chamfer can be quite adequate, keeping in mind that applying edge chamfers is generally an aesthetically risky discretionary activity. The relative size of a product and of its GPF components may also effect the choice of edge chamfer dimensions. For example, a relatively small handheld product may best have smaller edge chamfers in the range of 0.5 to 1.5mm, whereas a desktop inkjet printer may allow for larger edge chamfers in the range of 2-5 mm or more. For this project, edge chamfers much larger than 5-10 mm would be considered more as a shear operation (8.22. Figure).

dimensional variation. Varying edge chamfer dimensions on the same GPF, or where two or three edges come to a corner, is not recommended (8.44. Figure). Corners that join GPF edges that are chamfered can be a significant visual problem, which is why using chamfers on edges is visually risky.

sophistication. There are certain edge chamfer variations possible with CAD software programs. Varied edge chamfer angles other than the common 45 degree equidistant version may be implemented on GPF edge(s) and these can add to the aesthetic quality of an edge chamfer. This can provide an asymmetrical chamfer that is often more interesting and attractive (as on the Apple Lisa: Dresselhaus, 2017, pp. 8 & 51) than the conventional 45 degree symmetrical edge chamfer. This variation may be executed via setting two dimensions for the chamfer, or by setting an angle and a dimension. In the case of “tapered” edge chamfers, whether by tapered angle or by tapered dimension, these are not recommended as they are aesthetically “risky."

large chamfers. In a case where it is expedient for ergonomic safety, visual interest or perception (8.33. Figure), or functional form reasons, to add a large chamfer to an edge (and therefore create a surface) that is in the range of 15-20 mm or larger, depending on the relative size of the GPF volume, this would be identified as a shear operation that creates a larger angled surface. The transition from an edge chamfer to a shear operation is a dimensional gray area, but the point is that larger chamfers tend to be angled form surfaces (shears) rather than edge chamfers (8.22. Figure). Such major shear operations should be executed earlier in the CAD modeling process.

Parting Gaps. Each of the basic geometric forms of a GPF composition may be visually divided with appropriate parting gaps (commonly called “parting lines," though they are not technically just lines) to indicate a geometric form distinction, and/or reflect the realities of product manufacturing, accessibility, service, part joining, material, venting, texture, color, openings, doors, hatches, etc. (8.45. Figure). Parting gaps may be real (actual joining of two GPF parts), or simulated to either extend an actual parting gap, or as a visual separation feature.

Value and Color. The variation of a GPF surface treatment in value, color, or both, can add a significant level of interest, communication, and contrast to a product form. Sometimes this will depend on the surface material, or, by using such treatments as painting, the value and/or color can be varied widely. Color can especially and powerfully affect appearance contrast, or distinguish aesthetic and functional features, and should be used wisely (8.46. Figure).

Surface Texture. GPF surface textures can vary between polished to lightly dimpled to heavily convoluted and deep—the variety of surface textures and surface treatments available is nearly unlimited. The material of the surface will have a great influence upon what textures are appropriate or possible. Such treatments of GPF surfaces can have a strong visual affect on the appearance and the communication of the product features/forms to the user: contrast, distinction, functionality, usability, or simply aesthetic attractiveness and variation (8.47. Figure). Simply using different materials alone can create visual surface distinctions of texture, color, or value.

4.4.5. GPF Design Execution Method Steps

This project's GPF design execution method aims to be a definitive step by step product design process that can be taught to, and learned and executed by, engineering product designers, and others with STEM knowledge and skills. The method follows a “form follows context” principle where human need-finding, product design concept development, product context and parameters, and various synthesized factors from project research, are determined and applied prior to the execution of a final GPF design for the total product.

The following is the sequential GPF design stepped execution process that was synthesized in this project. It is based on the foundational principles found in the Project Results, Parts 1-3, and this author’s product design career experience. The process is proposed as a way to achieve adequate and attractive GPF designs for UTPs within engineering product design that will perform successfully with users, all stakeholders, and in the marketplace. An overview graphic of this design method process is summarized in the 8.12. Figure. Though presented as linear, this process is necessarily iterative as well, since each step may identify issues requiring attention in certain previous steps. Note that Steps 1-7 should be done before any total GPF design is attempted for the final product, since any proposed GPF composition should be based on the results of these first steps.

Step 1: Human Need-Finding and Early Product Concept(s) Design. The product concept design (PCD) five-phase process (8.12-1. & 8.13. Figures) is to be executed first to discover human need(s), their root cause(s), and design insights (IDEO.org, 2015). One or more human-centered initial product concepts are then created that resolve the discovered human need(s), root cause(s) and insights developed. These early concepts are then the basis for the next steps of product design and development, including the eventual total GPF design. The resulting early product concepts will preliminarily define the main product function and the sub-function transformations required (Tjalve, 1979, p. 6), the main product affordances (Norman, 2013, pp. 10), and the general product context (Alexander, 1971, pp. 15). This effort should include early ideas for functional means technologies. All of the results of this step should be documented in text, data, mockups, models, diagrams, sketches, video, photos, and CAD models as is appropriate.

It should be noted that the human need description, and even a product concept direction, may already be specified by others, such as by a corporate or startup marketing team. These may be right or wrong depending on how they were discovered and developed. Regardless, at least a minimal PCD exploration should be done to confirm any such preliminary product specifications. As Norman (2013) indicates, he never resolves the initial problem specification, as it is often wrong.

STEP 1 OUTCOMES: These should be—

a. specific human need(s) descriptions and the root cause(s) are the most important outcomes—without a found, validated, and defined human need and root cause (Norman, 2013, p. 43), there is no resulting product design that means anything, and
b. one or more rough product concept designs that meet the functional requirements of the found human need and root cause. However, these concepts are preliminary at this point and may be modified during Step 2.

Step 2: Determination of Product Context Attributes and Parameters. This Step 2, with Step 1, should ideally be done in tandem (8.12-1. & 8.12.-2. Figure). These product context parameters and issues should be determined within the total context of the found human need and root cause, and the proposed product concepts based upon the PCD results of Step 1. Use of a comprehensive product design checklist is highly recommended to cover all the context factors possible. A checklist of all potential related stakeholders and their issues should be developed at this point. Based on the results of this Step 2 and the human need and root cause results of Step 1, the product concept(s) from Step 1 are then modified appropriately to reflect the Step 2 context parameters and issues list to accommodate them as much as possible. A single “best” refined product concept should be then selected. The product concept main function and its sub-function transformations (Tjalve, 1979, p. 6) should also be confirmed so that they accomplish the required resolution of the human need, root cause, and human-centered product purpose and functional requirements.

STEP 2 OUTCOMES: These should be—

a. a single refined product concept that resolves the found human need, its root cause, and the context parameters from Steps 1 and 2 as combined results, but where the product concept is mainly transformational in nature,
b. a clear main function and its sub-functions that accomplish the product purpose of meeting the found human need and addressing the root cause, and
c. a comprehensive list of all context parameters and stakeholder issues as a preliminary Product Requirements Document (PRD).

Step 3: Determination of Product Functional and Sub-Functional Means. Once a transformational product concept direction has been determined, and the main function and its sub-function(s) transformations are determined that resolve the human need and the product purpose from Step 1, and the total product context of Step 2 has been evaluated and all contextual issues listed, then the various technological means for accomplishing the main product function and its sub-function transformations should be determined (8.12-3. Figure). Some functional means may already have been preliminarily determined the previous steps. There may be more than one main functional or sub-functional means for any single function or sub-function, and these different means may also be able to be utilized in different sets of means combinations. These different means sets will require different relational configurations for each possible set of functional means, and may also affect a variety of other design issues further down the process. This would especially include compositions of the total GPF.

STEP 3 OUTCOMES: These should be—

a. a comprehensive list of all functional and sub-functional means possibilities for each functional transformation of the product, and
b. a preliminary look at which different functional means can be combined into different sets of means to accomplish the product purpose.

Step 4: Create the Product Relational Configurations. Determine the possible product relational configurations ("basic structure" of Tjalve, 1979, p. 9) by schematically relating the functional transformation relationships of the product by their functional means. This process should be a two-dimensional graphic diagram using manual sketching or digital graphics (8.12-4. Figure). There should be one relational configuration for the product concept for each preliminary set of functional means from Step 3. As this Step 4 proceeds, more combination sets of functional means may be developed, and these should all be captured in diagrams of the resulting additional relational configurations. With multiple functional means, and possibly multiple combination sets of these means, there would thus be more than one possible relational configuration (8.27. Figure).

After diagramming and considering all viable relational configurations of means sets, try to eliminate as many of these relational configurations as possible due to non-viability or undesirability—the fewer options, the faster the design resolution will be. Again, the product main function and its sub-functions are product purpose transformations and should be firmly set—they are based on the determined product human need and root cause requirements, also firmly set.

STEP 4 OUTCOMES: These should be—

a. ideally one, but no more than a very few, selected relational configurations for the product concept in diagram form, with functional means identified clearly for each, and
b. a list of all functional technology means specifications for all relational configurations.

Step 5: Create All Product Functional Means Simulations. From the Step 4 list of functional means specifications, create both CAD models (Dresselhaus, 2016, p. 37) and physical mockups (Tjalve, 1979, p. 184-185; Dresselhaus, 2016, p. 75) of each of the functional means elements and components required. Ideally create these at full scale (extremely large products may require scaled physical mockups). Both methods are recommended to be done since digital CAD design lends itself to further refinement and precision, while physical mockups, though perhaps not as detailed, lend themselves to a physical and kinesthetic "feel" and spacial arrangement (8.12-5. Figure).

These simulations can start with only key schematic physical features, but with accurate dimensions. This dimensional accuracy will lend itself later to easier further refinement and details, both digital and physical, as the process proceeds and gets more advanced. In using AF360 for CAD modeling, each product functional means element and component should be modeled as separate AF360 Components for best manipulation and refinement (8.39. Figure), possibly even as separate discreet model files for later use in multiple specified configuration assemblies.

For the physical mockups, a variety of methods and materials may be used, including, but not limited to, cardboard (rough), foam (rough), illustration board (precise), wood (precise), or toys and parts such a Legos®, or with 3D printing technology (precise and detailed), among others, or by combinations of these (8.40. Figure). It is also a good idea to create multiple copies of the physical element and component mockups to allow for varied iterations of specified configurations. If there are multiple functional means options there will likely be more than one specified configuration to compare for each product relational configuration. Thus, why more than one set of physical mockups needed for each of these (CAD models can be used multiple times, so only one of these is necessary for each functional means). The actual means components or elements can also be used, but this is not recommended since these will likely be heavy, rare, expensive, and harder to manipulate.

STEP 5 OUTCOMES: These should be—

a. a full set of product functional means elements and components modeled in CAD, at least with preliminary gross precise dimensions from specifications, ideally in parametric form, and in files that allow for multiple assemblies of means for multiple specified configurations, and
b. multiple sets of schematic physical mockups in light materials of all product functional means elements and components with precise gross dimensions and key conceptual features.

Step 6: Determine the Interaction Areas and Restricted Volumes. Most of these two factors may be determined for each of the product functional means components and elements at this time, both external and internal (Tjalve, 1979, p. 48)—they may be external human access related, or internal service or space related, such as for air flow, interconnection, etc. However, certain of these may also need to be created relative to the composed specified configurations as well, since there may be interaction areas and restricted volumes that only arise when the specified configurations are assembled (8.12-6. Figure).

When possible (now or during the next step), determine the size, shape, volume, and dimensions of each of these two factors, and where they are best located relative to the functional means, for product users, for relevant stakeholders, and the context checklist. These areas and volumes may depend specifically on certain functional and sub-functional means (technologies and components) utilized, or on the specified configuration they are included in. These areas and volumes should also be modeled in AF360 CAD, and as physical mockups, both for use in the specified configurations—simulations of interaction areas and restricted volumes should be treated as “components" that must be properly positioned and arranged.

STEP 6 OUTCOMES: These should be—

a. a full set of simulated interaction areas and restricted volumes modeled in CAD, at least with preliminary gross precise dimensions, ideally in parametric form, and in files that allow for multiple assemblies using them for future specified configurations, and
b. multiple sets of schematic physical mockups in light materials of all the interaction areas and restricted volumes, with precise gross dimensions and key conceptual features.

Step 7: Create Product Specified Configuration(s). Using sketches, physical mockups, and CAD models, create specified configurations (“quantified structures” of Tjalve, 1979, p. 12, and “architectural configurations” of Dresselhaus, 2016, pp. 83-84) with the product functional means elements and component sets for each product relational configuration. These should be viable 3D “assemblies” that show specific architectural, structural, functional, and spacial relationships for a potentially viable product functional means element/component arrangement (8.12-7. Figure). It is recommended that one use all three simulation methods for this—sketches, CAD models, and physical mockups, appropriately taking advantage of each of method’s benefits and advantages. The specified configuration sketch versions can be drawn in multi-view orthographic mode, the CAD model versions can be assembled spatially, and the physical mockups versions will need to be creatively assembled in space by various means (Tjalve, 1979, pp. 184-185). Each specified configuration simulation should be captured via an appropriate documentation vehicle, such as screenshot, photograph, or video, for comparison, analysis, and reference purposes (8.28. Figure).

In addition, preliminary considerations should also be given to such issues as manufacturability, modularity, interconnection, service and repair, and other practical product design checklist and stakeholder factors. However, the primary goal at this point is functional performance and ergonomics/usability—total product design issues and details can be worked out during the detail engineering design of the product. It is especially important that all stakeholders of the product review the proposed specified configurations in both CAD and physical mockup form for design input and issues that any users/stakeholders may have (assembly, manufacturing, testing, service, safety, shipping, purchasing, etc.). Ideally, only one final specified configuration should be chosen by team/user/stakeholder consensus, but at most only a very few.

STEP 7 OUTCOME: This should be, ideally, only one final team-selected relational configuration and one consensus-selected associated specified configuration of the product concept component and element assembly—more of either of these will require more work and time to resolve the final product form and development.

NOTE: After Step 1 has been completed by determining the human need, root cause, and main function and purpose of the product, with rough concept designs, *most all of the work after that, and up to this point, is primarily "engineering" based: functions, technologies, components, means, configurations, technical relationships, specifications, etc. It is now that the final GPF design can be started, and the creative visual aspects of engineering product form design come into play. It is fruitless to attempt to determine a final GPF for a product prior to this component and element specified configuration work. But, such as is often the case, making dozens and dozens of industrial design concept form sketches prior to this point is wasteful—it is now that a reasonable and logical potential GPF can be created by using the preferred specified configuration(s) developed through these steps to this point.*

The good news is that it is also now that the creative visual aspects of engineering product form design can be implemented. This will take visual and aesthetic sensitivity, craftsmanship, and care, and using the GPF design language and method factors from this Project Results.

Step 8: Creation of the Total GPF Design. This is the step, and its sub-steps, that determine the total visual form composition of the product design (8.12-8. Figure). As with all the steps so far, this will be an iterative process. There may be reasons to go back to previous steps and readdress certain issues that may need to change, which may effect this form-giving step. Keep in mind that even when the relational configuration and specified configurations are well done with existing components, elements, and technologies, these may still result in unattractive overall product form design possibilities—too big, too convoluted, too complex, too "fat," too heavy, etc. This may then require finding better components, structures, and/or elements, or even designing/inventing new ones, that better fit what would be superior overall product form design possibilities.

These are the Step 8 sub-steps for creating the overall GPF:

a. With the engineering product design team, be certain that the PCD process is well done and the determined human needs, root causes, and the transformational product concept are optimum.
b. Thoroughly evaluate the final selected product relational configuration and its final associated specified configuration(s) for the product concept. Try to select a single specified configuration as the most optimized to be further developed and enclosed via GPF design. If more than one is considered viable and necessary to be explored, minimize these as much as possible and as quickly as possible.
c. Explore enclosing the selected specific configuration(s) with geometric volumes. A starting point would be a single rectangular prism, or a right cylinder, or combinations thereof. Consider the primary, secondary, and tertiary form levels, with possibly starting with the intersect visual operation. This can be done most easily by first printing the pictorial and orthographic views of the modeled CAD specific configuration(s), manually sketching GPF over them in all three views, and pictorially in perspective views, and then modeling these sketched concepts into CAD

over the specified configurations. After some work, this will provide several preliminary overall gestalt GPF options. These options should be captured visually with screenshots and photos for reference.

d. As appropriate, apply visual operations singularly, or in combination, to the GPF rendition(s) created above in CAD models. This may take several iterations and operations to get attractive results. Each GPF version should be captured by saving the form composition in CAD for later reference as well as taking a number of screen shots of various views for visual review.
e. After exploring these visual GPF options, select a maximum of three of the "best" gestalt overall product form composition renditions for detailing. Only select the three (if that many) that the engineering product design team would approve of for final design if any of the three were finally chosen (it is <u>not good</u> if marketing or top management chooses to finalize a form design that the engineering product design team is not committed to!).
f. To the three selected "best" gestalt overall designs, add the appropriate quaternary forms and features appropriate for functional and visual requirements, e.g., actual and simulated parting gaps, edge radii, air venting, signifier and control details, surface texturing, color and value, etc. There may be several variations of these quaternary features and details for each of the three versions. These quaternary additions may also effect the overall form design as well.
g. Visually examine carefully the CAD models in their un-rendered forms created from the above sub-steps. Are the product functions, affordances, signifiers, and usability clearly visually communicated (Norman, 2013, p. 10)? Are the total product forms unified, simple, concinnous, and attractive (Coates, 2003, pp. 243-245)? All visual, functional, ergonomic, and stakeholder aspects of the three proposed designs should be evaluated by the appropriate actors—essentially a comprehensive design review at the design and engineering level prior to any management/client review.
h. Make any modifications and refinements necessary to visually refine and detail the designs and forms based on the design review above.
i. Create realistic CAD model renderings in various viewpoints of each of the final three renditions of the total product form design.
j. Create physical external appearance models with all external visual detailing of the three form design options.
k. Review the three design renderings and appearance models as appropriate with the engineering product design team, user/customer team evaluators, and client/management for refinement and final choice of a single version.
l. Per this high-level design review, refine the CAD model and appearance model of the final chosen design to reflect the design review results.
m. Create realistic renderings of several canonical views of the CAD model and a final appearance model from the CAD model for photography and presentation.

STEP 8 OUTCOME: This should be one single GPF final product form design, presented in photo-realistic CAD renderings and a precision appearance model, that communicates product functionality, usability, and aesthetic beauty!

Step 9: Product Total Electromechanical Design and Details. Based on the final product form design, complete the overall product design and development of all engineering design details and design for manufacturing, and with all stakeholder issues resolved (Dresselhaus, 2016, p. 97). This is in the 8.12-9. Figure.

STEP 9 OUTCOME: This should be a thoroughly designed and engineered final product system ready for manufacturing and production.

Step 10: Ship It!!! (8.12-10. Figure)

STEP 10 OUTCOME: This should be a successful product launch with market profitability.

4.5. Part 5: GPF Language and Method Demonstration (Results)

4.5.1. Part 5 Objective (Results)

The objective of this part of the Project Results was to present a demonstration of the project's GPF design language and method developed in Part 4 after applying it to several existing product designs and to several so-called common converged product designs. This demonstration is here visualized and presented in various simulations and images.

The GPF design method proposed in this project was validated and demonstrated using two different approaches. The first was by reconstructing existing product designs into their main compositional forms. The second approach was to construct common converged products into their composed GPFs.

4.5.2. GPF Deconstruction Demonstrations

Existing GPF Product Designs. These products were selected and then broken down into their respective gross aesthetic geometric form compositions via CAD modeling in AF360. The demonstrations show the breakdown of existing product designs into their hierarchical components of primary, secondary, tertiary, and quaternary forms, and are referenced to visualizations in related figures.

desktop simulator. Manufacturer: Zycad Corporation; Design: Dresselhaus Design Group—Gary Gehrke and Bill Dresselhaus.

The three main forms for this product are:

a. the main enclosure body (primary form),
b. the rear interconnection body (secondary form), and
c. the front bezel (tertiary form).

The quaternary forms are the thermal venting, the front bezel controls and indicators, and the rear interconnection details. Shown also are the interior components and structure around which the GPF was composed (8.48. Figure).

large simulator. Manufacturer: Zycad Corporation; Design: Dresselhaus Design Group—Gary Gehrke and Bill Dresselhaus. This floor-standing simulator product was mechanically packaged and form-designed by this author's product design firm. Though the product was relatively complex in its interior, the exterior form was essentially an intersection of three cuboid forms with added edge radii, value, color, and texture.

The three main forms for this product are:

a. the main enclosure body (primary form),
b. the intersecting main body form (secondary form), and
c. the front bezel column (tertiary form).

The quaternary forms are: the front panel textured surface, the thermal venting, the front bezel column controls and indicators, and the rear interconnection details. Shown are also the interior components and structure around which the GPF was composed (8.49. Figure).

atmosphere controller. Manufacturer: TransFRESH Corporation; Design: Dresselhaus Design Group product design team. This carbon dioxide and oxygen monitor and controller was designed for keeping global in-transit fruits and vegetables from being spoiled during shipping in cargo containers. It was mechanically packaged and GPF-designed by the product design consulting firm.

The three main forms for this product are:

a. the main front enclosure (primary form),
b. the rear enclosure (secondary form), and
c. the front panel (tertiary form).

The quaternary forms are the front thermal venting, the rear electronic and gas port connections, and the gasket details. Shown also are the interior components and structure around which the GPF was composed (8.50. Figure).

Converged GPF Product Designs. Products that have been around for some time, and have consistently been composed of GPF, are so-called converged products due to their common legacy use. These were conceptually broken into their basic GPF as a demonstration of how they are created and have become converged in form. The following demonstrations show product designs in existing product categories based on contemporary features, functions, ergonomics, and forms. These products generally have nearly identical functions and usability, and therefore also have converged common gestalt forms. Thought the gestalt overall forms of these are very similar, shown are GPF detail variations that make them distinctive.

digital projector.

The two main forms of this product are:

a. a rectangular prism for the main body (primary form), and
b. a right cylindrical form for the lens (secondary form).

A third form (tertiary form) may be added for interest and various visual form operations applied appropriately if desired. The quaternary feature forms would be the connector bank, the controls, and the air venting. There may be other quaternary forms (8.51. Figure).

espresso machine.

The three main forms for this product are:

a. the vertical base column form (primary form) with water container,
b. the top delivery form (secondary form), and
c. the base tray form (tertiary form).

The quaternary feature forms are the controls, the delivery mechanisms, the gratings and venting, and any fastening details (8.52. Figure).

interactive kiosk.

The three main forms for this product are:

a. the frontal display form (primary form),
b. the support column (secondary form), and
c. the base form (tertiary form).

The quaternary forms are any controls or venting or other details (8.53. Figure).

various converged products. Display screen, checkout machine, desktop printer, and computer tower. These converged products are executed with less detail in this case for demonstration purposes (8.54. Figure).

5. PROJECT DISCUSSION AND CONCLUSIONS (D. & C.)

This section discusses the Project Results, relevant issues, and related conclusions.

5.1. Part 1: GPF Design Education Evaluation (D. & C.)

The results and success of these early GPF design experimental courses for engineers (8.5. & 8.6. Figures) points to much better teaching success in the future. The learnings from this experience were directly applicable to this project's synthesized GPF design language and method. This more defined and refined prescribed framework can and should be taught in engineering courses again to validate its viability. This is proposed in the Project Recommendations section. Due to its logic and simplicity, GPF design appears to be an excellent method, when properly taught, for engineering product design in both learning and execution without intervention by industrial designers.

5.2. Part 2: GPF Common Use Analysis (D. & C.)

5.2.1. Red Dot Awards Competition Results

As can be seen, these data results (8.7. & 8.8. Figures) from this product design awards competition indicate that not only is GPF design language a common and viable product form-giving method in all categories of the competition, but is predominant in more technical product categories. Consciously or unconsciously, intentionally or unintentionally, many of the various designers/firms in the competition clearly used a GPF design language and method for the selected GPF designs. It should be noted that, as this project targets as well, the highest use of GPF design was primarily in the UTP related categories.

It should also be noted that although many of the Red Dot Award competition products were not logged as being GPF due to their apparent OPF character or features, it appears that many of them could easily be transformed into very similar GPFs without seriously compromising their original OPF design intent. This is proposed as a research project in the Project Recommendations section and would potentially support the idea that in many situations OPFs are simply not necessary.

5.2.2. Celebrated Designers/Firms Results

As can be seen in this case, as well as for the Red Dot competition, these data results (8.9. & 8.10. Figures) from celebrated designers/firms, and primarily of UTPs again, indicate that even the best of globally recognized product design work is based on a GPF design language. Here again it should be noted that the celebrated designers/firms may not have consciously or intentionally created their product designs via a systematic GPF design language or method—it is not articulated or mentioned in the sources for this analysis. However, the product designs identified are clearly GPF in nature from their photographs. It may be that GPF is the designers/firms "natural" and intuitive GPF language and method, though unstated. Or, they may realize they are using a GPF design language and method, but are unwilling to admit so, thus “saving face” for using such a prescribed and definitive approach.

5.2.3. GPF Language Demonstration.

As can be seen from the 8.11 Figure, where several of the Red Dot Award products are deconstructed into their GPF compositions, these products are clearly composed of geometric forms and have a geometric aesthetic form structure.

5.2.4. GPF Utilized Language

Again, as with the early education courses, both the Red Dot Award designers/firms and the celebrated designers/firms used the same GPF language elements and details for creating their product designs. This confirms an arguably universal approach to GPF design when it is utilized by a broad cross-section of designers/firms. Their form language includes such GPF features as uniform edge radii, rectangular prisms, right cylinders, radial curved surfaces, visual operations such as shear/shift/intersect/rotate, and geometric signifiers and controls.

5.3. Part 3: Existing Design Form Principles (D. & C.)

As this project unfolded, it was surprising to find that these principles were already extant and presented in definitive, logical, and orderly geometric frameworks, but mainly in related areas to product design such as architecture and graphic design. It is notable that few of the directly applicable or stated principles came from industrial design sources. The bulk of academic industrial design form research was nearly useless in creating a definitive and prescriptive design language and method. It seems that discipline consistently eschews formal methods of product form creation as limiting creativity and artistic freedom. Most of these principles also came from “older” design and engineering books (Tjalve, 1979; Coates, 2003; Ashford, 1969; Cain, 1969; Alexander, 1971), and also from “older” celebrated industrial designers/firms such as Rams/Braun, Esslinger/Frog, and Sottsass/Bellini/Olivetti (Klemp, 2020; Esslinger, 2013; Bellini, 2018). In addition, the historical record in architecture of geometric form design is the “oldest” of all, going back millennia (Elam, 2011; Bass, 2020).

One possible explanation of these principles being predominantly from “older” resources is the philosophical trend today away from the idea of objective or absolute truth, and toward subjective/relative truth (Pearcey, 2017). In tune with that mentality, there is a general feeling today that there is, nor perhaps can there be, any logical or objective prescriptive approach to product form design—it is purely personal and subjective (Alexander, 1971, pp. 10-11).

5.4. Part 4: GPF Language and Method Synthesis (D. & C.)

Once the principles in the Results section of Parts 1-3 were considered altogether, synthesizing them into a GPF design language and method was exciting. It should be noted that much of the early project's GPF design process is based upon the Tjalve (1979) overall method. However, this book was not discovered by this author until later during the delivery of the engineering courses on product form design at HongIk University (2016). However, this author, after reviewing the book carefully and completely, recognized that his own process throughout his product design career was quite similar to the Tjalve process. This was so much so that it was quite surprising to see it so completely presented and amazingly familiar. Many of the principles used in that process were nearly identical to what this author had professionally practiced for decades. Tjalve had given names and clarity to much of what this author had often practiced. However, though Tjalve utilized a clear geometric form approach, he did not articulate or define in detail such an approach, which is what this project is primarily concerned with.

5.4.1. GPF Design Execution Method Steps

This project's synthesized GPF design language and method is essentially composed of three parts, all influenced and integrated with the learnings from Parts 1-3.

a. Step 1 is the product concept design process this author learned from his product design and visual thinking education at Stanford University in the 1970s, and refined over the years.
b. Steps 2-7 are primarily the Tjalve (1979) methods and process, refined and adapted for this project.
c. Step 8 is the core product form creation using the synthesis of all the found and discovered design principles, applied as a specific and definitive GPF product form language and method of geometric principles, and from previous learnings.
d. Steps 9 and 10 briefly complete the product design and development comprehensive process.

5.5. Part 5: Demonstration of GPF Language and Method (D. & C.)

The 8.48.-8.54. Figures indicate that the GPF design method prescribed in this project can be executed to create attractive GPF products. This is demonstrated as a viable GPF design method for UTPs. In this project's GPF demonstrations, several existing products have been used as a basis, though throughout the various Figure demonstrations and simulations there are also new GPF creations. In the Project Recommendations section is a proposal for developing new, real-world, complex UTP specifications to test the GPF method on, as Tjalve (1979) does in the last chapter of his book (Chapter 5).

5.6. The Geometric Advantage

OPFs may be required in certain situations such as in products with aerodynamic needs (e.g., airplanes, rockets, and some high-speed ground vehicles), or in those with fluid dynamic needs (e.g., water craft), or in human ergonomic needs (e.g., body conformable devices such as seating or head devices). But GPF design, due to its familiarity, objectivity, and logical simplicity, will tend to increase objective concinnity (Coates, 2003, p. 192). In the case of subjective concinnity (p. 218), this project bypasses some of Coates' principles on this topic and redefines this term as being relative to personal and primarily cultural/societal differences.

Geometric forms have high objective concinnity and human understanding. Tjalve (1979, p. 147) agrees that, "it is natural [for humans] to think in terms of [vertical and horizontal] directions." Elam (2011, p. 5) quotes the famous graphic designer, Max Bill, as saying that mathematical thinking can be a foundation for an art form. She also quotes the master painter and engraver, Albrecht Dürer, as stating that one cannot be a true artist without geometry. Le Corbusier (1931) states that "Geometry is the language of man…." Bürdek (2015, p. 161) talks about geometric design and forms as an "integral" approach.

GPF design, when done well, has a number of advantages over OPF design. These advantages are presented and described below, as well as some of the disadvantages of OPF design and why.

5.6.1. Execution

Systematic. A functionalist, geometric-based product form-giving approach can be systematized into both education and application methods, and learned and executed by capable engineers as hybrid product designers (Dresselhaus, 2018; Jee, 2012). This empowers a new breed of comprehensive engineering product designers that, contrary to most industrial design education, combines an application of STEM knowledge and product functionality with attractive product aesthetics design.

Objectivity. GPF compositions tend to have more "objective concinnity" (Coates, 2003, p. 211) due to their simple mathematical and familiar nature. The more objective concinnity a product form has, the more understandable (Norman, 2013, p. 3), logical, and aesthetically durable and sustainable (Harper, 2017, p. 3) it generally will be. In contrast, OPFs, by their complex and often arbitrary mathematical nature, tend to risk having more "subjective concinnity" (often from the designer), and inappropriate "novelty" (Coates, 2003, pp. 247-248), depending on their quality of execution. OPFs are therefore often more open to unattractiveness, decreased novelty over time, and short aesthetic durability and sustainability, especially if poorly done.

Simplicity. Contrary to the design of OPFs that are often generated arbitrarily (Tutorial Books, 2020b) with a complex mathematical basis using Bezier curves (or T-splines in AF360), GPF compositions are created with a very simple, clear, and basic menu of understandable (Krippendorff, 2006, p. xiii) forms and operations. These forms are primarily rectangular prisms, right cylinders, and parts thereof, as well as planar and radial surfaces, all generally with rectilinear and orthogonal alignments.

CAD Modeling. GPF compositions lend themselves more easily to CAD modeling design, modification, and refinement than do OPFs (Tutorial Books, 2020a). CAD design of straight lines, radial curves, flat surfaces, cylindrical surfaces, basic geometric volumes, and simple radii, chamfers, and similarly simple geometric features and details, are easier to create than are the complex organic equivalents. Such complex OPFs are often difficult for even experienced CAD modelers to create, where organic surface joinery, closure, and manufacturability can be problematic.

GPF compositions can also be easily created in the solid modeling mode of a CAD modeling program that also has parametric capabilities as well as materials, weight, CoG, FEA, assembly, animation, design documentation capabilities, rendering, realistic physics, and geometric constraints. OPF designs are generally required to be created in a so-called “sculpting” CAD surfacing environment or mode, and are often subject to unrealistic and arbitrary variation and risk of unmanufacturable forms. The OPF results from novices, such as students, can be unpredictable, unattractive, lumpy, inconsistent, and unmanufacturable.

Modification. GPF compositions lend themselves more easily to modification and revision. When GPF features need to be added, removed, or refined, this can be more easily done than with OPF features due to the simplicity of the geometric forms. Especially when large or small dimensions or volume changes to GPF compositions are required due to functional issues, component changes, or brand needs, these are more easily accomplished than with OPFs that have complex and arbitrary surfaces and volumes. OPFs may change visually and aesthetically negative when modified significantly and lose their original design form intent. In addition, GPF compositions can more easily be adapted to parametric modeling since geometric forms lend themselves to simple dimensioning (Shih, 2019).

Handoff. In the case of a binary paradigm, such as the ID/ED system, when creating the product aesthetic form first by industrial design (ID), and then giving it to engineering design (ED), GPF compositions are more easily and reliably “handed off” from the initial ID form creators to ED or manufacturing (Dresselhaus, 2016, p. 102) . With the handing off of OPF surfaces from ID to ED it is often the case where such surfaces are not easily reproduced in the CAD environment of engineering, or, even with the same CAD environment, there may be design issues to resolve by ED that require modifying the original form design intent (p. 38). Such ED changes to OPF surfaces can be problematic design intent changes, whereas GPF surface changes are more easily dealt with and resolved.

5.6.2. Form

Curves. Geometric form design does not exclude curves, though such curves and curved surfaces are radial or cylindrical, and are not complex organic curves or surfaces. Many arbitrary OPFs can be reconstituted with geometric forms and radial curves that are more defined and precise. The arbitrariness of sculptural organic forms is frequently unnecessary.

Precision. GPF compositions are generally perceived as having a “natural” and inherent precision and craftsmanship, generally seen as a positive aesthetic factor. The orthogonality, flatness, radial curvatures, and arrangements of the various geometric forms are perceived as precise and ordered. The familiarity of precision making methods, either manually or by machines, as applied to manufactured objects, adds to this human perception of precision and quality.

Description. GPF compositions lend themselves to simpler and more efficient technical, engineering, and manufacturing description. They can often be described with simple drawings, or even hand sketches, with linear and radial dimensions (Tjalve, 1979, p. 147). Complex OPF surfaces can only be described via master physical surface models or digital CAD models, and rarely by simple, straightforward dimensioning. In addition, OPFs cannot be easily measured or verified regarding precise design intent, and thus be potentially compromised over time with little detection. Often, only sophisticated digital surface scanning comparisons can detect organic design form intent flaws or shifts. Not so with geometric surfaces and forms.

5.6.3. Aesthetics

Attractiveness. Even though any responsible product form design must first “follow” appropriately from a product’s context of functionality, usability, ergonomics, manufacturing, signifiers, and affordances (Alexander, 1971, Preface), it must also appeal to human aesthetic sensibilities (Norman, 2013, p. 4). Creating GPF compositions has many opportunities for creative, unique, and attractive aesthetic options available to the product designer.

Family Look. GPF compositions are more amenable to an aesthetically durable product “family look and feel” (Tjalve, 1979, “house style," p. 100) as well as a sustainable “brand look and feel” than are OPFs. Geometric forms, being inherently based on simple, recognizable, and familiar mathematical shapes, can be visually related more easily across a family product line, even by different designers, and even by different companies, when geometric form is used. Using GPF compositions as a corporate brand language can be more successfully “styled” and implemented than artificially created OPFs.

5.6.4. Usability

Order. The human mind, when viewing an object (such as a product form composition), first attempts to create a logical and unified (gestalt) visual order out of what it sees (Tjalve, 1979, p. 100; Arnheim, 2004a, Chapter 2). GPF compositions, when properly created within the primary, secondary, and tertiary hierarchical framework (Hannah, 2002, p. 52-53), with understandability and discoverability factors (Norman, 2013, p. 3), and information and making sense aspects (Coates, 2003, p. 26; Bürdek [on Butter], 2015, p. 183), they lend themselves to a quickly recognizable order better than OPF compositions.

Understandability. GPF compositions are more easily understood by both users and creators, and therefore developed and executed more easily by product form designers. OPFs are often arbitrary and subjective, and more complex to understand and execute, often requiring skills with Bezier curves, or T-splines, and complex surface design. GPF compositions have an inherent visual logic to them due to their simple mathematical basis and human familiarity (Coates, 2003, p. 155; Tjalve, 1979, p. 147). On the other hand, OPFs are mathematically complex, often without an associated and obvious rationale or logic. Norman (2013, p. 3) indicates that understandability is a very critical key factor in a product design.

Familiarity. This project is about designing UTPs for generally developed, modern cultures, and where both culture and creator have a familiarity with geometric forms. This familiarity only enhances the logical understanding of such forms and the ease of design. Consider the very common children's early toys of simple geometric building blocks, or even the globally common Lego® brand toys composed of a multitude of geometric block forms, mostly of rectangular and cylindrical forms.

5.6.5. Sustainability

Modularity. GPF compositions lend themselves better to a modular design, important to product sustainability, where the interface, interconnection, and fastening designs are critical between modules, including third party accessories or components. Geometric modules and interfaces are less complex than organic ones and much simpler to create, maintain, specify, and fit together. Regardless of a product external aesthetic form, most internal technology components (e.g., fans, drives, connectors, chips, displays, frames, motors, power supplies, and circuit boards) will be generally geometric in nature due to manufacturing favoring geometric, rectilinear forms (Tjalve, 1979, p. 147). 3D printing will change some of this, but not for everything.

Analysis. GPF compositions lend themselves more easily to CAD-based analysis and to auto-generation than do OPF compositions. Organic curves can be evaluated in CAD for quality of curvature and for refinement or improvement (Autodesk, 2021), but geometric lines, curves, and surfaces need little such analysis—they are already mathematically simple and consistently defined. Generative design can automatically create structurally "optimized" organic forms from various input parameters (e.g., interaction areas and restricted volumes), but these forms still require a designer's intentional and active refinement. Geometric forms would require much less "optimization" due to their geometric and mathematical simplicity, and require much less refinement. Often, generative design outcomes are highly organic and must be 3D printed—or converted to simpler geometric forms and elements that can be fabricated by more conventional means.

Manufacturability. GPF compositions tend to be easier to manufacture and lend themselves more easily to materials such as sheet metal, machining, or welding. As already noted, internal product components such as power supplies, fans, connectors, electronic components, motors, and printed circuit boards are also commonly geometric in form (Tjalve, 1979, p. 147). A geometric internal structure will lend itself to be more spatially optimal and easier to have a GPF enclosure and organize its internal geometric components and volumes than will an OPF enclosure. GPF enclosure parts are more easily and precisely fitted to one another than are OPF enclosure parts which have complex 3D curved surface joints to mate.

Branding. By simply using a GPF approach, a brand will already have a family-based "look and feel" by nature of the consistent and inherent geometric forms and details (Tjalve's "house style," 1979, p. 100). In addition, the appropriate application of GPF details and materials, textures, and color features, can enhance a brand distinction in a more straightforward, understandable, and honest manner

(Rams, 1984). Applying arbitrary organic curves, surfaces, forms, and details to a product family purely to create a unique or novel "brand language" or "corporate style" can appear arbitrary, and risk aesthetic durability, brand recognition, and sustainability.

Quality Assurance. GPF compositions lend themselves to easier and simpler quality assurance and dimensional validation. Straight, orthogonal, and radial lines and corners, and flat and radial surfaces, are much easier to measure and dimensionally validate, even manually, than are arbitrary organic curves and surfaces that often require scanning to validate their precision, accuracy, and design intent conformity.

5.6.6. Education

All of the previous GPF advantages translate directly into the teachability of GPF design, especially to engineering product designers. The GPF design language and method will especially resonate with those who already have a solid STEM education in many areas already heavily based on basic geometry and CAD solids modeling. Integrating and incorporating such a language and method for aesthetic GPF design into an engineering product design and development process will be much easier and simpler than one based on OPF design (Dresselhaus et al, 2018).

5.7. General Comments and Conclusions

5.7.1. The Engineering Product Design Option

In the end, it is believed that the GPF design language and method synthesized and prescribed in this project is quite viable and adequate as an aesthetic product form-giving method in a holistic approach to engineering product design—clearly defined, logical and reasonable, effective and efficient, and quite applicable. It is especially valid for the holistic design of UTPs by engineering product designers, especially by mechanical engineers, mechanical designers, industrial engineers, and engineering technologists. This is assumed to be true due to the potential of the extensive STEM education and capabilities of engineers, but coupled with an appropriate training in product form and visual aesthetics, making them the better product integrators of both aesthetic form and technical knowledge. Regardless of desire, all engineers should be minimally trained in form and aesthetics basics since, as has been previously stated, all engineered objects have the inherent attributes of form, appearance, and language, whether one likes it or not, and therefore must be properly addressed even at the lowest levels for responsible engineering design (de Vere, 2009; Faste, 1995).

However, whether or not any engineers will take on this additional role of aesthetic product form-giving in a holistic engineering product design process is not clear. Or whether engineering schools will even allow for any basic training in aesthetics or visual design. The early educational experiments at HongIk University by this author (Dresselhaus, 2018; Jee, 2012) indicated that engineers can learn and do this activity quite well, as the students demonstrated with enthusiasm and interest. But there are still engineering academic and cultural barriers to making this a reality.

On the academic culture side, the common complaint of engineering schools is, “There is already too much to learn in engineering without adding more courses!” On the business culture side, industrial design has already gained such a foothold in industry as the “owners” and “experts” of aesthetic product form-giving, that an engineering approach to this may be difficult or impossible to foster. Industry has been brainwashed for decades that it is industrial design styling that creates product demand and is the competitive edge. Of course, as Ashford (1969, p. 1) states, it has been the engineering schools and its tutors, and engineers themselves, that have helped create such an environment. Only time will tell if engineering schools, academic engineering instructors, and engineers themselves, will embrace such an approach to holistic engineering product design as proposed in this project. Without that effort and a demonstration of its success, industry acceptance is impossible. Otherwise, this is just another doctoral project to put on the shelf.

5.7.2. Product Form Optimization via Concurrent Iteration

Design Optimization. Clearly, the goal of the proposed stepped process (8.12. Figure) is to ultimately create a final product form design that optimizes both the outside and inside of the whole product system—an attractive and appealing external visual form result that conforms to the product context, functionality, usability, and ergonomics, but that also has logical and sensible relational and specified configurations (8.27. & 8.28. Figures) that meet all stakeholder and context parameter issues. There must always be a sensitivity to this optimization issue—though beauty is the last level of design concinnity after function and usability (Coates, 2003, p. 39), attractive form and appearance remain highly important. Optimizing a product design holistically must be addressed properly. This somewhat relates to Coates and Plato regarding their “ideal" forms (Coates, 2003)—the idea that a product’s overall form may “want” to be, or “should” be, of a certain aesthetic, usability, ergonomic, and functional character.

For example, the proposed stepped process may end in a number of possible specified configurations due to functional component and technology requirements, but with potential product form designs that are not optimal: either too large, too heavy, too awkward, too dangerous, too unattractive, or worse. This would result in either abandoning that particular specified configuration, or potentially revising or reinventing better components and/or technologies for a better “fit”, or compromising the context requirements, parameters, technologies, or components (the latter being an undesirable approach).

A Select Few. Applying the proposed stepped process may, then, in many cases, not result in an attractive overall form in the end, regardless of the effort. Obviously, for a complex UTP composed of many different functional components, there will be a myriad of possible specified configurations, viable or not. This author’s professional experience has found that most of these will be (often clearly obvious upon only brief consideration) not viable for a variety of reasons, and properly abandoned. Out of all possible specified configurations there will likely be only a few that are viable and worthy of consideration—those that obviously make logical sense and order, and conform to the design parameters, but also have good potential GPF possibilities.

Form Concurrency. The solution to this dilemma of creating an optimal outside/inside product form and configuration design via the proposed stepped method is to include an approach of concurrent iteration. Just as in concurrent engineering process (Prasad, 2011), when executing the proposed stepped process of product configuration design and aesthetic form-giving, both of these must be simultaneously considered on an initial/immediate conceptual level. This means concurrently looking at potential aesthetic exterior forms that relate to the specified configurations as they are developed—considering both outside/inside forms/ architecture as each specified configuration is assembled. The proposed method correctly delineates the creation of specified configurations, but potential exterior form concepts must also be considered concurrently so that each specified configuration has a potentially desirable external form. Frankly, this means that each developed viable product specified configuration would also be driven by potential exterior aesthetic form possibilities simultaneously.

Design Iteration. After applying the proposed GPF stepped method, and confronted with a viable specified configuration and accompanying viable exterior aesthetic form concept, but that are not quite "fitting" optimally together, iteration is required. The methods of form variation and form division, configuration variation, and possible redesign of functional components, can be used iteratively to refine and bring both the specified configuration and the GPF aesthetic form into an optimal integrated relationship.

Best Practice. The main objection is against using two unfortunately common and dysfunctional approaches: a) where industrial design aesthetic product "styling" work is done first, but without proper engineering input (and often via only a profuse sketching approach), and then requiring engineering to force their work into a "pre-styled" product form that was improperly created without considering all of the relevant design parameters, and b) where engineering design alone determines both the product configuration and aesthetic form design, but without having any appreciation, sensitivity, knowledge, or training in aesthetics and form-giving process. Using a collaborative/concurrent iterative design process is the proper way.

However, for the hybrid holistic engineering product designer who can competently execute both product aesthetic form and product engineering configuration and structure, this author's Stanford product design mentor's admonition comes to mind. Prof. Robert McKim (1980) told his hybrid product design students that to do integrated binary product form/engineering well, one must be "schizoid", appropriately alternating between the right-brained aesthetic artist and the left-brained engineering designer.

5.7.3. The Engineering Technology Option

One potential solution to the product design education dilemma may be outside of both traditional engineering schools and traditional industrial design schools. Too often it is true that engineering schools go too far in teaching of complex engineering theory courses and not enough practical engineering application (Sheppard et al, 2008; de Vere, 2009). It has been this author's experience that often the better realistic and productive product designers have been those educated in engineering technology and basic mechanical design rather than in full mechanical engineering, some even only having had two years of engineering technology school. In a similar way, many European industrial design schools are adopting an "industrial design engineering" approach that combines more technology education with traditional industrial design (Zijlstra, 2020; Warell, 2001). Unfortunately, both the engineering technology approach and the industrial design engineering approach often continue to have their flaws—lack of form and aesthetic/visual training on the engineering technology side, and lack of solid STEM education on the industrial design engineering side. A primary purpose of this project is to remedy the engineering side of this issue.

The essential educational features of the engineering product designer in training and expertise are as follows:

a. external product visual form and appearance, usability, ergonomics, and functionalism;
b. internal component and structural configuration and design;
c. product level knowledge and data on materials, manufacturing, methods, technologies, and components;
d. holistic product design synthesis into a product whole based on comprehensive product context; and
e. acting as the default product system integrator between the various corporate silos, technologies, issues, and departments.

5.7.4. The System Integrator Function

Based on this author's professional product design experience, and as can be seen from this project's product design synthesis method, engineering product designers must deal with a variety of issues, departments, technologies, and components (Dresselhaus, 2016, p. 13). The engineering product designer is essentially, by default, whether recognized as such or not, a product system integrator (p. 11). In most cases, each relevant discipline of the stakeholders (Bürdek [on Krippendorff], 2015, p. 183) for a product design (e.g., marketing, sales, electronics, optics, testing, manufacturing and assembly, safety, shipping, purchasing, etc.), all basically deal with developing their particular technology alone for the product within their own silo during a project. This often leaves the engineering product designer as the default system integrator who must consider this entire set of silo results as context to holistically create a product design. Often this includes assisting (or driving, as it may require) each silo/department/stakeholder with the necessary various product parameters for their specialized solutions to be able to "fit" into the product development (e.g., form, size, and interconnection scheme of custom designed product components, or other technology modules, or branding/marketing/packaging schemes).

5.7.5. A Solved Problem?

Having reviewed a number of books, articles, and papers for this project, this author feels it is quite possible that good product design, especially engineering product design of UTPs, is essentially a solved problem, with much of the industrial design research notwithstanding—searching for some “holy grail” of a product form paradigm that allows complete “artistic freedom." Though Brezing & Löwer (2008) make it clear that industrial design has little to show for defined and orderly process, articles such as from Dieter Rams (1984) seem to clearly define a quite definitive and resolved approach to good product design, and he has also clearly demonstrated that in his own work. For good product design and development, especially in engineering and its education, that part has been defined well for some time (Norman, 2013; Cain, 1969; Ashford, 1969; Tjalve, 1979; Coates, 2003; Ulrich et al, 2020; Alexander, 1971).

If one follows the principles and processes in these seminal books, products to a large extent tend to “design themselves.” If, as these authors generally say, that a product’s function and context define its form, and if a product’s form is to communicate its function and usability, then much has already been clearly determined if it is properly investigated. The balance is for the product designer to apply logical principles and aesthetic sensibilities to finalize an already largely predetermined product form direction. Some “artistic freedom” is available yet, but it should not violate the product need/function/context/ergonomic/communication/durability/stakeholder direction already predefined.

6. PROJECT RECOMMENDATIONS

This project has made progress in creating a specific and definitive GPF design language and method for use by engineering product designers to design aesthetic physical product form within a holistic and integrated product design process. However, there is much that can still be done to refine and systematize this approach for both teaching and professional application, as well as investigate related categories of interest. Areas of further work are recommended below.

6.1. Are Engineers Interested?

An implied premise of this project is that there actually exist engineers who would be interested in taking on the visual product form design activities of industrial design as presented in this project. Whether or not this is true should be validated, though the early courses used in this project (Dresselhaus, 2018) clearly were occupied by interested engineering students. Such a research experiment should be a survey or questionnaire, properly designed, that would measure the interest of certain groups in their level of product form-giving desire. Such groups would be: engineering students, practicing engineers, engineering technology students, and practicing engineering technologists, and perhaps many others.

6.2. Visual Catalogue of GPF Possibilities

Though this project has already done much visualization of GPF design, creating an inspirational visual catalogue of possible GPF compositions could be beneficial as a design form reference. Di Mari & Yoo (2013) do some of this abstractly with basic geometric forms for architecture, and Ms. Kostellow in Hannah (2002, pp. 48-57) also does this for her three-form geometric hierarchy. She extensively explores organic abstract forms as well, as does Strebel (2015). However, this author feels much more could be done based on the form meaning concept of Krippendorff (2006, p. 58). Strebel's (2015) video of experimenting with abstract organic form is an example of how this might be done for GPF, but with a more definitive product purpose, context, and functional approach. A purely abstract approach can easily lead to useless efforts without the constraints of real product context (Alexander, 1971).

A printed and/or digital catalogue using only GPF compositions and details, applied both abstractly and to specific products, functions, and contexts could be created. Both physical and digital models could be used for the visuals and the experimentation. Parametric CAD modeling could also be utilized as well as 3D printing. Such a catalogue of forms could be published for inspiration and reference for engineering product designers, with a downloadable CAD model of each form available that can be modified as needed. Such a catalogue might include not only the main three-form hierarchy compositions (Hannah, 2002), but also GPF for controls, displays, venting, textures, and other product elements, details, and features that are often difficult to integrate aesthetically. Such a catalogue could also be updatable by others online, with added visualizations or CAD models of elements and designs. The visuals could include variations on existing product forms and converged product forms, as well as hypothetical ones. The possibilities for this are many!

6.3. Human Product Form Preference

Quite absent in the literature are rigorous scientific studies of the human perceptual preferences of actual GPF compositions versus OPF compositions. There is some existing work that states that geometric forms are more ordered, logical, and rational (Coates, 2003, pp. 197-201; Tjalve, 1979, p. 147; Ashford, 1969, chapter 4; Elam, 2011). There is also work that validates the golden ratio (and ratios near it) as preferred by humans (Coates, 2003, p. 200; Elam, 2011, pp. 6-7; Tjalve, 1979, p. 157; Bass, 2019; Meisner, 2018; Bejan, 2009). However, there seems little that specifically addresses human preference for geometric versus organic product forms.

The following are suggestions for three research experiments in this area. Such research might include a variety of functional products that would include consumer, technology, and industrial products.

Experiment #1. One research project could measure human cognitive preference between identically functional products whose gestalt forms are designed in both geometric and organic compositions. This should entail existing products, but would likely be difficult to find both renditions extant—perhaps re-modeling in CAD the existing version (OPF or GPF) and also the opposing version (GPF or OPF) for comparison.

One research avenue could be that of having multiple designers create such product forms, both existing and new products. One set of designers would do their best at geometric form, and the other set would do their best at organic form for the same identically functional products.

Experiment #2. Another approach could be to have a set of designers reconstruct existing OPF products as "twin" GPF alternatives. Then evaluate the comparison of the human preference responses to the two product form renditions, organic versus geometric, by users and consumers. This approach would be to redesign certain OPF products into very carefully reproduced GPF renditions, but using only geometric form. This would mean any bezier or organic surfaces would be simulated with radial and tangential geometric renditions as simply, but as closely as possible. Human preference studies would then be done to see which forms, OPF or GPF, were preferred, or if they could even be distinguished by normal users/ consumers. It would also be especially interesting to see if the effort to create the complex original forms was worth it, or if the geometric forms, possibly simpler and easier to construct, would be quite acceptable. In other words, does anyone care, or even detect, if something is OPF or GPF?

For these above experiments, questions should be asked and answered regarding the two form versions of a product, GPF versus OPF, such as:

a. Surveying a variety and number of consumers and users about a single product form design, and which version, GPF or OPF, is preferred aesthetically?

b. Surveying engineers and designers similarly, but regarding which version is faster and/or easier to create?
c. Surveying product users: which version seemingly accommodates usability better?
d. Surveying engineers and makers: which version accommodates manufacturing better?
e. Surveying retailers, distributors, shippers, and other stakeholders: which version accommodates shipping, storage, logistics, and packaging better?

6.4. Teaching GPF Design Language and Method

This project validates the use of GPF design and creates a systemized method for the design of GPFs for engineering product designers. The earlier product form design courses indicate that teaching a less refined language and method is successful. However, it would be incumbent to test this project language and method by teaching it to engineering product design students to validate its viability. This also suggests further work to provide a quality comprehensive instructional course for teaching GPF design composition to engineering students.

The content of this teaching would be in three parts:

a. an overview of comprehensive product design and development principles and process (essentially the Tjalve, 1979, process, with support from Ulrich et al, 2020),
b. an overview of basic aesthetic principles and their application to product design, and
c. teaching this project synthesized design language and method of creating aesthetic GPF for product design.

The instructional method would be delivered and validated via a visual slide set with related narration and instruction, either in an online course, or via a live onsite course. This instructional system would then be analyzed using various parameters (such as before-and-after work results) as to its success in instructing engineering students in aesthetic GPF design.

6.5. Architecture vs. Industrial Design Collaboration

This project has made a theoretical case for architectural design being a much better total design model for product aesthetic form design and engineering product design. This architectural paradigm model can be used for training engineers in product aesthetic form creation. The following are possible experiments to conduct regarding this.

Experiment #1. Create a new UTP design challenge requiring the collaboration of form designers and engineers. Have one (or more) team made up of traditionally trained industrial designers (ID) and mechanical engineers (ED), and have one (or more) team made up of traditionally trained architectural designers (AD) and mechanical engineers (ED). Have both (sets of) teams execute the product development for both aesthetic form and engineering content, at least to a full concept level—perhaps stop before detail design. When done, evaluate the following ID/ED vs. AD/ED collaborations:

a. How well did the collaborators work together?
b. How well did each collaboration project efficiently flow and proceed well to a solution?
c. How well did the two collaboration sets turn out with comparison in both aesthetic form and engineering product design?

Experiment #2. A variation on this experiment could also be done where the same projects are implemented and evaluated, but in each case the aesthetic form designers are traditionally trained (art school) industrial designers versus architecture trained industrial designers (that had switched to product design).

6.6. Engineering Product Design Education

This research could create either a small set of courses within engineering design specifically for product design, or, better yet, a complete program within engineering design as a specialized product design discipline or minor. This was attempted by the early Stanford Product Design Program (Kunkel, 1997, p.13; Dresselhaus, 2017, pp. 2-3; 2016, p. 117), but has not completely fulfilled what this current project envisions. This project aims to help return the natural role of comprehensive and holistic product design, one that includes human-centered attractive aesthetic form and ergonomics/usability design, back to engineering design and education (Ashford, 1969; SendPoints, 2018).

Though this project addresses the topic of a GPF design language and method executed via engineering product design, a comprehensive educational approach should be addressed. An entire curriculum of a product design program in engineering design should be developed and tested. The key premises of this project are that engineering designers, when capable and interested:

a. can and should be educated in product design human factors of aesthetics, ergonomics, and usability,
b. can and should be trained to execute attractive GPF compositions that are functionally, ergonomically, and aesthetically of high quality, sustainability, and durability, and
c. can and should avoid creating OPFs, since these are difficult to create and generally unnecessary for most UTP form applications.

In bringing back human-centered aspects to engineering design, it is inherent that a unique and well-defined discipline of product design is also taught as well (Rams, 1984). It is incumbent upon engineering design education and practice to have a distinct discipline, and even a separate engineering curriculum, as Stanford University once did (Roth, 1973; Faste, 1995; HongIk University, 2016; de Vere, 2009), of designing comprehensive finished products for human use, and not only focus on the engineering design of technologies, devices, and mechanisms. Product design goes beyond only the functional and technological aspects of products and systems, but also incorporates the human aspects of ergonomics, usability, repair, maintenance, aesthetics, and other factors that directly affect the human user and the entire set of a product's stakeholders (Ashford, 1969; Cain, 1969; Tjalve, 1979; Rams, 1984).

6.7. GPF Design Automation

Much of what has been developed in this project for a GPF design language and method can possibly be incorporated into a CAD modeling parametric algorithm that could make some of the steps in this method more automated. There must still be a significant element of designer judgement, decision making, and sensitivity for both interim and final considerations of attractiveness and quality. However, it may be possible that some of the steps, or parts thereof, could be set to parametric and algorithmic execution in some manner. Coates (2003, pp. 46-52) talks about this possibility of CAD software and computers doing the hard work of the designer with parametric algorithms and even "computers with good taste" that could create aesthetic product forms. Some of what he proposes is even now possible with so-called generative design software, though primarily for organic forms (Autodesk, 2021; Shih, 2019; Tutorial Books, 2020b). As discussed earlier, the Golden Ratio (Bejan, 2009; Meisner, 2018) and related proportions for product forms could be explored as parametric features and dimensions.

These are possible experiments in this direction.

Experiment #1. Once CAD models of basic forms for all product elements and components have been created and put into a very rough and approximate specified configuration that conforms to the product relational configuration, it may be possible to use a parametric-based algorithm that would re-orient, reposition, and space the elements and components optimally based on various input parameters—automated configuration variation. The resulting specified configurations would include interaction areas, restricted volumes, controls and displays, thermal issues, cabling, service access, fastening, etc. Such an algorithm could be driven by designer-controlled input constraints and parameters entered prior to activation. This could be cycled many times with variable parameters to see what options are possible in the specific architectural arrangement for optimization prior to GPF overall form design.

Experiment #2. Once an optimized specified configuration is created in a CAD model of all product elements and components, either using Experiment #1 above, or manually, then execute a parametric-based algorithm that automatically encloses the specified configuration with GPF volumes in various ways using automatic form variation and form division methods (Tjalve, 1979). Such an algorithm would be driven by designer-controlled constraints and parameters entered prior to activation and would be guided by the GPF design language and method developed in this project. This effort could be cycled many times with variable parameters to see what options are possible in the specific architectural arrangement for optimization of the several external overall GPFs.

Experiment #3. In the most extreme and optimistic case, all product elements, components, features, parameters, constraints, dimensions, variables, and appropriate product context issues could be entered into a parametric and algorithmic based CAD software that would accomplish most or all of what the first two experiments above would do (Coates, 2003). Generative design (Autodesk, 2021) could be adapted and used to generate GPFs in this case instead of the organic forms it currently produces.

6.8. GPF Language Exploration

This proposed research would focus specifically on which GPF design elements and factors communicate function, ergonomics, beauty, and usability. This would entail discovering how certain GPF arrangements, forms, details, elements, compositions, etc., communicate to the product user how to use the product, what it does, and how it works. In other words, examine GPF designs that successfully communicate and "talk" to the user via visual form design language (Krippendorff & Butter, 1984; Krippendorff, 2006; Harper, 2017; Coates, 2003). Much has been written and presented regarding so-called "product form semantics" (Krippendorff & Butter, 1984; Krippendorff, 2006), but what is needed are actual GPF visual designs and models that do such specific semantic communication. The GPFs that communicate various messages would be created in CAD models and physical models for testing and evaluation with users.

6.9. GPF Education Design Projects Development

This proposed research would focus on developing substantial engineering student projects for GPF design development in engineering product design courses (Dresselhaus, 2016, p. 30-31). Too many industrial design course projects and form research have product projects that are far too trivial for engineering work: fruit bowls, computer mice, old mobile phones, toasters, printers, etc. The final chapter project in Tjalve (1979) is an excellent example in designing a complex medical laboratory product from start to GPF design. However, these are difficult to find and take significant work to develop, as well as always be contemporary. Such projects for GPF design courses would need real-world components, constraints, configurations, functions, sub-functions, materials, thermal issues, cabling, electronics, etc., to be realistic for engineering students to design to. Industry cooperation would be necessary, as is often currently the case with purely engineering design projects.

6.10. Comprehensive Product Design Checklist

A comprehensive product design checklist is needed of design principles, product needs, all stakeholder issues, and visual and functional applications that are to be considered appropriately and applied as necessary during the product design and development process. This would apply especially to the GPF design method proposed in this project. Some of such a checklist might be in a general considerations section, and then further elements in detailed sections.

Though this kind of checklist is available a number of places in product design and development publications, sites, and resources, few are totally comprehensive, easy to use, or necessarily address the kind of physical product design of UTPs that is addressed in this project. What is needed for the physical product design of UTPs as in this project is a checklist that is comprehensive, easy to use, covers all essential elements and areas, is digital for tracking and history purposes, and is free of too much complex verbiage.

This checklist might be in spreadsheet or database form, or in another highly usable format, for continuous tracking as well as improvement and addition of new elements and revisions.

6.11. User-As-Designer Kit and Exercises

This proposed research would be based upon the work of Liz Sanders, her book, *Convivial Toolbox* (2013), and generative design research. It would deal with the common problem of professional designers designing products often biased on their own design priorities (e.g., aesthetic styling and form), which may conflict with user priorities (Zhu et al, 2006). The research would develop a user-as-designer GPF kit of physical form tools for non-design users to work with engineering product designers in developing product forms for various types of products (Dresselhaus, 2016, pp. 79-80). This effort would engage ordinary users in the process of form-giving of products from the user perspective of usability, aesthetics, communication, and ergonomics. The engineering product designers would act as facilitators to assist in engaging the users in a human-centered and user-centered form-giving process. The engineering product design facilitators would take the users through various exercises of creating forms for different products from the GPF kit. Such exercises would be documented with text/audio notes, photos, and video for later analysis.

6.12. Engineering vs. Industrial Design Form-Giving Perceptions

This proposed research would entail the psychological aspects of the two ID/ED design groups based on the previous work of Brezing and Löwer (2008), where surveys, questionnaires, interviews, and other appropriate means would investigate the perceptions of engineering product designers versus industrial designers. This would entail topics such as product form-giving, product design process, and perceptual priorities regarding aesthetics, form, usability, ergonomics, etc. Much is often said about the perceptual and priority differences between product engineers versus industrial designers. However, a thorough research project that would clarify these differences (or not) could be quite beneficial, and possibly even surprising.

6.13. Engineering Product Design Management

Quality engineering product design process requires competent management based on the particular philosophy and method being used to develop product form for total product systems (Dresselhaus, 2016, p. 10). This research would develop an engineering product design management protocol, method, philosophy, and experience, since this project proposes what would likely be new to many engineering organizations (i.e., engineers executing aesthetic product form design within the product design and development process). This would include comprehensive management training for engineering product design managers (and clients!) in proper product design and development process that includes aesthetic product form design language and methodology.

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8. PROJECT FIGURES

This section presents the textual, numerical, graphical, visualization, and illustrative figures referenced in this project regarding the GPF design language and method principles and applications presented. A common method of distributing figures in a document such as this is to put a figure right after the content text that the figure directly relates to. Alternatively, a section of figures and tables can be presented in the front matter of a document such as this. However, due to the large number and size of most all figures in this work, it was deemed better to have a separate figures-only section, and put it near the end of the document, rather than in the front matter due to its size. The figures in this section are referenced and cited where appropriate in the related main body text.

These figures primarily depict the principles and concepts presented in the Results section of this project work, though a few are in earlier sections. This includes, though not necessarily in this order, the following:

a. General visual design principles for application to product aesthetic form.
b. The basic geometric volumes of rectangular prism and/or right cylinder, with appropriate dimensional variations and compositions of them.
c. Spatial operation “verbs” that can be applied in modifying various GPF design compositions.
d. Other types of features and design language principles as applied to various GPF combinations.
e. Various visualizations and demonstrations of the project's GPF design language and method application to products.
f. The common use analysis of GPF design language and method for the Red Dot Award competition books and the celebrated designers/firms publications.

All three-dimensional visual CAD form and model illustrations in these figures were created with AF360 software by this author, unless otherwise noted.

8.1. Figure—OPF Designs

Gaming Controller: Google Stadia Controller
Manufacturer: Google Inc., Mountain View, CA, USA;
In-house design

Rasierapparat: Shaver Series 300
Manufacturer: Royal Philips, Eindhoven, Netherlands;
In-house design: Philips Design

In-Ear Headphones: Jabra Vox
Manufacturer: GN Netcom A/S, Denmark;
Design: Johan Birger

Protective Face Mask: RAPTOR
Manufacturer: Invent Medical Group, s.r.o., Ostrava, Czech Republic;
In-house design: Petr Chapcak, Ales Grygar

Inhaler for Horses: Aservo® EquiHaler®
Manufacturer: Boehringer Vetmedica GmbH, Ingelheim, Germany;
Design: DESIGNquadrat, Cologne, German

Digital Vest: SmartVest
Manufacturer: Lenovo, Shenzhen, China;
In-house design: Lenovo Smart Lifestyle Innovation
and Incubation Center, Ying Jia Yao, Run Yang, Pei Yin Yang

Sound Processor: Neuro 2
Manufacturer: Oticon Medical, Smørum, Denmark; Design:
Lockenwitz, Christian Lockenwitz, Copenhagen, Denmark

Sport Glasses: Adidas 3D
Manufacturer: Silhouette International, Linz, Austria;
In-house design: Roland Keplinger

Sports Car: Ferrari 812 Superfast
Manufacturer: Ferrari S.p.A., Maranello (Modena), Italy;
In-house design: Ferrari Design, Flavio Manzoni

Battery Grass Shears: GARDENA ClassicCut Li & ComfortCut Li
Manufacturer: GARDENA GmbH, Ulm, Germany;
In-house design: Martin Rauch, Mait Mahlapuu

Hearing Aid: Unitron Moxi Jump R
Manufacturer: Unitron Hearing, Kitchener, ON, Canada;
In-house design

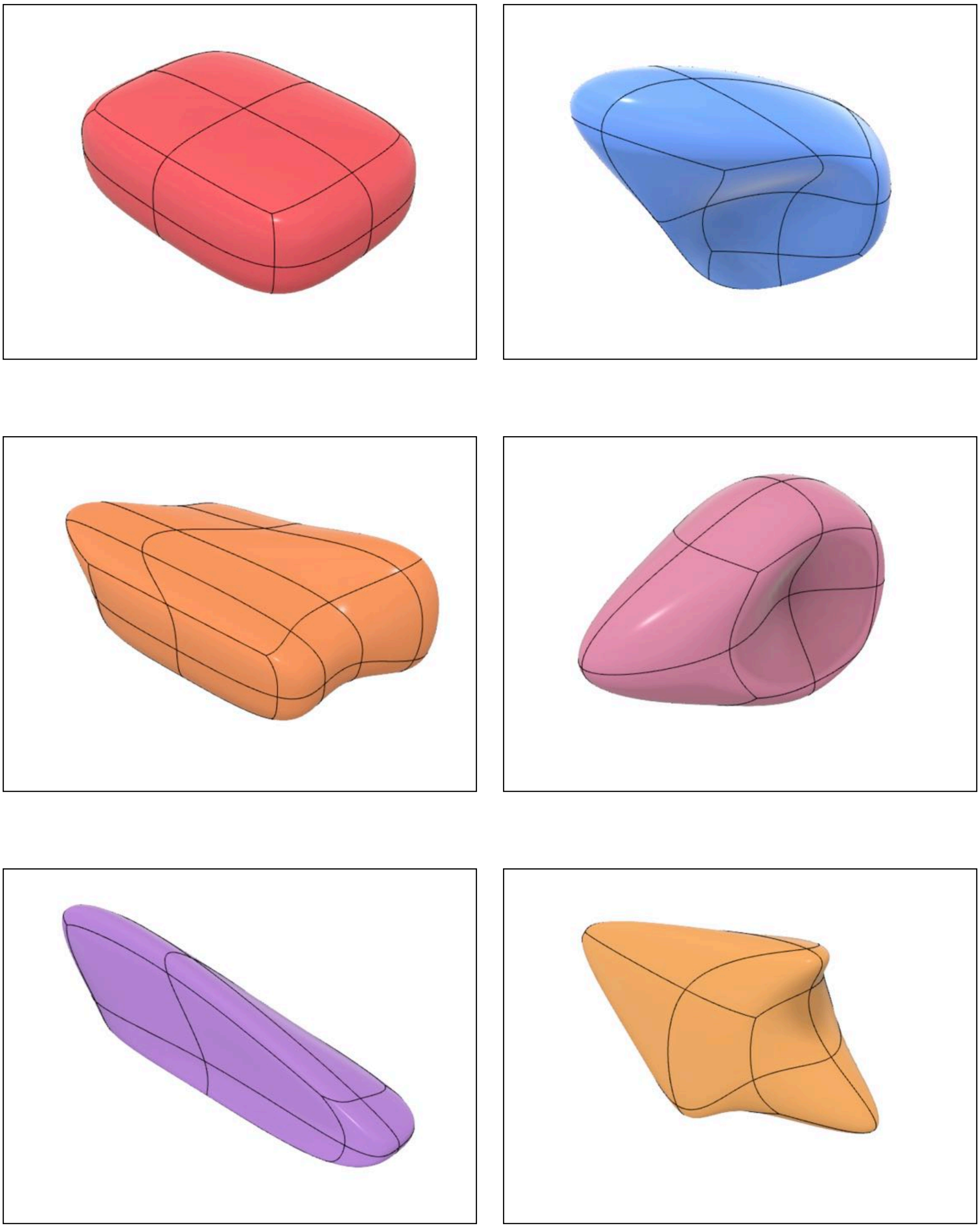
Welding Device: Multi Handy 80
Manufacturer: Shanghai HI-ZONE Welding Equipment Manufacture Co., Ltd.
Shanghai, China; In-house design: Haohe Liu

Lounge Chair with Massage Function: NOUHAUS
Manufacturer: NOUHAUS Co., Ltd., Seoul, South Korea; In-house design:
Taek Kim, Eun A Jeong, Shaoyun Yuan, Eunji Yang

Safety Shoe: uvex 1 G2
Manufacturer: uvex Arbeitsschutz GmbH, Fürth, Germany; Design:
Scherfdesign Concept & Development, Cologne, Germany

Clean Catch
Institution: Massey University Nga Pae Mahutonga, The School of Design,
New Zealand; Faculty Advisors: Lyn Garrett, Yueyun Song;
Design: Samantha Hughes

XiM20 - An Autonomous Ride-Share Interior
Company: Yanfeng Automotive Interiors, China; Design Lead:
Han Hendriks, Tim Shih; Design: Jiunn Tyng (JT) Chen, Volker Dreisbach,
Brian Dykema, Lucas Eyl, Danny Larsen, Tyler Newkirk,
Amit Patankar, Xiaofei (Phil) Xue, Fan Yang



Note. The first set of products have OPFs composed of complex organic curves, surfaces, and volumes. They are from the international Red Dot Award competition. The photos are used by permission and are captured from the online exhibition at *red-dot.org*. Proper credits are provided with each image. The last six images are representative organic forms created in the “sculpting” mode of AF360 and are not recommended for engineering product design. Such organic forms are difficult to create with precision, clarity, and attractiveness, especially as applied to UTPs, and are thus to be avoided as unnecessary. Too often, there is a common misperception that creating such product forms is “adding design” to a product.

8.2. Figure—GPF Designs

Sirius Stiletto
Manufacturer: Sirius; Design: Sohrab Vossoughi, Ziba Design, Portland, Oregon.
Photo used by permission. Ziba Design, Portland/Tokyo. © 2020 Ziba Design.

TDK Audio System Component
Manufacturer: TDK/Imation; Design: Sohrab Vossoughi, Ziba Design, Portland, Oregon.
Photo used by permission. Ziba Design, Portland/Tokyo. © 2020 Ziba Design.

TDK Audio System
Manufacturer: TDK/Imation; Design: Sohrab Vossoughi, Ziba Design, Portland, Oregon.
Photo used by permission. Ziba Design, Portland/Tokyo. © 2020 Ziba Design.

Ma ya
Manufacturer: KEFAN Houseware & Furnishings Intelligent Manufacturing Co., Ltd., Foshan, China; Design: Rifeng Enterprise Group Co., Ltd., Jianying Huang, Jiangming Peng, Xiaozhou Qiu, Xiaobing Yang, Zhengbing Qu, Qingyun Ai, Jincui Zhan, Puhua Zhong, Foshan, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Cranes
Manufacturer: Rifeng Enterprise Group Co., Ltd., Foshan, China; In-house design: Jianying Huang, Jiangming Peng, Xiaobing Yang, Donghong Xiao, Zhengbing Qu, Qingyun Ai, Jincui Zhan, Puhua Zhong.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Multifunctional Smart Lock
Manufacturer: AIGANG GmbH, Munich, Germany; In-house design: Lijuan Wang; Design: Top Industrial Design Co., Ltd., Kaipeng He, Wanqi Li, Hangzhou, China; Top Design Co., Ltd., Jiqing Zhang, Lin Zhou, Shenzhen, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Huddly IQ
Manufacturer: Huddly AS, Oslo, Norway; In-house design: Stein Ove Eriksen, Knut Helge Teppan, Mats Gabriel, Love Johansen, Mona Kleven Lauritzen, Niklas Schmidt; Design: Frost Produkt AS, Sindre Widerberg, Kjartan Vaaland, Karin Ekwall, Sondre Frost Urstad, Oslo, Norway.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Bosma X1
Manufacturer: BOSMA Corp., Guangzhou, China; In-house design: Jason Wong.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Wallbox Copper
Manufacturer: Wall Box Chargers S.L., Barcelona, Spain; In-house design; Design: ESNE – University of Design, Innovation and Technology, Madrid, Spain.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

70mai Dash Cam Pro
Manufacturer: 70mai Co., Ltd., Shanghai, China; In-house design: Qing Xu.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

CM51
Manufacturer: China Mobile IOT Company Limited, Chongqing, China;
In-house design: Pengfei Huang.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Charge Pal
Manufacturer: Shanghai Sunmi Technology Co., Ltd., Shanghai, China;
In-house design: Sunmi Design Center, David Protet.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

nanoArch S140
Manufacturer: BMF Material Technology Inc., Shenzhen, China; Design: LKK Design Shenzhen Co., Ltd., Weilin Ding, Zhaoxun Jia, Shenzhen, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

HP Engage
Manufacturer: HP Inc., Palo Alto, California, USA;
In-house design: HP Design Team.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

HL5
Manufacturer: Hangzhou Rosou Electronic Technology Co., Ltd., Hangzhou, China; In-house design: Chang Jin.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Bosch Aqua 7100 P
Manufacturer: Bosch Thermotechnology (Beijing) Co., Ltd., Beijing, China; Design: Bosch Thermotechnik GmbH, Fabian Kollmann, Wernau, Germany; Bosch Thermotechnology (Shanghai) Co., Ltd.; Xuefei Liu, Shanghai, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

CIROO Series (CHP-7300R, CHP-6310L)
Manufacturer: Coway, Seoul, South Korea;
In-house design: Nari Lee, Soyeon Lee.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

SIMATIC IPC647E, SIMATIC IPC847E
Manufacturer: Siemens AG, Nuremberg, Germany; In-house design: Stephan Hühne; Design: at-design GbR, Jan Andersson, Fürth, Germany.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

FRA
Manufacturer: Yushin Precision Equipment Co., Ltd., Kyoto, Japan; Design: ICI Design Institute Inc., Yoshiaki Iida, Yayoi Kuroda, Osaka, Japan.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

WMF Lumero
Manufacturer: WMF Consumer Electric GmbH, Jettingen-Scheppach, Germany;
In-house design: Ernst Köhler.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Dometic PLB40
Manufacturer: Dometic, Solna, Sweden; In-house design: Samuele Meda, Jens Nybacka, Mikael Thelin, Kristoffer Olsson.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

iMuto Power Station S5
Manufacturer: iMuto Limited, Hong Kong; In-house design; Design: Shenzhen Tianbaotong Technology Co., Ltd., Ray Lee, Shenzhen, China, Shenzhen DBK Electronics Co., Ltd., Chuang Wu Zhang, Terry Zeng, Shenzhen, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Handheld Work Light
Manufacturer: AEC Lighting Solutions Co., Ltd., Shanghai, China;
In-house design: Aixia Bian.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

CUBA
Manufacturer: Ningbo Utec Electric Co., Ltd., Yuyao, Zhejiang, China;
In-house design.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Doblocks
Manufacturer: Shenzhen Science Technology Co. Ltd., Shenzhen, China; In-house design: Liangqiu Liu; Design: Shenzhen Qifang Design Studio, Jiyong Wang, Jie Chen, Shenzhen, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Philips PerfectBeam gen.2
Manufacturer: Signify, Eindhoven, Netherlands;
In-house design: Signify Design Team.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

ROOMOR
Manufacturer: Wever & Ducré BVBA, Kortrijk, Belgium; In-house design.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Track&Trace
Manufacturer: TRUMPF GmbH + Co. KG, Ditzingen, Germany;
In-house design: TRUMPF GmbH + Co. KG;
Design: Phoenix Design GmbH + Co. KG, Stuttgart, Germany.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

piccolo 1
Manufacturer: ATAGO Co., Ltd., Tokyo, Japan; In-house design: Hideyuki Amamiya; Design: Michio Akita, Tokyo, Japan.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

FP-Z5000
Manufacturer: FUJIFILM Corporation, Tokyo, Japan;
In-house design: Kunihiko Tanaka.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

concept active
Manufacturer: clearaudio electronic GmbH, Erlangen, Germany;
In-house design: Patrick Suchy.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Sendai Pro
Manufacturer: Hase Kaminofenbau GmbH, Trier, Germany;
In-house design: Fernando Najera.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Vodafone Super WiFi
Manufacturer: Vodafone Group Services GmbH, Düsseldorf, Germany;
In-house design: Daniel Schubert, Anja Einwag, Yuan Liu;
Design: studiomem GmbH, Munich, Germany.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Cabas Life
Manufacturer: GID International Design, Shanghai, China; In-house design.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Power+Data Kit
Manufacturer: Zimi Corporation, Nanjing, China; In-house design.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

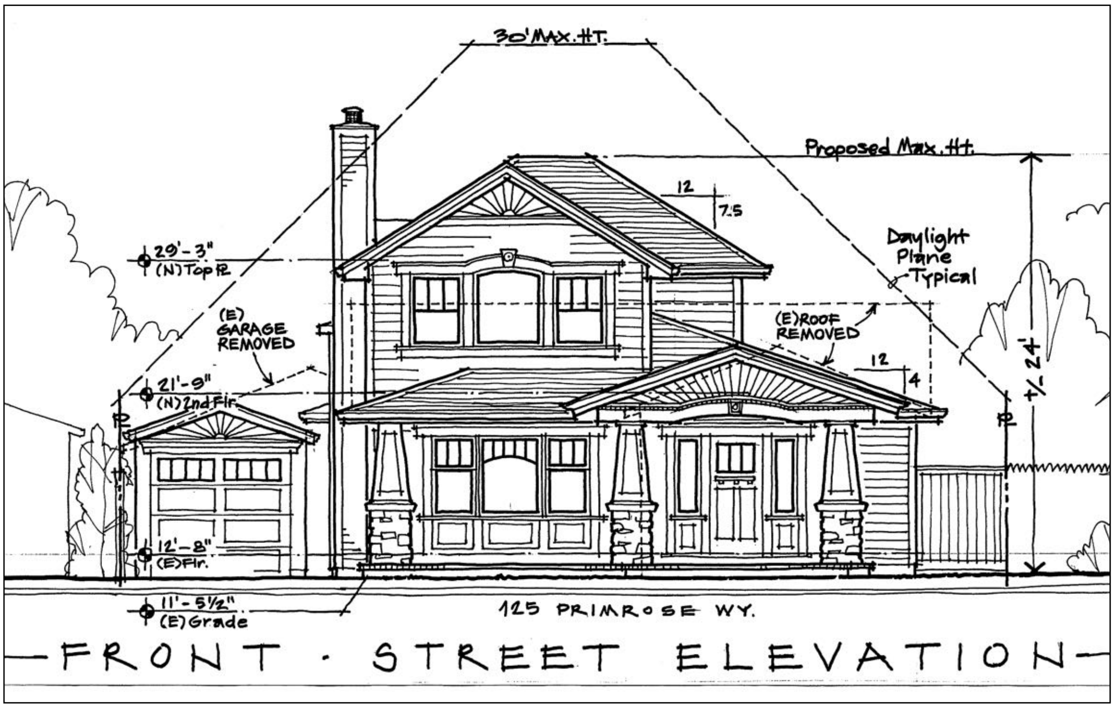
Xiaomi Laptop Powerbank
Manufacturer: Zimi Corporation, Nanjing, China;
Design: Xiaomi Inc., Beijing, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

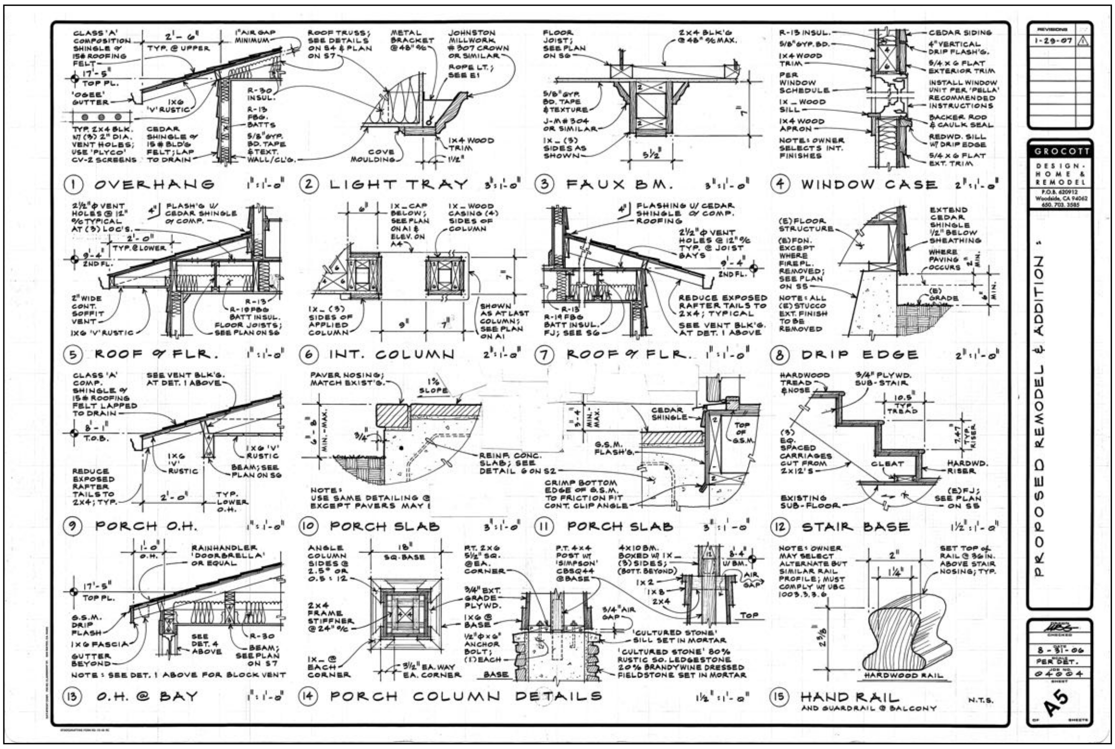
Haier H3 Epilator
Manufacturer: Haier Group, Qingdao, China. Design:
Haier Innovation Design Center, Wang Jingshuang, Yang Guang, Gao Zishuai,
Wang Lili, Qingdao, China, Lingli Sci-Tech Company Ltd., Beijing, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

HP Officejet Pro Printers
Manufacturer: HP Inc., Palo Alto, CA, USA; Design: HP Global Experience
Design Team, Vancouver, WA, USA.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

Note. These products have GPFs composed of simple geometric forms and details. Each could be deconstructed into its simple elemental geometric shapes, surfaces, volumes, and details. The images are from the international Red Dot Award competition and other sources. All photos are used by permission. Proper credits are provided with each image. Most all images are captured from the Red Dot Award competition website of red-dot.org, except for a few from other indicated sources.

8.3. Figure—Total Design: Architectural Drawings



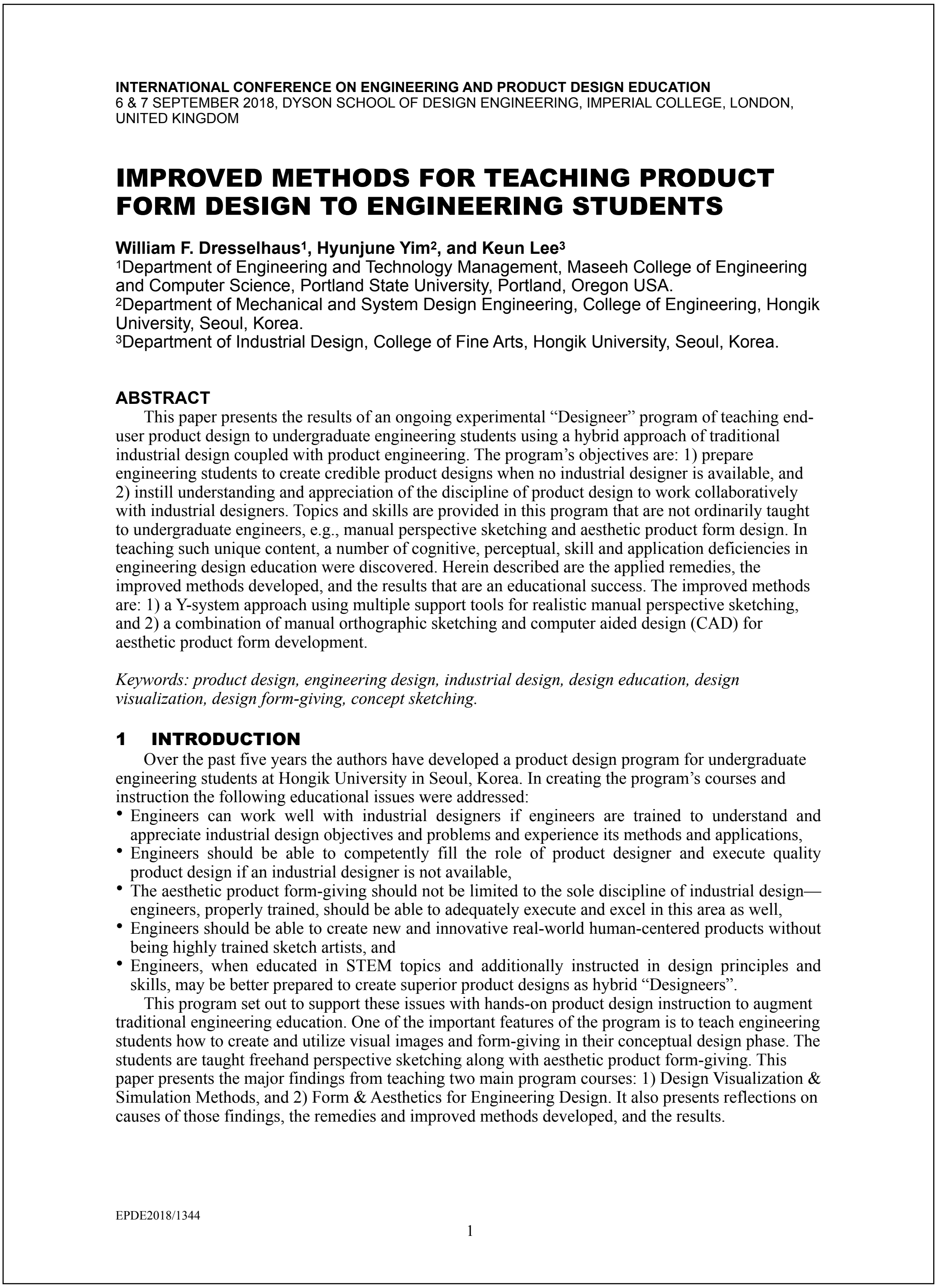


Note. These are two examples of quality architectural drawings/sketches. Both are manually created. These demonstrate an architectural total design model of outside/inside/details for comprehensive holistic design: creating both the exterior form design as well as the details of construction, both interior and exterior. Created by Matt Grocott, Grocott Design, California, USA. Used by permission.

8.4. Figure—Cultural Forms: Form Follows Function

Note. These are two items that would not necessarily be recognized by someone who had no cultural background or experience concerning Asia. The first image is of common (to Asia) chopstick sets. But to the naive about Asia, and first time observer, they may not obviously be meant for eating. The second image is of a Korean junkman “scissors." Their form, at first encounter, might seem they are for cutting. But their function is not cutting at all (which they cannot do), but is for noise-making to announce the presence of the Korean vendor. However, each of these object functions can be understood after a single explanation/demonstration. Their form does follow their function when explained and demonstrated clearly once.

8.5. Figure—GPF Engineering Education: Research Paper



INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
6 & 7 SEPTEMBER 2018, DYSON SCHOOL OF DESIGN ENGINEERING, IMPERIAL COLLEGE, LONDON, UNITED KINGDOM

IMPROVED METHODS FOR TEACHING PRODUCT FORM DESIGN TO ENGINEERING STUDENTS

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ABSTRACT

This paper presents the results of an ongoing experimental "Designeer" program of teaching end-user product design to undergraduate engineering students using a hybrid approach of traditional industrial design coupled with product engineering. The program's objectives are: 1) prepare engineering students to create credible product designs when no industrial designer is available, and 2) instill understanding and appreciation of the discipline of product design to work collaboratively with industrial designers. Topics and skills are provided in this program that are not ordinarily taught to undergraduate engineers, e.g., manual perspective sketching and aesthetic product form design. In teaching such unique content, a number of cognitive, perceptual, skill and application deficiencies in engineering design education were discovered. Herein described are the applied remedies, the improved methods developed, and the results that are an educational success. The improved methods are: 1) a Y-system approach using multiple support tools for realistic manual perspective sketching, and 2) a combination of manual orthographic sketching and computer aided design (CAD) for aesthetic product form development.

Keywords: product design, engineering design, industrial design, design education, design visualization, design form-giving, concept sketching.

1 INTRODUCTION

Over the past five years the authors have developed a product design program for undergraduate engineering students at Hongik University in Seoul, Korea. In creating the program's courses and instruction the following educational issues were addressed:

- Engineers can work well with industrial designers if engineers are trained to understand and appreciate industrial design objectives and problems and experience its methods and applications,
- Engineers should be able to competently fill the role of product designer and execute quality product design if an industrial designer is not available,
- The aesthetic product form-giving should not be limited to the sole discipline of industrial design—engineers, properly trained, should be able to adequately execute and excel in this area as well,
- Engineers should be able to create new and innovative real-world human-centered products without being highly trained sketch artists, and
- Engineers, when educated in STEM topics and additionally instructed in design principles and skills, may be better prepared to create superior product designs as hybrid "Designeers".

This program set out to support these issues with hands-on product design instruction to augment traditional engineering education. One of the important features of the program is to teach engineering students how to create and utilize visual images and form-giving in their conceptual design phase. The students are taught freehand perspective sketching along with aesthetic product form-giving. This paper presents the major findings from teaching two main program courses: 1) Design Visualization & Simulation Methods, and 2) Form & Aesthetics for Engineering Design. It also presents reflections on causes of those findings, the remedies and improved methods developed, and the results.

1.1 Literature and research background

Freehand manual sketching has been and still remains the major means for creating, communicating and explaining conceptual ideas for all types of designers [1-7], with the manual medium being often both paper and digital means. Likewise, CAD software has been adopted as the standard tool for most engineering design and much industrial design as well [7, 8]. In the engineering development process, three-dimensional (3D) CAD models are indispensable—not only used for the design stage, but also for the following stages such as computer-aided engineering (CAE), computer-aided manufacturing (CAM), and so on.

A great number of research papers and articles in the literature have addressed whether freehand sketching in the initial conceptual creative design stage can be supported or even replaced by CAD [4-7]. A majority of researchers and design practitioners believes that freehand sketching is still the core conceptual tool [1-4], although a few case studies show that this stage involves more verbal activities and digital work than sketching [4]. Therefore, significant research and development [5,6] has been done in developing computer-aided sketching (CAS) tools that assist freehand sketching with digital media. CAS tools are valuable because they can aid in the smooth transition from sketches to CAD, and then to CAE, CAM, etc.

In spite of the number of related papers, it is difficult to find studies on recent teaching freehand perspective sketching or aesthetic product form design to engineering students similar to that taught to industrial designers. Close ones are primarily about the relative time spent on and sequence of the use of freehand sketching and CAD by students and/or practitioners during design projects [3,4,7], but are primarily about schematic, orthographic and/or axonometric delineation. Therefore, the present paper has a unique contribution in presenting first-hand experiences in teaching realistic freehand perspective sketching and aesthetic product form development to engineering students, observing the student difficulties, finding causes of difficulties, devising remedies, improving teaching methods, and concluding with statements on teaching product design to engineering students and needs for rigorous future studies.

1.2 Program student makeup

Though the work that supports this paper was executed at Hongik University in Seoul, Korea, to primarily Korean engineering students, the program participants included some engineering and design exchange students from Germany, France, Philippines, and several other non-Korean countries. Students were primarily junior and senior mechanical engineering students with a few from other engineering disciplines such as industrial, software and/or electrical. There were around 30-40 students in each class with a mixture of male and female students, averaging 20-25% female. Almost all the of the students had previous instruction in design thinking, innovation, design process and creativity, but initially had a generally low level of sketching ability as early testing determined. Very few had any previous instruction in industrial design or product form-giving.

2 TEACHING MANUAL PERSPECTIVE IDEA-SKETCHING

Product form development is a visual enterprise and form creators must be able to produce good, clear visual representations of their form concepts. Due to its inherent nature, expressing aesthetic product form requires visual precision and accuracy—without such, the reality of the presented form cannot be perceived properly. The original program plan was for engineering students to develop product form concepts using primarily freehand perspective sketching. Sketching in perspective was generally new to the students since engineering education almost exclusively relies on orthographic and axonometric delineation, in contrast to industrial design and architecture where students are extensively trained and practiced in realistic perspective sketching. All students were instructed in three-view orthographic and one-, two- and three-point perspective and tested for their understanding, resulting in a roughly 90% comprehension rate for each class. However, the issue was not understanding the mathematical foundation of perspective—the problem was students being able to execute realistic manual perspective sketches of form designs. The authors' philosophy for teaching design sketching is:

- Design idea-sketching is about developing a final creative concept, and not about fancy art,
- Extensive and sophisticated manual sketching is not only usually impossible for most engineering students, but can also be detrimental to the form-giving process with too much focus on the sketching style and quality rather than on the form design itself,
- Idea-sketching is a universal and valuable form of human externalized thinking and creative

enhancement using eye-hand-brain coordination to visualize new ideas and concepts,

- Once a product idea or concept has been adequately sketched, it should then be taken to CAD for precision execution and refinement, rather than with more over-wrought additional sketching, and
- Any supporting device or method that assists in manual idea-sketching may be used.

2.1 Difficulties in perspective sketching

In the product visualization course, the predictable student hesitation to sketch was found immediately. In addition, several rather surprising issues were also discovered in the students' work. First, most of the students had great difficulty with manual perspective sketching as shown in Figure 1 (a, b). After initially allowing only unassisted manual freehand sketching, the students were then instructed in and allowed to use assisted perspective sketching using the following devices and methods:

- Orthographic and perspective underlay grids as guides,
- Preliminary bold blocking-out of rough forms to use as underlays,
- Straight edge rulers and curved guides, and geometric shape, circle and ellipse templates,
- Tracing paper overlays for multiple sketch iterations, and
- Photocopies of product images, partial sketches, and CAD images for over-sketching.

The students were also instructed extensively in a so-called Y-system of perspective sketching with an accompanying grid underlay shown in Figure 1 (d) that utilizes only a single canonical central perspective view for all sketches. In this method students always sketched their form ideas and concepts from the same perspective viewpoint. This facilitated a sketching practice and execution with a high consistency of geometric shapes, forms and elements (e.g., cuboids and ellipses) between sketches as in Figure 1 (c).

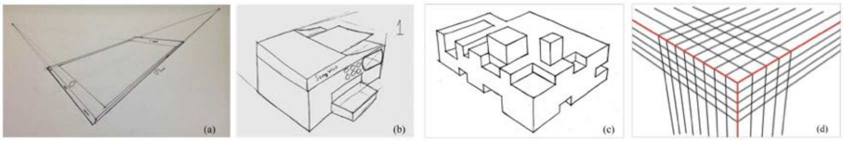


Figure 1. Wrong perspective (a, b), improvement using the Y-system (c), Y-system underlay (d)

2.2 Difficulties in perspective perception

Many of the engineering students had another surprising difficulty of "seeing" perspective, even in their later CAD modeling. The visual education of engineering students is typically limited to orthographic and axonometric drawings and pictorials, numerical dimensioning, and computational exercises such as free-body diagrams. Orthographic and axonometric CAD drawings do not represent what is seen by the human eye and are distorted from perspective reality. The student difficulty may also be due to engineers seldom making layout or production drawings manually, but relying almost exclusively on CAD for this. The authors feel this scenario appears to hinder an engineer's ability to both see and sketch in perspective reality by hindering a sense of realistic space and form. It seems almost as if the exclusive use of the visually skewed orientation of orthographic and axonometric CAD visualization contributes to a non-realistic visual reality perception!

2.3 Difficulties in size and proportion perception

The engineering students also often had a lack of "seeing" a correct perception of actual sizes, proportions and shapes. The students were often inaccurate in their execution in both sketches and CAD models of realistic dimensions and proportions. Their early product designs were frequently unrealistic and their product features and elements often had strange shapes that were unreasonable or unattractive or both. It was also assumed that engineering students would naturally be able to apply their previously learned STEM principles to real-world product design. However, it was found that they had difficulty in applying this knowledge to even common machines, products and tools. This may indicate a deficiency in engineering education, which often focuses on abstracted situations and seldom considers real-world design of electromechanical product systems that require a sense of layout among their elements.

Students were pushed to "see", understand and execute realistic product design and consider product internal electromechanical functionality and layout that often drives external product form. They were instructed to sketch internal electromechanical product components and layouts in schematic form with proper proportions, sizes, shapes, ergonomics and manufacturing by the following means:

- Showing cross-sections of interiors and components of a variety of actual high-tech products,
- Showing a variety of typical product components such as fans, power supplies, electronics boards, motors, cabling, displays, connectors, controls, etc.,
- Bringing actual products into the classroom and doing "design forensics" where the students take apart the products to experience their electromechanical design hands-on,
- Having students sketch orthographic cross-sections of various high-tech products and their internal electromechanical components and layout as in Figure 2 (a),
- Instruction and practice via manual sketching and CAD modeling of various configurations and architectures of different real-world product internal component layouts as in Figure 2 (b), and
- Having students execute "forensic modeling" by completely disassembling and reassembling an entire high-technology product and while doing so measure and model in CAD every single part, component, dimension and detail (by the students' own admission, this process alone resulted in their learning more about real product design than in any other single way!).

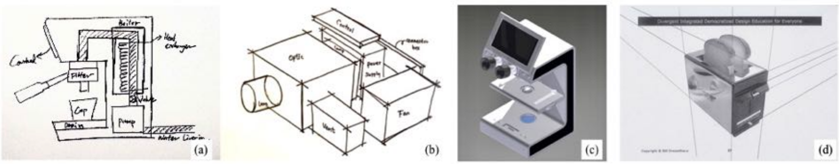


Figure 2. Internal components sketch (a), 3D configuration sketch (b), non-perspective CAD model (c), perspective view demonstration (d)

3 IMPROVED METHOD FOR AESTHETIC PRODUCT FORM DEVELOPMENT

As described previously, the students' difficulty with manual perspective sketching overwhelmed any reasonable expression of realistic product form—they simply could not sketch adequately enough to create and develop realistic perspective sketches. Thus a "detour" method was developed which resulted in a much improved educational outcome.

3.1 The improved form-giving method

As indicated, the engineering students could generally sketch orthographically. After a brief three-view orthographic drawing review, they were instructed to first sketch their basic product form concepts in simple orthographic two- and three-views for initial exploration. They then proceeded to develop their best initial ideas in CAD modeling for precise perspective realism and form detailing. Switching to this two-fold form development method—creating simple orthographic form sketches manually and then going directly to CAD modeling—worked incredibly well! This improved design methodology:

- Bypassed the intensive manual perspective form sketching, normally practiced by industrial designers, that engineering students were mostly incapable of,
- Used easily understood and created rough orthographic two- and three-view form concepts,
- Did not use extensive manual sketching or rendering as the final product form rendition but created final CAD-rendered photorealistic product form designs,
- Had the advantage of instructor design critiques being focused directly on the student 3D CAD product form models rather than dealing with manual sketching quality (or its lack thereof),
- Utilized CAD advantages over manual sketching, e.g., physical accuracy, unlimited viewpoints, "perfect" perspective, model animation, easy form changes, and parametric variation, and
- Utilized visualization methods known, familiar and practiced by most engineering students.

3.2 Student instruction in aesthetics and form development principles

To develop product designs, students were also trained in basic aesthetic design principles such as:

- Fundamentals of proportion, contrast, alignment, shape, space, size, color, symmetry, position, stability, unity, balance, value, harmony, orientation, novelty, light, shadow, and composition,
- Utilizing only simple geometric forms versus organic forms, surfaces, and aesthetics due to the complexity and difficulty of using organic forms, surfaces and aesthetics,
- Dominant, subdominant and subordinate geometric forms, intersections and combinations [9],
- Applying consistent and appropriate edge, intersection and corner radii and chamfers,
- Creating appropriate parting lines, gaps and reveals between product enclosure parts,
- Applying appropriate product materials, surface texture and colorization,
- Developing product family “look and feel” designs of multiple products,
- Using ergonomic features on product functional and human interaction usability areas, and
- Integration of appropriate enclosure manufacturing principles with aesthetic form development.

3.3 Recurring difficulties in CAD perspective perception

As indicated previously, students often had difficulties in “seeing” and executing perspective. This perceptual problem was also observed as well in their early product form CAD models. Many of the students’ failed in “seeing” and detecting perspective, or the lack thereof, in their own CAD model images such as in Figure 2 (c), even though in CAD it is a simple button click to switch to perspective view. To remedy this situation the following was done:

- Demonstrations of the visual reality of perspective using photos of actual objects, scenes and products with the indicated horizon line, vanishing lines and vanishing points as in Figure 2 (d),
- Quizzes given with images of various scenes, sketches and products that were in both perspective and non-perspective views where the students must identify the difference, and
- Exercises and quizzes that required the students to over-draw the horizon line and vanishing lines to the imaginary vanishing points on a photocopy image of an actual object, scene or product.

4 FINAL STUDENT WORK RESULTS

The students' final product design perspective sketching and aesthetic form work [10] was significantly improved and much more realistic and refined than their initial work, as shown in Figure 3. In the end, they successfully adapted to new perceptions and improved methods and created realistic product designs in both manual sketches and CAD models, each in a one-semester course timeframe. It is felt by the authors that much of their final work quality rivaled that of many competent industrial design students.

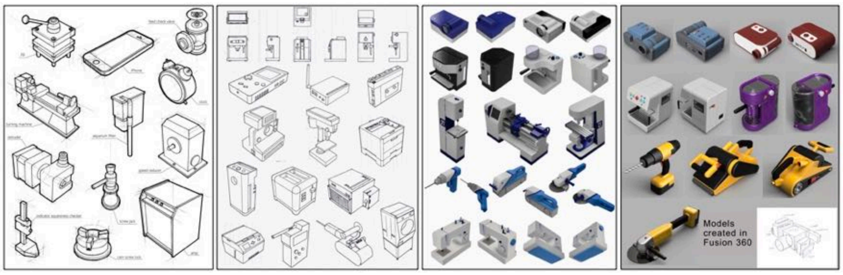
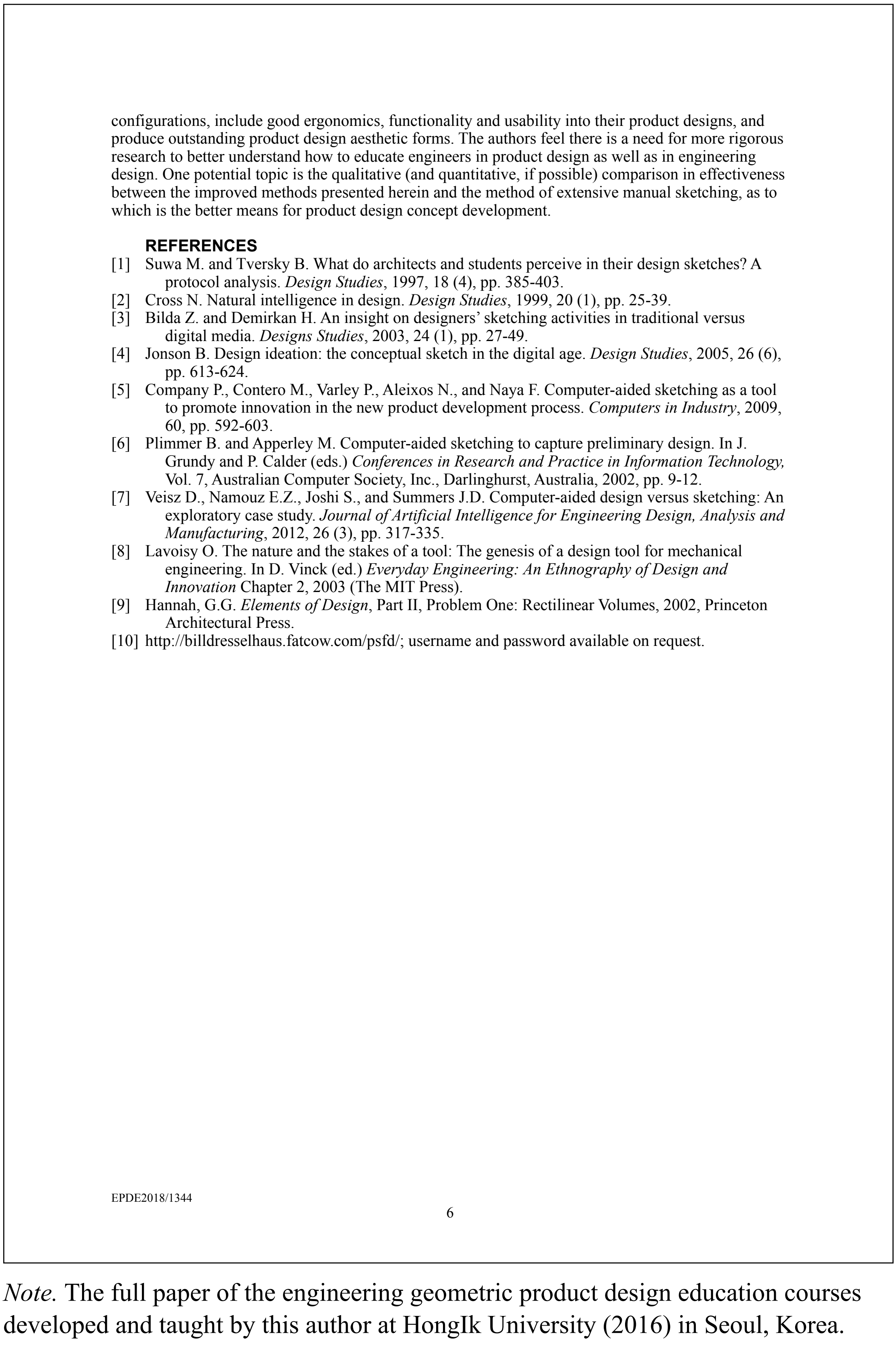


Figure 3. Final sample product sketching and aesthetic form posters of engineering students

5 CONCLUSIONS

The results of this program indicate that realistic perspective sketching and aesthetic product form-giving are quite teachable to engineering students, but require the use of familiar tools and skills and improved instructional and execution methods as essential means for success. Using this approach, engineers can be educated as hybrid “Designeers” and create quality perspective sketches of products and machines, create designs of various products, tools and machines with proper layout



configurations, include good ergonomics, functionality and usability into their product designs, and produce outstanding product design aesthetic forms. The authors feel there is a need for more rigorous research to better understand how to educate engineers in product design as well as in engineering design. One potential topic is the qualitative (and quantitative, if possible) comparison in effectiveness between the improved methods presented herein and the method of extensive manual sketching, as to which is the better means for product design concept development.

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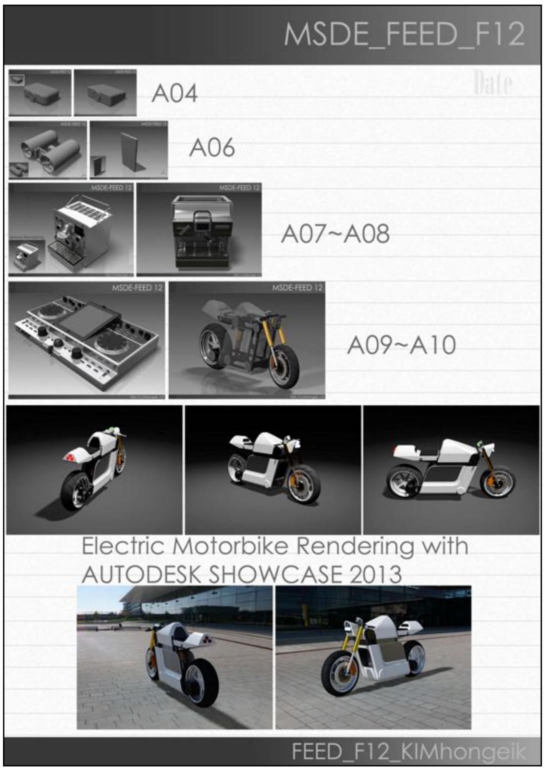
[10] http://billdresselhaus.fatcow.com/psfd/; username and password available on request.

Note. The full paper of the engineering geometric product design education courses developed and taught by this author at HongIk University (2016) in Seoul, Korea.

8.6. Figure—GPF Engineering Education: Research Results



Form&Esthetics for Engineering Design

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Form & Esthetics for Engineering Design

Industrial Engineering B011247 HONGjoonseok

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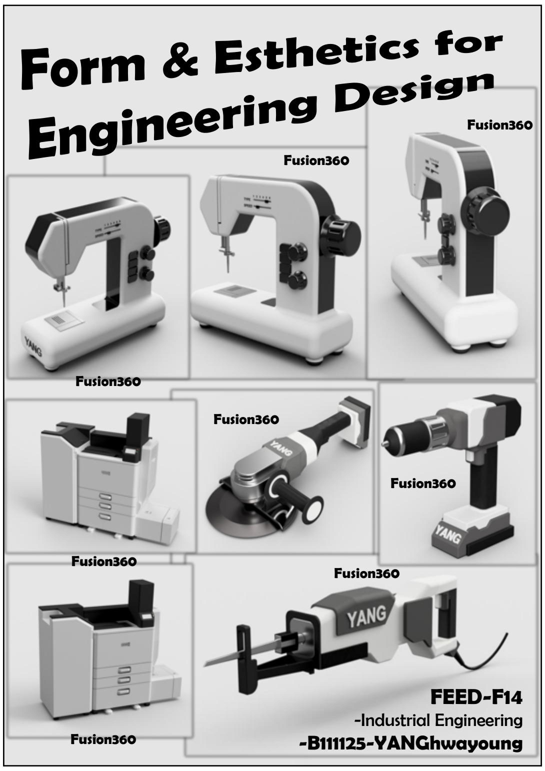

Form & Esthetics for Engineering Design

FEED-F14
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-B111125-YANGhwayoung

Form Esthetics for Engineering Design

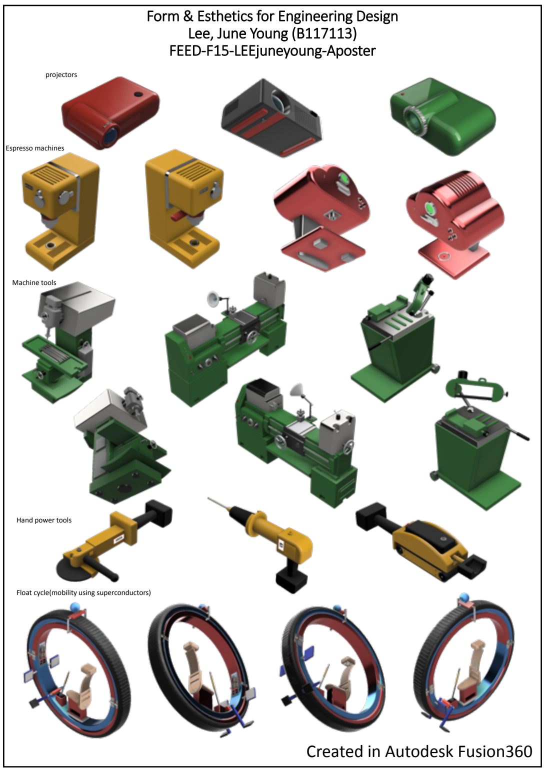
FEED-F15-JEONGhyejin-Aposter
MSDE-B017161-JEONGhyejin

CREATED IN AUTO DESK_FUSION360

Feed Esthetic for Engineering Design
HANmyeongdeok

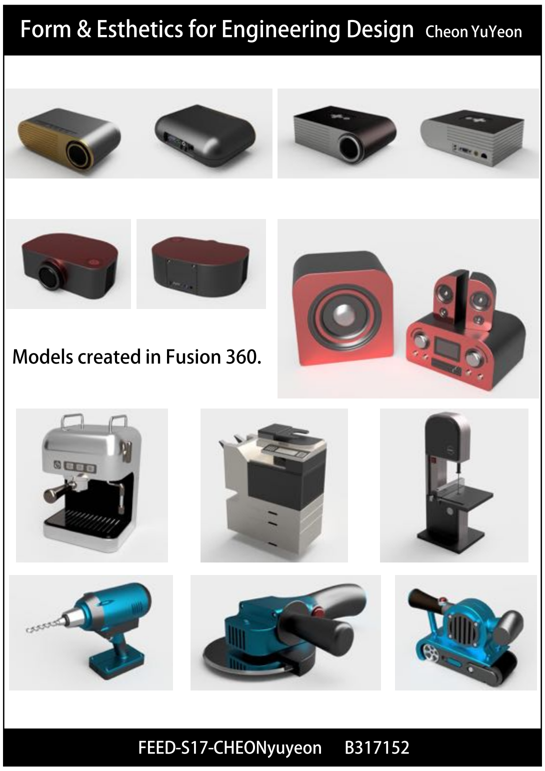
Models created in Fusion 360.

FEED - S17 - HANmyeongdeok - B117179



Form & Esthetics for Engineering Design
Lee, June Young (B117113)
FEED-F15-LEEjuneyoung-Aposter

Created in Autodesk Fusion360



Form & Esthetics for Engineering Design Cheon YuYeon

Models created in Fusion 360.

FEED-S17-CHEONyuyeon B317152

Form & Esthetics for Engineering Design

Prof. Bill Dresselhaus Designed by LEE Dong Hoon

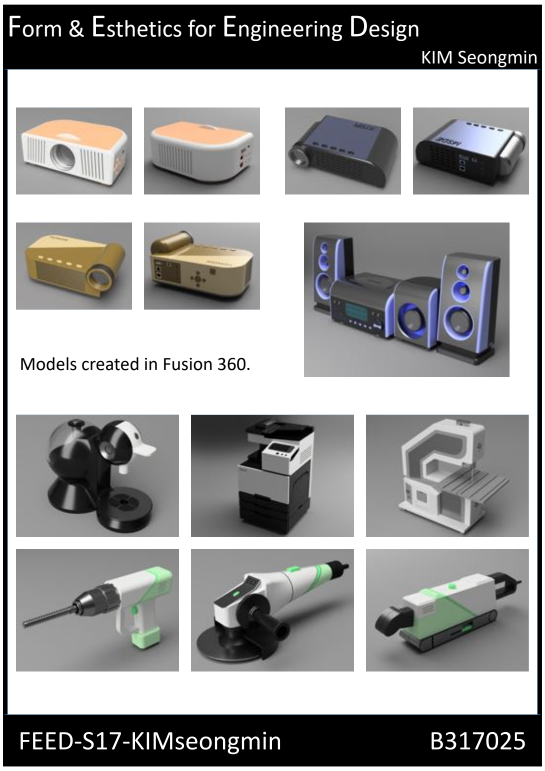
Models created in Fusion 360

FEED-S17-LEEdonghoon-B217113

FEED LEEhyunjeong

Models created in Fusion 360.

FEED-S17-LEEhyunjeong B117202



Form & Esthetics for Engineering Design

KIM Seongmin

Models created in Fusion 360.

FEED-S17-KIMseongmin B317025

FEED KYOUNGchangguen

Models created in Fusion 360

FEED-S17-KYOUNGchangguen B417173

Note. These are images from the MSDE engineering product design courses at HongIk University (2016) in Seoul, Korea, that were developed and taught by this author (Dresselhaus et al, 2018). Engineering students learned GPF design at a less refined level than the method in this project. These were experiments to explore if engineering students could learn GPF principles and apply them successfully.

8.7. Figure—GPF Use Analysis: Red Dot Awards

Red Dot Award Book: *Living*

Interior design. The percentage of GPF products versus total products in this category was 76.15%. This is a high number since many of the entries were of an architectural nature and therefore quite geometric.

Living rooms and bedrooms. The percentage of GPF products versus total products in this category was 53.85%. This is another high number due to the significant number of architecturally based entries and related accessories that were geometric.

Kitchens. The percentage of GPF products versus total products in this category was 55.90%. Again, a relatively high number. Much of this was due to large appliances that tend to be very geometric in nature.

Bathrooms and sanitary equipment. The percentage of GPF products versus total products in this category was 39.34%.

Lighting and lamps. The percentage of GPF products versus total products in this category was 56.25%.

Urban design and public spaces. The percentage of GPF products versus total products in this category was 28.57%.

Total for the *Living* Book. The percentage of total GPF products versus total products in this book was 58.40%.

Red Dot Award Book: *Doing*

Babies and children. The percentage of GPF products versus total products in this category was 18.57%. This is somewhat low, but substantial for this category since a large number of the product entries were soft, ergonomic, body-conformable organic designs such as children's car seats and soft safety-based products.

Household. The percentage of GPF products versus total products in this category was 65.12%. This is a large percentage. Much of it is due to several kitchen cooking ranges, refrigerators, and laundry machines that tend to traditionally be geometric.

Tableware and cooking utensils. The percentage of GPF products versus total products in this category was 25.00%. A low, but significant proportion. Many entries of tableware and cookware were of an OPF composition.

Garden. The percentage of GPF products versus total products in this category was 22.22%.

Tools. The percentage of GPF products versus total products in this category was 20.59%. A low, but significant proportion. Many entries of power tools were of an OPF composition, but which could have easily been acceptable in a GPF redesign. This is a result of a common industrial design penchant for OPF creation when often unnecessary.

Cameras. The percentage of GPF products versus total products in this category was 32.69%. A moderate, but significant proportion. Many entries of cameras were by nature highly geometric due to their mechanical requirements, however, since many had elements that were of an OPF nature, they were not counted as GPF products.

Communication. The percentage of GPF products versus total products in this category was 48.67%.

Robots. The percentage of GPF products versus total products in this category was 17.39%.

Total for the *Doing* Book. The percentage of total GPF products versus total products in this book was 34.91%. This is a significant number given the category explanations above.

Red Dot Award Book: *Enjoying*

Bicycles. The percentage of GPF products versus total products in this category was 0.00%. This was due to all products having some OPF aspect.

Vehicles. The percentage of GPF products versus total products in this category was 18.33%. This is a quite low number, though still significant in a category that had a high number of cars and vehicles that are naturally aerodynamic and traditionally organic in form.

Sports and outdoor. The percentage of GPF products versus total products in this category was 8.89%. This is an extremely low number due to the nature of the category which had many products that were required to conform to the organic forms of the human body.

Leisure and games. The percentage of GPF products versus total products in this category was 21.05%.

Entertainment. The percentage of GPF products versus total products in this category was 33.33%.

Spas and personal care. The percentage of GPF products versus total products in this category was 11.11%.

Fashion, lifestyle and accessories. The percentage of GPF products versus total products in this category was 8.82%.

Watches and jewelry. The percentage of GPF products versus total products in this category was 7.69%.

Total for the *Enjoying* Book. The percentage of total GPF products versus total products in this book was 18.90%.

Red Dot Award Book: *Working*

Office. The percentage of GPF products versus total products in this category was 43.48%. A moderately to high number. This was perhaps due to the ergonomic human form requirement of several seating devices.

Computer and information technology. The percentage of GPF products versus total products in this category was 80.53%. This is another relatively high number. Much of this was due to the large number of computer laptop entries and display screen entries, all of which tend to be strongly geometric by their nature.

Industrial equipment, machinery and automation. The percentage of GPF products versus total products in this category was 79.52%.

Heating and air conditioning technology. The percentage of GPF products versus total products in this category was 79.10%. This is a very high number reflecting the significant industrial aspects of the entries and their inherent geometric nature as UTPs. This is also a common area for engineering product design to dominate.

Life science and medicine. The percentage of GPF products versus total products in this category was 28.05%.

Total for the *Working* Book. The percentage of total GPF products versus total products in this book was 64.71%.

Total for All Four Red Dot Award Books: The percentage of total GPF products versus total products in this entire four-book set was 45.41%. This is still a significant percentage approaching nearly half of the total products, even though several categories had quite low percentages of GPF as explained in each category.

Totals for Selected UTP Categories in All Four Red Dot Award Books: Of interest is the percentage of GPF products versus total products in only the UTP categories. The following categories from all four Red Dot Award books are deemed UTP categories. The selection of these categories as UTP is based on whether or not the products included have some level of technology content.

Two levels of UTP categories are defined and computed for this analysis:

UTP Category Level A: For all product categories in all four Red Dot books that have relatively moderate to high levels of technology content.

UTP Category Level B: For all product categories in all four Red Dot books that have relatively only high levels of technology content.

Level A Categories and Percentages
Book: *Living*; Category: Interior design; Percentage GPF: 76.15%.
Book: *Living*; Category: Kitchens; Percentage GPF: 55.90%.
Book: *Living*; Category: Lighting and lamps; Percentage GPF: 56.25%.
Book: *Doing*; Category: Household; Percentage GPF: 65.12%.
Book: *Doing*; Category: Tools; Percentage GPF: 20.59%.
Book: *Doing*; Category: Cameras; Percentage GPF: 32.69%.
Book: *Doing*; Category: Communication; Percentage GPF: 48.60%.
Book: *Doing*; Category: Robots; Percentage GPF: 17.39%.
Book: *Enjoying*; Category: Bicycles; Percentage GPF: 00.00%.
Book: *Enjoying*; Category: Vehicles; Percentage GPF: 18.33%.
Book: *Enjoying*; Category: Sports and outdoor; Percentage GPF: 8.89%.
Book: *Enjoying*; Category: Entertainment; Percentage GPF: 33.33%.
Book: *Enjoying*; Category: Watches and jewelry; Percentage GPF: 7.69%.
Book: *Working*; Category: Office; Percentage GPF: 43.48%.
Book: *Working*; Category: Computer and IT; Percentage GPF: 80.53%.
Book: *Working*; Category: Indus. equipment, etc.; Percentage GPF: 79.52%.
Book: *Working*; Category: Heating and AC Tech.; Percentage GPF: 79.10%.
Book: *Working*; Category: Life sci. and med.; Percentage GPF: 28.05%.

LEVEL A: AVERAGE PERCENTAGE OF GPF = 41.76%
NOTE: These particular UTP categories in Level A have significant numbers of products that also have relatively low technology levels. The final percentage indicates a significant proportion of GPF products in this level.

Level B Categories and Percentages
Book: *Doing*; Category: Tools; Percentage GPF: 20.59%.
Book: *Doing*; Category: Cameras; Percentage GPF: 32.69%.
Book: *Doing*; Category: Communication; Percentage GPF: 48.60%.
Book: *Doing*; Category: Robots; Percentage GPF: 17.39%.
Book: *Enjoying*; Category: Bicycles; Percentage GPF: 00.00%.
Book: *Enjoying*; Category: Vehicles; Percentage GPF: 18.33%.
Book: *Enjoying*; Category: Entertainment; Percentage GPF: 33.33%.
Book: *Enjoying*; Category: Watches and jewelry; Percentage GPF: 7.69%.
Book: *Working*; Category: Office; Percentage GPF: 43.48%.
Book: *Working*; Category: Computer and IT; Percentage GPF: 80.53%.
Book: *Working*; Category: Indus. equipment, etc.; Percentage GPF: 79.52%.
Book: *Working*; Category: Heating and AC tech.; Percentage GPF: 79.10%.
Book: *Working*; Category: Life sci. and med.; Percentage GPF: 28.05%.

LEVEL B: AVERAGE PERCENTAGE OF GPF = 37.64%

NOTE: These particular UTP categories in Level B, in some cases, have some products that have relatively low to moderate technology levels, as well as a number of products that, by their nature, have high OPF. The final percentage, notably and surprisingly lower than Level A, still represents a significant proportion of GPF products in this level.

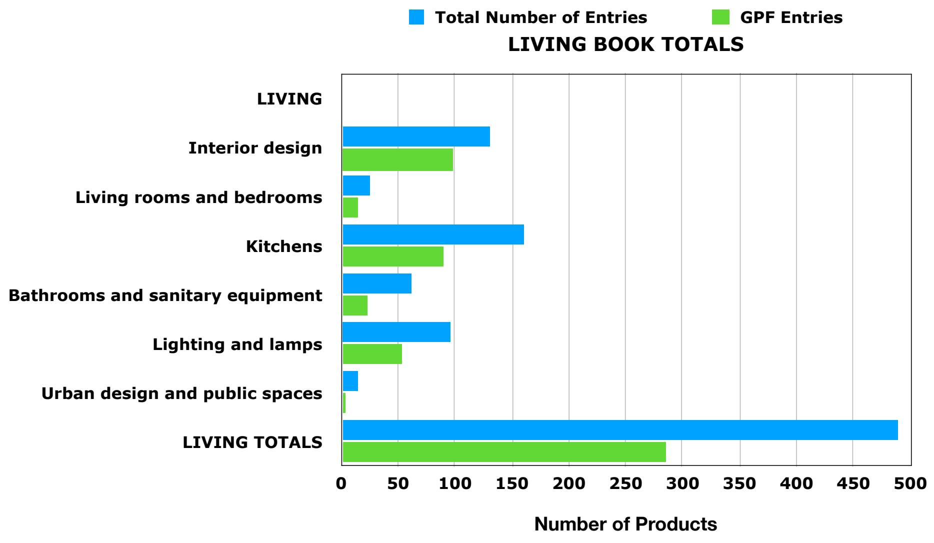
Level B ADJUSTED Categories and Percentages
Book: *Doing*; Category: Tools; Percentage GPF: 20.59%.
Book: *Doing*; Category: Cameras; Percentage GPF: 32.69%.
Book: *Doing*; Category: Communication; Percentage GPF: 48.60%.
Book: *Doing*; Category: Robots; Percentage GPF: 17.39%.
~~Book: Enjoying; Category: Bicycles; Percentage GPF: 00.00%.~~
~~Book: Enjoying; Category: Vehicles; Percentage GPF: 18.33%.~~
Book: *Enjoying*; Category: Entertainment; Percentage GPF: 33.33%.
~~Book: Enjoying; Category: Watches and jewelry; Percentage GPF: 7.69%.~~
Book: *Working*; Category: Office; Percentage GPF: 43.48%.
Book: *Working*; Category: Computer and IT; Percentage GPF: 80.53%.
Book: *Working*; Category: Indus. equipment, etc.; Percentage GPF: 79.52%.
Book: *Working*; Category: Heating and AC tech.; Percentage GPF: 79.10%.
Book: *Working*; Category: Life sci. and med.; Percentage GPF: 28.05%.

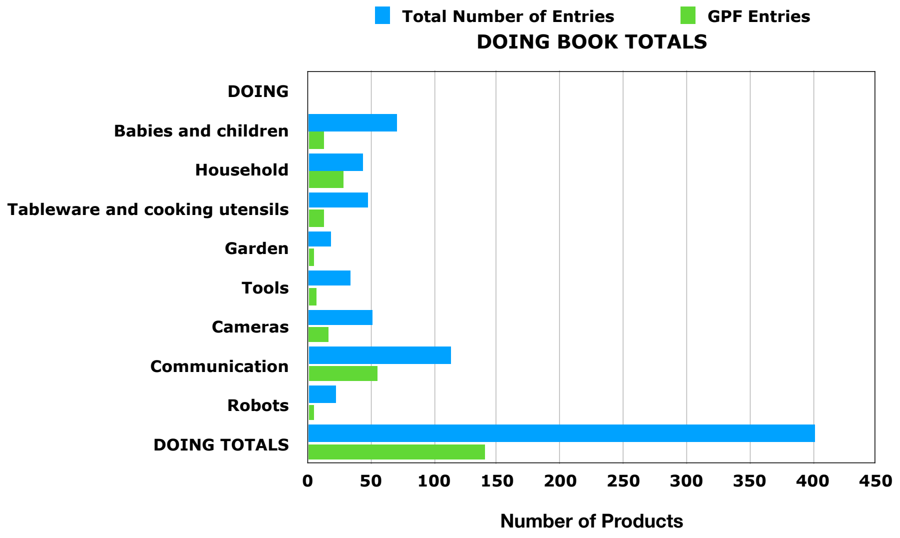
LEVEL B ADJUSTED: AVERAGE PERCENTAGE OF GPF = 46.33%
NOTE: The three categories above that are lined through for this Level B Adjusted analysis were not included due to their high level of OPF products by their design nature (Bicycles and Vehicles), and due to having a high mix of very low technology products (Watches and jewelry). Interestingly, this adjusted percentage is very near that for the Level A broader category selection set.

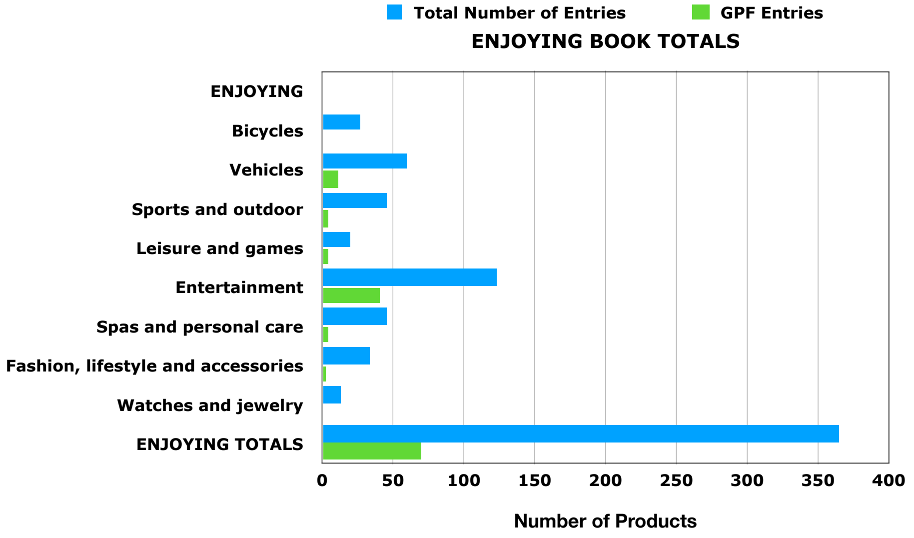
8.8. Figure—GPF Use Analysis: Data for Red Dot Awards

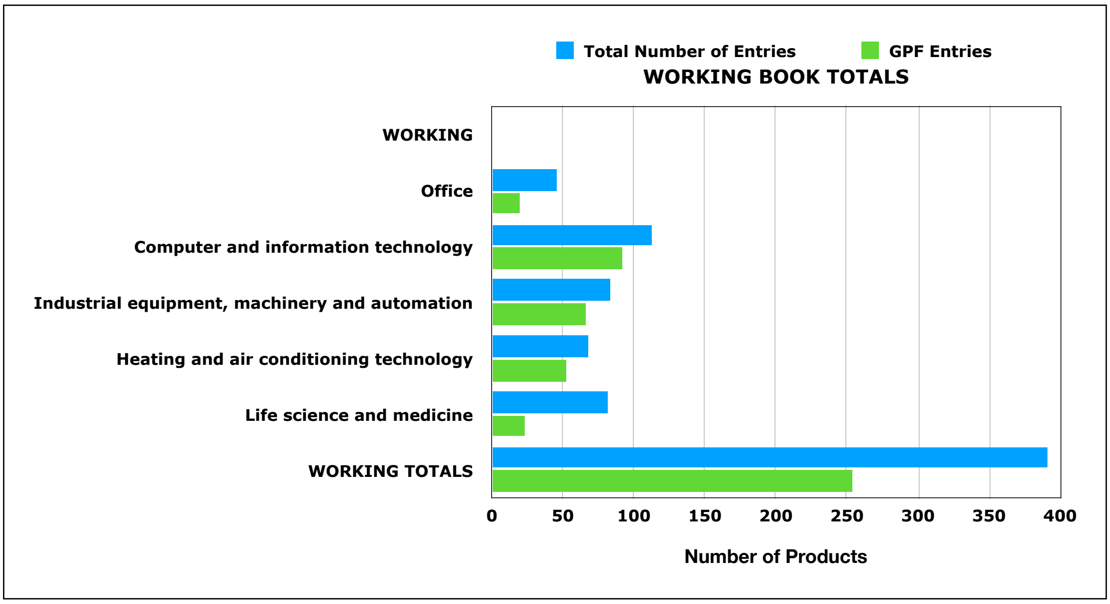
William F. Dresselhaus Doctoral Dissertation GPF Validation Research Data

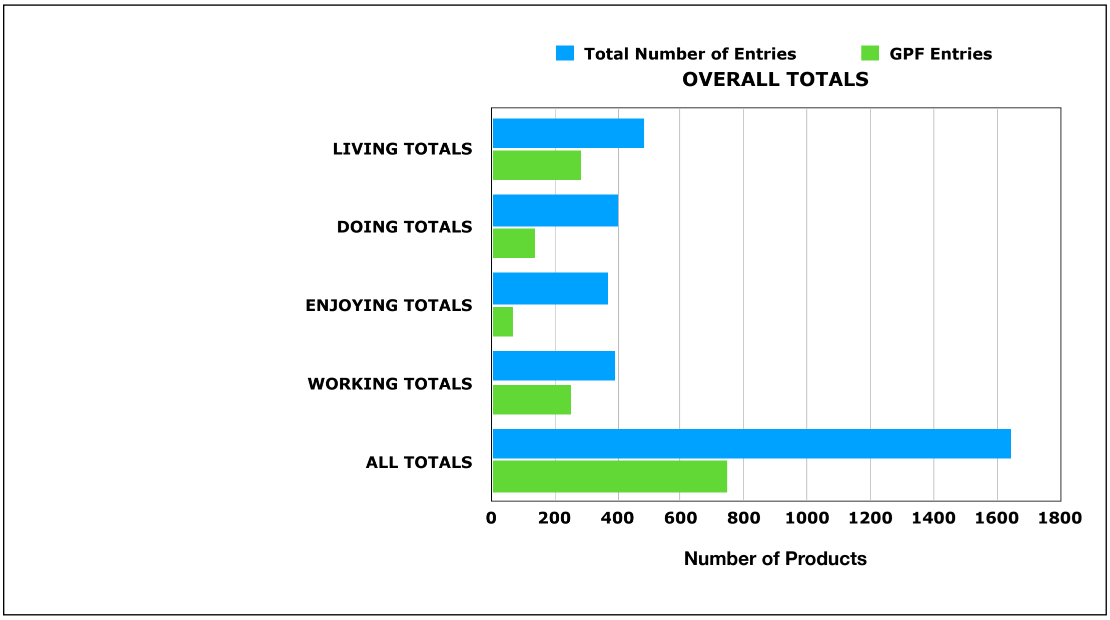
Red Dot *BOOK* & Category	Total Number of Entries	GPF Entries	Percent of GPF Entries over Total
LIVING			
Interior design	130	99	76.15%
Living rooms and bedrooms	26	14	53.85%
Kitchens	161	90	55.90%
Bathrooms and sanitary equipment	61	24	39.34%
Lighting and lamps	96	54	56.25%
Urban design and public spaces	14	4	28.57%
LIVING TOTALS	**488**	**285**	**58.40%**
DOING			
Babies and children	70	13	18.57%
Household	43	28	65.12%
Tableware and cooking utensils	48	12	25.00%
Garden	18	4	22.22%
Tools	34	7	20.59%
Cameras	52	17	32.69%
Communication	113	55	48.67%
Robots	23	4	17.39%
DOING TOTALS	**401**	**140**	**34.91%**
ENJOYING			
Bicycles	26	0	0.00%
Vehicles	60	11	18.33%
Sports and outdoor	45	4	8.89%
Leisure and games	19	4	21.05%
Entertainment	123	41	33.33%
Spas and personal care	45	5	11.11%
Fashion, lifestyle and accessories	34	3	8.82%
Watches and jewelry	13	1	7.69%
ENJOYING TOTALS	**365**	**69**	**18.90%**
WORKING			
Office	46	20	43.48%
Computer and information technology	113	91	80.53%
Industrial equipment, machinery and automation	83	66	79.52%
Heating and air conditioning technology	67	53	79.10%
Life science and medicine	82	23	28.05%
WORKING TOTALS	**391**	**253**	**64.71%**
ALL TOTALS	**1645**	**747**	**45.41%**


Total Number of Entries
GPF Entries
LIVING BOOK TOTALS
LIVING
Interior design
Living rooms and bedrooms
Kitchens
Bathrooms and sanitary equipment
Lighting and lamps
Urban design and public spaces
LIVING TOTALS
0
50
100
150
200
250
300
350
400
450
500
Number of Products


Total Number of Entries
GPF Entries
DOING BOOK TOTALS
DOING
Babies and children
Household
Tableware and cooking utensils
Garden
Tools
Cameras
Communication
Robots
DOING TOTALS
0
50
100
150
200
250
300
350
400
450
Number of Products


Total Number of Entries
GPF Entries
ENJOYING BOOK TOTALS
ENJOYING
Bicycles
Vehicles
Sports and outdoor
Leisure and games
Entertainment
Spas and personal care
Fashion, lifestyle and accessories
Watches and jewelry
ENJOYING TOTALS
0
50
100
150
200
250
300
350
400
Number of Products





Note. The first image is the spreadsheet data results for each Red Dot Award book and for each category in each book. The next bar graphs visually depict the spreadsheet results. Each selected GPF product is identified in each Red Dot Award book by a round dark label so that each selected GPF product can be verified by outside sources.

8.9. Figure—GPF Use Analysis: Celebrated Designers/Firms

Dieter Rams Book (Klemp, 2020)

Each different product image was counted in this book for the total product count. Then only the GPF products were counted for the geometric count. For this publication, there were 300 different product photos designed or directed by Dieter Rams. 245 of those were of geometric form in composition. That means that 81.67% of all products in this book of the work of Rams were of GPF design.

Keep It Simple Book (Esslinger, 2013)

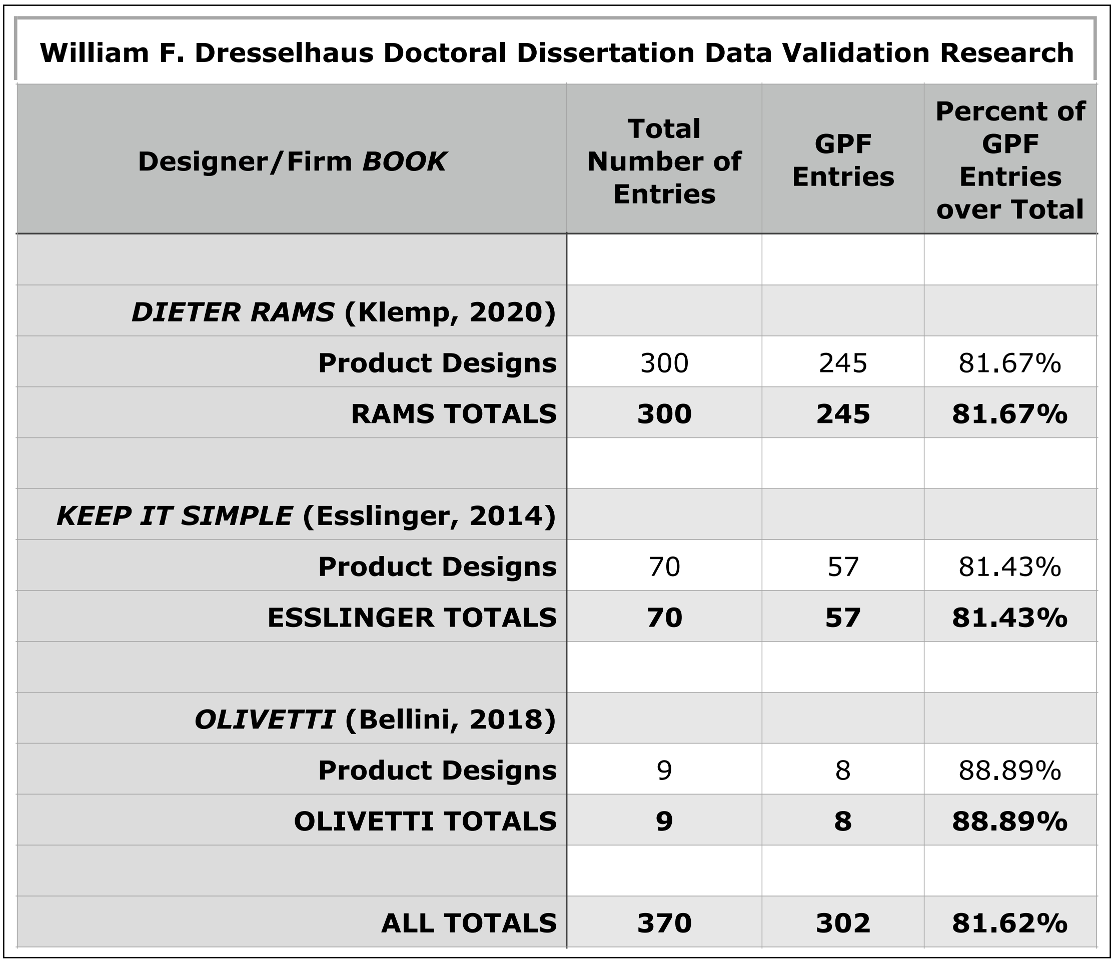
Each different product image was counted in this book for the total product count. Then only the GPF products were counted for the geometric count. For this publication, there were 70 different product photos designed or directed by Hartmutt Esslinger. 57 of those were of geometric form in composition. That means that 81.43% of all products in this book of the work of Esslinger were of GPF design.

Olivetti Book (Bellini, 2018)

Each different product was counted in this ebook for the total product count. Then only the GPF products were counted for the geometric count. For this publication, there were 9 different products designed by Olivetti designers. 8 of those were of geometric form in composition. That means that 88.89% of the products in this ebook of the work of Olivetti designers were of GPF design.

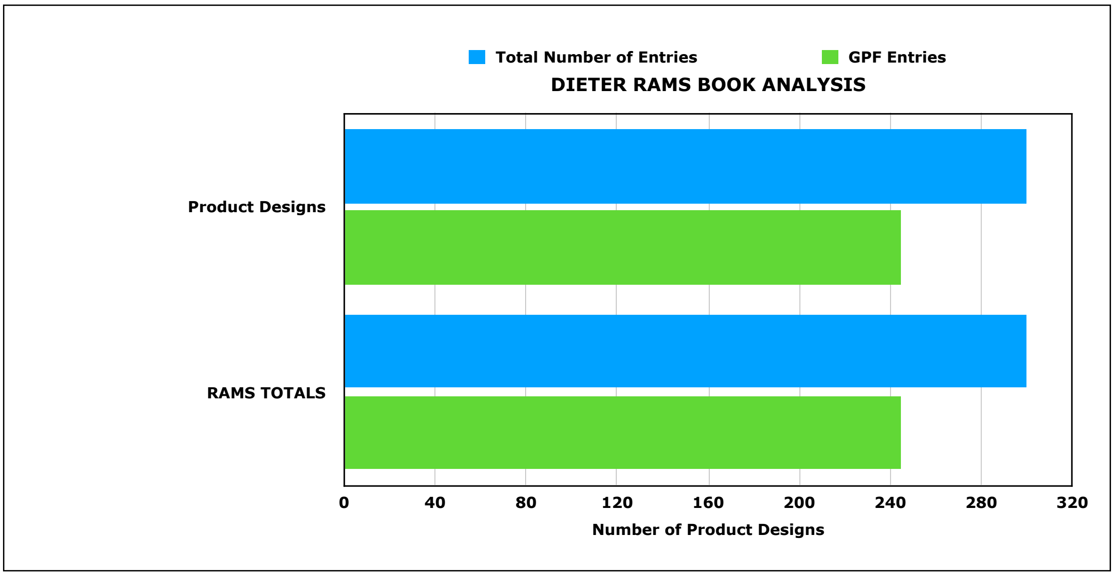
Total for All Three Celebrated Designers/Firms Books: The average percentage of total GPF products versus total products in this set of three selected designers/firms books was 84.00%. This is a significantly high percentage of GPF for this category.

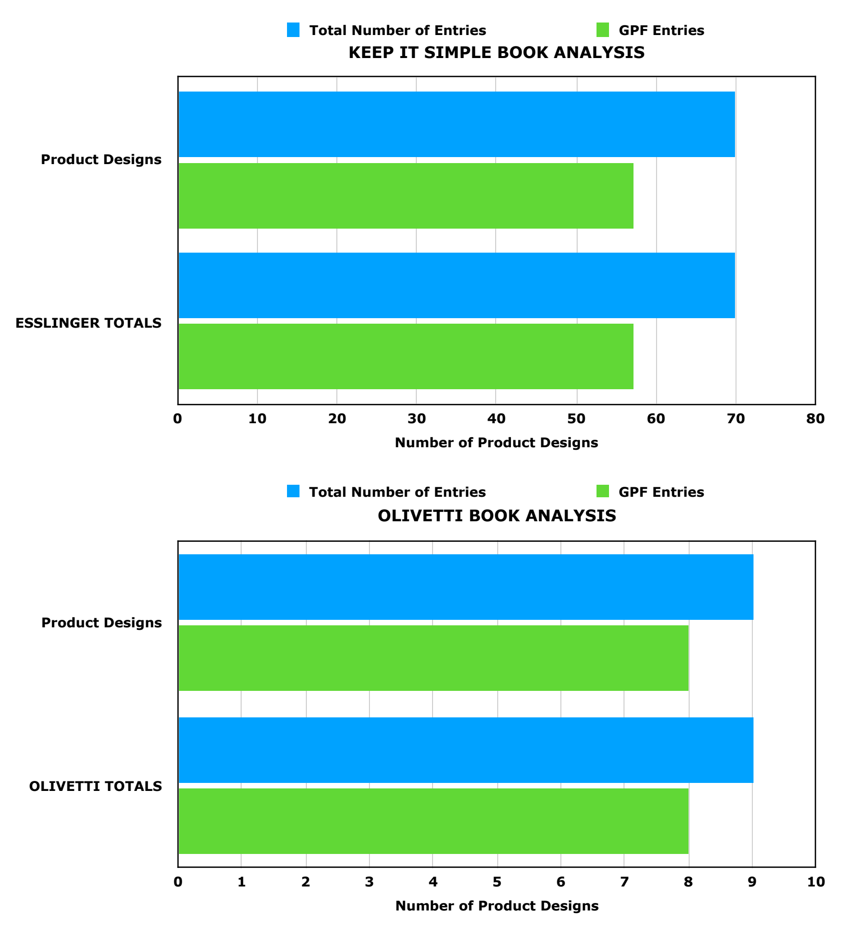
8.10. Figure—GPF Use Analysis: Data for Designers/Firms

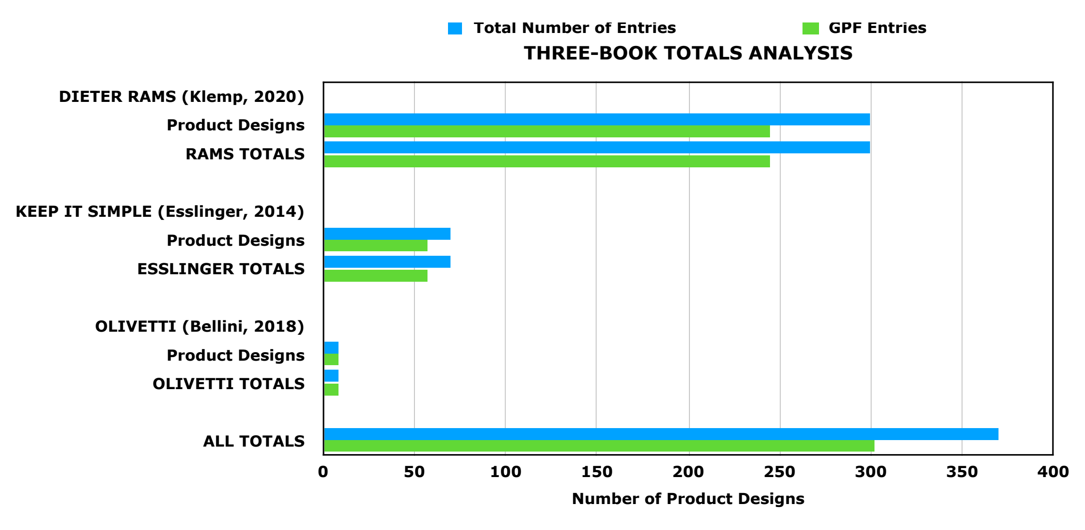


William F. Dresselhaus Doctoral Dissertation Data Validation Research

Designer/Firm *BOOK*	Total Number of Entries	GPF Entries	Percent of GPF Entries over Total
***DIETER RAMS* (Klemp, 2020)**			
Product Designs	300	245	81.67%
RAMS TOTALS	**300**	**245**	**81.67%**
***KEEP IT SIMPLE* (Esslinger, 2014)**			
Product Designs	70	57	81.43%
ESSLINGER TOTALS	**70**	**57**	**81.43%**
***OLIVETTI* (Bellini, 2018)**			
Product Designs	9	8	88.89%
OLIVETTI TOTALS	**9**	**8**	**88.89%**
ALL TOTALS	**370**	**302**	**81.62%**



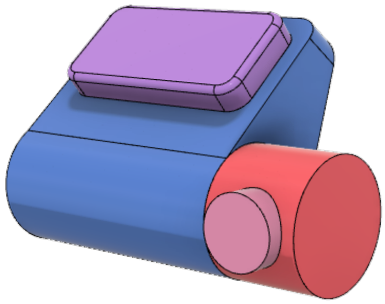




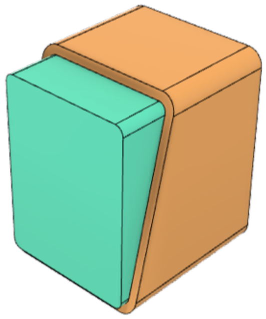
Note. The first image is the spreadsheet data results for each designers/firms book. The following bar graphs visually depict the spreadsheet results.

8.11. Figure—GPF Use Analysis: Product Deconstruction

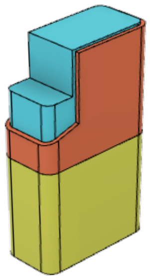
70mai Dash Cam Pro
Manufacturer: 70mai Co., Ltd., Shanghai, China; In-house design: Qing Xu.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.



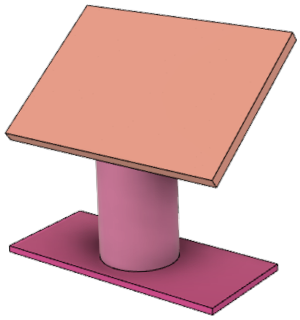
nanoArch S140
Manufacturer: BMF Material Technology Inc., Shenzhen, China; Design:
LKK Design Shenzhen Co., Ltd., Weilin Ding, Zhaoxun Jia, Shenzhen, China.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.



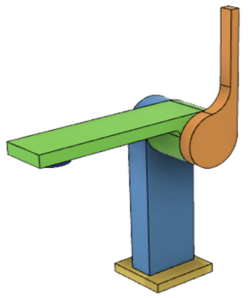
Charge Pal
Manufacturer: Shanghai Sunmi Technology Co., Ltd., Shanghai, China;
In-house design: Sunmi Design Center, David Protet.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.



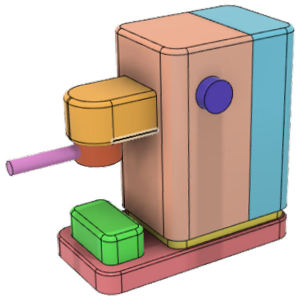
HP Engage
Manufacturer: HP Inc., Palo Alto, California, USA;
In-house design: HP Design Team.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.



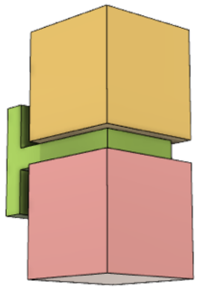
Cranes
Manufacturer: Rifeng Enterprise Group Co., Ltd., Foshan, China; In-house design:
Jianying Huang, Jiangming Peng, Xiaobing Yang,
Donghong Xiao, Zhengbing Qu, Qingyun Ai, Jincui Zhan, Puhua Zhong.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.



WMF Lumero
Manufacturer: WMF Consumer Electric GmbH, Jettingen-Scheppach, Germany;
In-house design: Ernst Köhler.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.

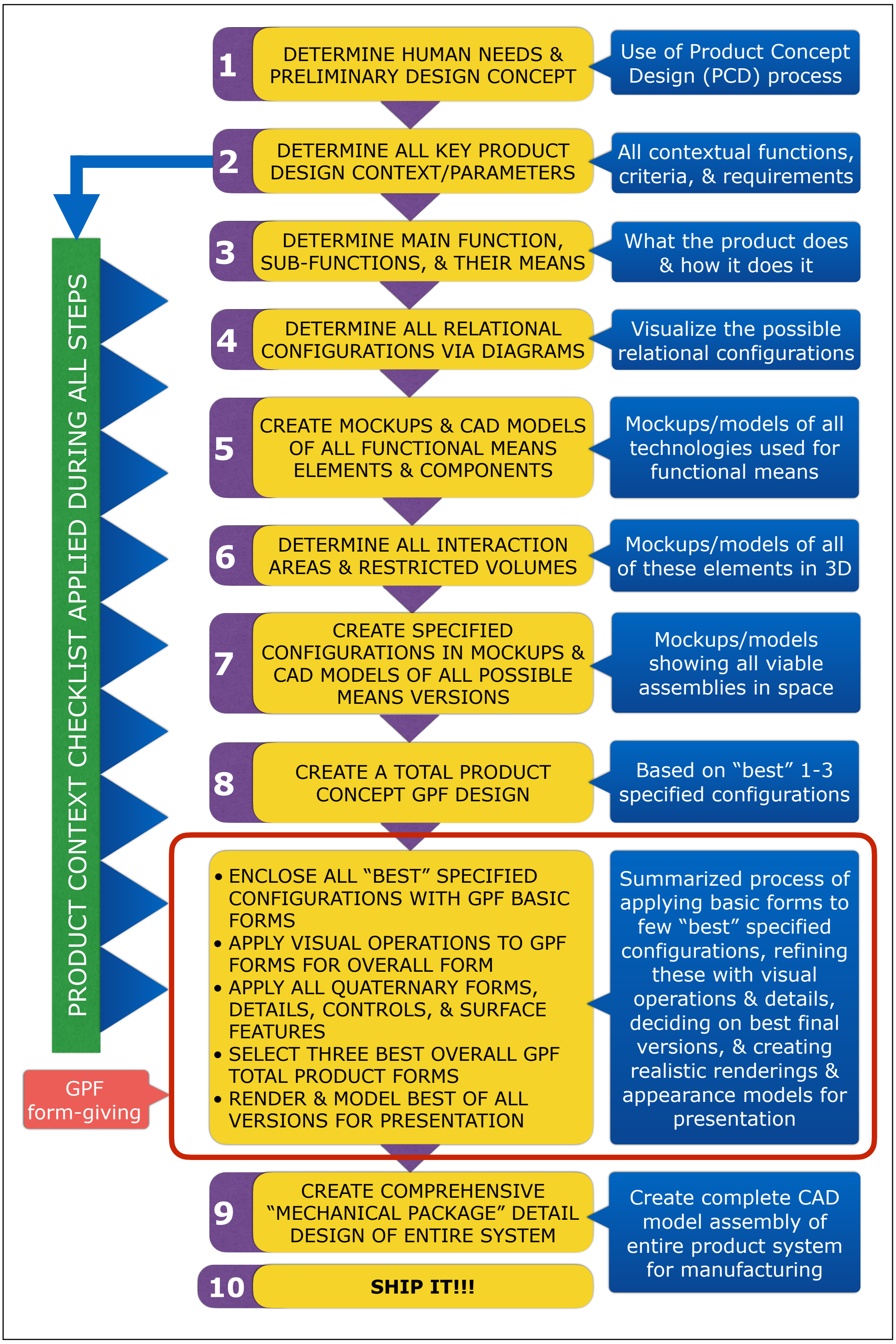


CUBA
Manufacturer: Ningbo Utec Electric Co., Ltd., Yuyao, Zhejiang, China;
In-house design.
Photo used by permission. Red Dot (Product Design) Awards: 2019. © Red Dot 2020.



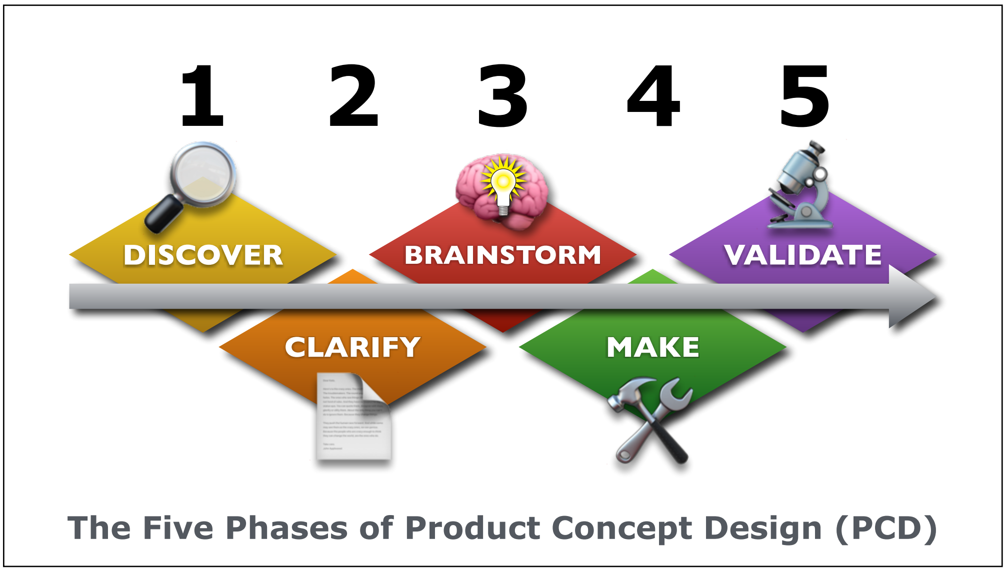
Note. These images are Red Dot Award competition products from the online site, *red-dot.org*. In the image sets, the left image is a photo of the actual product, and the image on the right is a deconstructed breakdown into the GPF component volumes with a different color for each distinct volume element. This demonstrates the product composition into its basic GPF components. The representative CAD model dimensions are approximate and created visually from the Red Dot Award product photos. Photos used by permission.

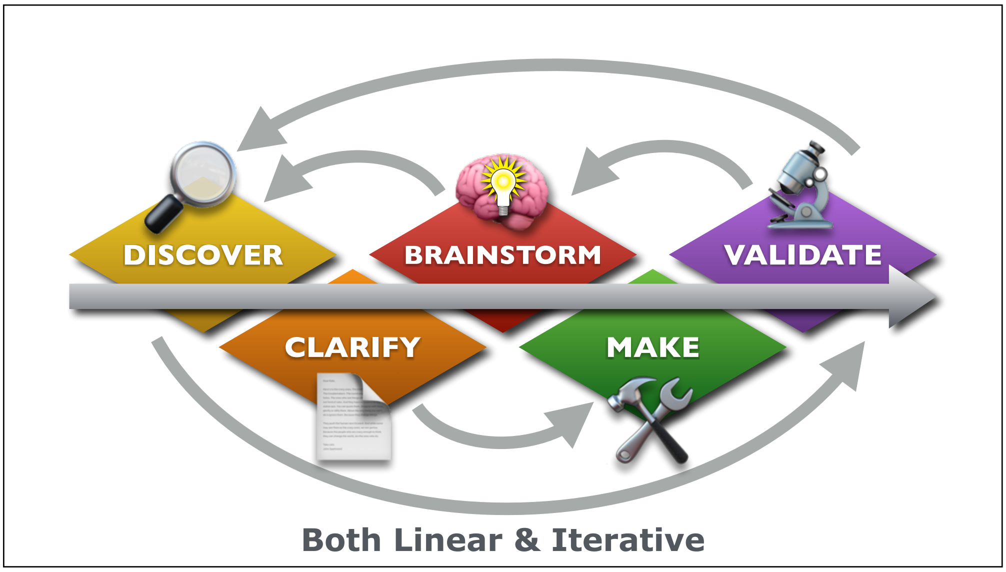
8.12. Figure—Product Design Synthesis: Total Process

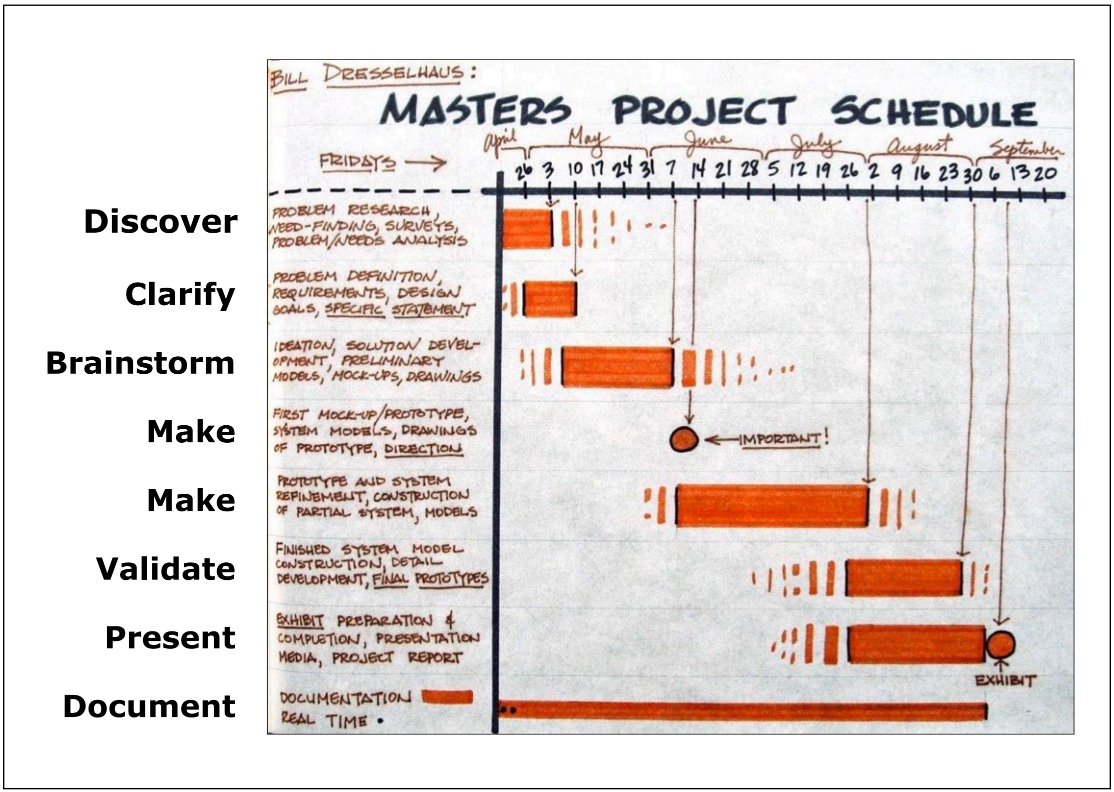


Note. This is a summarized graphical version of the synthesized and stepped GPF design method. Partially adapted from Tjalve (1979, p. 8), with project additions.

8.13. Figure—Product Concept Design (PCD): Process

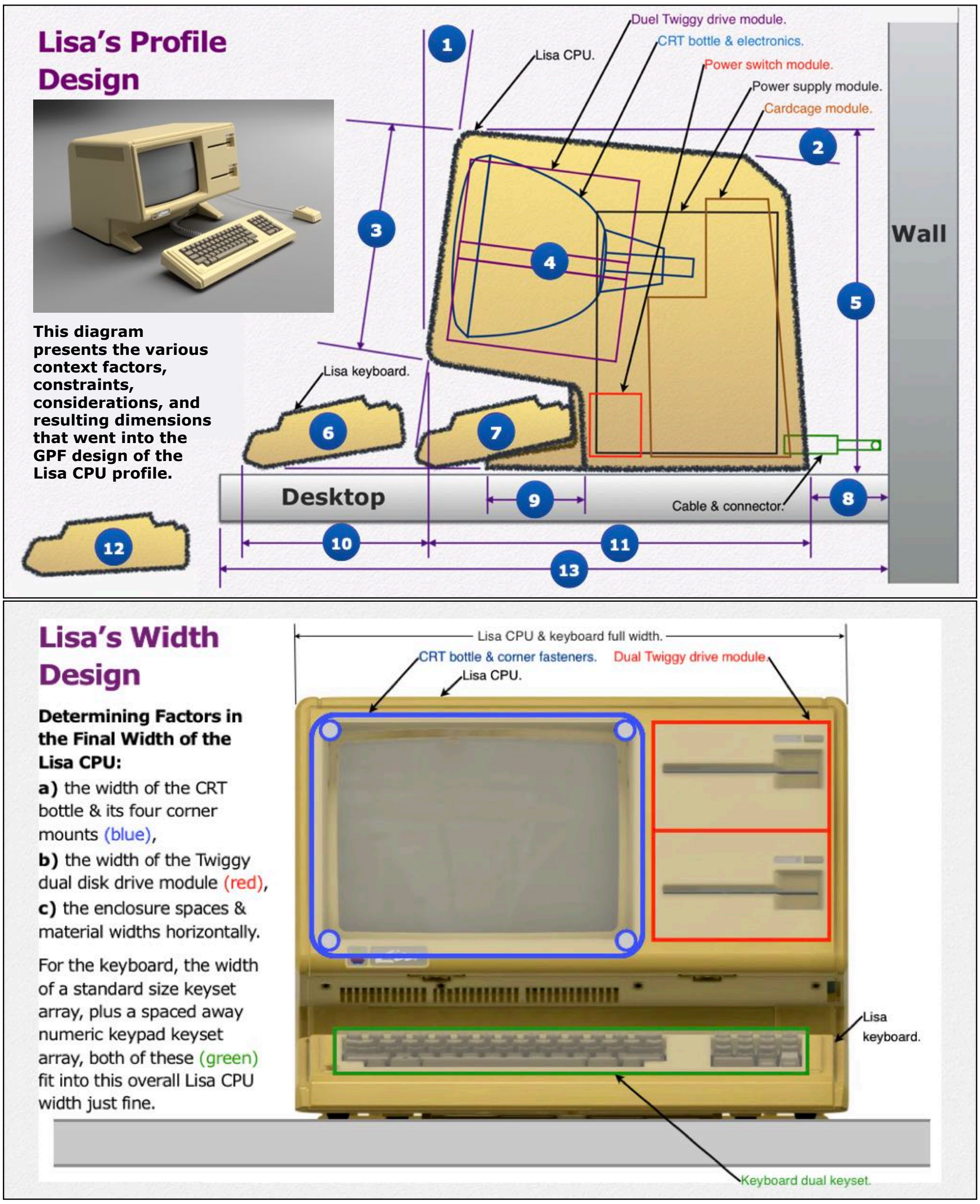






Note. Depicted here are graphical renditions for the process of early product concept development that this author calls product concept design (PCD). It is a blend of this author's professional product design experience (9. CURRICULUM VITAE), a bit of design thinking (Brown, 2019, p. 73), the diverge-converge diamond process, and this author's early visual thinking education in the Stanford University Product Design Program (Kunkel, 1997, p. 13). The last image depicts a page from this author's 1974 masters project sketchbook at Stanford University that shows the very early beginnings and thinking (1972-1974) regarding a product concept design process inspired by this author's Stanford professor, Robert H. McKim (1980).

8.14. Figure—Form Follows: Context & Constraints



This diagram presents the various context factors, constraints, considerations, and resulting dimensions that went into the GPF design of the Lisa CPU profile.

Determining Factors in the Final Width of the Lisa CPU:

a) the width of the CRT bottle & its four corner mounts (blue),

b) the width of the Twiggy dual disk drive module (red),

c) the enclosure spaces & material widths horizontally.

For the keyboard, the width of a standard size keyset array, plus a spaced away numeric keypad keyset array, both of these (green) fit into this overall Lisa CPU width just fine.

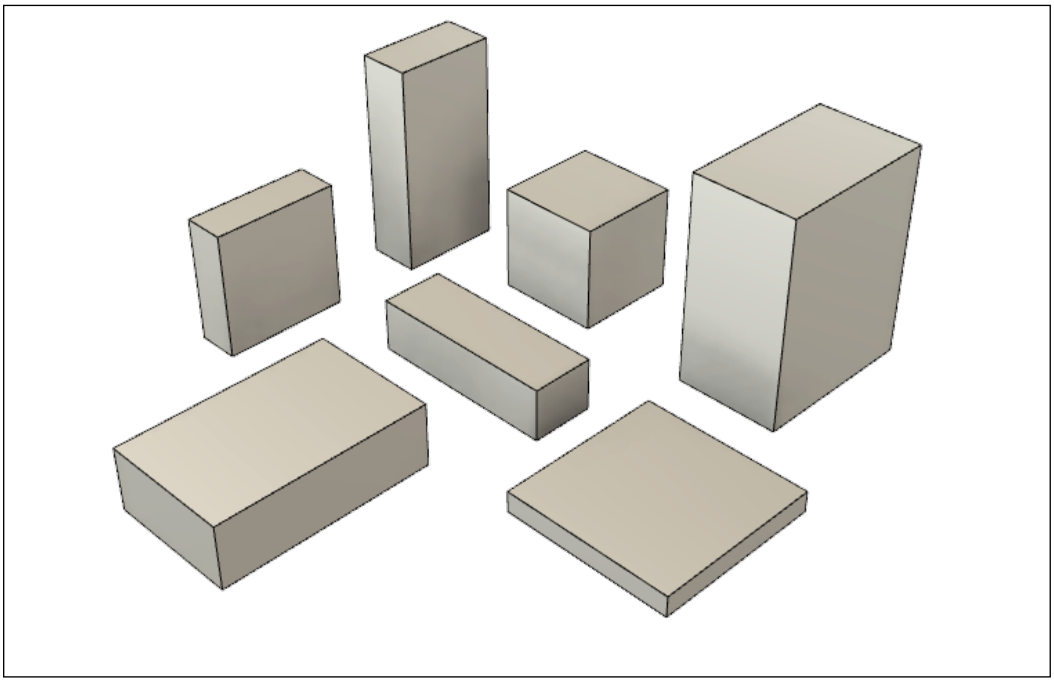
Note. This is a demonstration of the necessity of a GPF design "following" a product ergonomic, usability, configurational, and environmental context and constraints. The following are related to the top layout drawing reference numbers:

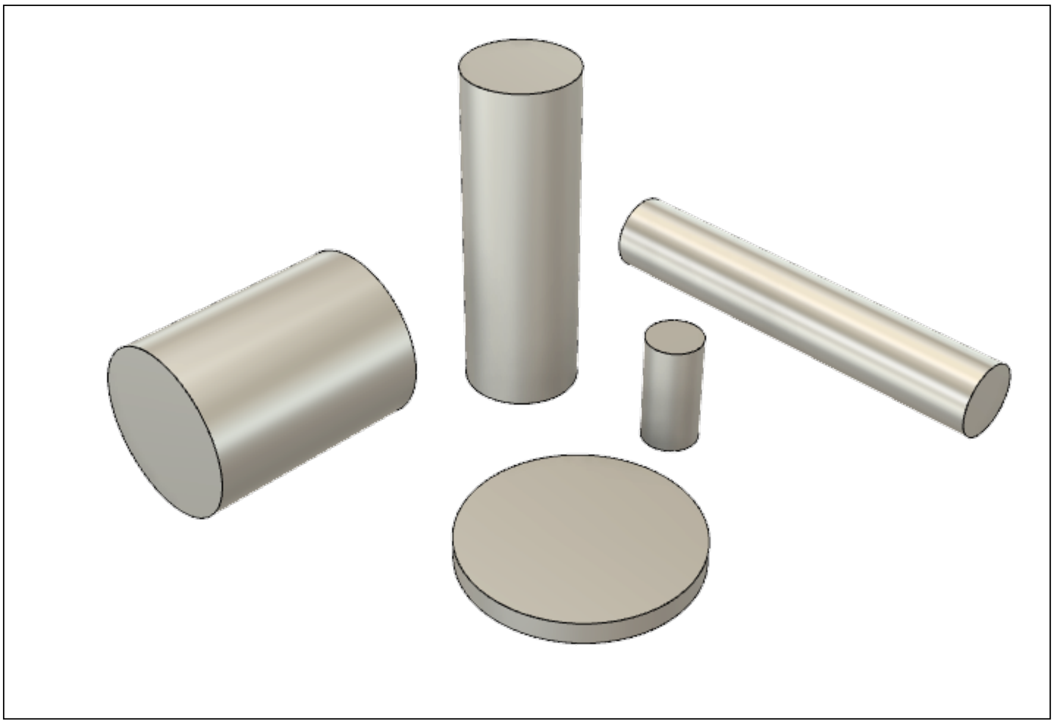
1. Angle off vertical of the CRT (cathode ray tube) display and front bezel presented to the user. This angle was optimized for ergonomic viewing. This angle was also affected by several other geometric constraints, especially the Lisa overall height. Tilting the CRT bottle and display screen back for increased viewing angle tended to either reduce internal component and hardware space or increase the overall Lisa height. This angle was set at the minimum allowed per current ergonomic standards at 11 degrees off the vertical and provided optimum interior space.

2. Angle of the top surface of Lisa off of horizontal. Besides a positive aesthetic effect, this had a practical function of deterring users from putting objects or drinks on top of the unit that could accidentally fall or spill and damage the computer.
3. Dimension of the overhang height of the front bezel and Lisa "face" presented to the user. It had both aesthetic and functional effects on the enclosure. Its value was determined by the overall height of the display CRT bottle plus enclosure thickness and clearance dimensions and details surrounding it.
4. Due to the heavy CRT bottle overhang and its forward CG (center of gravity), plus the heavy dual Twiggy floppy drive subassembly, the CG of the CPU (central processing unit) was towards the user. This CG location created the risk of ~50 pounds of Lisa falling forward into the lap of the user! Thus the Lisa front feet.
5. Dimension of the overall height of Lisa off the desktop. Steve Jobs wanted this optimized for enclosure volume for components and hardware, but low enough for the user to see over the top while sitting and doing work.
6. Furthest out allowed for a usable working position of the Lisa keyboard on a standard 30-inch deep desktop. It just permits a proper user working condition.
7. Position of the stowed keyboard that Steve Jobs required. It had to be fully under the overhang and within the extended plane of the front bezel surface as shown. This geometry affected the keyboard overall depth dimension and the overhang depth.
8. The minimum clearance distance for Lisa rear connectors and cables to a rear wall for a 30-inch deep desktop. Determined by the largest possible connector and bent cable assembly connected to a port on the rear of Lisa.
9. Due to the risk of the heavy Lisa CPU falling forward onto the user and also pass the tip test for UL safety certification, the Lisa Foot part was created. Located in the lower front of the CPU, it was a structural and robust part of two protruding feet on either side of the front under the Lisa overhang. These feet were in the keyboard stowage area and had to be nested under the stowed keyboard.
10. Dimension that indicates the furthest that the Lisa keyboard could be positioned from the CPU while still remaining on a 30-inch deep standard desktop. A further distance needed a deeper desktop or the keyboard on the user's lap.
11. Dimension of the full depth of the Lisa CPU front to back. Maximized to fit the depths of all internal components, e.g., CRT display and electronics, Twiggy dual floppy drive subassembly, and card cage and electronics, plus cabling, enclosure spaces, airflow space, and materials. Determined by a standard desktop depth, space for rear connectors and cables, and a desktop in-use keyboard position.
12. User's lap position of the Lisa keyboard made possible due to the keyboard coiled extension cord. This permitted the keyboard to also be stowed on top of the CPU.
13. Dimension of a standard American desktop depth of 30 inches. The rear connector and cable space, plus the overall Lisa CPU depth, plus the outboard keyboard desktop position, all taken altogether, could not exceed this dimension.

Adapted and revised from Dresselhaus (2017, pp. 32-33). Used by permission.

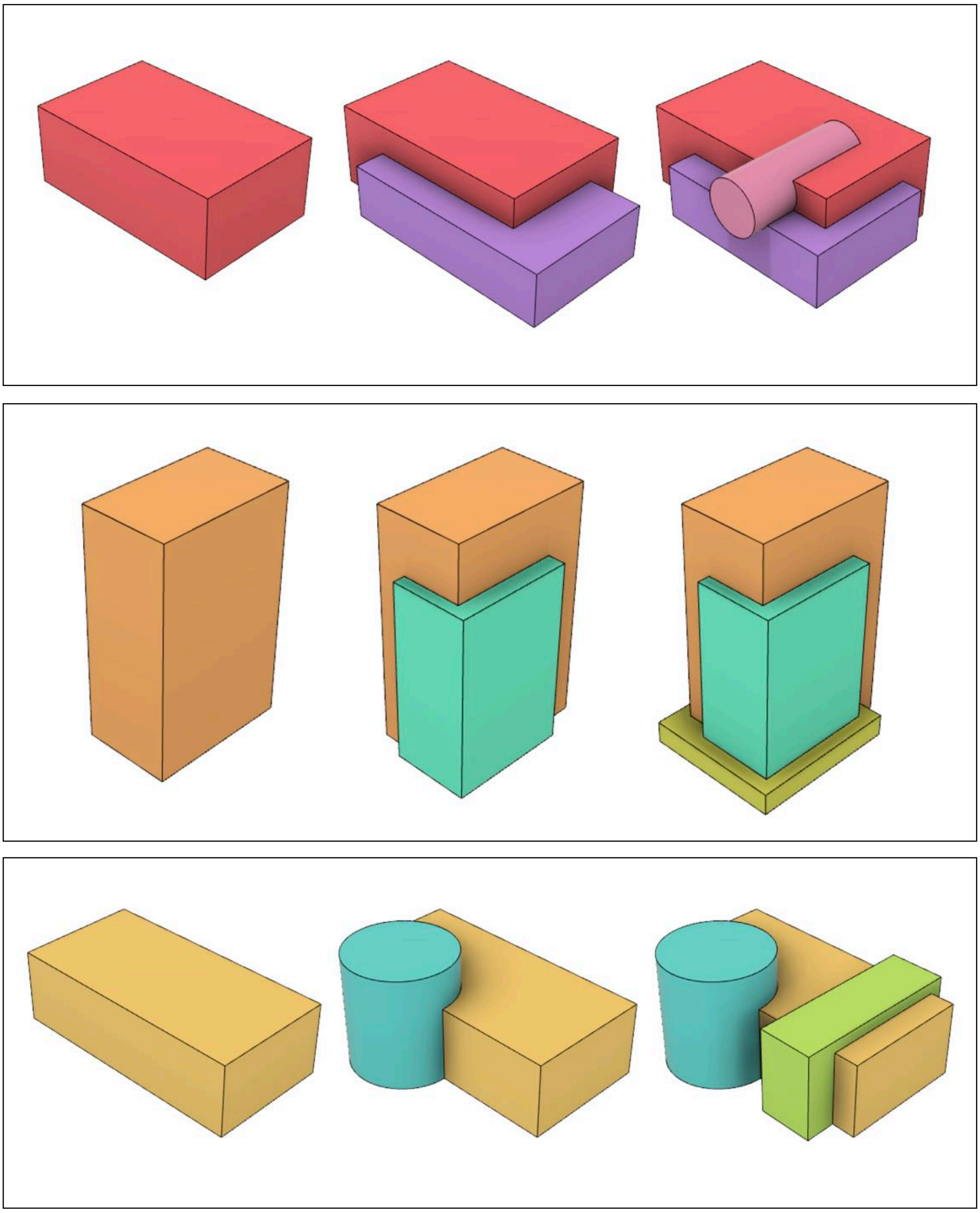
8.15. Figure—GPF Design: Basic Volumes





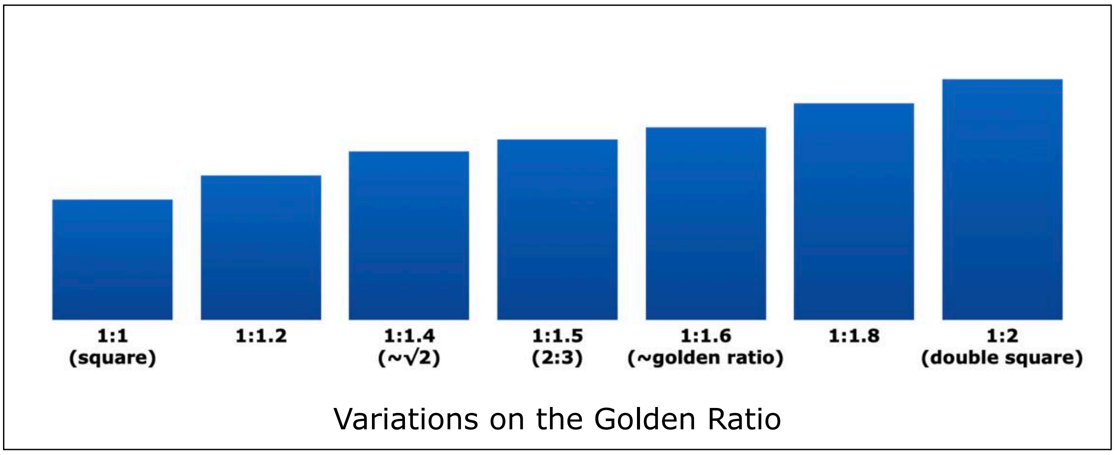
Note. Shown are the two basic volumes utilized in this project's GPF design language and method. They are the rectangular prism and the right cylinder. Most all GPF design compositions can be made from singular or combinations of these two forms. Applying various visual principles and form operations to these and their product compositions, and then adding finishing details, colors, textures, and other features, provides a vast array of aesthetic form design opportunities and artistic freedom.

8.16. Figure—GPF Design: Form Hierarchy

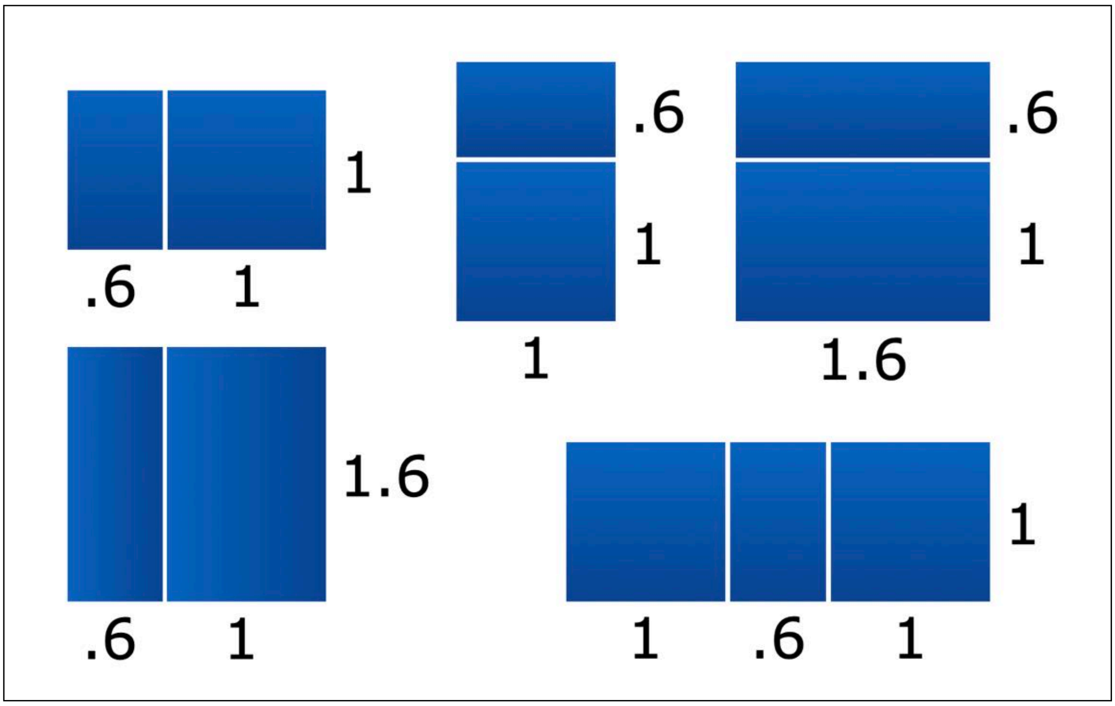


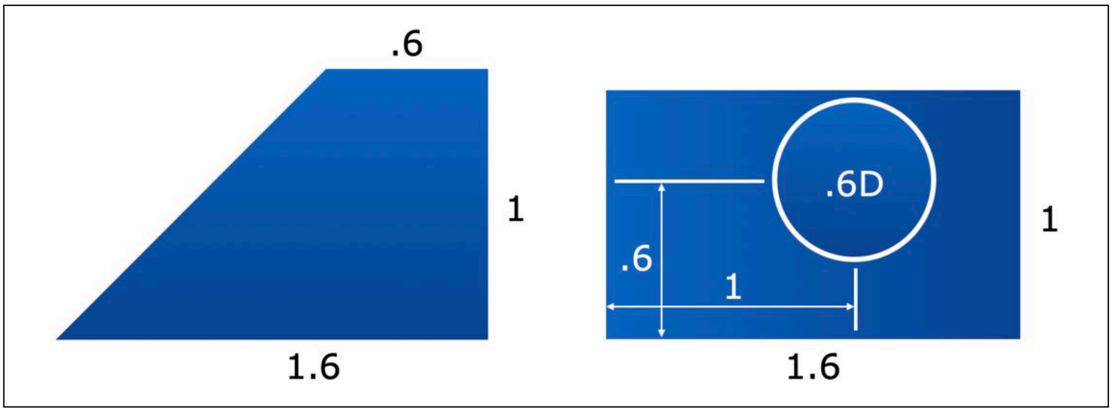
Note. These images demonstrate the recommended three-tiered hierarchy of GPF compositions: primary (largest), secondary (medium), and tertiary (smallest, except for quaternary forms). The fourth level is quaternary, which includes visual form finishing details such as edge radii and chamfers, parting gaps, controls and signifiers, displays, venting, fastening features, and similar quaternary features. Generally, creation of these forms should be from primary, secondary, tertiary, and to quaternary, in that order. Hierarchy concept adapted from Hannah (2002, pp. 52-57).

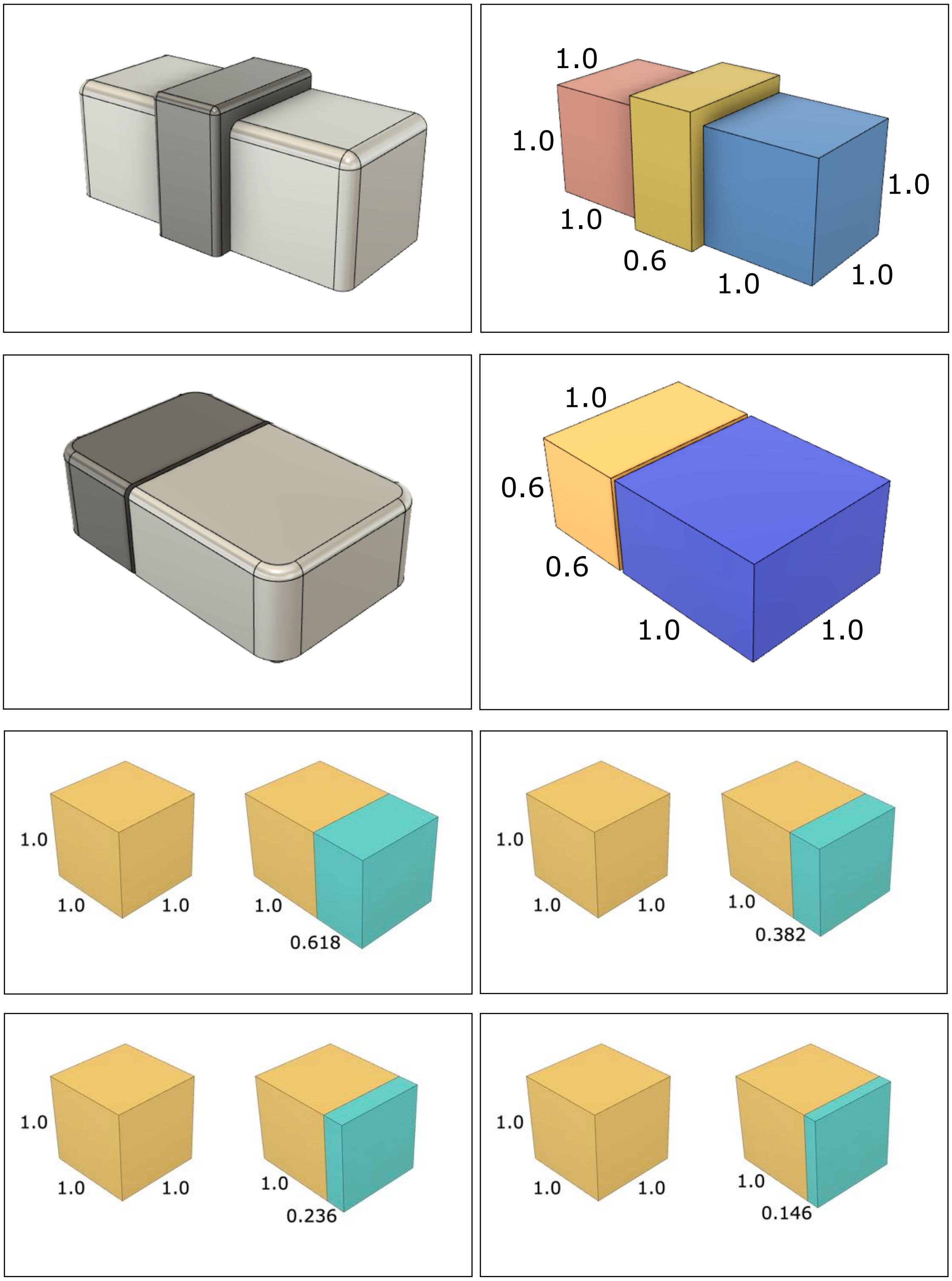
8.17. Figure—GPF Design: Preferred Proportions



Variations on the Golden Ratio

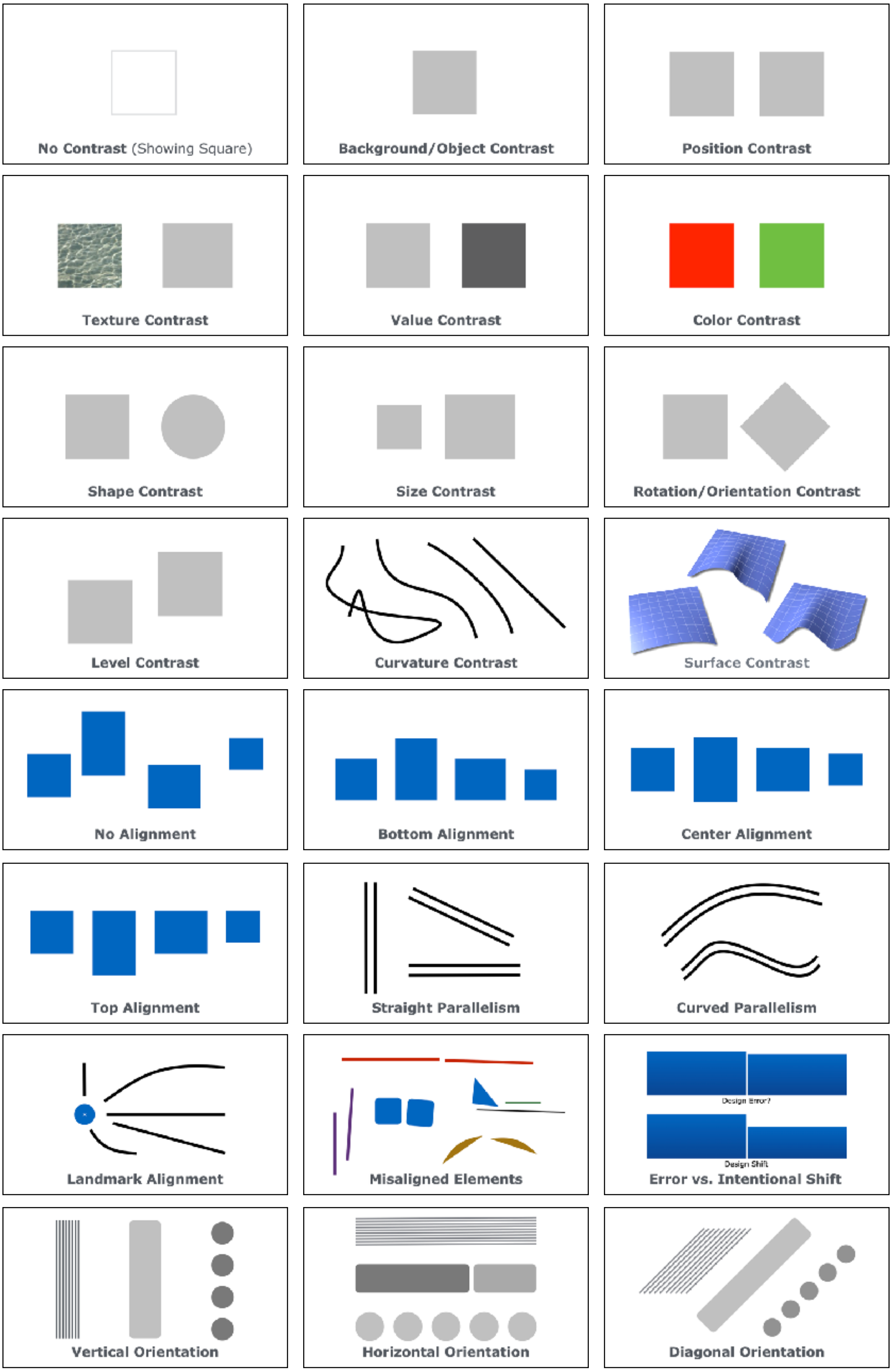






Note. The so-called Golden Ratio, or Phi = 1.618…, and ratios near it (e.g., only 1.6 or 1.5), are generally preferred by humans and may be used as a starting point for GPF design proportions. The first set of images represent these ratios in two dimensional graphics. The second image set is of 3D forms based on the Phi scale (Bass, 2019, p. 51), all also applicable to GPF design appropriately. Adapted also from Coates (2003), Elam (2011), Meisner (2018), Bejan (2009), and Dondis (1973).

8.18. Figure—GPF Design: Visual Principles



No Contrast (Showing Square)

Background/Object Contrast

Position Contrast

Texture Contrast

Value Contrast

Color Contrast

Shape Contrast

Size Contrast

Rotation/Orientation Contrast

Level Contrast

Curvature Contrast

Surface Contrast

No Alignment

Bottom Alignment

Center Alignment

Top Alignment

Straight Parallelism

Curved Parallelism

Landmark Alignment

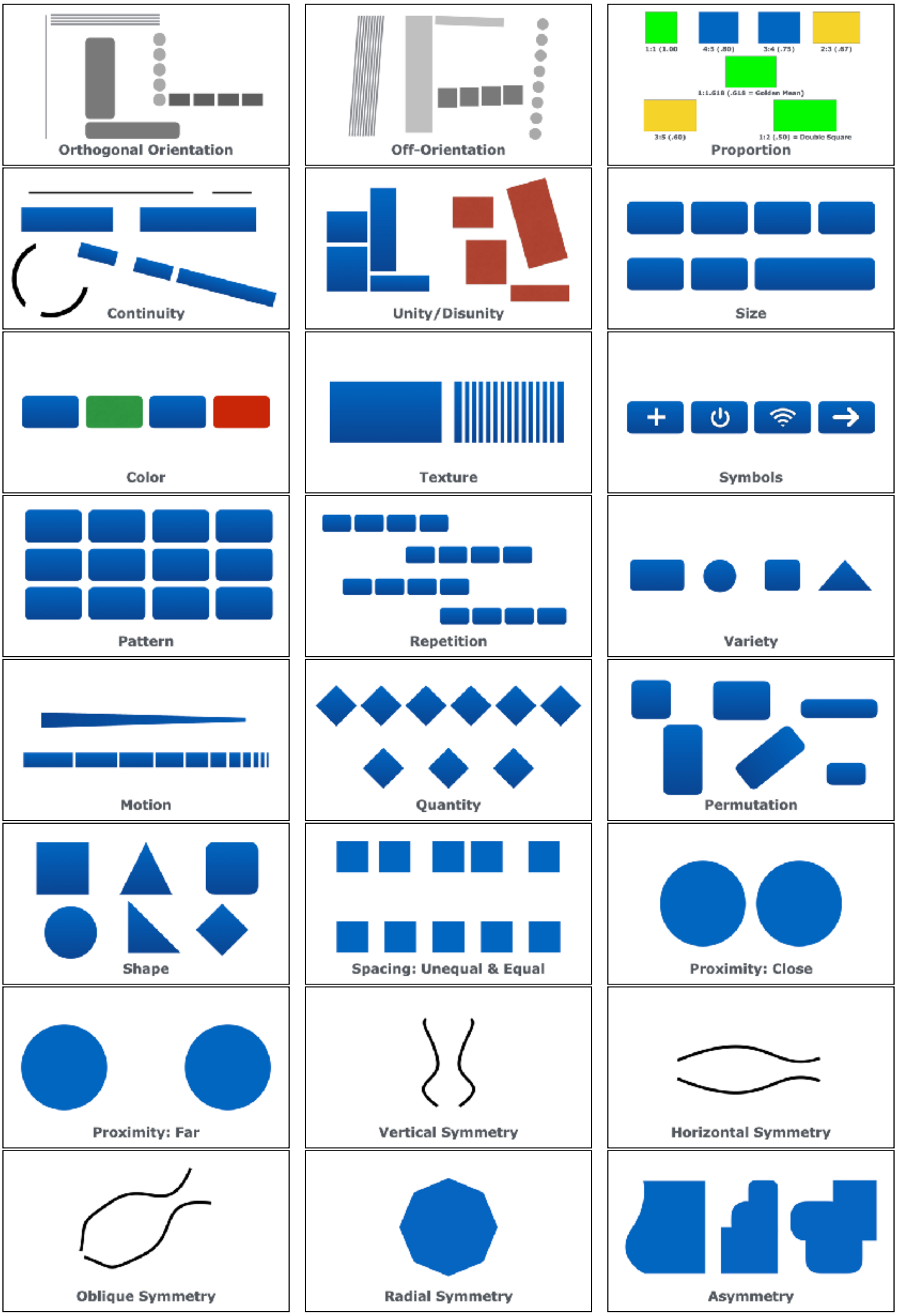
Misaligned Elements

Error vs. Intentional Shift

Vertical Orientation

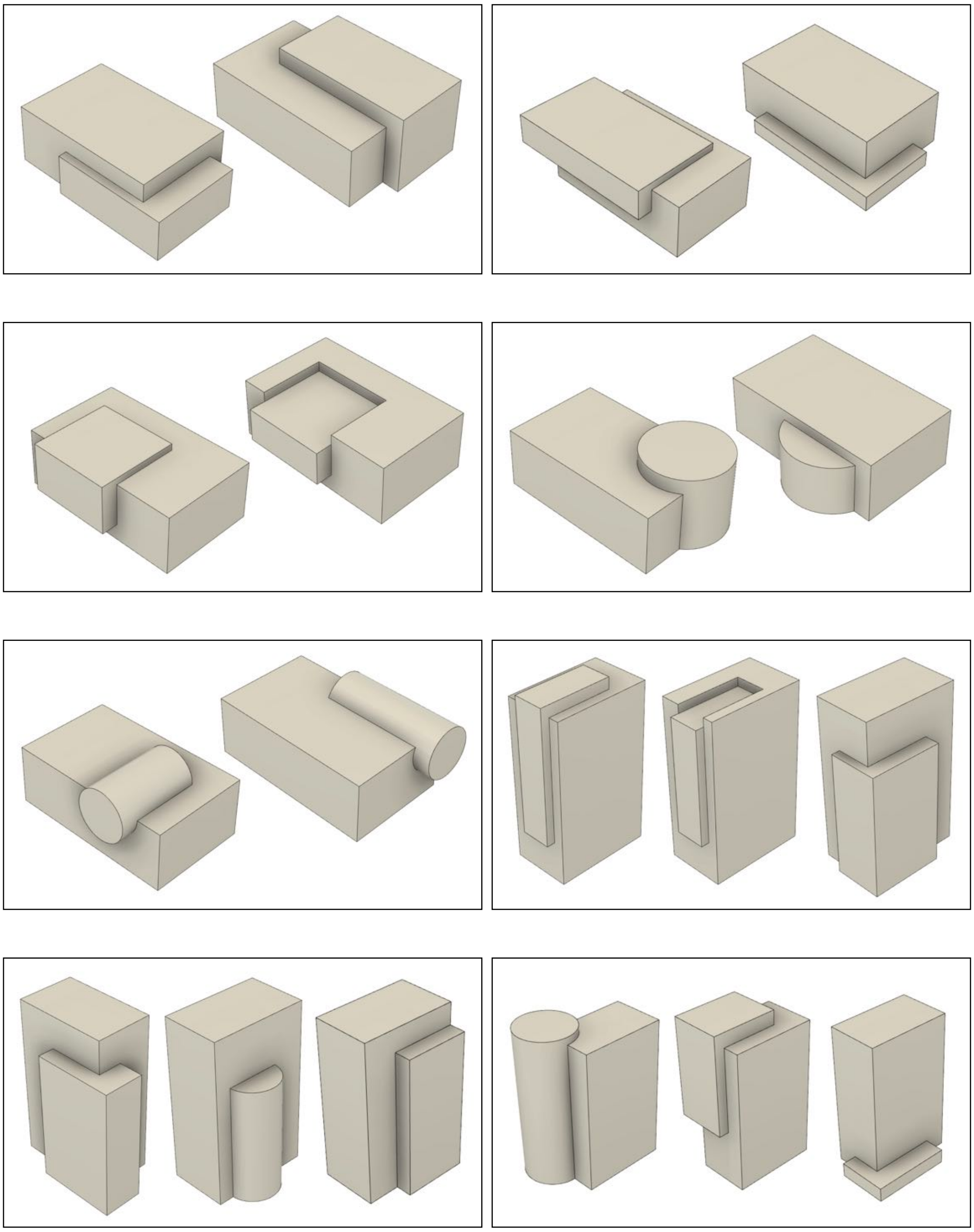
Horizontal Orientation

Diagonal Orientation



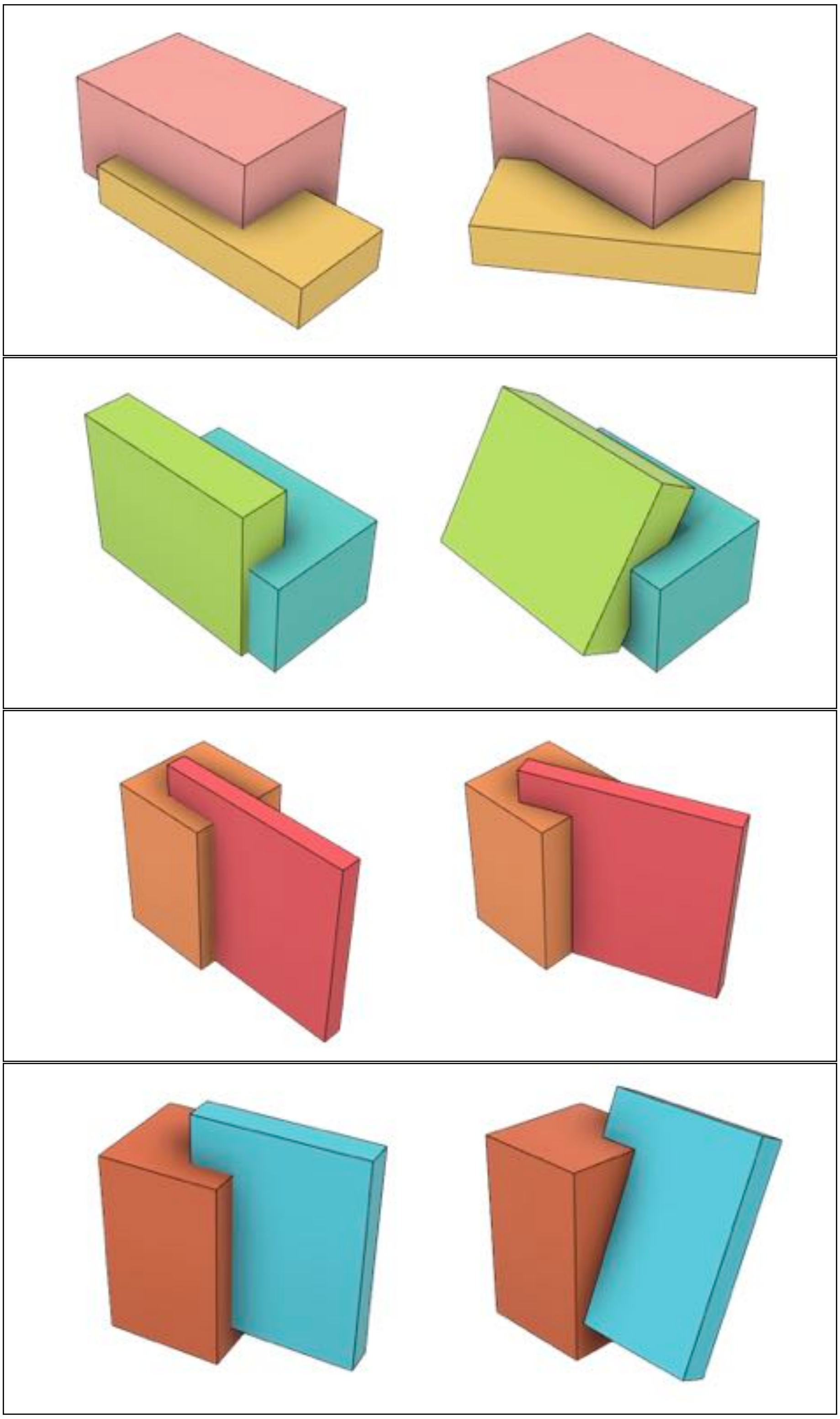
Note. These are the primary visual principles used in this project's GPF method. They are to be applied properly to the GPFs and details in creating product compositions. Adapted from Dondis (1973), Leborg (2006), Coates (2003), and others.

8.19. Figure—GPF Operation: Intersect (with Shift)



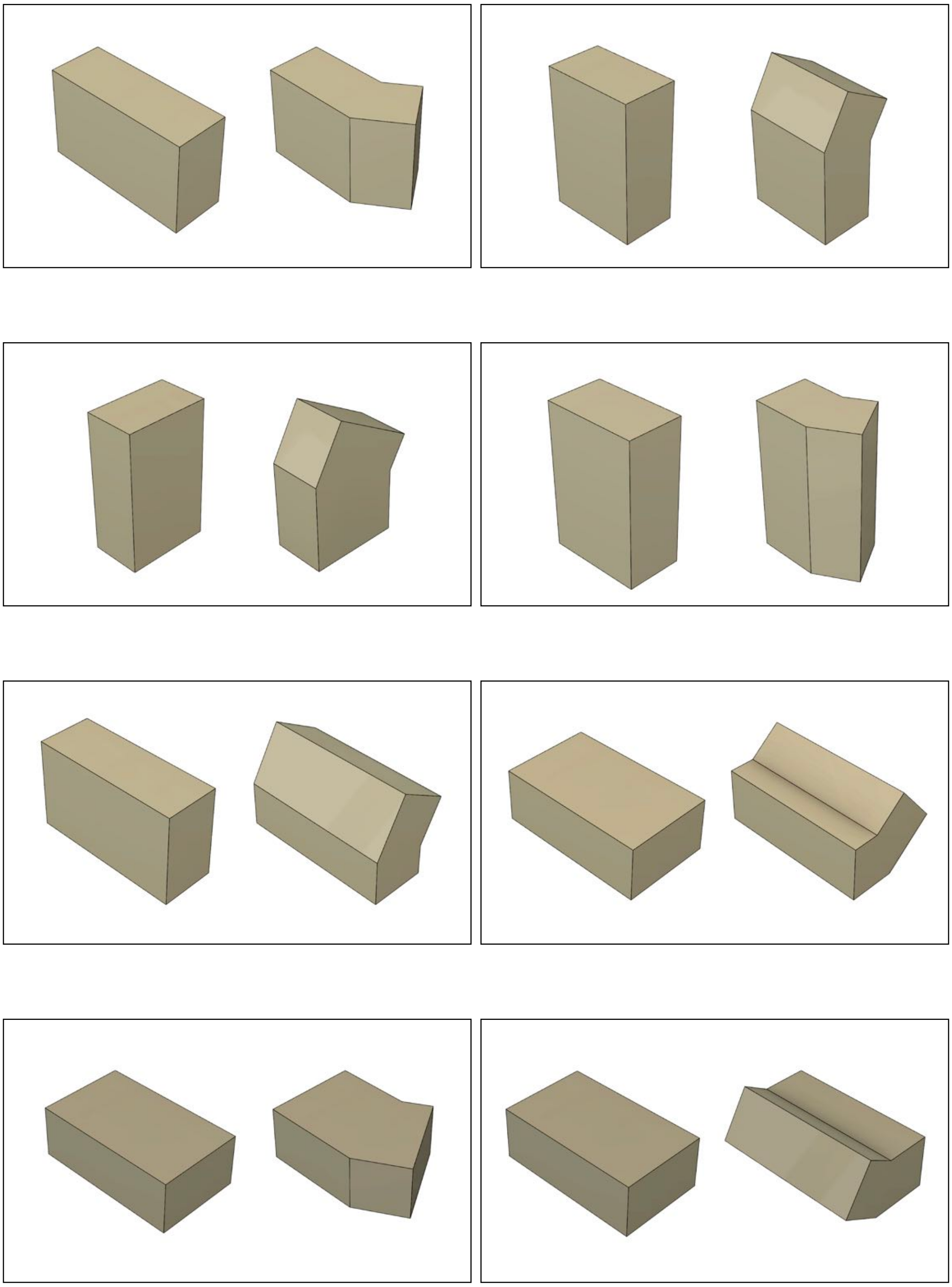
Note. These images illustrate two form operations: intersect and shift. One form is shifted orthogonally relative to the other after intersection with the other form so that the form surfaces are not coincident, but offset and shifted. When intersect is used alone, especially for rectangular prisms, the intersection may not be perceptible (due to coplanar surfaces) without a parting gap. Thus, both intersect and shift are generally used together. Adapted from Di Mari and Yoo (2013).

8.20. Figure—GPF Operation: Rotate (with Intersect & Shift)



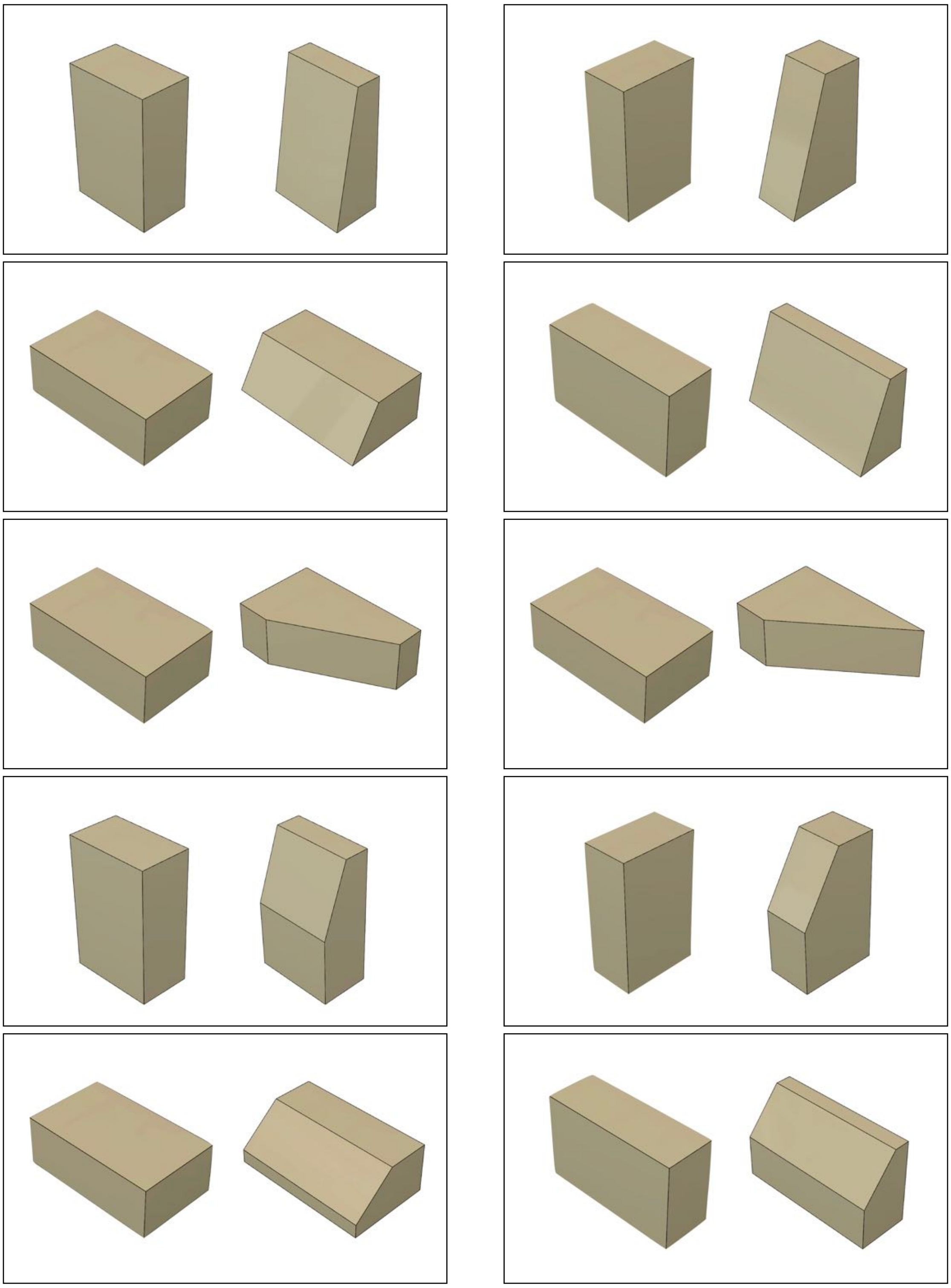
Note. Shown here is the GPF visual operation of rotate, also with intersect and shift, applied to the secondary form of two GPF intersecting forms. The secondary form is intersected with the primary, rotated, and shifted for appropriate visual appearance.

8.21. Figure—GPF Operation: Bend



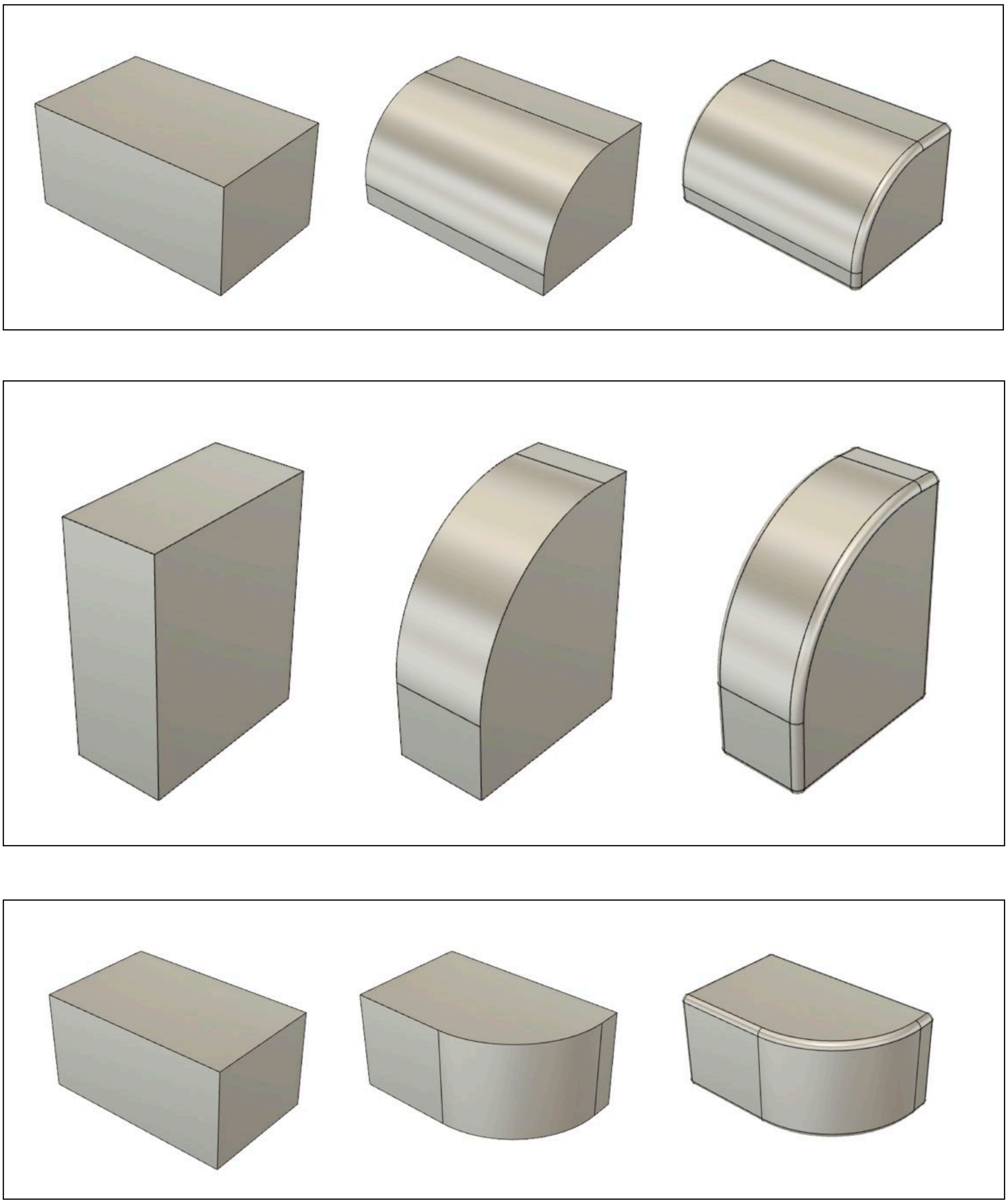
Note. The GPF operation of bend is here applied to a single rectangular prism in various orthogonal positions. This visual operation may be applied to any single or combined GPF composition form alone or in combination with other visual form operations. Adapted from Di Mari and Yoo (2013).

8.22. Figure—GPF Operation: Shear



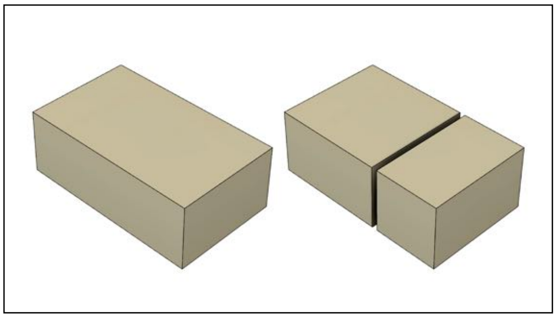
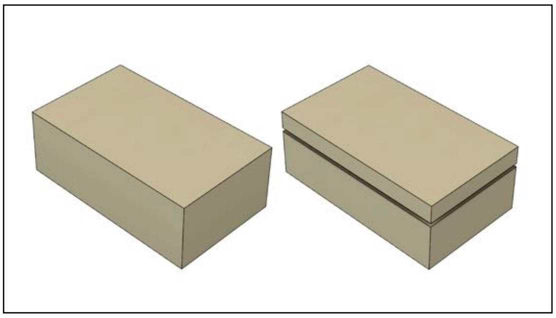
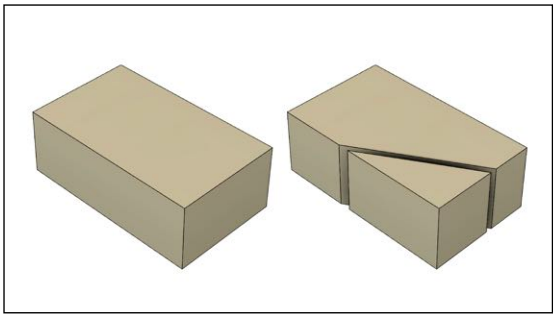
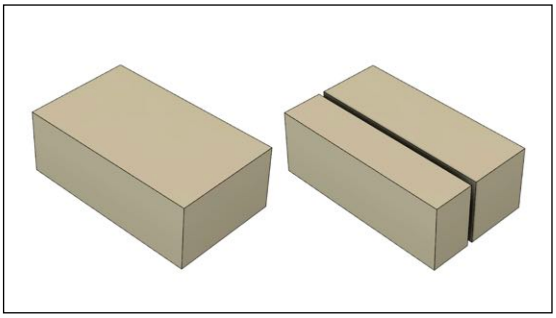
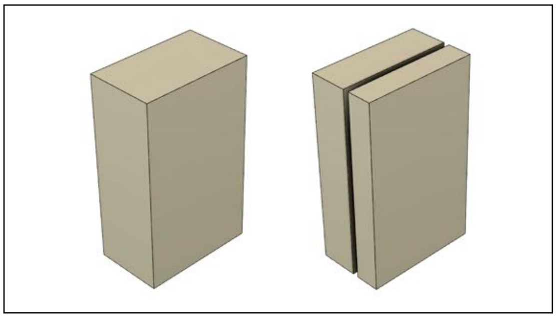
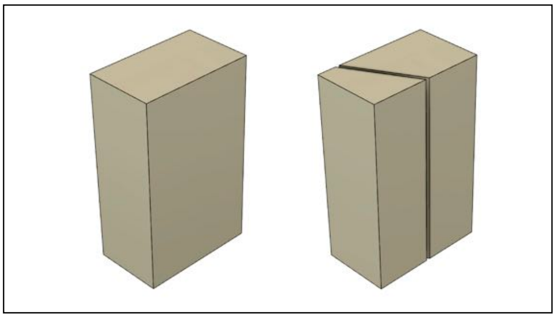
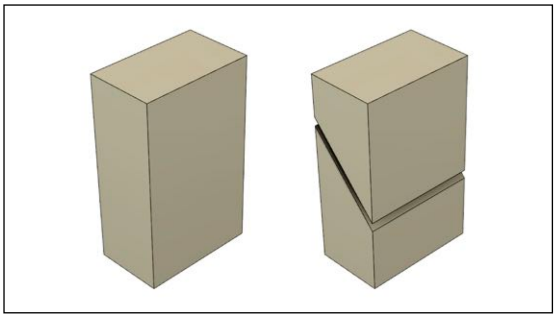
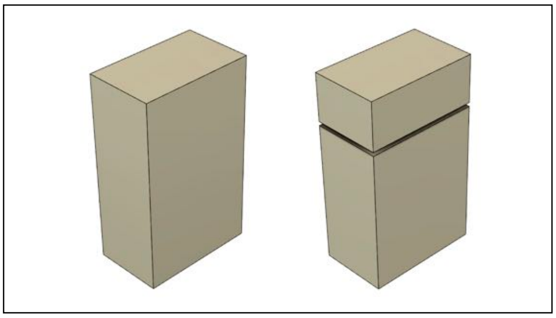
Note. The GPF operation of shear is here applied to a single rectangular prism in various orthogonal positions. This visual operation may be applied to any single or combined GPF composition form alone or in combination with other visual form operations. Adapted from Di Mari and Yoo (2013).

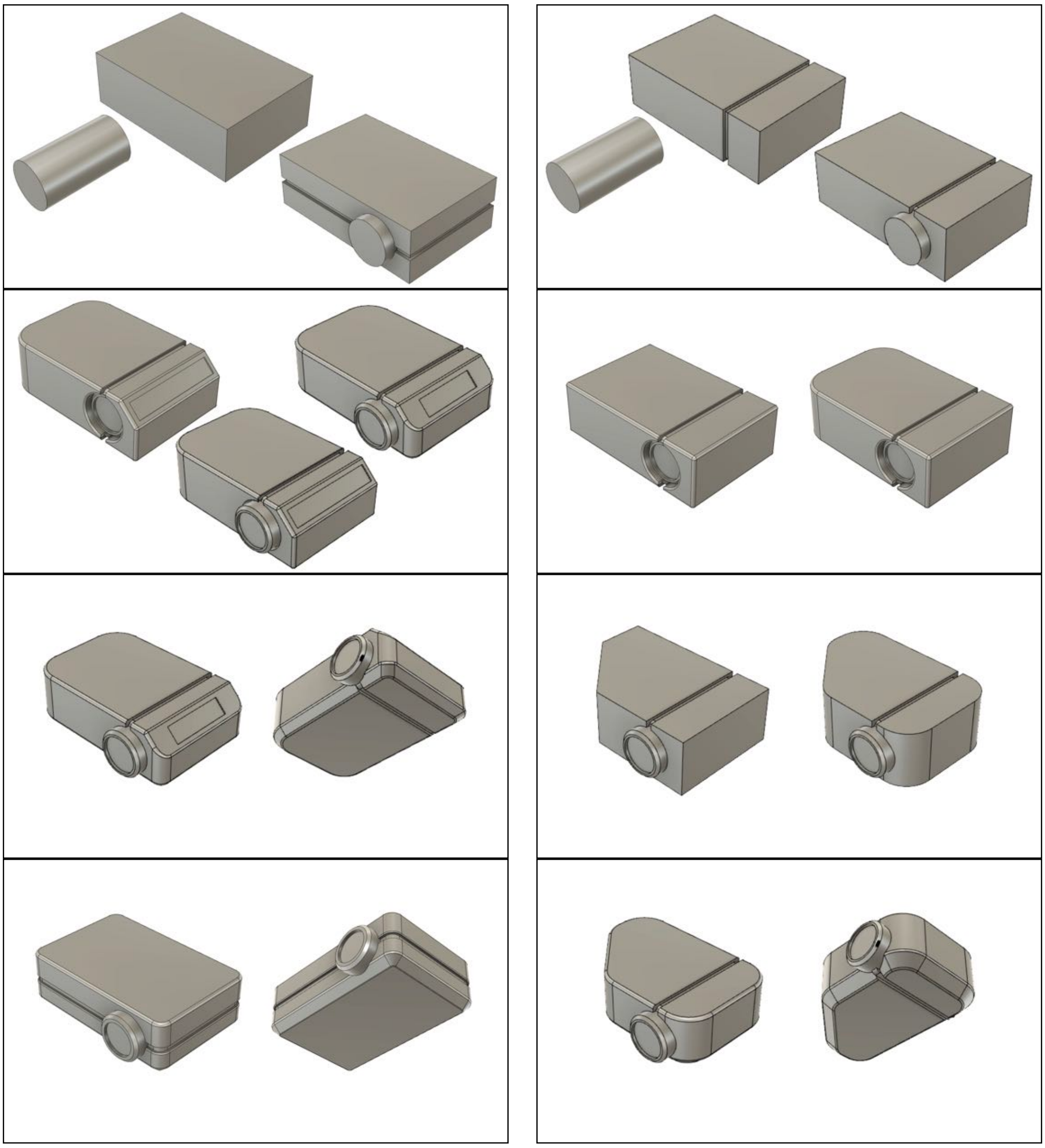
8.23. Figure—GPF Operation: Radial Surface



Note. Shown here is the GPF visual operation of radial surface applied to a single rectangular prism. This visual operation may be applied to any single or combined GPF composition form alone or in combination with other visual form operations. This is the form operation of applying a large radius, much larger than an edge radius, to a GPF to create a large radial surface. In each image is first shown the basic rectangular prism, then the radial surface applied alone, and then the visual effect of adding a small edge radii all around on all edges. Adapted from Di Mari and Yoo (2013).

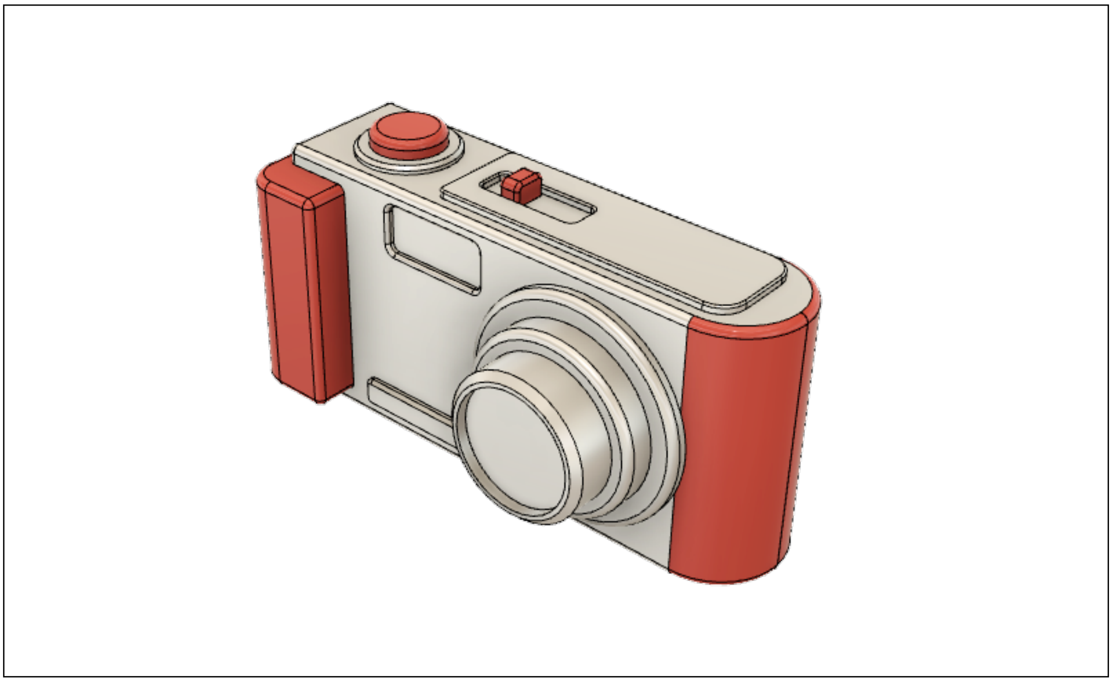
8.24. Figure—GPF Operation: Fracture

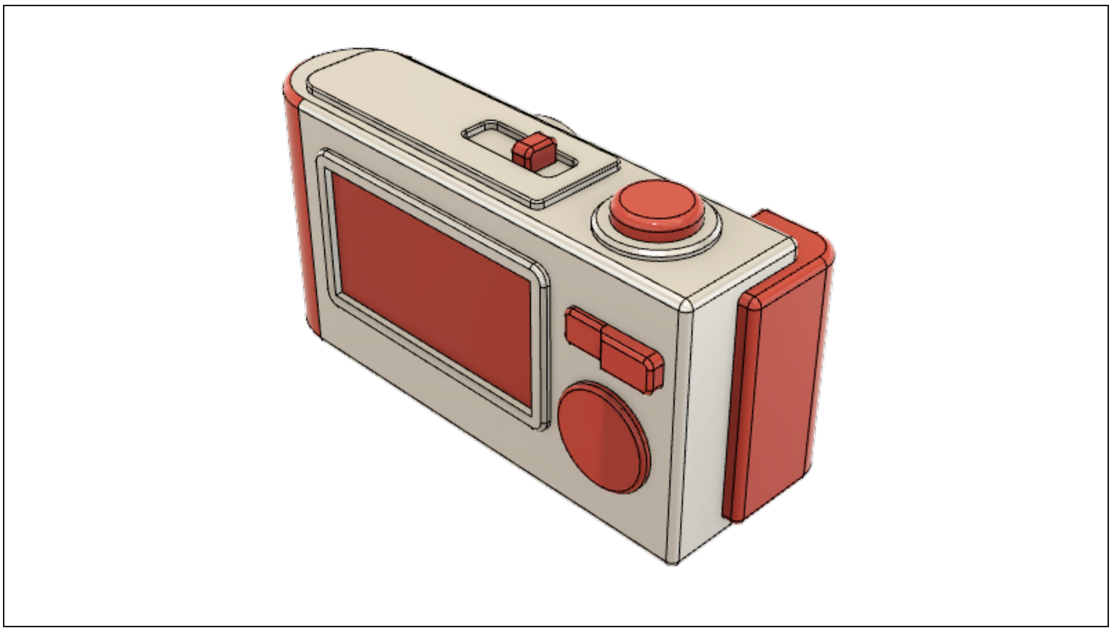











Note. The GPF operation of fracture is here applied first to a single rectangular prism in various orthogonal positions. This visual operation may be applied to any single or combined GPF composition form alone or in combination with other visual form operations. Fracture is similar to “parting gap," but not the same. A parting gap is smaller in gap size and depth, and identifies a product part separation, or simulates one for visual effect. A fracture is a large separation of two significant parts of a single GPF volume indicating a composite form with a gap separating the two. A moderate size fracture gap is shown here—it could be wider within reason. The second set of images shows how fracture can be applied in different ways, positions, and planes to a digital projector form. Visual operations of shear and radial surface are added in some cases. Various details such as edge radius and chamfer are then added, with signifier controls, to both options to show how the final form development might take place after the fracture operation is applied. Adapted from Di Mari and Yoo (2013).

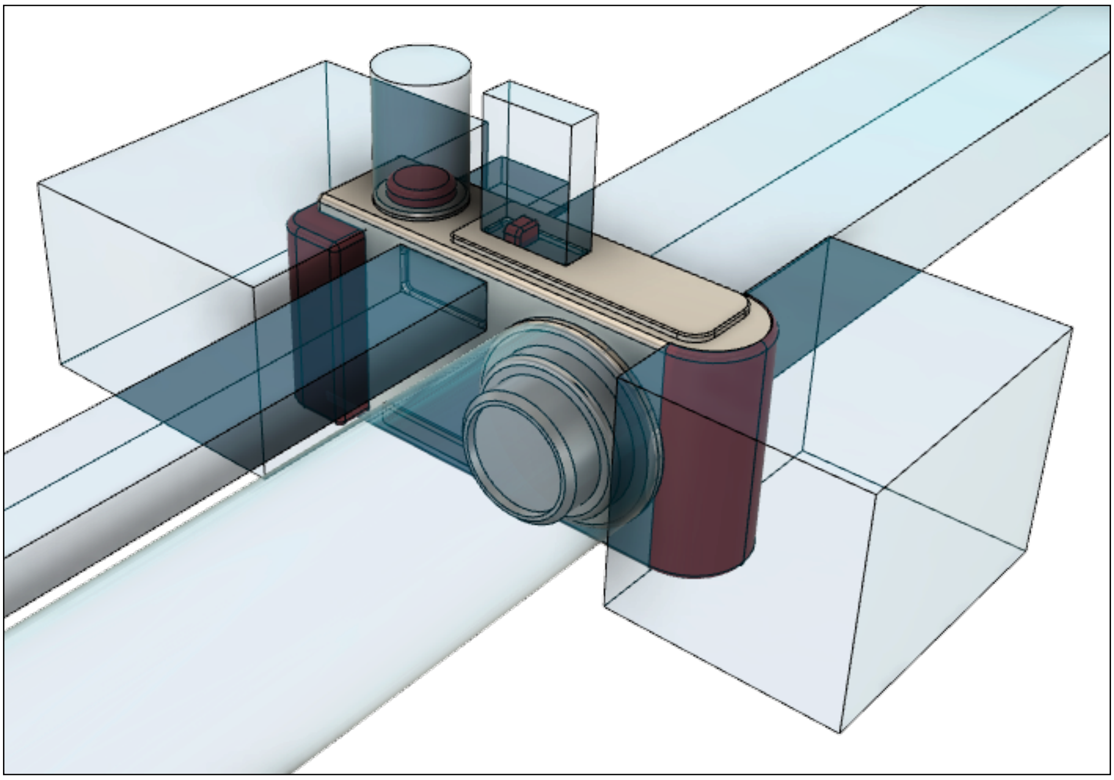
8.25. Figure—GPF Design: Interaction Area

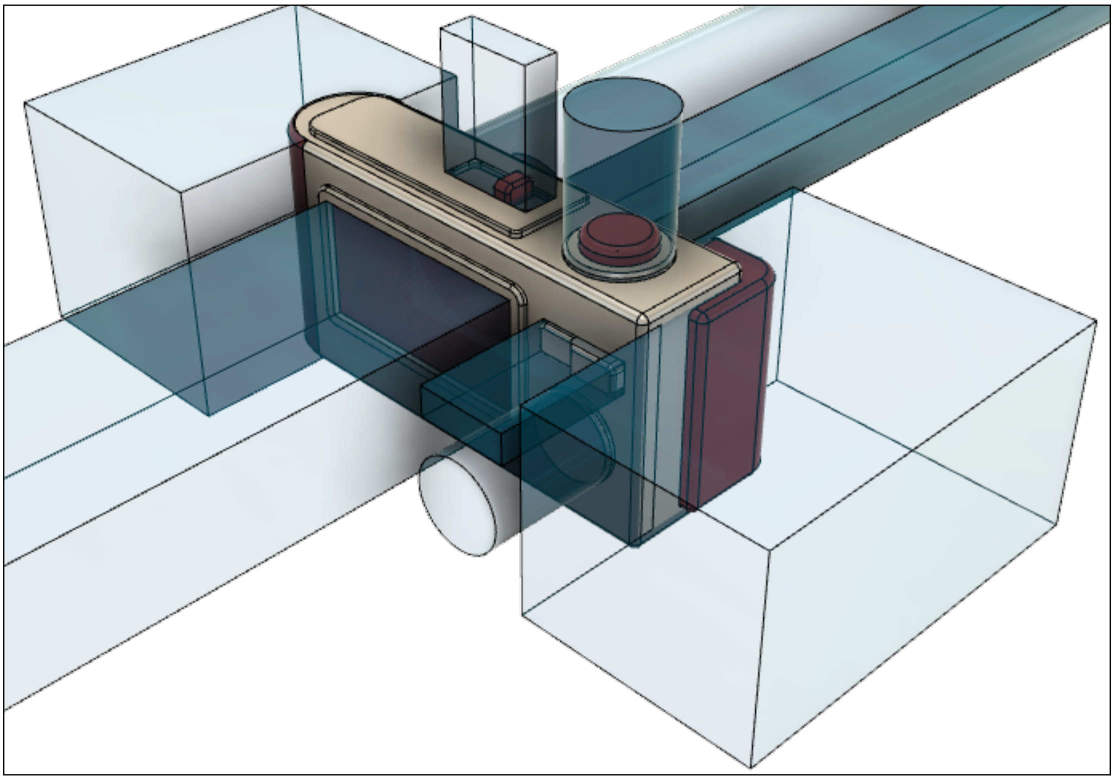


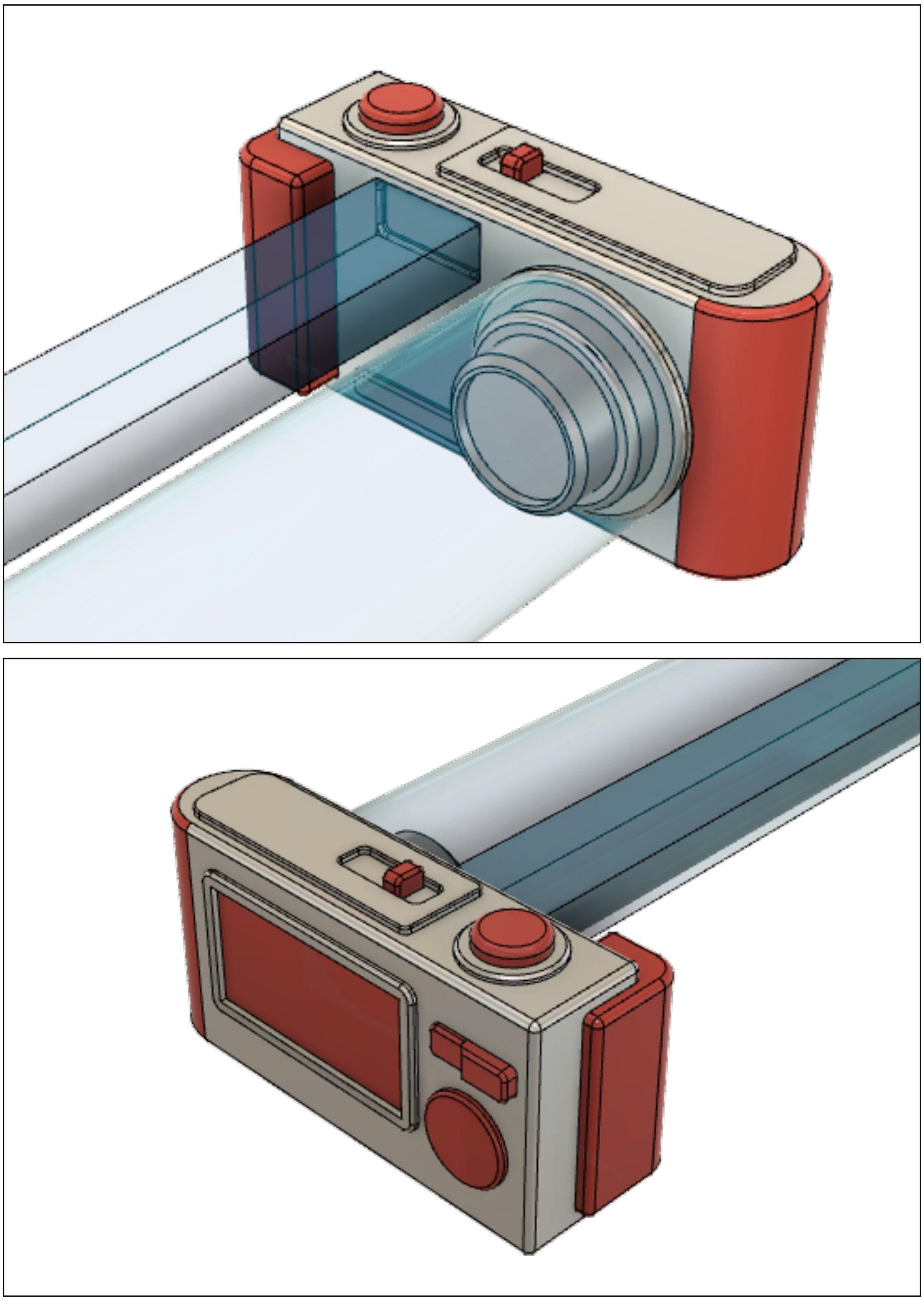


Note. The original functional surface concept is taken from Tjalve (1969, p. 48) and is renamed as interaction area for this project. In these two illustrations, the areas identified in red color are the camera interaction areas where users interact manually to use the camera (the rear display is a touch screen). As explained in the next figure, it can be assumed that these interaction areas must also have some associated restricted volume as well for the user's hands or a robotic activation device.

8.26. Figure—GPF Design: Restricted Volume

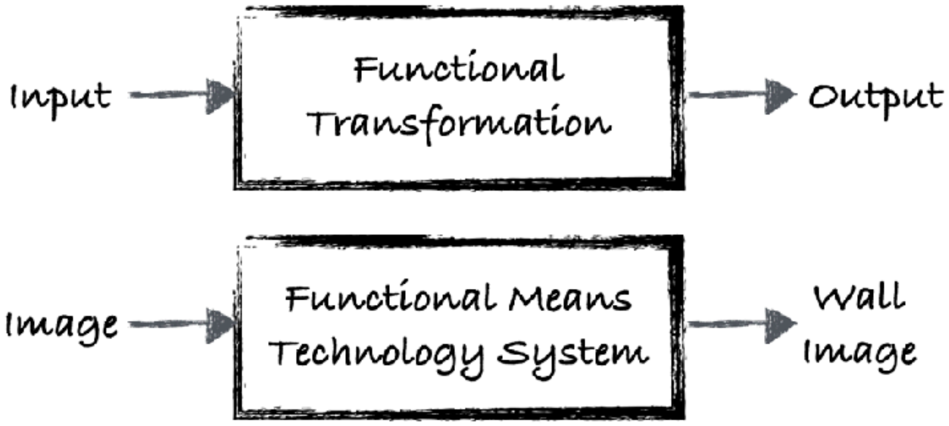




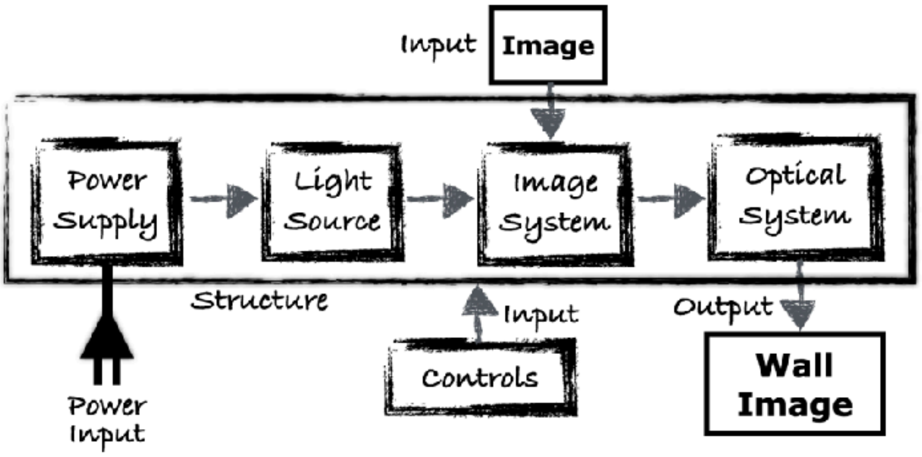


Note. The restricted volumes identified for this camera example that are in translucent blue are spaces where nothing can be as an obstruction inhibiting the use or function of the camera. The first two images show restricted volumes for each interaction area. However, since it is obvious that for virtually all interaction areas (usually being some form of control area) there must also be an inherent restricted volume around them as a space for either a user's activating hand, or a robotic element, these need not be shown. The second two images show only the restricted volumes around elements that have no direct user interaction, but must be kept clear for proper functional reasons (in this case for the view finder and the auto-telescoping lens).

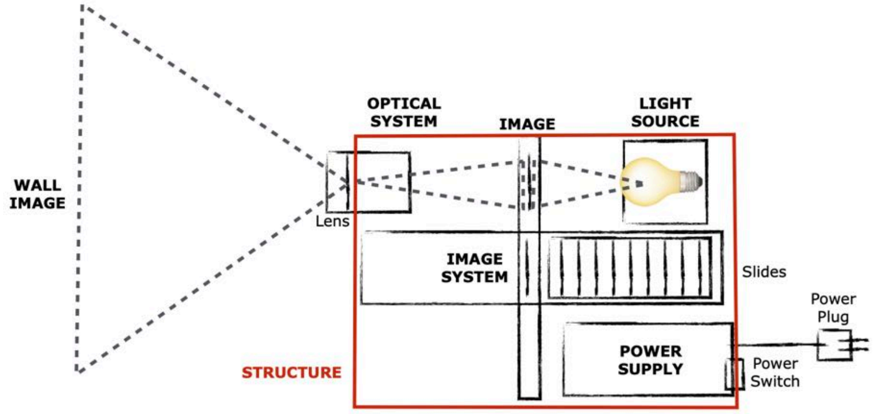
8.27. Figure—GPF Design: Relational Configuration



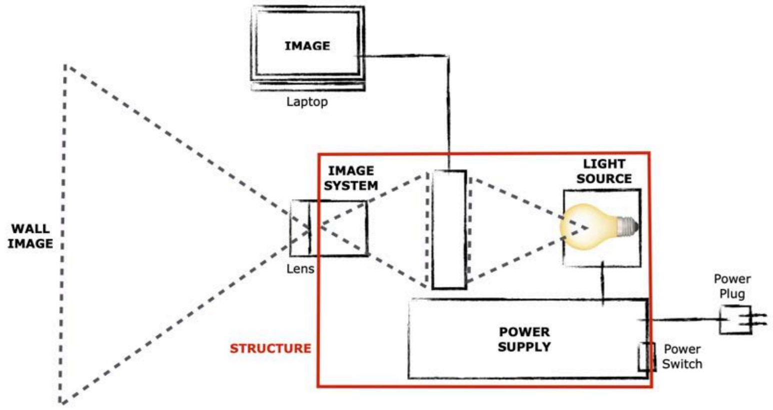
Functional Transformation Diagrams for All Three Projectors



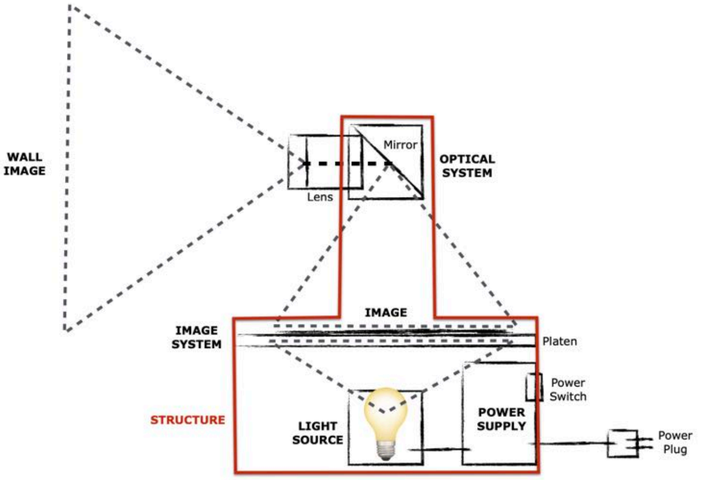
General Relational Configuration for All Three Methods



Relational Configuration for a Film Slide Projector



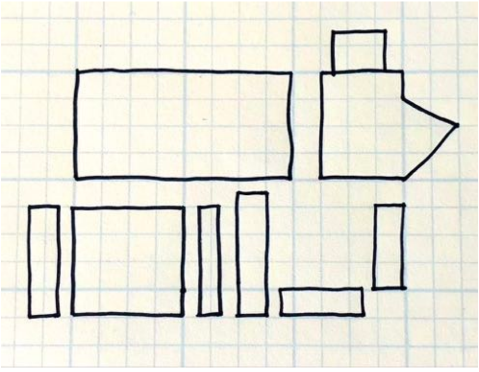
Relational Configuration for a Digital Projector



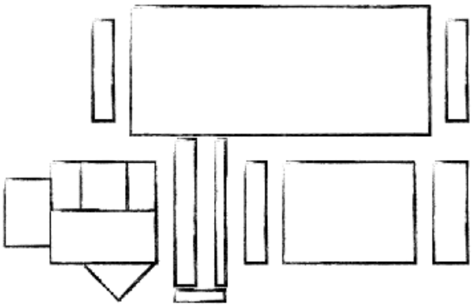
Relational Configuration for an Overhead Projector

Note. If the human need is for a group of people to see a small image at one time, then one solution is projecting it onto a large area for all to see (there are other solutions, e.g., digital bluetooth goggles). An overhead projector, a slide projector, and a digital projector can all do that. And they all need somewhat similar technologies to function. But the functional technology means of each are all different: different optical systems, light sources, power supplies, controls, structures, imaging components, and their forms. The general transformational and relational configurations are virtually the same for all three methods of projection (first two images). But each of these, which perform the same functional transformation (large image projected from a smaller image) would have different relational configurations (last three images, each with possible different technology arrangements). Each of these would lead to probable multiple different specified configurations (with different physical component and element features, forms, and sizes), leading to all quite different overall GPF designs. Relational configurations are just that—technologies relative to one another—e.g., the slide projector could also have a carousel for slide delivery, or the digital projector could have added mirrors to change the optical path.

8.28. Figure—GPF Design: Specified Configuration

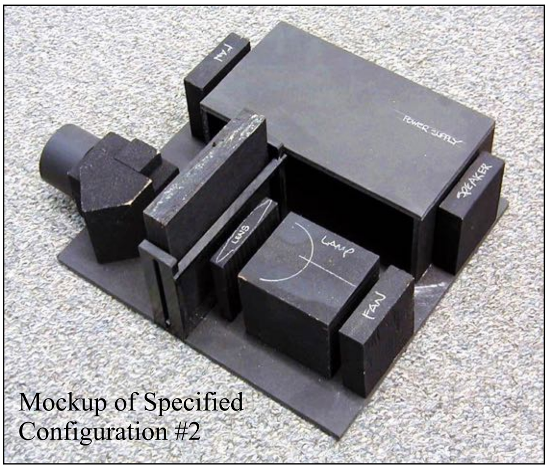


Manual Sketch of Specified Configuration #1

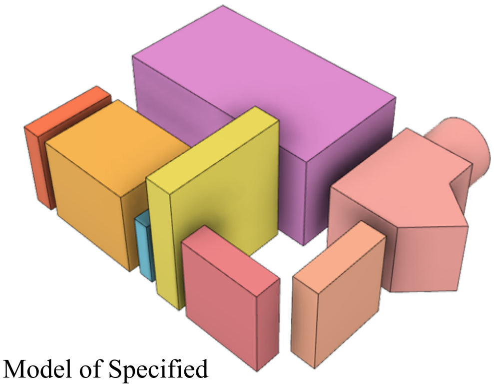


Digital Sketch of Specified Configuration #2

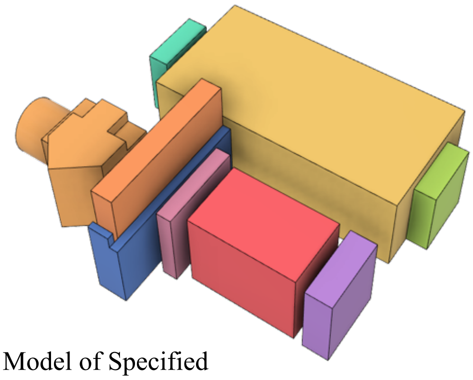
Mockup of Specified Configuration #1



Mockup of Specified Configuration #2



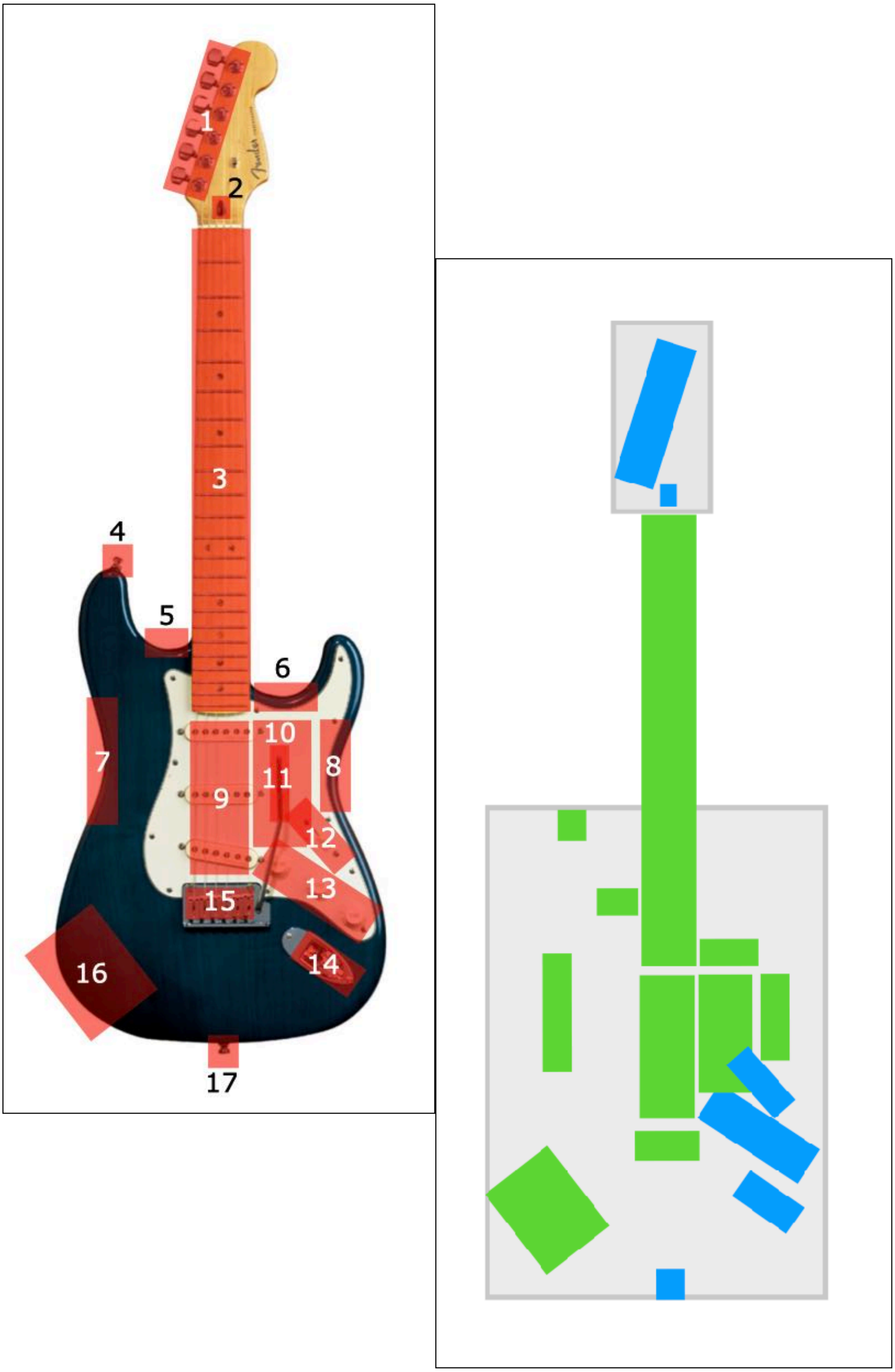
Model of Specified Configuration #1

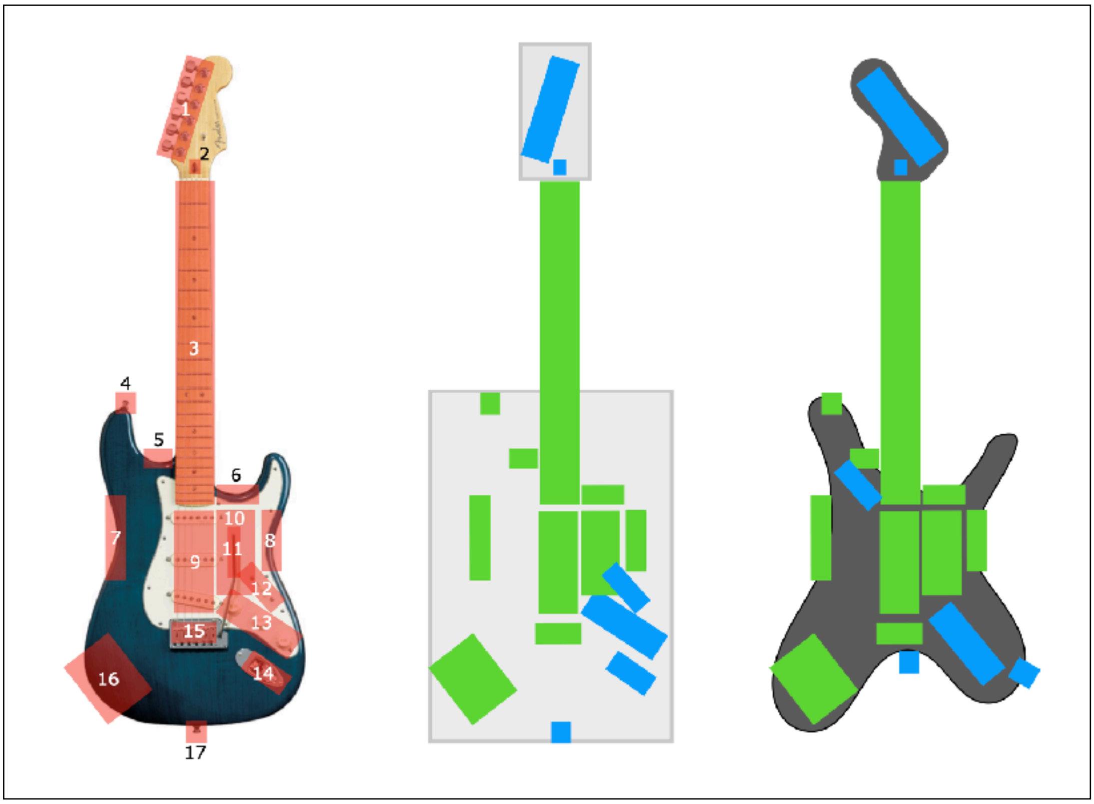


Model of Specified Configuration #2

Note. A product specified configuration is based on a relational configuration, and on a specific physical arrangement based on the product context. Different specified configurations may have the same or different functional means, components, or elements. In this digital projector example, two specified configurations are shown, each having the same main function (projecting a digital image), but different components. Each specified configuration may result in different product final forms.

8.29. Figure—GPF Design: Form Variation Method

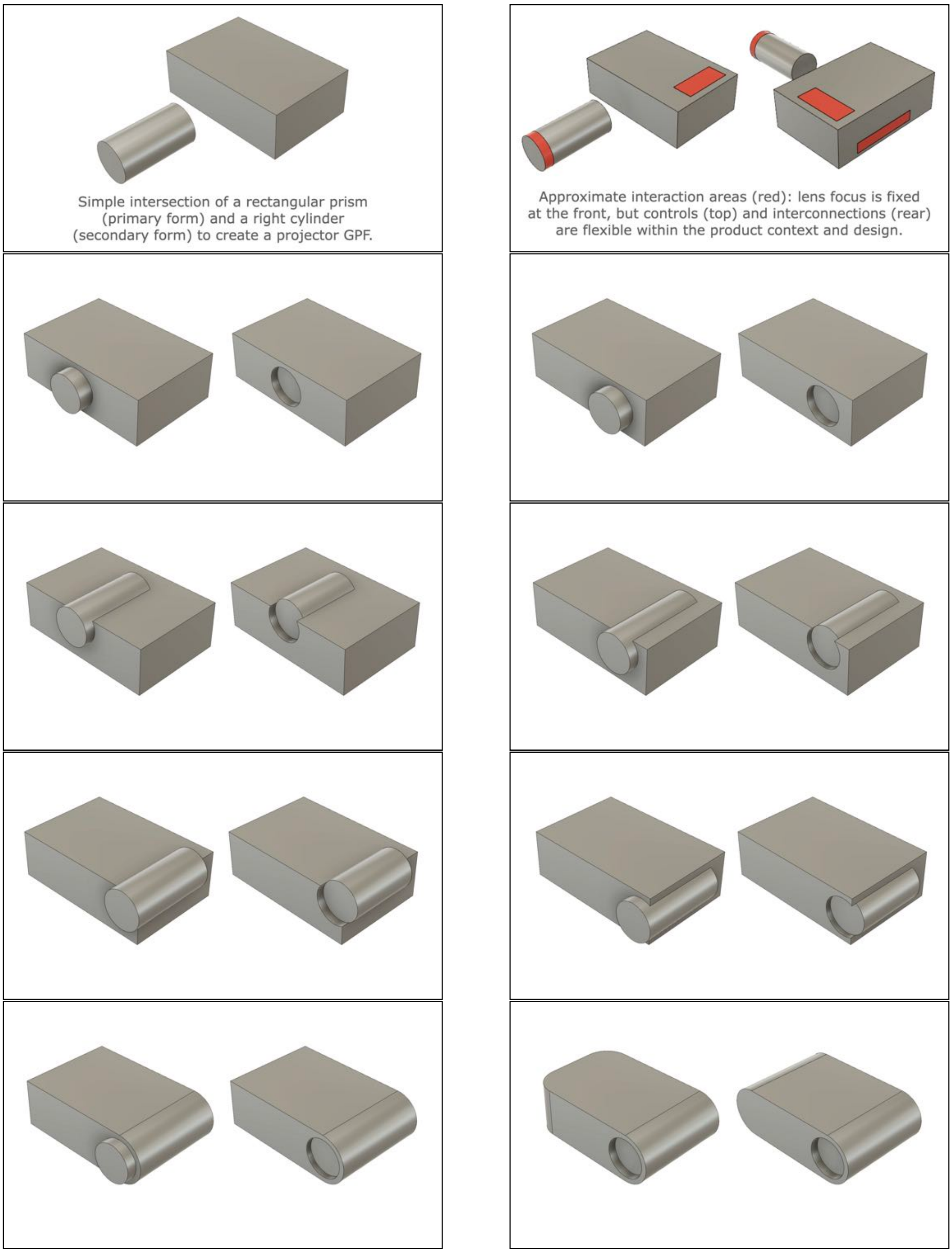




Note. Using the form variation method, based on interaction areas and restricted volumes, offers GPF design flexibility and innovation. As long as the interaction areas and restricted volumes are specified and conformed to, the final overall form design is flexible. In the first image set, shown on the left are the various interaction areas for the Fender® Stratocaster® guitar: 1) tuning machines, 2) truss rod adjustment, 3) fretboard, 4) upper strap button, 5) left hand thumb cutaway, 6) left hand finger cutaway, 7) “tummy" rest/cutaway, 8) leg rest, 9) picking/strumming area, 10) picking/strumming clearance, 11) “tremolo" bar grip, 12) pickup switch, 13) tone/volume controls, 14) cable jack, 15) bridge adjust, 16) forearm rest, and 17) lower strap button. On the right are the interaction areas shown without the guitar. The green areas are relatively fixed as to ergonomics, but the blue areas can be moved to other positions, within reason, commonly done on other guitar designs. The two gray box areas offer flexibility in form design of the body and headstock.

In the second image set is shown on the left the classic and enduring Fender® Stratocaster® body and headstock form designs repeated. In the center is repeated the image of the interaction areas previously described and the gray boxes that allow for flexible body and headstock form design using the form variation method. The third image on the right is an example of what has happened repeatedly in many unfortunate electric guitar body and headstock form designs: body “blobs”! These form designs clearly conform to the rules set forth previously, but whether or not these forms are attractive is left to the viewer. A visual presentation of many of the more common electric guitar body form designs can be found at: *https://cdn.notonthehighstreet.com/fs/86/88/d9e0-3b6b-43a8-b2e2-b94f99139bbb/original_iconic-guitar-body-shapes-print.jpg*

8.30. Figure—GPF Variation Method: Projector

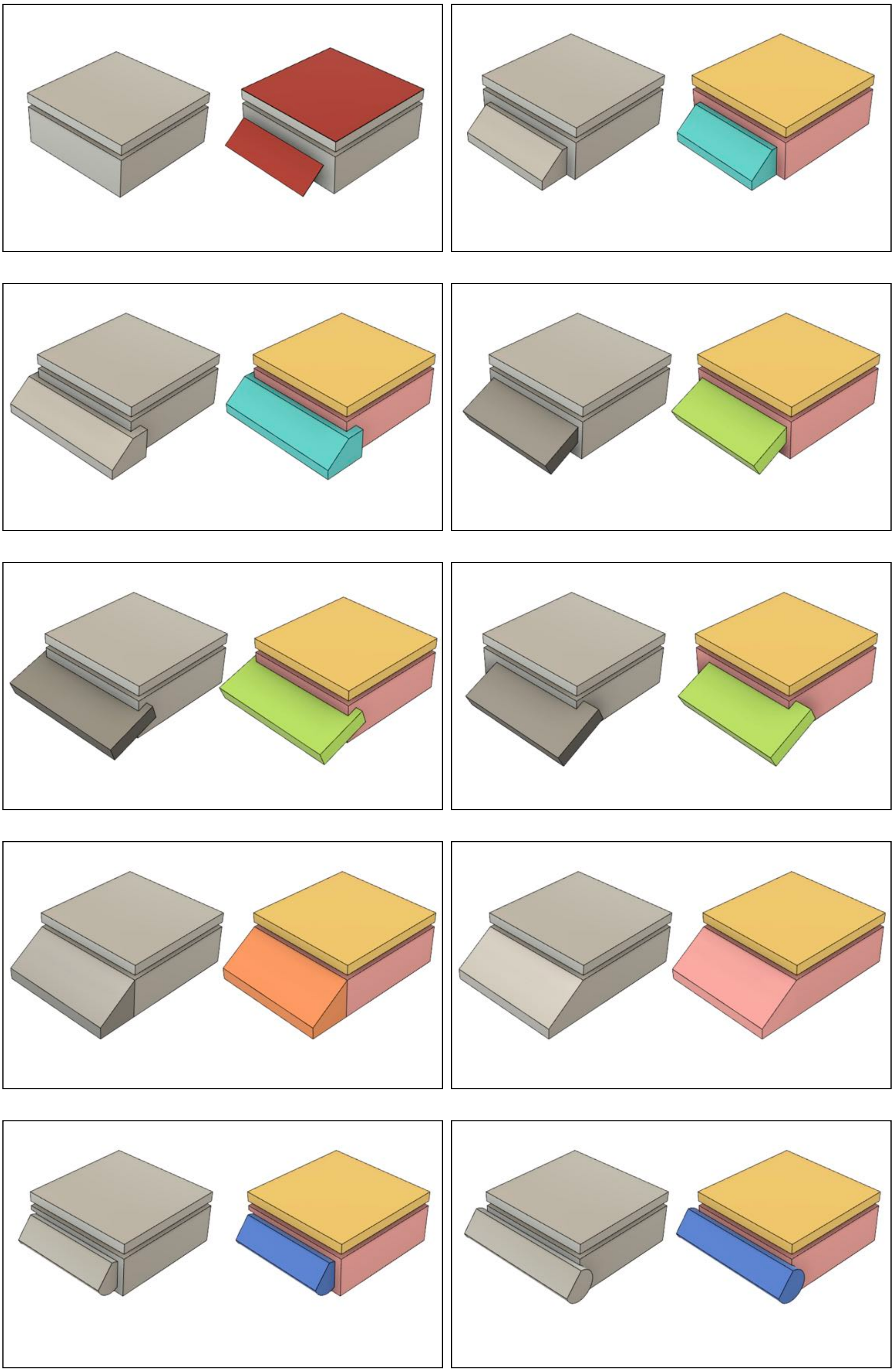


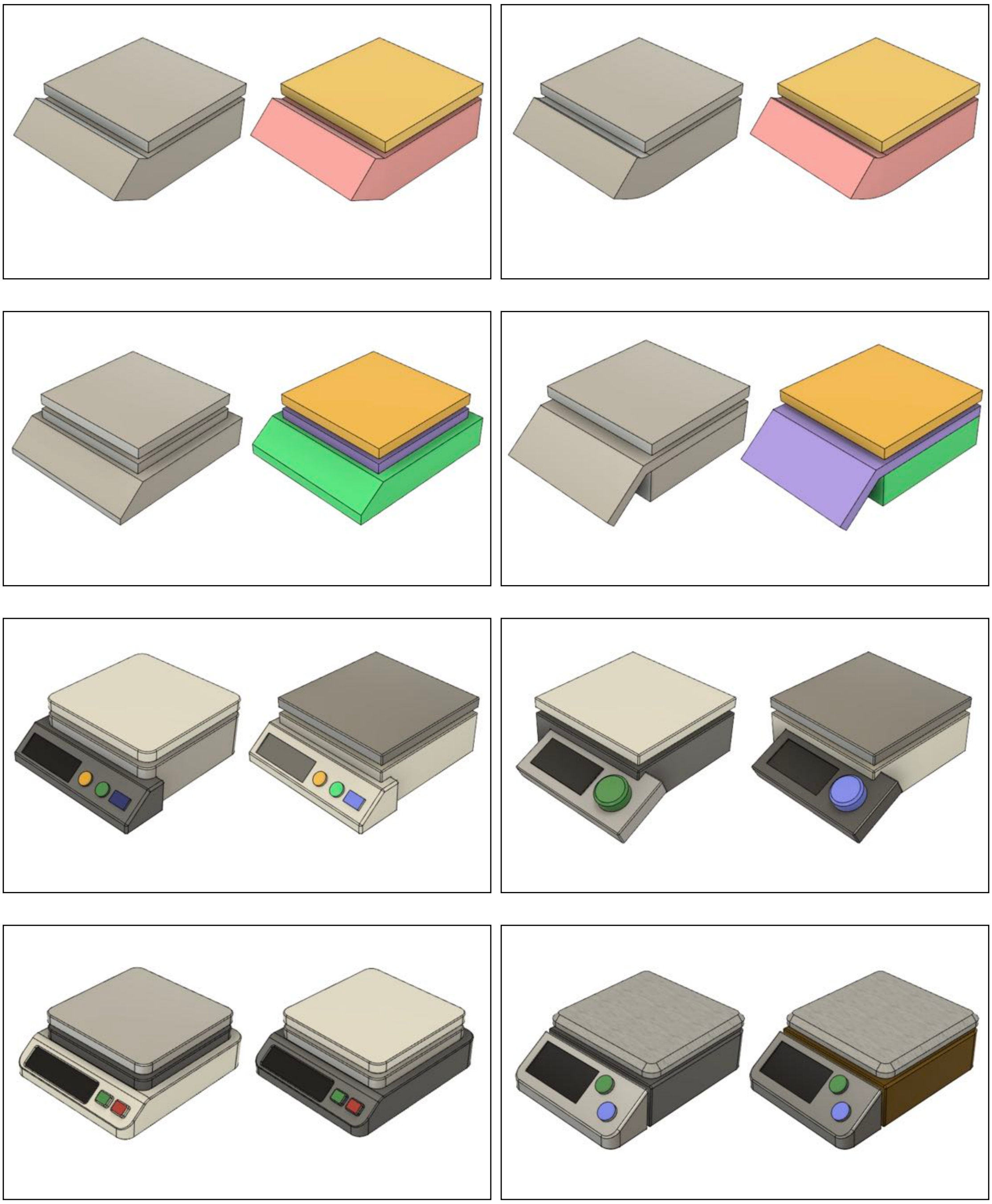
Simple intersection of a rectangular prism (primary form) and a right cylinder (secondary form) to create a projector GPF.

Approximate interaction areas (red): lens focus is fixed at the front, but controls (top) and interconnections (rear) are flexible within the product context and design.

Note. The form variation method (Tjalve, 1979, pp. 48 & 74) is here applied to a projector GPF. The two basic forms are intersected and shifted in different ways to create varied overall GPF design compositions. The interaction areas of controls and interconnections in red can be properly integrated into each of the GPF designs in various mechanical ways. Detail refinements, such as edge radii, are not executed.

8.31. Figure—GPF Variation Method: Lab Scale



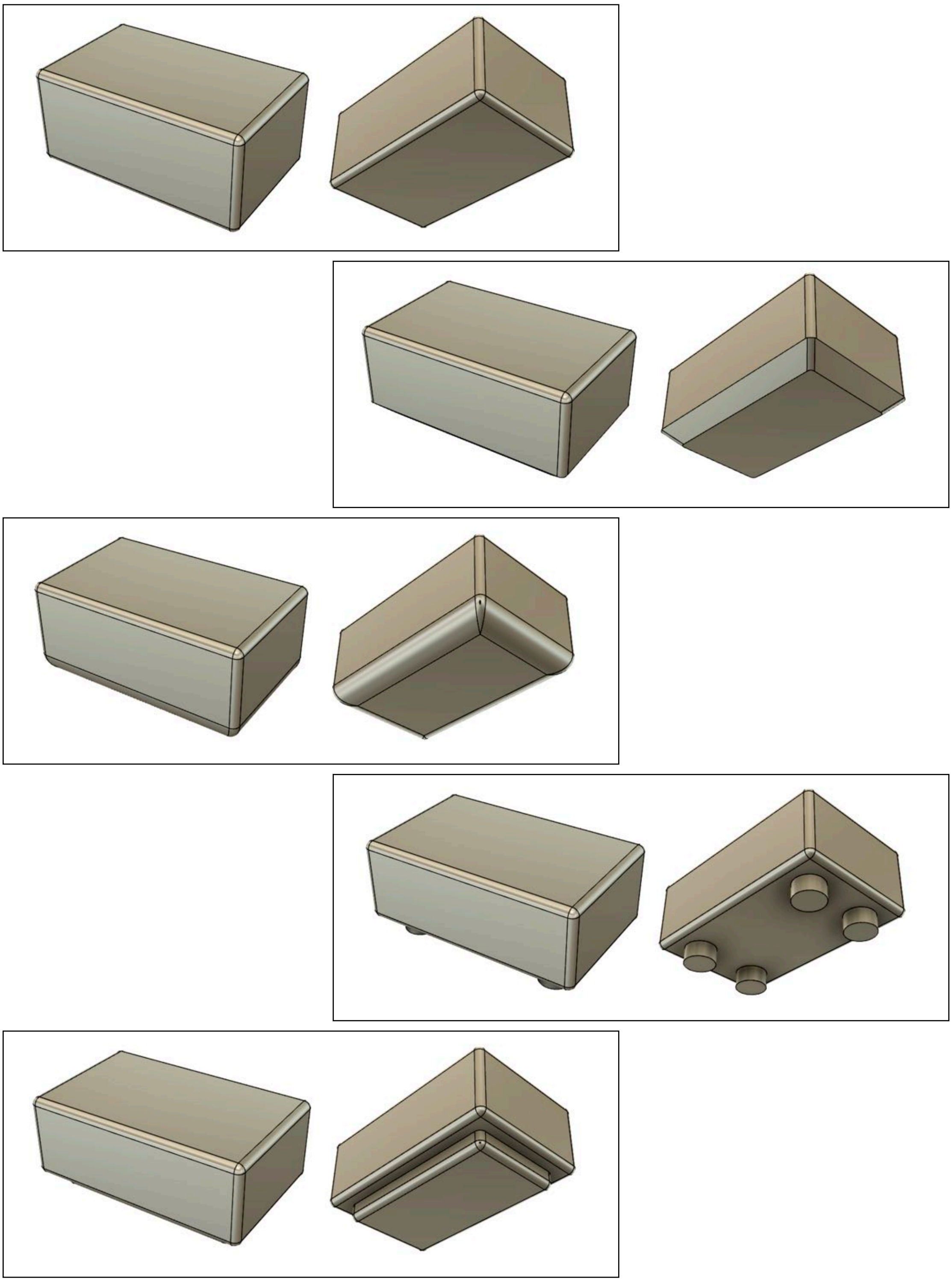


Note. The form variation method (Tjalve, 1979, pp. 48 & 74) is here applied to a laboratory scale GPF composition. The two or three basic forms are intersected, shifted, operations applied, and integrated in different ways to create varied overall GPF compositions. The interaction areas are shown in the first image: control panel and scale top surface. The controls can be integrated into each of the GPF designs in various ways. Various details, form, and value refinements and variations are shown in the last four images.

8.32. Figure—GPF Division Method: Controller

Note. The form division method is dividing the main primary forms into discreet parts for appearance purposes, as in these basic remote control device form composition. Several variations are shown where main forms are divided. The resulting form divisions can also be modified and detailed in various ways. As shown, visual form division can also be accomplished using color, value, texture, and material as well.

8.33. Figure—GPF Design: Visual Perception

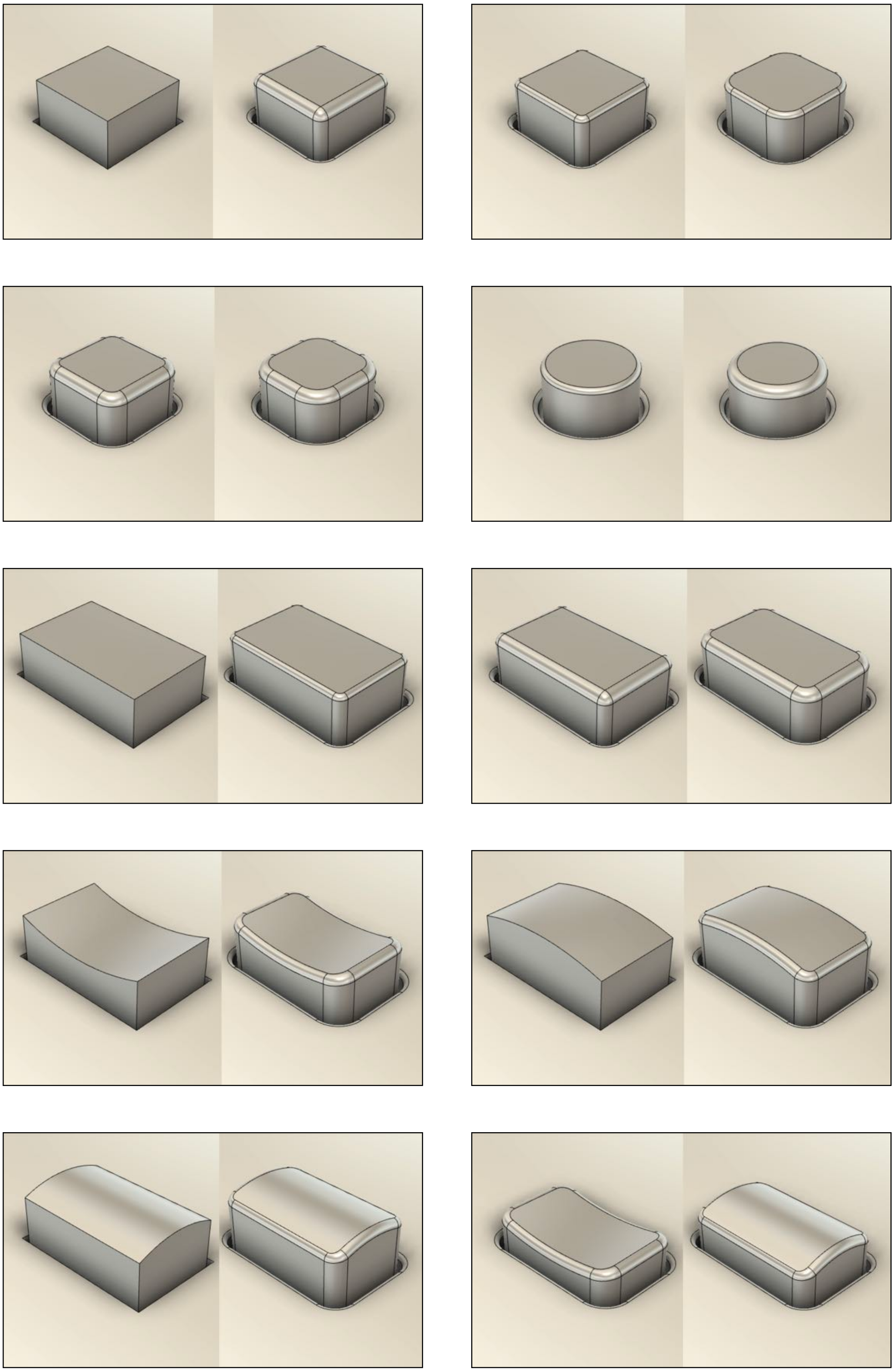


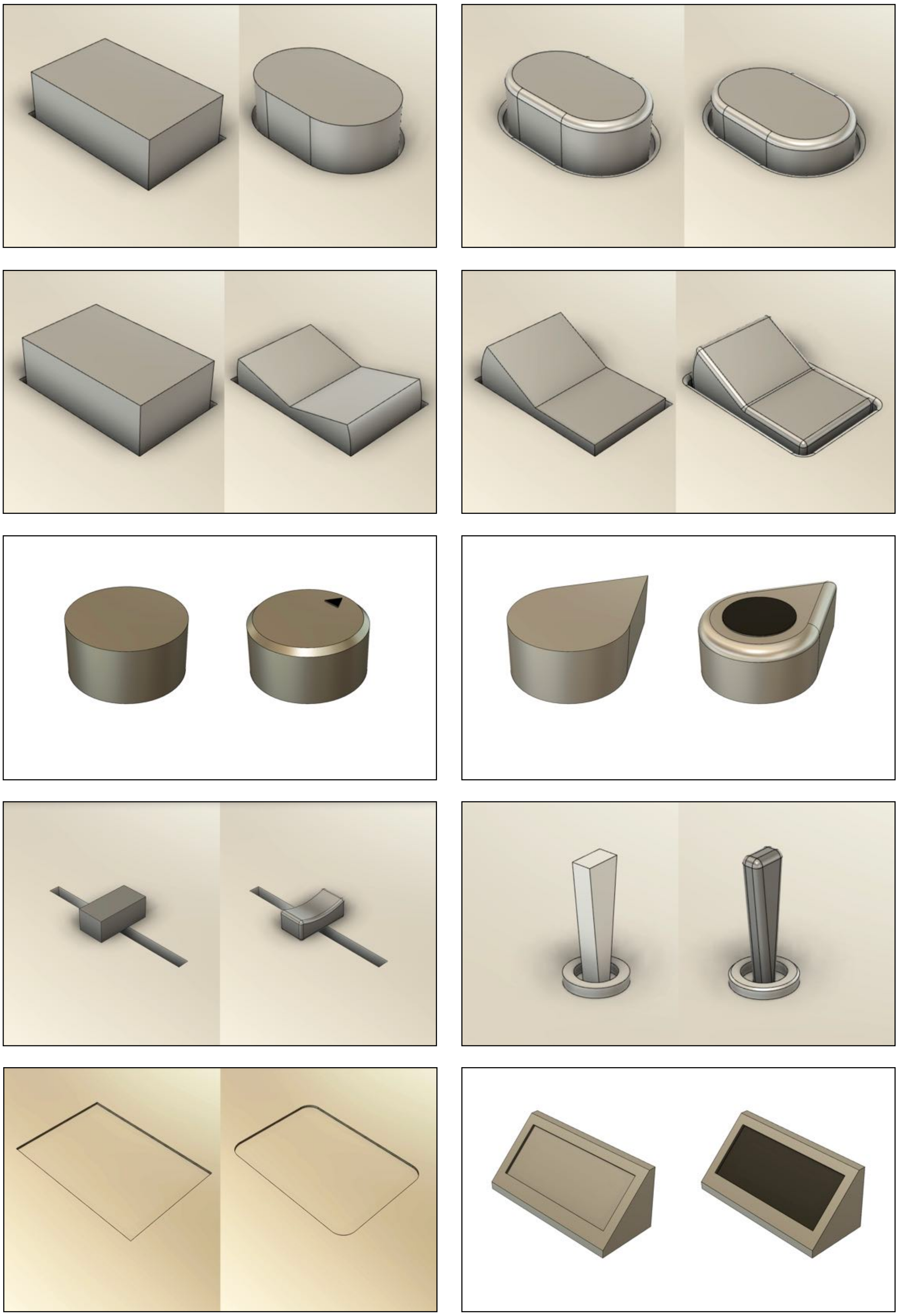
Note. Shown here is the effect that a GPF base modification has on visual size and “floating” perception. The top image is of a rectangular prism with only edge radii. Several base modifications are applied, and the size and floating perception is apparent. However, some methods and features work better than others.

8.34. Figure—GPF Design: Quaternary Forms

Note. These quaternary form examples should not be neglected in an overall GPF design composition. Often, the details of these are added near the end of the product modeling process, but many must be considered in earlier stages for their size and positioning due to their effect on appearance. For example, in many UTPs, thermal air venting areas can be significant form features affecting product appearance.

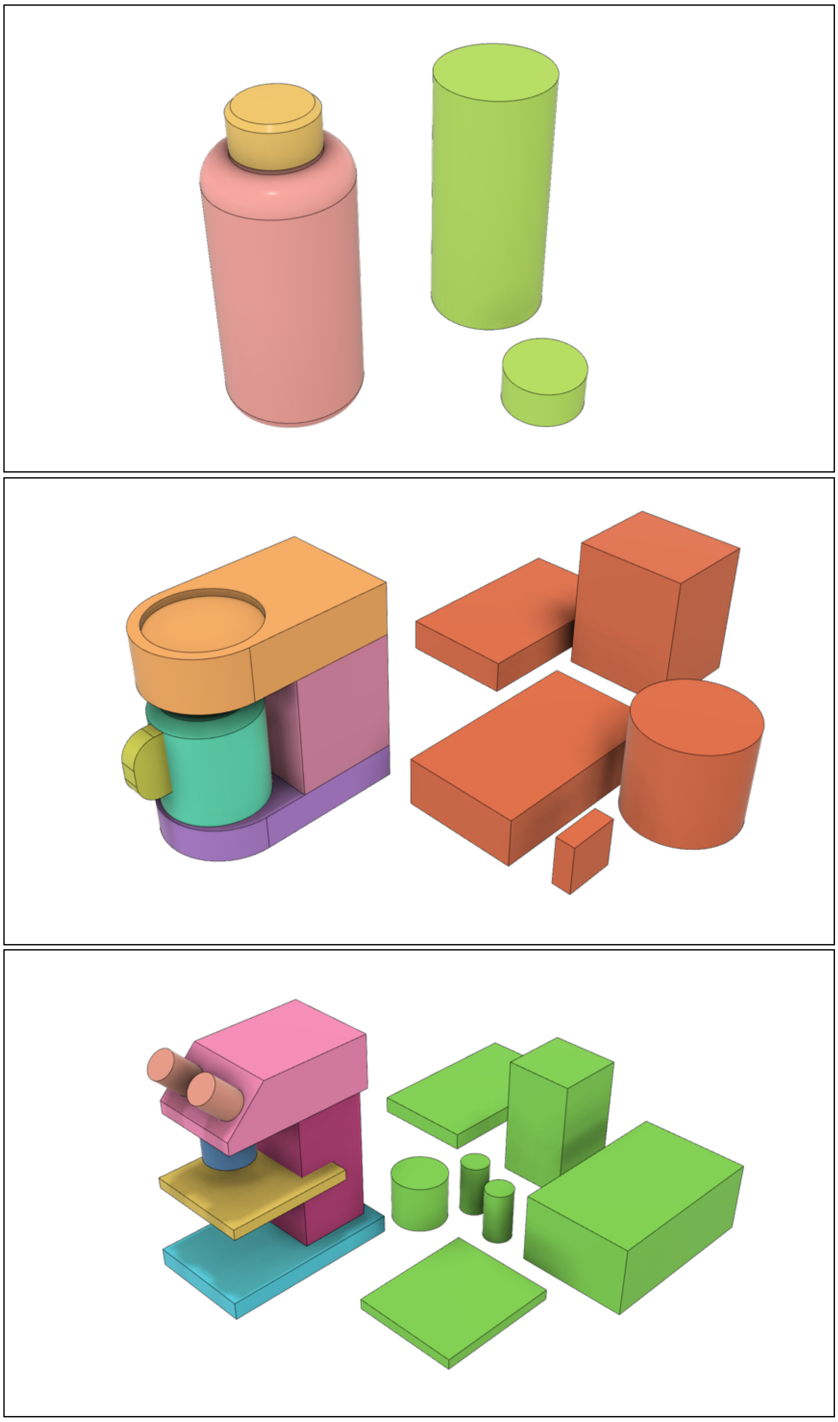
8.35. Figure—GPF Design: Signifiers & Controls





Note. Shown here are a variety of the quaternary forms of signifying control button and knob GPF designs, without and with edge radii or chamfers. The last two forms are trackpads and touch screen displays.

8.36. Figure—GPF Design: Form Meaning

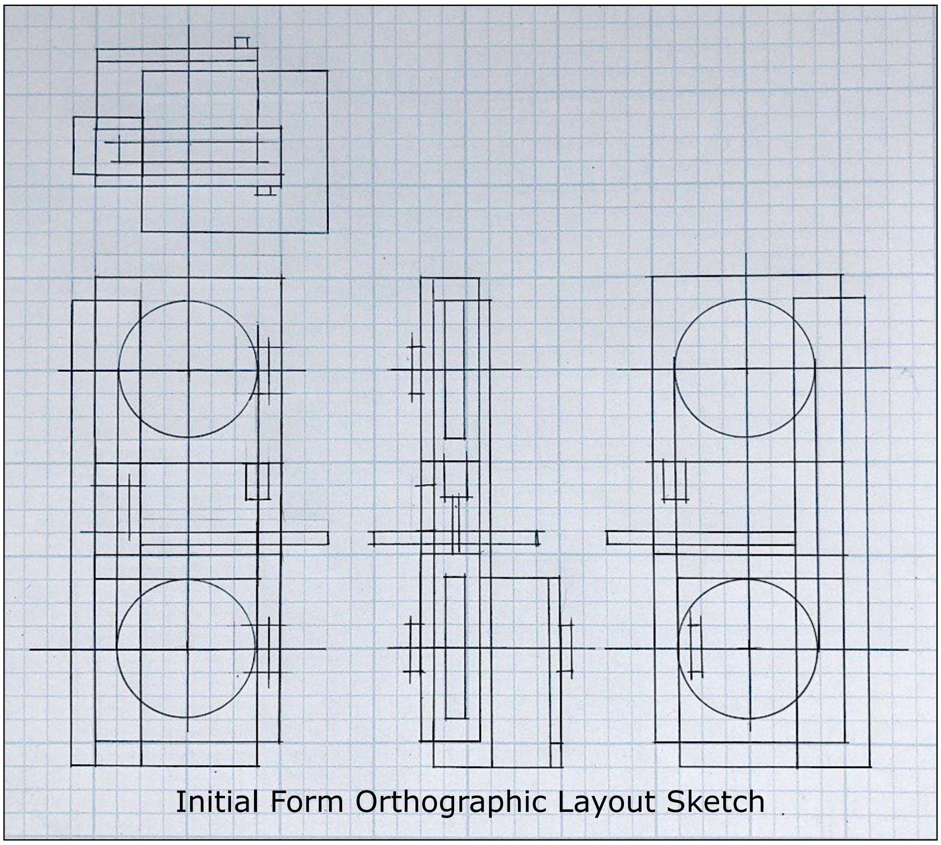


Note. Simple discreet geometric forms, with little intrinsic meaning themselves, in GPF composition, gain meaning and communicate what they might be, what they might do, or how they might be used, as a product (Krippendorff, 2006, p. 58). In these examples, the simple geometric forms on the right are composed together on the left, with form details added, to create an overall GPF composition that communicates product type, meaning, and function—liquid bottle, coffee maker, and microscope.

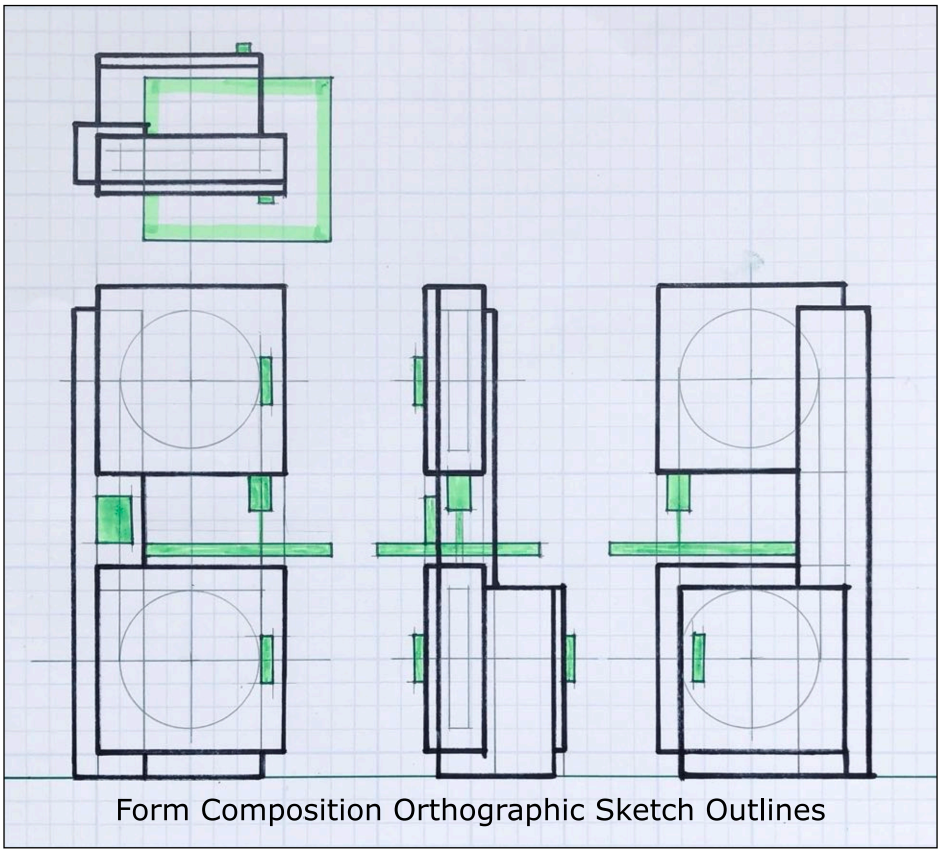
8.37. Figure—GPF Design: Family Look

Note. Each of the products in each family set shown here has a different functional purpose and use, but are in the same general category of product: hand power tools. They were created as hypothetically designed, produced, and marketed by the same company. By using GPF for the design of their outer enclosures and product forms, and using uniform visual characteristics such as color, texture, details, and materials, they have a "family look," causing them to appear to be from the same corporate brand. These photo-realistic images were rendered in AF360. All images are engineering student work from the GPF design courses for engineers at HongIk University (2016), Seoul, Korea (Dresselhaus et al, 2018).

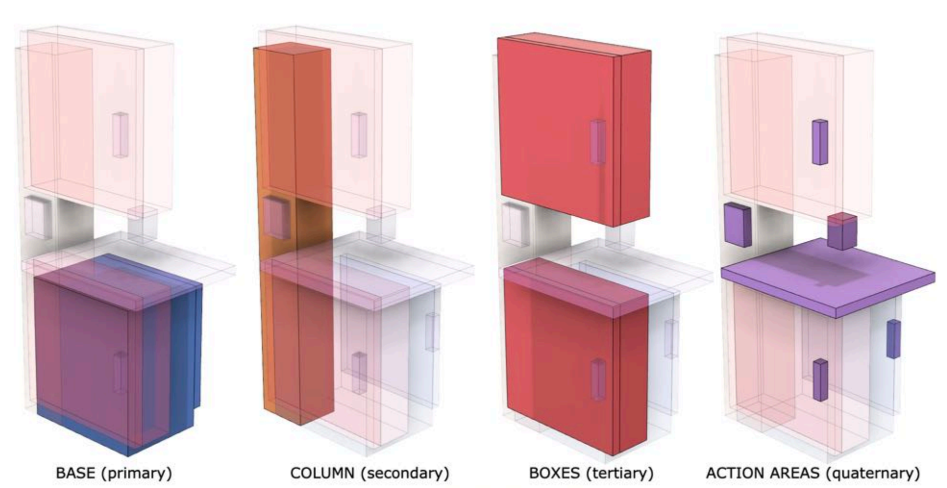
8.38. Figure—GPF Design: Sketch to Rendering



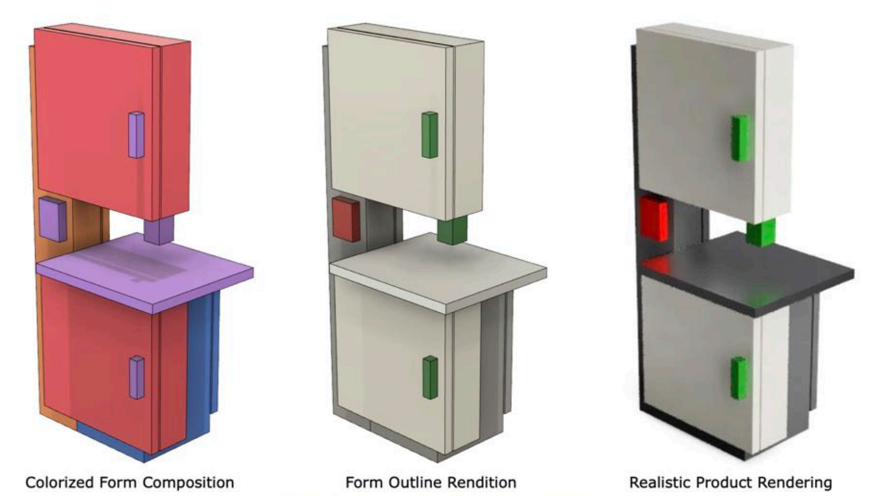
Initial Form Orthographic Layout Sketch



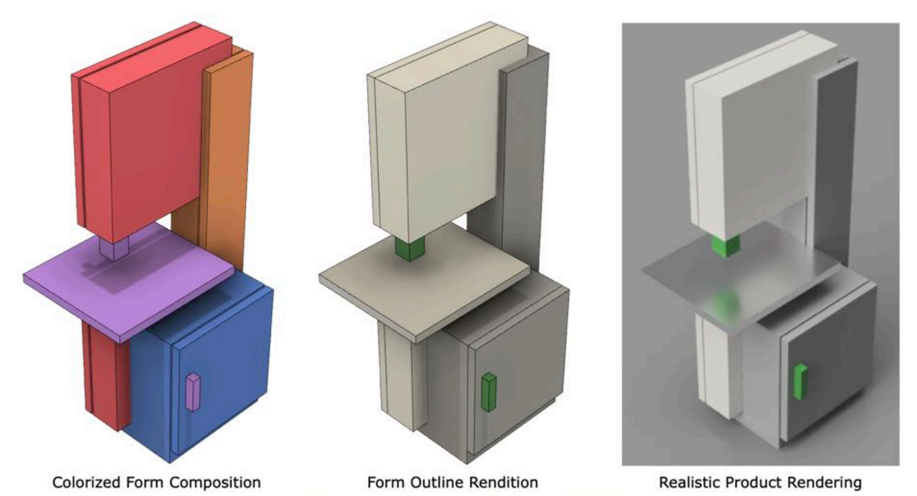
Form Composition Orthographic Sketch Outlines



GPF Composition



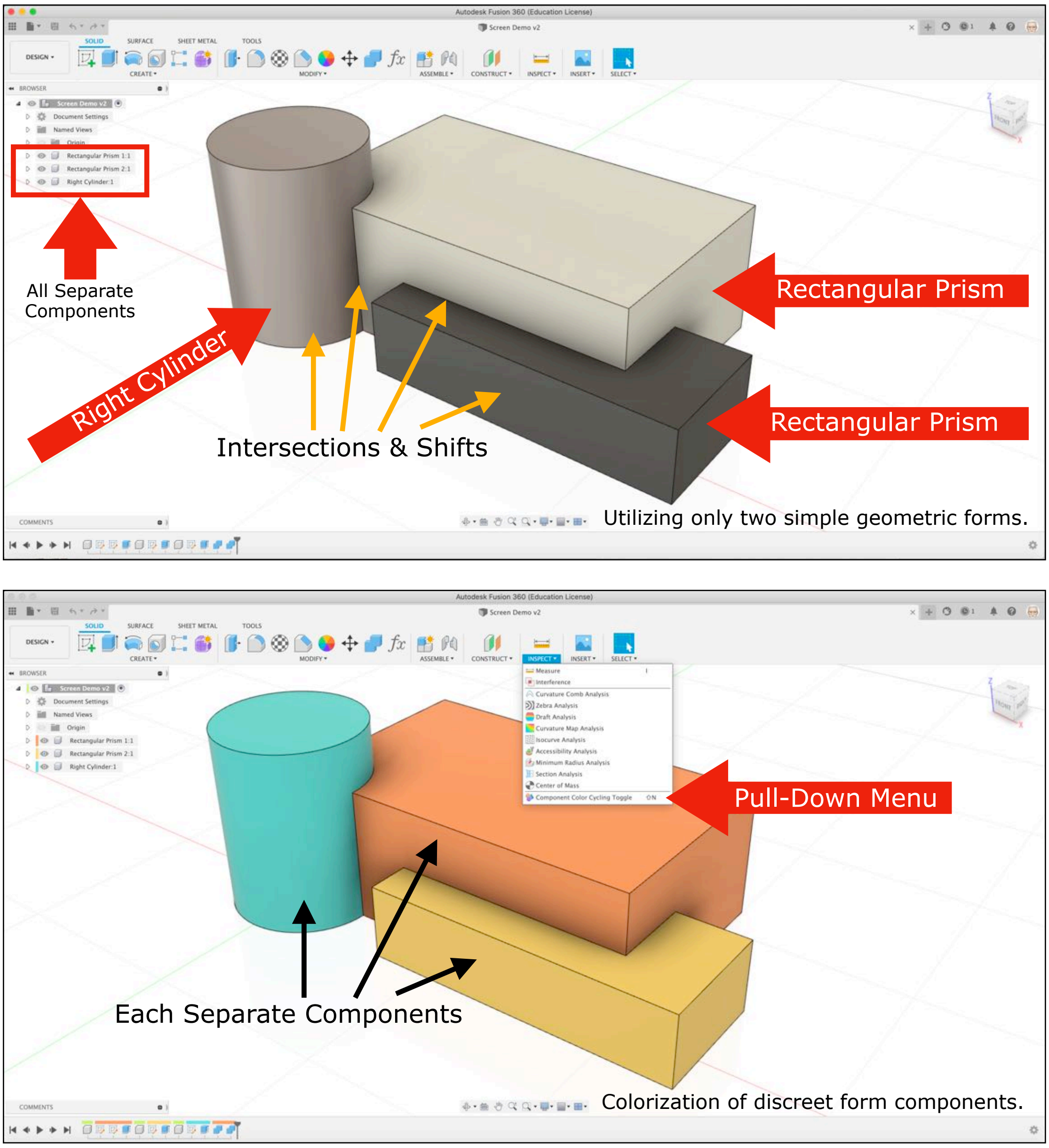
Product Visualizations



Rear View Visualizations

Note. These orthographic sketch layouts can be done freehand or with a straightedge — on gridded paper or not. These are then translated into a CAD model. The manual sketches may also be imported directly into CAD for over-sketching, if desired.

8.39. Figure—GPF Design: CAD Modeling

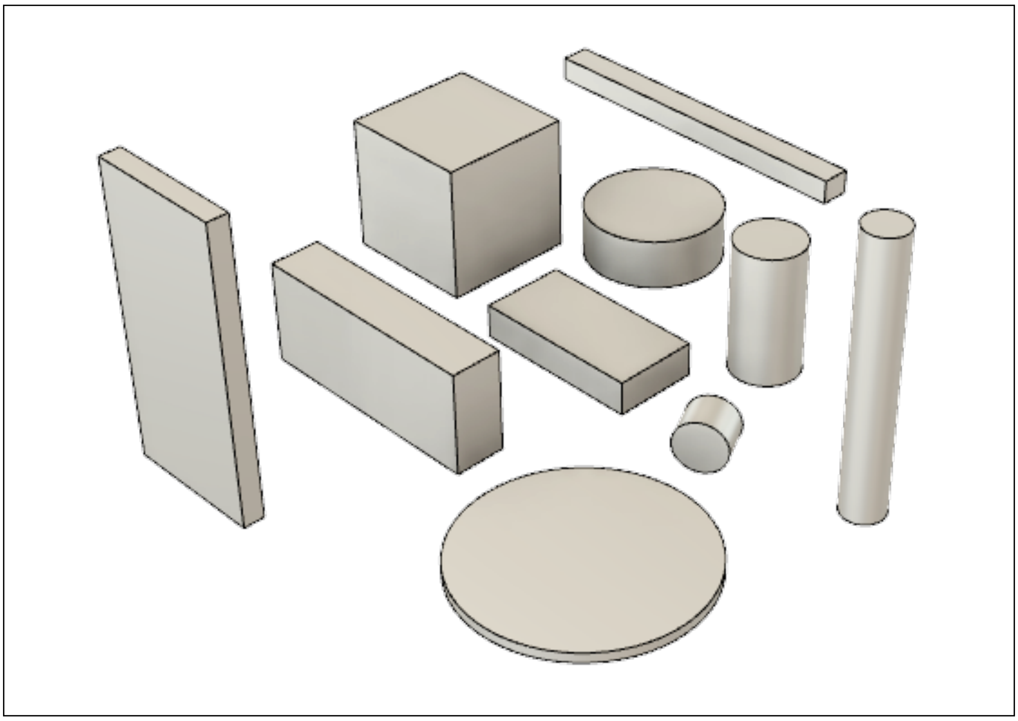


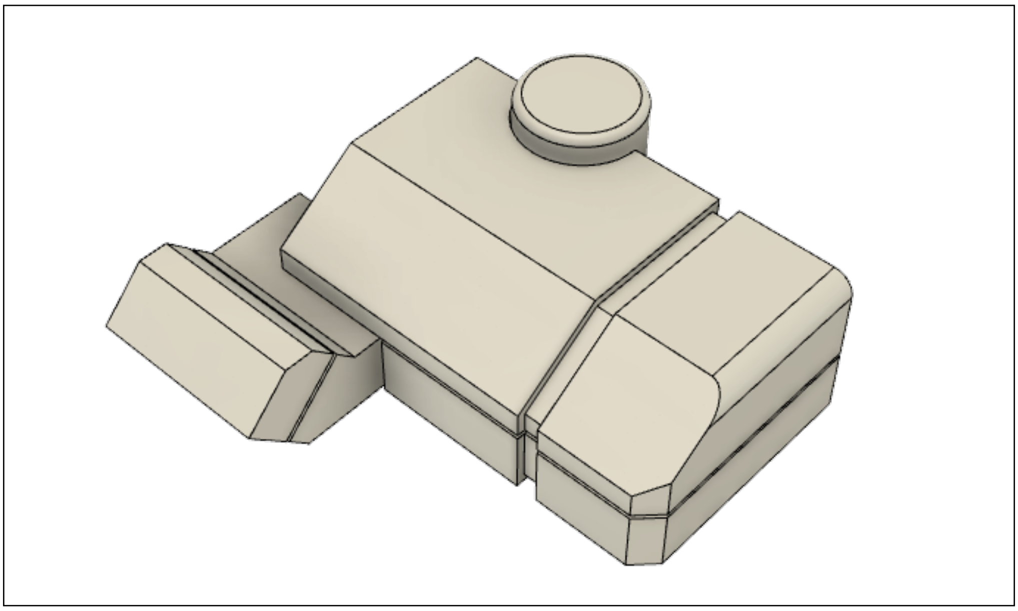
Note. These are examples of GPF design composition principles. First, decide on the overall GPF composition gestalt strategy, probably through rough orthographic sketching, and based on a particular specified configuration of components and elements. Then, create each of the primary, secondary, and tertiary forms as separate components in AF360, ideally around a modeled specified configuration. In this case, three separate forms are used, with intersection and shift operations applied. Only the two basic geometric forms of right cylinder and rectangular prism are used per the project method. Colorization of the component forms is to show their distinction as needed. One can then apply one or more (but few!) visual operations, such as shear, radial surface, bend, or fracture. Finally, visual form details would be added, such as edge radii, edge chamfers, parting gaps, textures, surface colors, and finishes.

8.40. Figure—GPF Design: Physical Mockups

Note. The use of physical mockups for GPF design process is essential, even though most detail design work may be done in CAD modeling. Physical mockups provide a kinesthetic design experience that sketches and CAD models cannot provide. As shown in these examples, mockups can be rough, or precise and detailed, as needed.

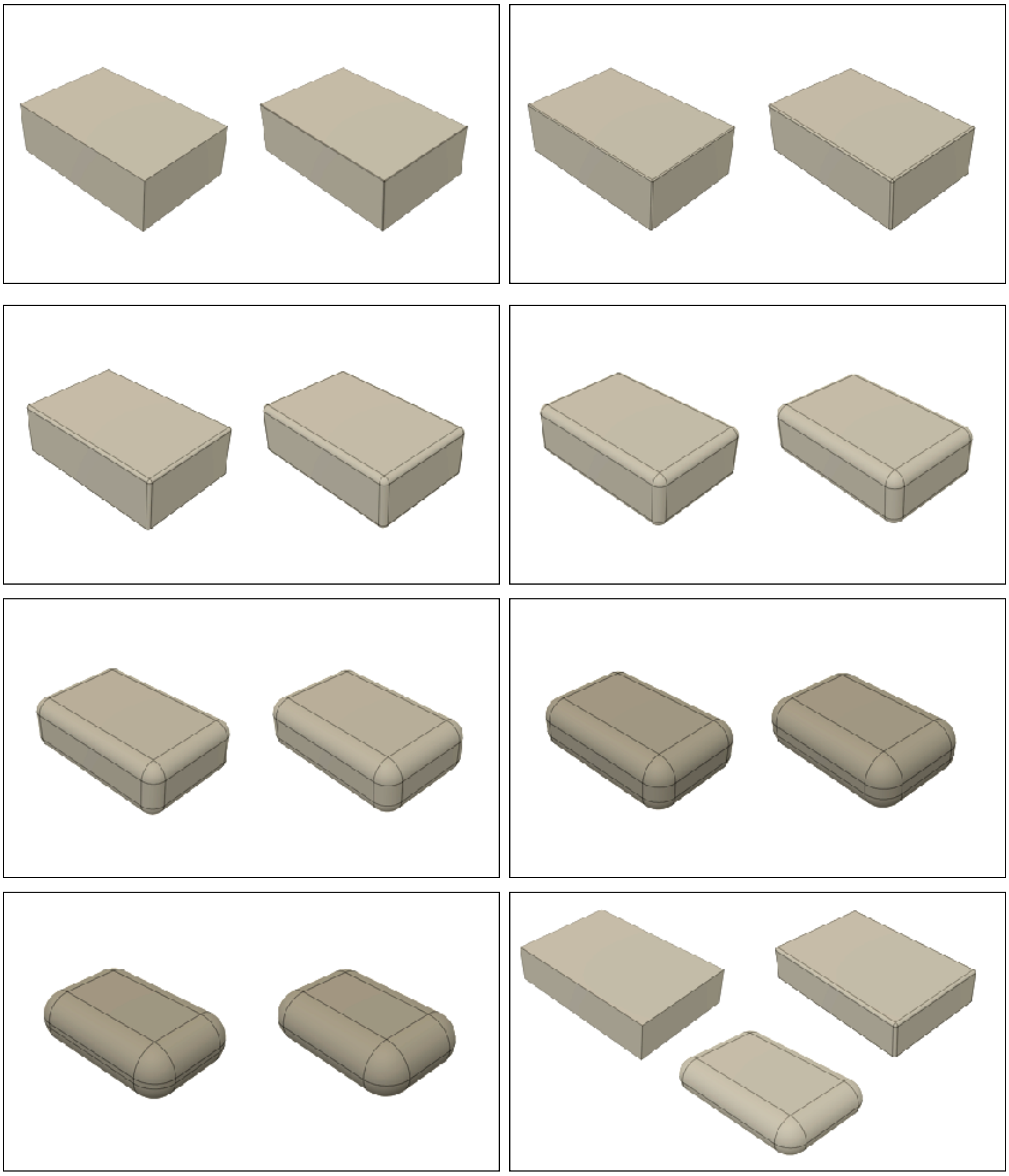
8.41. Figure—GPF Design: Forms & Features





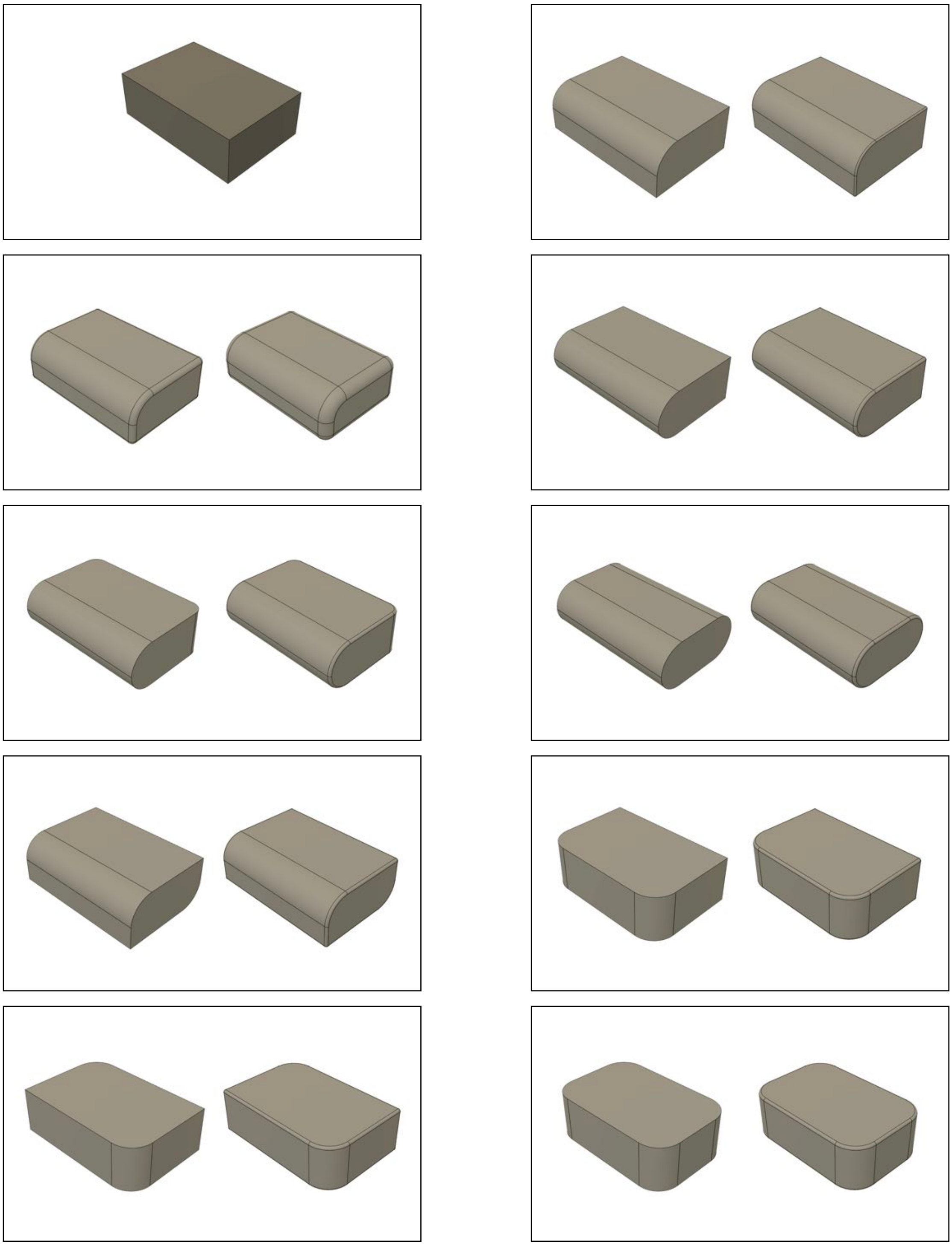
Note. The first image contains various versions of the two basic geometric forms used in this project for GPF design: the rectangular prism and the right cylinder. The second image is an arbitrary GPF composition for demonstration using the two basic forms, with added visual operations (intersect, shift, fracture, and bend), plus some geometric visual details (edge radius, edge chamfer, and parting gap). This example represents how the visual operations can be applied to a form composition of multiple basic forms. After the main visual operations are applied, various details of radius, chamfer, and controls can be applied. The final image is an arbitrary composition.

8.42. Figure—GPF Detail: Moderate/Variable Edge Radius



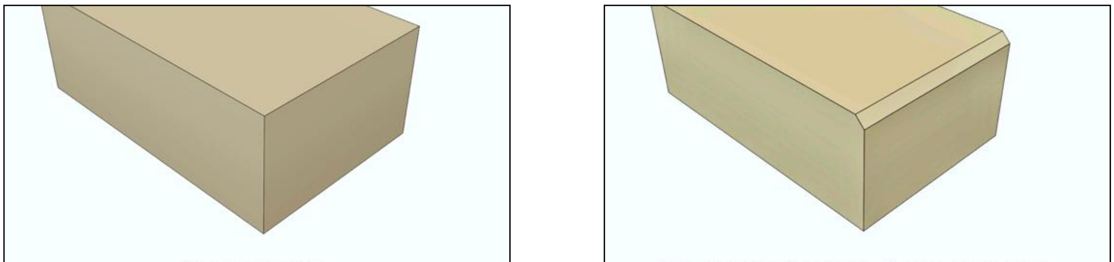
Note. Applying radii to GPF edges is the most common type of visual edge detail. Most all GPF edges should have some radius, even if very small (0.5-1.0 mm). Radiused edges are visually appropriate in almost all situations—it is a “safe” detailing method. However, only one, or a very few (2-3) different edge radii should be applied carefully to any single GPF edges. In the above images, a simple GPF is progressively given all edges the same radius of increasing size from an original sharp edged form. Once can see the visual effect this has on the form character, especially the perception of the form size. The last image (lower right) gives an indication of how edge radius affects the relative visual size of a form.

8.43. Figure—GPF Detail: Large Edge Radius



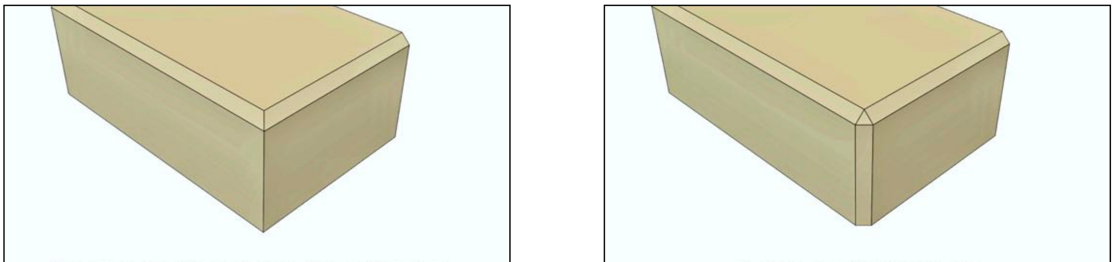
Note. Except for the first non-radiused base form image, each of the above shows the application of large radii to a rectangular form on the left and the addition of a small radius to the remaining edges on the right. These forms and applications of radii show what happens to a form's visual character when both large and small radii are applied to GPF volumes.

8.44. Figure—GPF Detail: Edge Chamfer



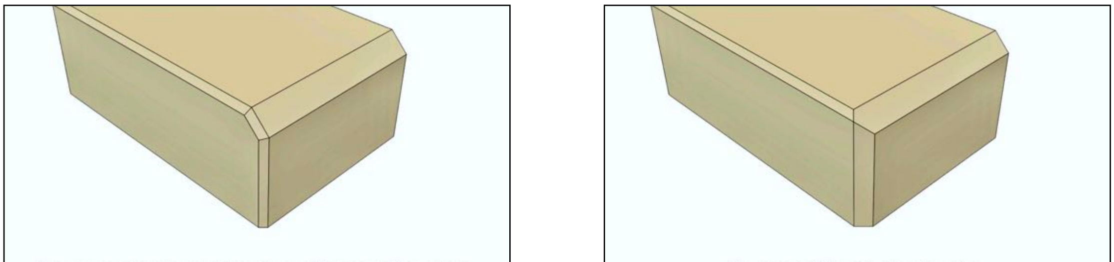
No edge chamfers.

Only one edge chamfered; all other edges sharp.



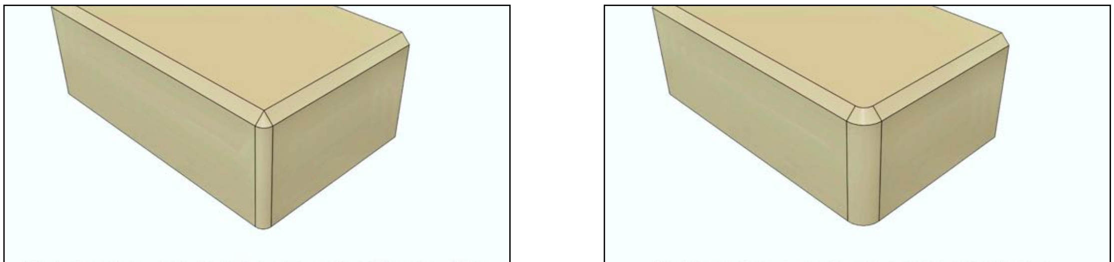
Top edges chamfered at same size; vertical sharp.

All edges chamfered same size.



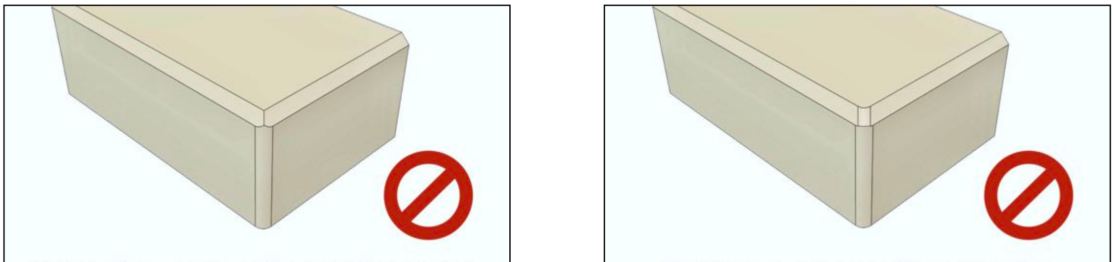
One large chamfered edge plus uniform smaller edges.

All edges different chamfer size.



Vertical radius = top chamfers size; radius after chamfers.

Vertical radius larger than top edges chamfer size.

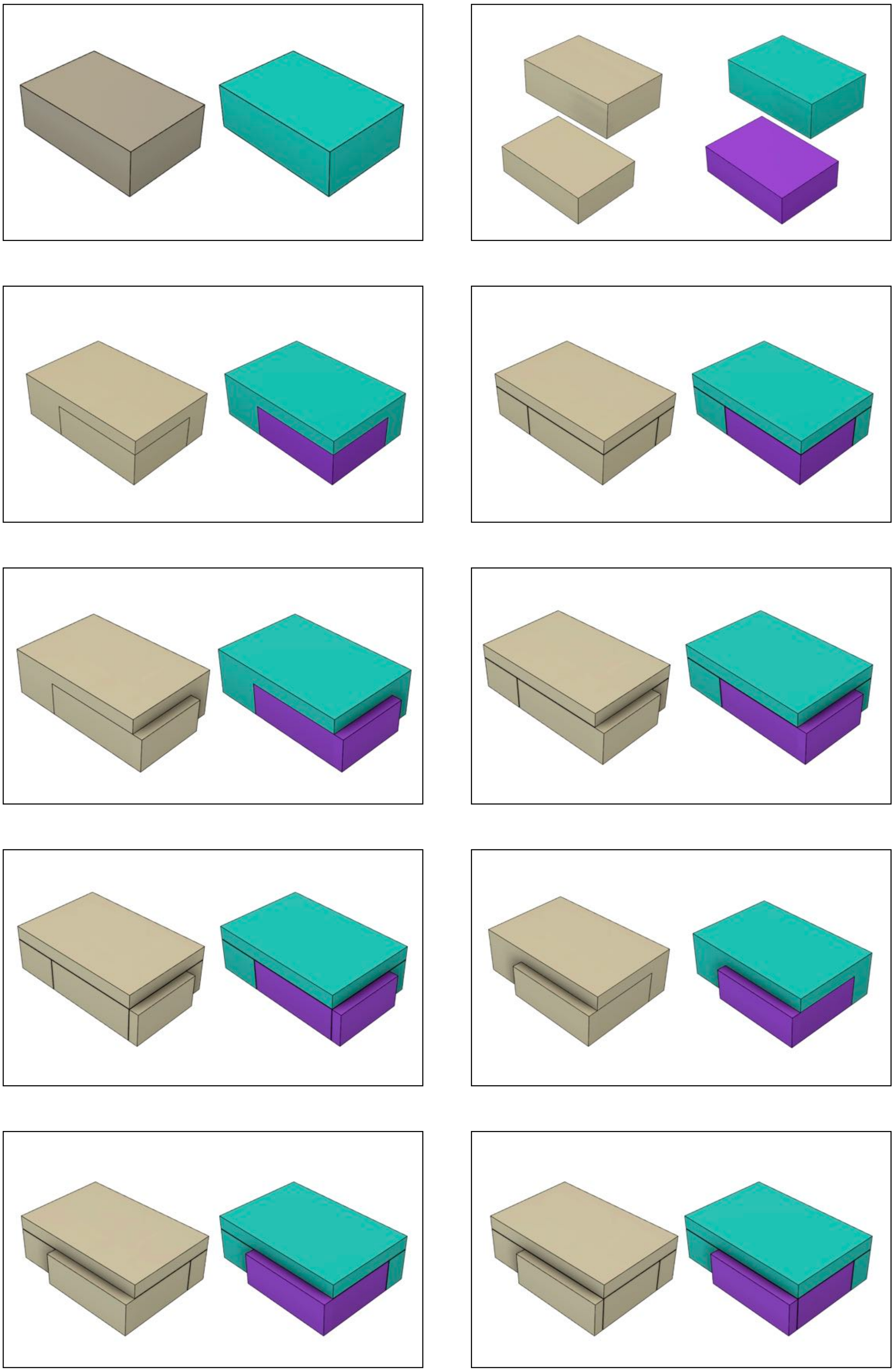


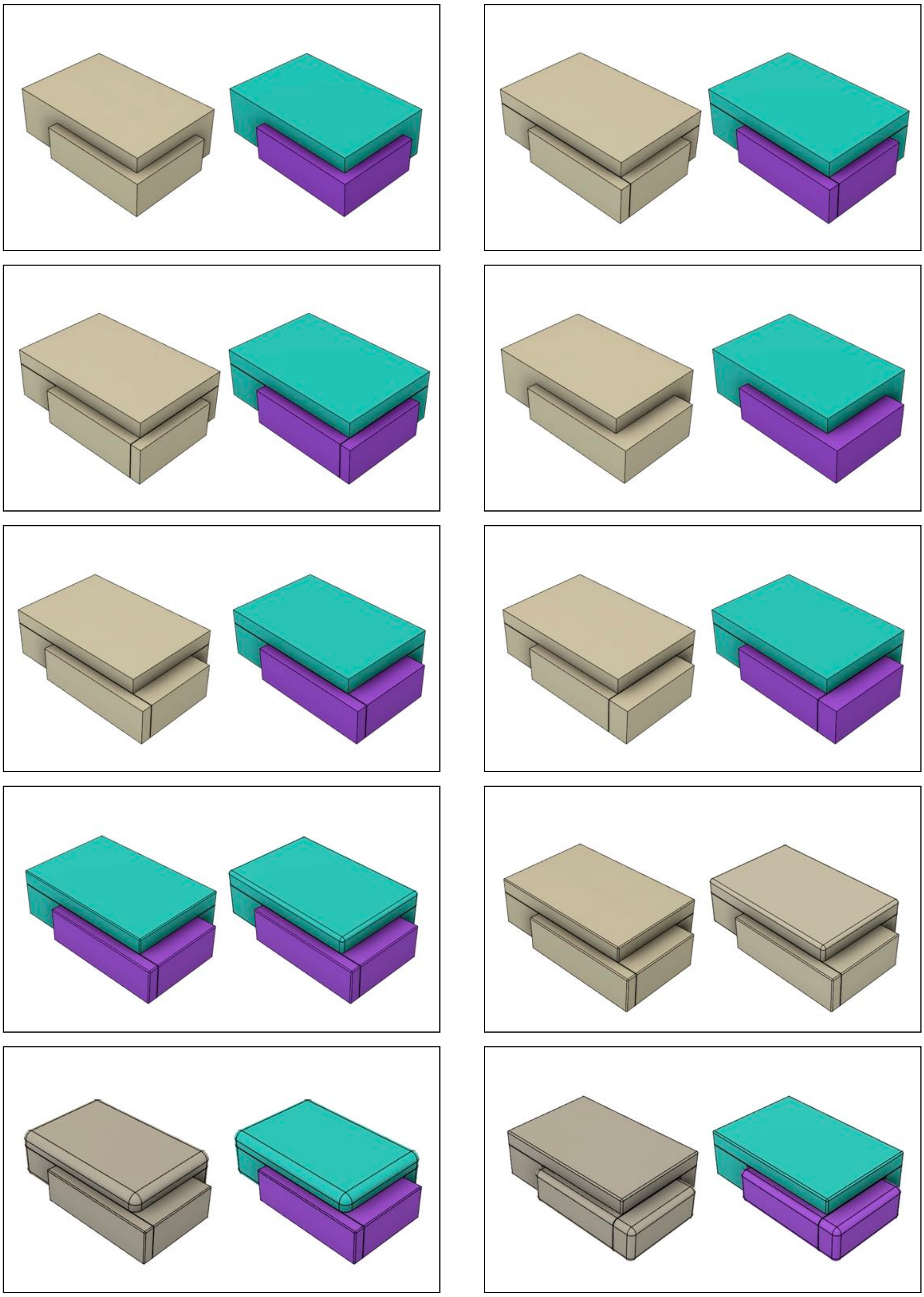
Vertical radius = chamfer; radius done before chamfers.

Chamfer corner radius done after vertical radius.

Note. Chamfering GPF edges should be done with discretion and considered carefully. Chamfered edges are visually appropriate only in certain situations. If in doubt about applying an edge chamfer, apply an edge radius instead—it is visually “safer."

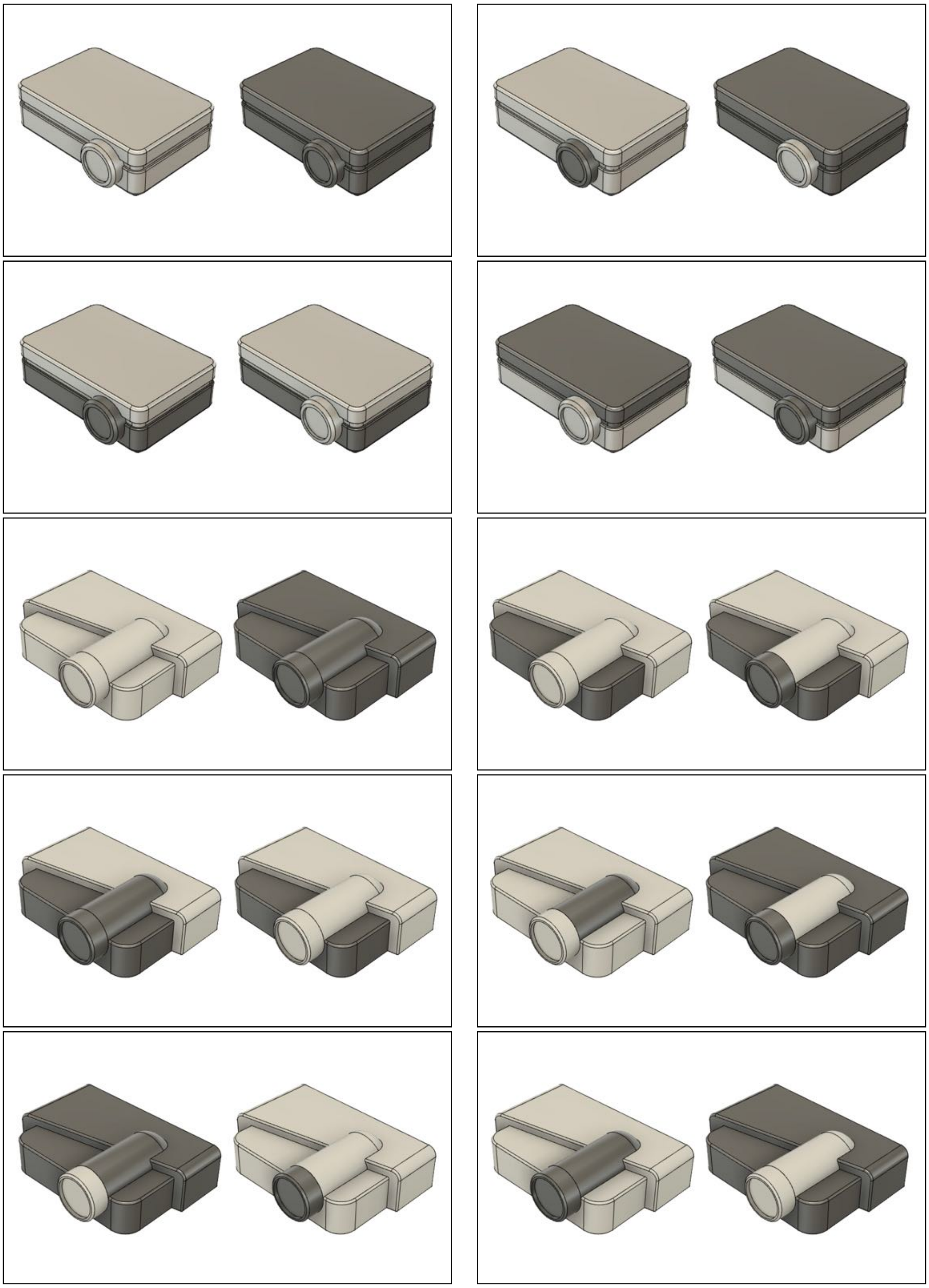
8.45. Figure—GPF Detail: Parting Gap





Note. Shown here are various intersections (some with the shift operation) of two different sized rectangular prisms in GPF compositions and how parting gaps could be applied in alignment with the intersectional breaks. The last four images also show how varied edge radii can also effect the visual perception of the intersections and parting gap arrangements. Parting gaps range between 1-2 mm wide and deep.

8.46. Figure—GPF Surface: Value & Color Variation



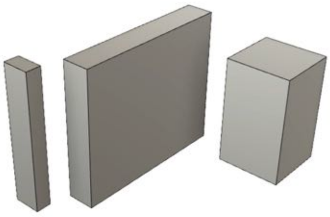
Note. These images show the perceptual effect on product appearance when the value or color of various parts of a GPF are varied between dark and light. Value or color differences can be strong or mild, but a very small difference is not recommended.

8.47. Figure—GPF Surface: Texture Variation

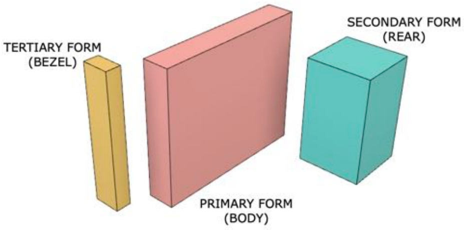
Note. Shown here are examples of how surface texture can effect the visual qualities and appearance of a GPF composition. The primary (larger) and secondary (smaller) GPFs are shown both without and with texture, demonstrating the visual effect of surface textures on form compositions in different ways. The last image shows how texture can be used on only one surface, or two textures used all over, as appropriate.

8.48. Figure—GPF Deconstruction: Desktop Simulator

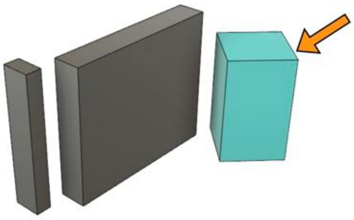
Deconstructing the Zycad Desktop Simulator into GPF



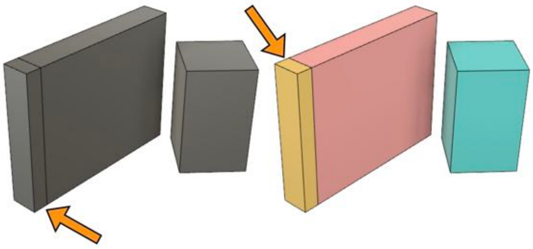
Three Main Forms: Primary, Secondary & Tertiary



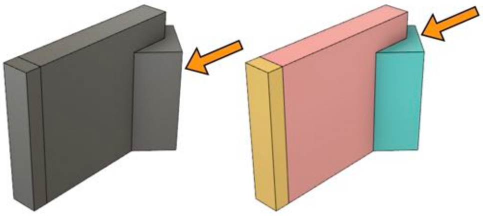
In Colors



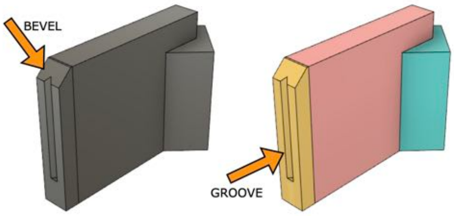
Secondary Rear Form Rotated 45 Degrees



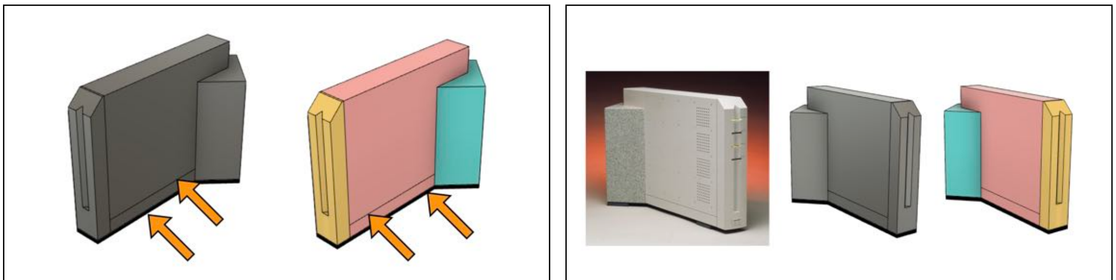
Tertiary Bezel Form Joined to Primary Body Form



Secondary Rear Form Intersected with Primary Form



Operation Details Added to Tertiary Front Bezel Form

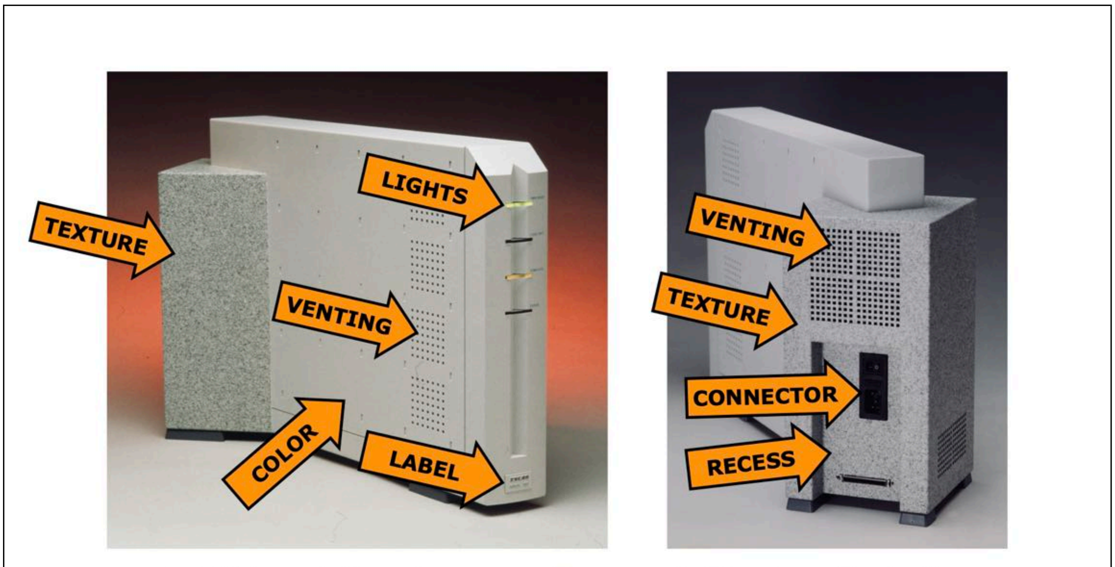


Parting Gap & Support Base Added to Unit

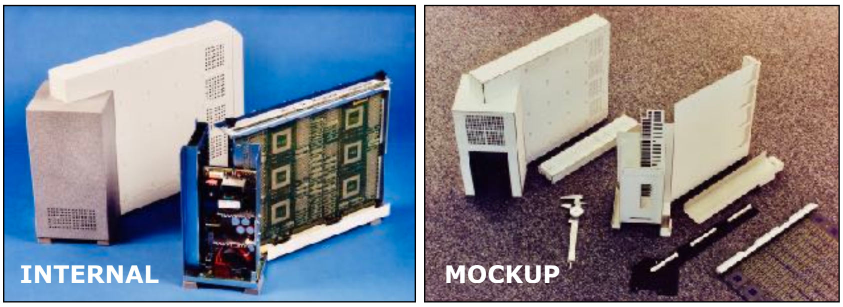
Left Side View of Actual Product & Its GPF Forms

Front View of Actual Product & Its GPF Forms

Rear View of Actual Product & Its GPF Forms

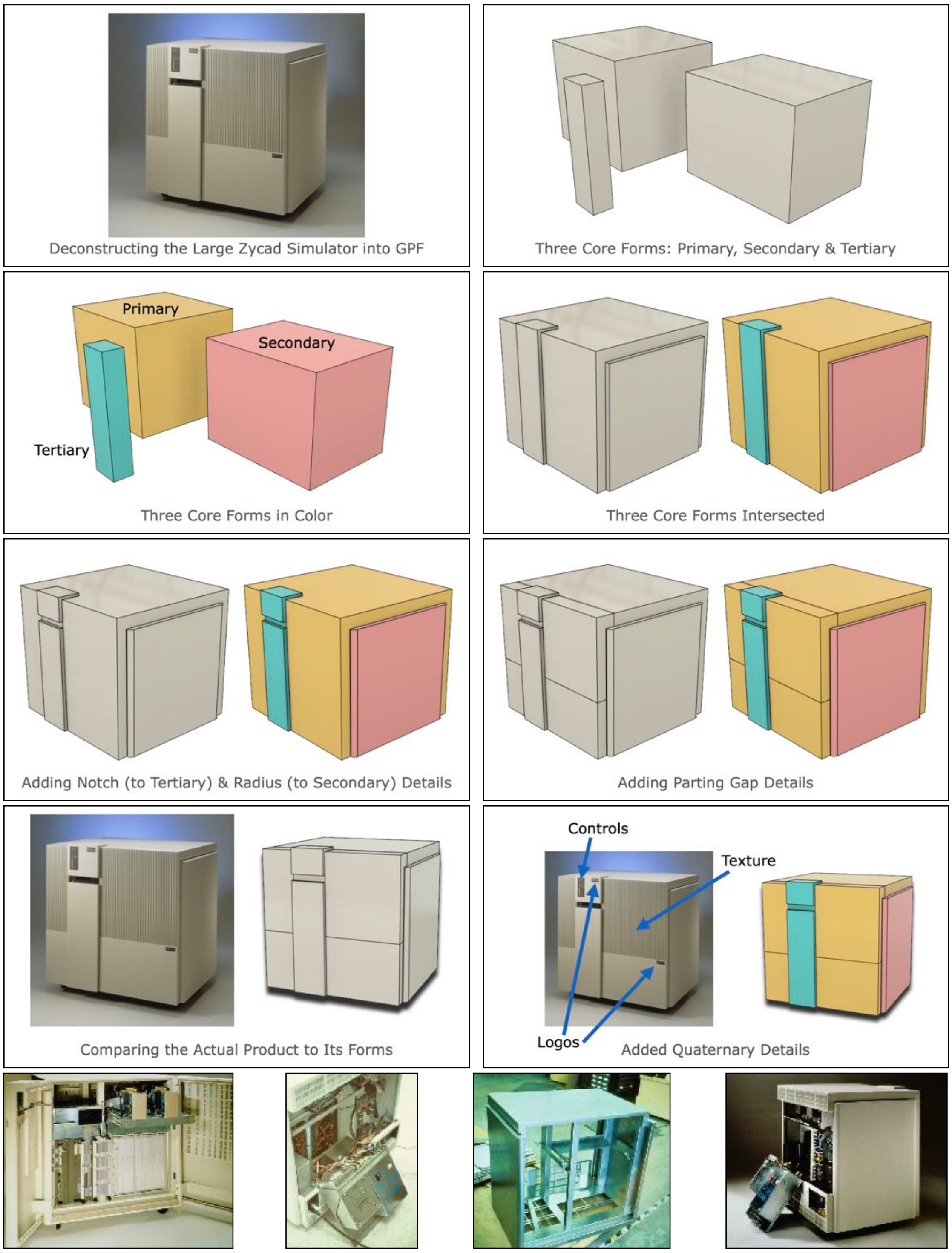


Additional Quaternary Forms & Design Details



Note. This product is here deconstructed into its basic GPFs, features, and details. The product was designed by Gary Gehrke and Bill Dresselhaus of Dresselhaus Design Group, Inc., for Zycad® Corporation. All aesthetic form design, and external and internal electromechanical, enclosure, and structural design, were executed holistically by the consultant firm. Photos used by permission.

8.49. Figure—GPF Deconstruction: Large Simulator



Deconstructing the Large Zycad Simulator into GPF

Three Core Forms: Primary, Secondary & Tertiary

Three Core Forms in Color

Three Core Forms Intersected

Adding Notch (to Tertiary) & Radius (to Secondary) Details

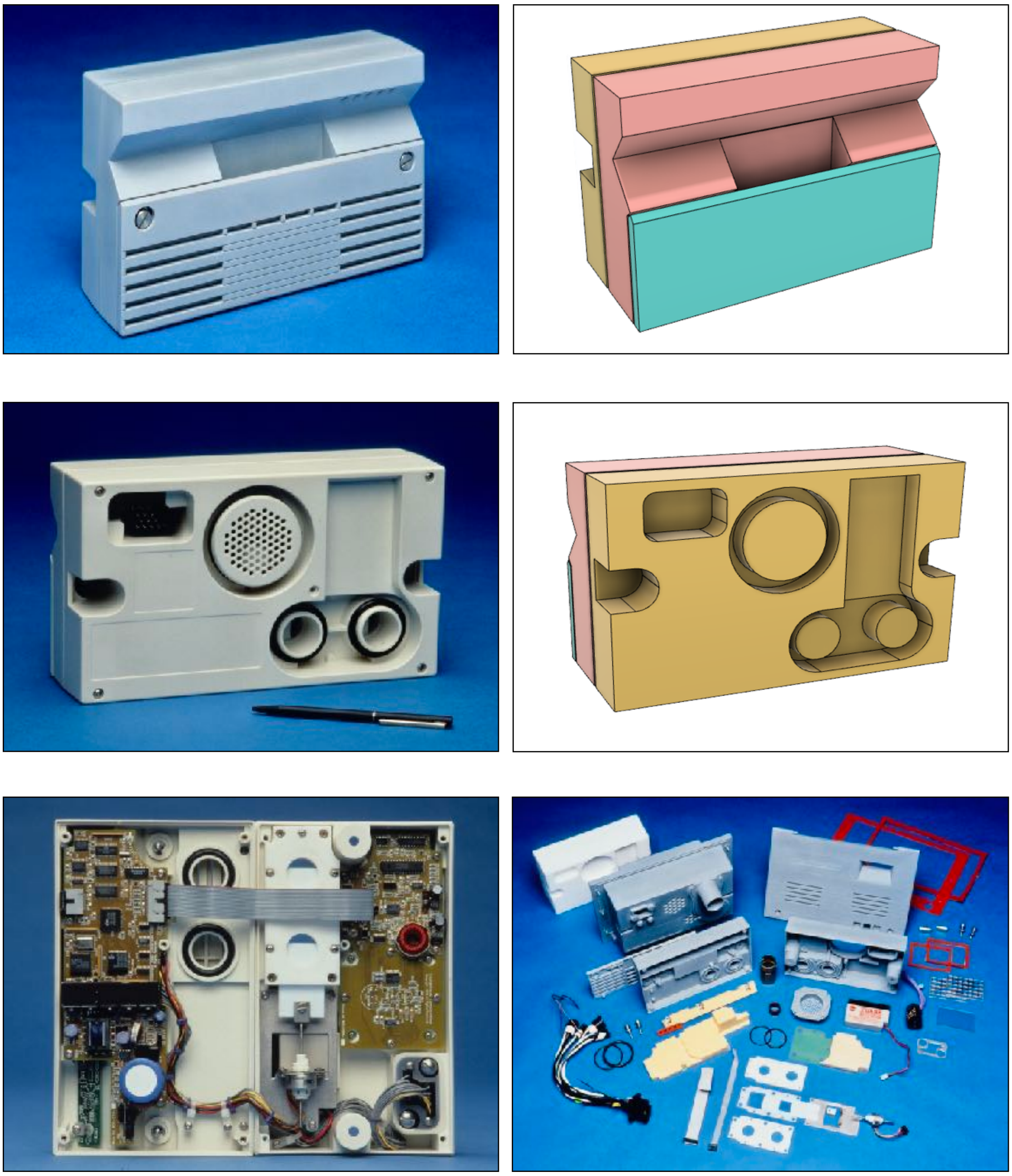
Adding Parting Gap Details

Comparing the Actual Product to Its Forms

Added Quaternary Details

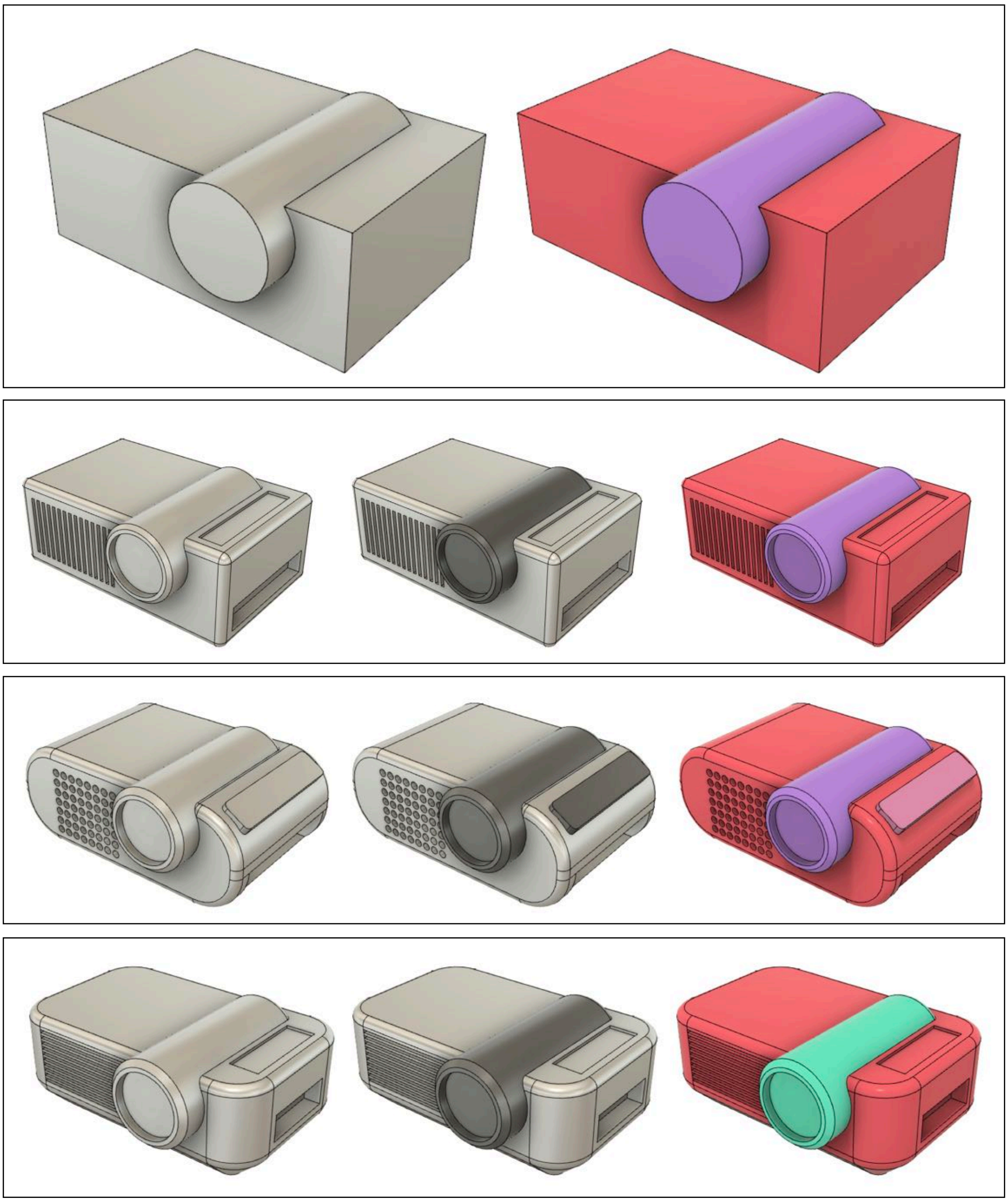
Note. This product is here deconstructed into its basic GPFs, features, and details. The product was designed by Gary Gehrke and Bill Dresselhaus of Dresselhaus Design Group, Inc., for Zycad® Corporation. All aesthetic form design, and external and internal electromechanical, enclosure, and structural design, were executed holistically by the consultant firm. Photos used by permission.

8.50. Figure—GPF Deconstruction: Atmosphere Controller



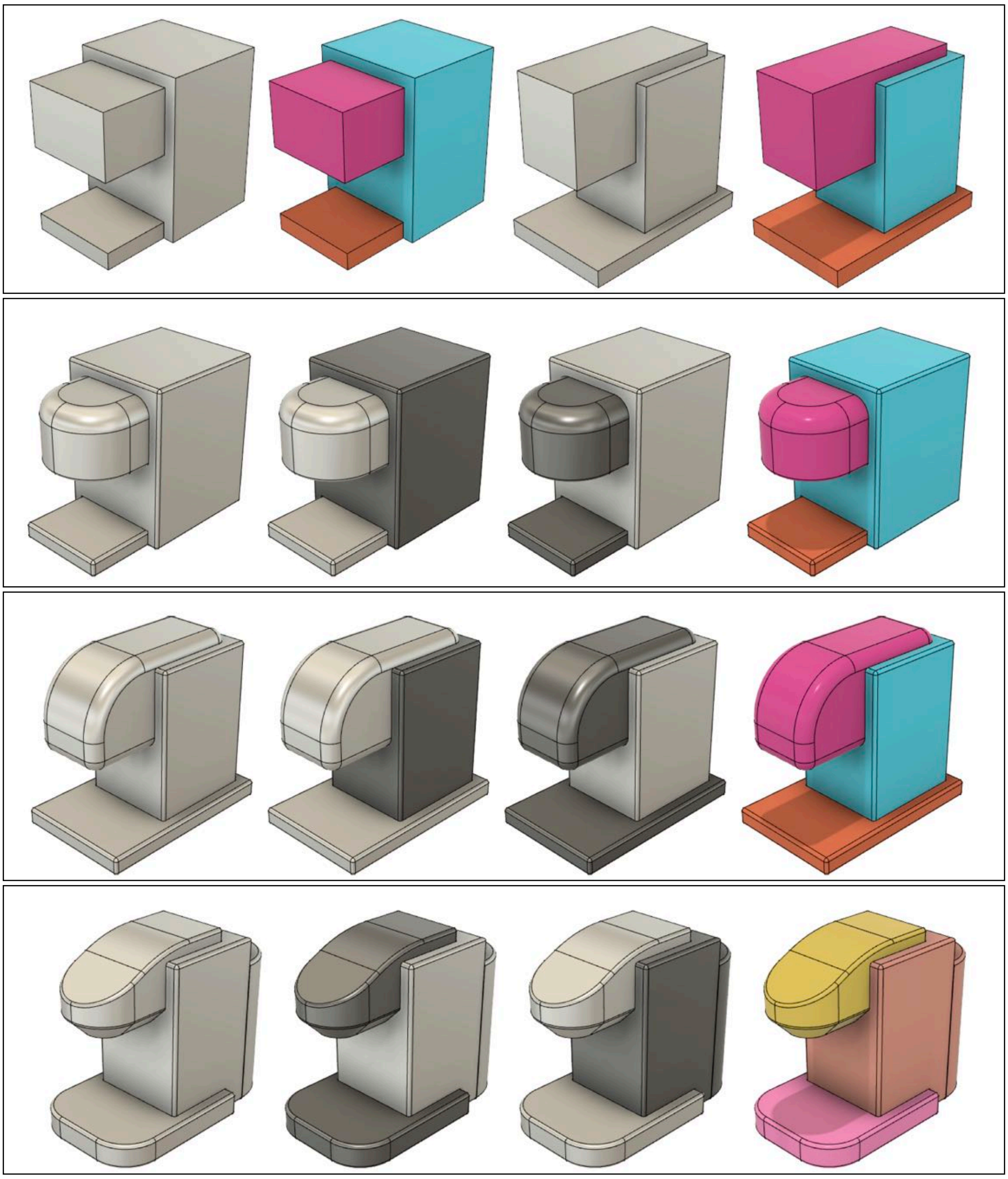
Note. This product is here deconstructed into its basic GPFs, features, and details. The product was designed by the project team of Dresselhaus Design Group, Inc., for TransFresh® Corporation. All aesthetic form design, and the external and internal electromechanical, enclosure, and structural design, were executed holistically by the consultant firm team. The lower two images show the internal component and functional layout, and the full prototype set of parts created for the project. Photos used by permission.

8.51. Figure—GPF Deconstruction: Converged Digital Projector



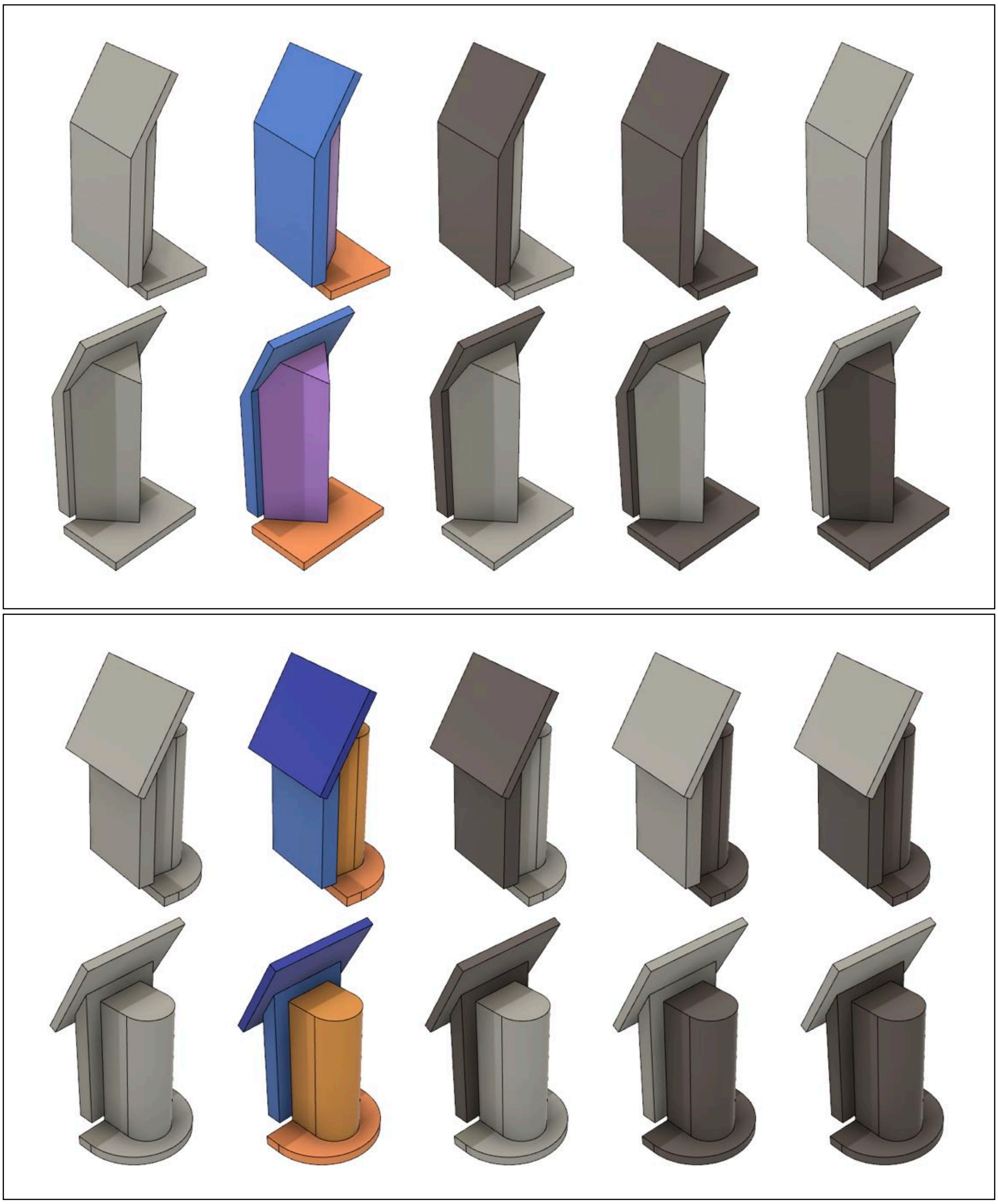
Note. Shown here are deconstructions of converged digital projector GPF compositions. The top image set shows the two basic geometric forms of rectangular prism and right cylinder that all of the compositions in this figure are composed of. The images in color show the two-level hierarchy of primary and secondary forms. The three lower sets of images are of three different projector GPF renditions, each with value variations, and with quaternary finishing detail variations of edge radii, controls, and air venting. However, all three sets have the same basic converged composition and element positions as the basic forms in the top set.

8.52. Figure—GPF Deconstruction: Converged Espresso Machine



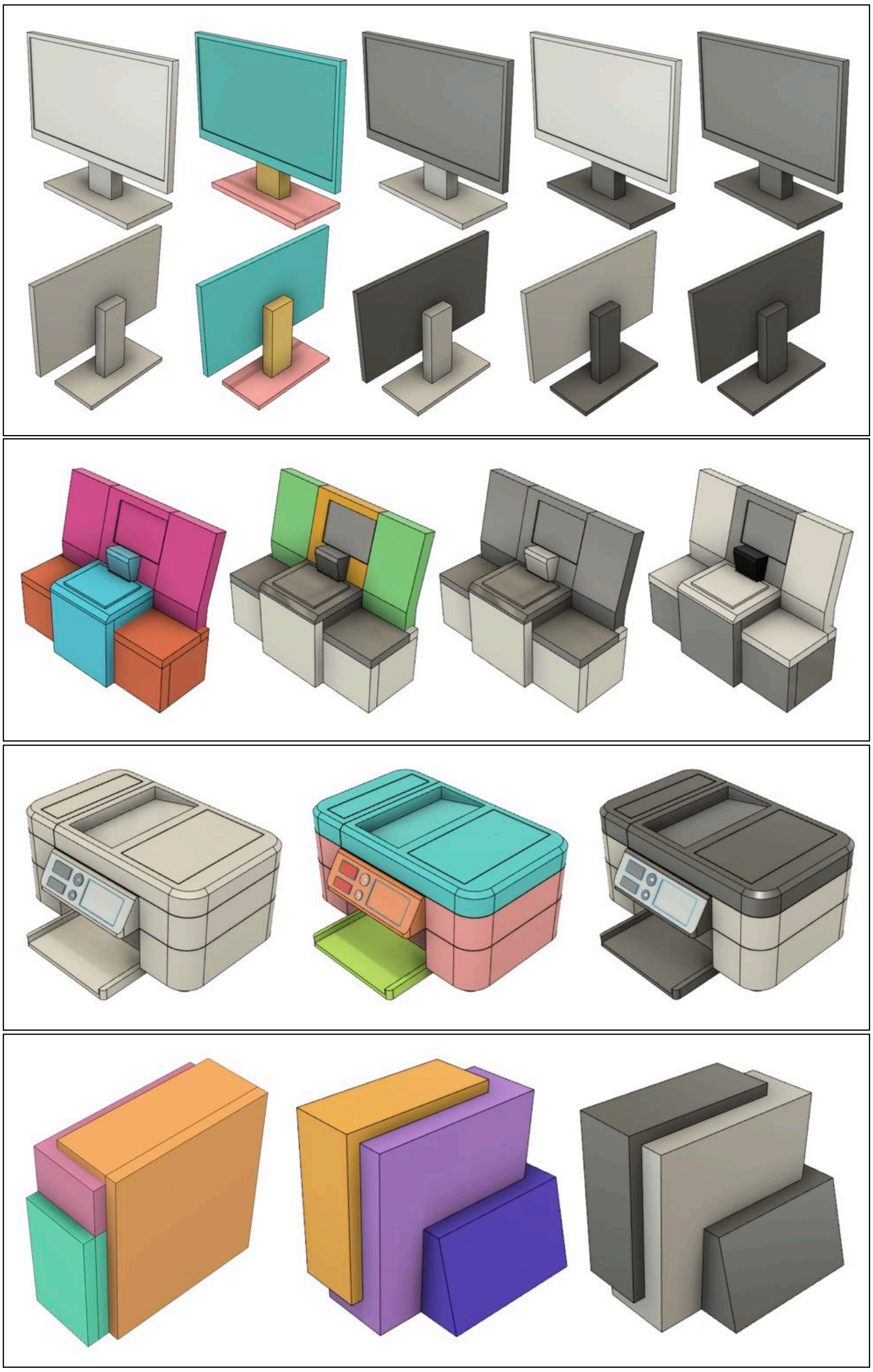
Note. Shown here are deconstructions of converged espresso machine GPF compositions. The top image set shows the two versions of the three intersected geometric forms of rectangular prisms that all of the compositions in this figure are composed of. The images in color show the three-level hierarchy of primary, secondary, and tertiary forms. The three lower sets of images are of three different converged espresso machine GPF renditions, each with varied form proportions and intersections, different visual operations, value variations, and with quaternary finishing detail variations of edge radii.

8.53. Figure—GPF Deconstruction: Converged Interactive Kiosk



Note. Shown here are deconstructions of converged interactive kiosk GPF compositions. The top image set shows one overall form composition version of three geometric forms and variations of value contrast. The images in color show the hierarchy of primary, secondary, and tertiary forms. The lower set of images is also of a converged interactive kiosk GPF version of somewhat different forms. Both versions, though composed initially of similar GPF, are each differently modified with visual form operations such as bend, intersect, shift, and radial surface. Again, some images show value variations.

8.54. Figure—GPF Deconstruction: Converged Various Products



Note. Shown here are deconstructions of several GPF compositions of converged products: display screen, checkout scanner, desktop printer, and computer tower. The images in color show the hierarchy level of forms. Other images show value/color variations.

9. CURRICULUM VITAE

Author Education

B.Sc., Chemical Engineering, University of Nebraska, Lincoln, 1967.
M.Sc., Chemical Engineering, Iowa State University, Ames, 1969.
M.Sc., Product Design Engineering, Stanford University, Stanford, CA, 1974.

Author Work Experience

Bill Dresselhaus is currently President/CEO of Dresselhaus Group, Inc., a product design and education consultancy. He is also an Adjunct Assistant Professor in the Engineering and Technology Management (ETM) Department in the Maseeh College of Engineering and Computer Science (MCECS) at Portland State University (PSU) in Portland, Oregon, USA. From September 2009 to August 2016, Bill was a Joint Invited Professor of Product Design and Design Management at the International Design school for Advanced Studies (IDAS), and at the Mechanical and Systems Engineering Design (MSDE) Department at Hongik University in Seoul, South Korea. In all of these teaching venues, he developed multiple courses and instructed non-design, design, and engineering undergraduate and graduate students in the principles and processes of product design, design thinking, and design management.

Bill was one of the early product designers in Silicon Valley, California, in the 1970s and 1980s. He was an early Product Designer at Apple Computer (Employee #316) and later Manager of Product Design in the Apple Lisa Division. He was the Principal Product Designer of the Apple Lisa computer, the forerunner of the Macintosh and “Mother of the Mac”, where he managed the product design and industrial design of the Apple Lisa and the industrial design of its mouse. Bill was Manager of Product Design, and later Acting Director of Opto-Mechanical Design, at InFocus Systems in Oregon, USA. He led product design teams there for three of its first market-leading digital media projector systems. He has worked with, for, managed, and/or hired, some of the best designers and design firms in the world: IDEO, Ziba, Frog, RKS, Lunar, Matrix, and Stratos. His product design clients include Apple Computer, InFocus, Hewlett-Packard, LG Chemical, Sun Microsystems, TransFresh, and many other global high-technology companies. In addition he has supported a number of international universities, organizations, and schools with their design education programs.

Bill is dedicated to design education and helping anyone to understand, learn, and practice the principles and processes of design thinking and product design. He has two masters degrees in engineering and product design from Iowa State and Stanford University respectively, and Executive Industrial Design training at Art Center College of Design in California, USA. He currently consults and teaches for a variety of organizations, and produces and delivers design thinking and product design education materials online.

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