Digital Co-Creation:
An Early Stage Product Personalization Methodology to Bridge the User-Designer Void

by
Timothy James Slama

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Honors Baccalaureate of Science in Mechanical Engineering
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AN ABSTRACT OF THE THESIS OF

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Modern product development is a complex combination of multidisciplinary processes ranging from market research to design, engineering analysis, and logistics. The product development process has a significant impact on the success or failure of new product launches. The majority of consumer product launches fail, resulting in significant sunk cost in research and development. These failures are commonly due to poor product-market fit which can occur when there is a lack of user involvement in the design process. This background research identified a void between consumer and company which is referred to as the user-designer gap.

Mass customization is a form of modern product development that aims to deliver customizable products in an attempt to close the user-designer gap. With a model like this, customers can change material, color, logos, and other modular features on existing products. However, these current mass customization practices fall short of true personalization as they are incapable of adapting form or function of the product to match customer needs. A methodology to address this shortcoming is proposed and is called Digital Co-Creation.

Digital Co-Creation aims to harness state-of-art product development tools to create an efficient framework where the user and designer can collaborate to produce a truly personalized product. It does this through two-way communication surrounding results of digital sketching, computer renders, virtual simulations, and augmented reality. This combination of tools to evaluate form and function of the product allow for streamlined development of products with continuous customer feedback. The end result is a product that has been specifically designed and manufactured for the customer at a lower price point than typical bespoke production.

A case study was conducted to evaluate the viability of the proposed methodology. For the case study, two contrasting users were presented, and their individual needs were taken into consideration as a unique prosthetic limb was designed for each of them. Finally, the findings were discussed and conclusions about the wider viability of the methodology were made.

Key Words: Design Engineering, User-Designer Gap, Product Design, Product Development, Mass Customization, Prosthetic

Corresponding e-mail address: slamat@oregonstate.edu

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APPROVED:

Onan Demirel, Mentor, representing Mechanical Engineering

Christopher Sanchez, Committee Member, representing Psychology

Raffaele De Amicis, Committee Member, representing Computer Science

Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Timothy James Slama, Author

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1. **Introduction**:

Modern product development is a complex combination of multidisciplinary processes ranging from market research to design, analysis, and logistics. Designers synthesize state-of-the-art technologies to deliver unique products to satisfy complex customer requirements. At the core, mechanical engineers and industrial designers are responsible for developing novel design methodologies, which can effectively capture customer needs and inject those into the final design of the product [1]. With today's fast-moving marketplace, the need for agile and creative design methodologies is at an all-time high [2]. Thus, product development strategies that reduce the overall design costs and time-to-market are key ingredients for market success[3]. Furthermore, as information becomes commoditized, design has become a crucial differentiating factor used by top consumer product companies to preserve and gain market share [4]. In this context, offering customers a unique product personalization experiences with the aim of winning their loyalty through representing unique needs and preferences becomes a major market success indicator.

Mass customization is regarded as the leading methodology that brings the flexibility of product customization based on highly variant products at the cost of mass production [5]. However, many mass customization techniques only partially capture the customer wants and fail to keep the customers in the loop during the design process. Current mass customization techniques use knowledge-based or model-based configurations to generate product variants which aim to provide extend amount of options to represent customer preferences. However, customers often get lost within the silos of preferences and options. Also, these methods keep the customer out of the design loop and do not allow voice of the customer to be heard by the designer. There is a need for flexible design methodologies that can tailor products around customer's specific needs and preferences while keeping the voice of the customer in the loop throughout the early design process.

Based around these needs for differentiation, this thesis proposes a customer-centric design framework as an alternative methodology to capture customer needs and preferences early in design via a co-creation framework. The goal of this project is to develop a computational design methodology that bridges the void between the users and designers and alleviate the challenges of mass customization through product personalization.

The first section of the thesis examines and identifies the benefits and shortcomings of existing technologies used in modern product development, specifically focusing on early design methodologies from a human-centered product design perspective. After the examination of the state-of-the-art practices, the paper progresses into tying together emerging technologies into the digital co-creation methodology that is proposed in this research. This methodology calls for collaborative design with the customer to create products tailored to their specific needs and preferences. The goal of this methodology is to produce personalized products at a comparable cost to mass-customization and shorten time-to-market when compared to traditional bespoke product development strategies. Finally, a case-study in prosthetics design is performed using the methodology as a proof-of-concept followed by a discussion of the findings. The case-study proposed in this research work illustrates how the design framework can be used for product personalization that is made through co-creation between designer (company) and customer.

2. Background Research:

To establish a baseline understanding of the state-of-the-art practices in product development a literature review was conducted in five key areas. These areas are mass customization, prototyping, digital human modeling, virtual and augmented reality, and product-market fit.

2.1 Mass Customization

Mass customization is an economic model that combines the low unit cost of manufacturing achieved during mass manufacturing with the unique customer-product fit that customization provides. This fusion of customization and mass manufacturing has long been a theoretical business model but historically has lacked the technologies necessary to accomplish it successfully. The benefits of mass customization are simple and promising, to achieve low cost per unit of manufacturing while also delivering products that match the unique needs of individual customers. Products created under this model carry significant value proposition over competitive products as customized products can be sold at a higher price point [5].

Today, mass customization has been implemented to varying degrees in several successful business models and is becoming a rising trend for startup consumer products. An example of this is Gillette's Razor Maker business category. The program allows users to choose from over 100 different razor handle designs and customize the choices related to grip, blade type, and the addition of text or logos. The razor handles are then 3D Printed on a stereolithography (SLA) printer and promptly shipped to the user [6]. Another similar example is the NIKE By You (formerly NIKEiD) customization plan wherein users pay a small premium to make color, material, and text choices to personalize existing Nike products [7]. Mass customization is also seen in the creation of custom mouth guards and hearing aids where end users utilize three-dimensional (3D) scanning at local doctor's clinics to create digital molds which are used to create perfectly fitting products specific to customer needs[8].

There are three major barriers that need to be overcome to successfully implement mass customization. The initial barrier is associated with the complex and customizable manufacturing techniques. This step requires a manufacturing assembly process that can be changed to create unique products based on specific customer needs with minimal time and resources. For example, tailored pants could be individually created with proper sizing based on a customer's submitted measurements. Historically, with the high cost of injection molding, casting, and other traditional manufacturing methodologies customization has not been a financially feasible option [9]. However, as digital fabrication technologies proceed, specifically with the recent advances in the additive manufacturing, the barrier of custom manufacturing continues to be reduced. This can be seen through an increased adoption of advanced manufacturing technologies that have small tooling costs such as Computer Numeric Control (CNC), and 3D Printing [10].

The second barrier to entry is the supply chain and logistics associated with creating or carrying large varieties of products. For example, with the rise of online shopping services such as Amazon Prime, customers expect short delivery times, this can be a challenge for many companies to implement.

The final barrier to entry is the high cost of collaborative product development. Collaborative product development is the process of including the end user early into the design process [11]. Before the introduction of digital tools, collaborative product development often meant hiring engineering consultants, flying across the country or world and paying large premiums for the ability to develop custom products. However, with the widespread growth of Computer Aided Design (CAD), Product Data Management (PDM), and other software, the ability to effectively collaborate on a global scale has been greatly improved. Despite this growth, the ability to communicate between non-technical end users and new product development teams has remained stagnant and a point of concern [12]. Prototyping and visual models have long proved to be one of the most effective ways of bridging communication gaps in new product development [13].

2.2 Prototyping

A prototype is a model or visual representation that is created to help represent or test feature(s) that will be in the final product [1,13]. Prototypes have been proven to be effective tools of communication in early-stage design [13,14]. As a tool for communication, the efficacy of prototyping comes as a direct result of the ability to see and test a representation of an idea in its infancy.

Prototypes come in a variety of forms and serve multiple functions. The largest motivation behind creating prototypes is the refinement of an idea/concept, followed closely by the motivation of communication of a concept [13]. Whether constructed through high-fidelity modeling or made from household materials, prototypes are tools to test, visualize, and refine product details. Prototypes can also take a digital format in the shape of CAD. By working through the physical or digital manifestation of an idea, initial thoughts, flaws, and potential issues can be flushed out and pilot testing can be conducted.

Digital prototyping is an emerging discipline that has seen sustained growth in the last three decades due to the negative aspects of physical prototyping (e.g. cost, time, fidelity) [15]. The utilization of parametric CAD models in software programs such as Siemens NX, SolidWorks, Creo, and Autodesk Fusion has become commonplace and a functional requirement in the modern product development and manufacturing environment [16]. Typical modern workflows are multi-prong approaches but often include the transformation of early stage digital models into physical prototypes via rapid prototyping technologies such as 3D-printing, speed milling or off-the-shelf component assembly. These physical prototypes can then serve as representation of ideas and rough starting ground for experimentation with various ideas.

In addition to transforming digital prototypes into physical prototypes, software capabilities have unlocked whole new ways of analyzing ideas and performing tests that previously would have required physical models to learn from [15]. One of these methods is Finite-Element Analysis (FEA), a modeling technology used to test devices for stresses, strains, and potential failures by subjecting the CAD model to virtual loads and simulating the effects that would result from them. Another method that can be used to test devices is Computational Fluid Dynamics (CFD), which allows design engineers to analyze fluid particle's movements as they pass around the object. These are just two examples of additional tools that can be used to inform digital prototyping and make changes to ideas in their infancy. Additional technologies are constantly being developed and refined and with the inclusion of these capabilities, engineers are deriving more value from CAD models and digital prototypes than ever before.

Finally, digital prototyping can be used to create visual representations of ideas in the form of digital renders or photorealistic rendering. Digital renders are images that are created allowing product designers to assign textures, materials, lights, and more to a rigid body model [17]. By utilizing this technology, a more refined version of the product/idea can be displayed to the customers and can be used as a tool for communication for important visual and structural decisions.

From an innovation creation standpoint, it has been found that the most important time to create prototypes is early in the design process [18]. Prototypes can also be purely visual with the focus on creating a model for industrial design critiques and improvements. One of the greatest benefits of early-stage prototyping is that it allows for testing of functionality and including human-product interactions [13]. Often the human-product interaction considerations are left until the end of the product development process when it is too late and costly to make changes that could improve the usability of a product [19].

Dilemmas that are associated with the use of prototypes are balancing the decision of when to continue prototyping versus moving on to a refined or closer to final version of the product [20]. The point of diminishing returns in prototyping is when the work that is being put into the creation of a prototype is less than the insight that will be gained from said prototype. This point is hard to identify without prior experience. The method of decision-making as to where this point lies is usually traced back to personal experience and trials, which can result in a messy and unkempt design process.

2.3 Digital Human Modeling

While FEA, CFD, digital rendering, and CAD serve as tools for the analysis of a product's physical characteristics, another type of digital analysis allows for the testing of a critical engineering requirement, product usability via ergonomics. The interaction between a product and the user is of the utmost importance when it comes to final functionality, especially in high stakes environments. Digital Human Modeling (DHM) is a technology that allows for the analysis of ergonomics and overall human-product interaction through computer simulation [21]. The benefit of this technology is its ability to assess a variety of ergonomics and environmental functionalities across variable population anthropometries without the high cost associated with human trials. Much as FEA does not serve to eliminate the use of destructive or physical testing, DHM does not completely replace human subject data collection but can serve as a tool for effective elimination of early-stage concepts and can result in better end products with expedited development cycles.

DHM allows engineers to place virtual users into the environment that the product is being used in and make immediate changes. This is especially useful in areas such as assembly line design, vehicle design, hazardous material handling, and occupational ergonomics. Simulations provide information with regard to visibility, accessibility, physical strain on the user and more. Several examples of practical use cases include using software to quantitatively determine visibility occlusion in a fleet of vehicles to help inform design decision making. By examining three vehicles and using various eye heights the researchers were able to predict specific cases in which the user would be unable to see road signage or other critical information [22]. Another use case of DHM is the analysis of product maintenance from an ergonomic standpoint. The process of oxygenation wrench installation was chosen and evaluated with the goal of optimization. A DHM software was used and the researchers were able to provide detailed, constructive feedback to the scenario with the goal of decreasing the likelihood of long-term injury from the process [22].

While DHM is a great tool, it is not without limitations. One of the limitations is the barrier of creating a custom DHM environment for the specific task. For many applications such as automotive design, aviation, and industrial assembly lines, the ground work has been done to enable the usage and analysis. However, if designers are seeking to create a DHM environment for a unique engineering task, it can be difficult to overcome the initial modeling barrier. Another shortcoming of DHM is that it is not yet a widespread technology so the software programs that are available are not as user friendly or accessible to beginners. With more adoption, a more refined and accessible software package will be available. DHM also faces an issue where the modeled human is incapable of making cognitive decisions based on the environment in which it is placed. Finally, a widely understood and agreed upon challenge of DHM is that of fidelity. Representing anthropometry, accuracy of motion in large degrees of freedom and the multitude of variables that exist in human interaction is a major limitation of the simulations [15].

2.4 Virtual and Augmented Reality as Tools in Product Development

Virtual reality (VR) is a technology that allows for humans to interact with a digital environment in a way that feels natural to the person experiencing the interaction [23]. This technology can take many forms, but it is most commonly seen in that of a headset which a user places over their eyes and images are displayed simulating an environment that was created and stored onto a computer. VR shows tremendous promise in the development and design of products that are intended for human interaction [15,22]. This includes prominent examples such as cockpit design for airplanes and ships or placement of surgical equipment in emergency medical room environments. These examples are not the only use cases and as the technology necessary to utilize hyper-realistic VR becomes more affordable the product will become more accessible to a wider range of industries.

The benefits of utilizing virtual reality in those previous examples is clear, it enables low cost adjustments to be made and accelerates the learning process when it comes to integration of user feedback. For example, if a button is out of reach for a user another model can be generated, simulated and experimented within minutes and real insights can be gained from user experience. The accessibility of this product would allow for integration of customers and end users into the design process at earlier stages than through traditional design methodologies.

The technology of VR is not without limitations that affect its usage in product development. One of these limitations is the interaction between user and virtual environment. While reaching, pressing, and other simple interactions are satisfactory, the simulation of more complicated interactions such as surgical procedures with fine motor movements have significant limitations in current accuracy of the sensors [24]. With the integration of ultrasonic echolocating devices into future headsets, the accuracy issue is being addressed and will be a valuable new tool [25].

Another similar technology is Augmented Reality (AR), which utilizes similar technologies in the manifestation of a digital model into a simulated world. AR varies from VR in its ability to provide a composite view of the model and the real world [26]. By overlaying the model into the world around the user, it enables and opens the opportunity to see how a product or item may look in relationship to other items. For consumer goods, this could include how a piece of furniture fits in a room, how varying colors of a product might complement the environment in which it is placed, how the attachment looks with various clothing etc.

AR promises to contribute to the development of products through the straightforward ability to display and communicate final product visions in natural environments before fabrication begins. The second most common reason for utilizing prototypes in the workplace is for communication of an idea and the increased accessibility of AR will open up many new potential pathways for utilization of the technology in ways that integrates the end user into the loop of product design [26]. This can be used in conjunction with mass customization to allow users to make decisions with regard to the product that they are purchasing from the standpoints of size, color, functionality or more.

Current problems that are associated with the utilization of AR in product development include that the live tracking of moving non-rigid objects [27]. This limitation often prevents the use case of physical product try-on, but strides are being made toward addressing this shortcoming. Additionally, programming custom AR applications for testing ideas is still somewhat unavailable to persons with a non-software engineering background. Finally, AR doesn’t currently fully allow for natural interaction between the user and the virtual product.

2.5 Product Market Fit

Product-market fit can be defined as a product that successfully solves a legitimate need or problem of customers [28]. Billions of dollars are spent annually by companies on market research to predict, estimate and understand what customers want in their product [29]. Poor product-market fit can be costly, resulting in large sunk cost into development of products that don't see market success [30]. As such, there have been numerous methods and practices developed that are used to identify potential needs where a product could find success in the marketplace.

One commonly accepted practice for market discovery is the use of a "design thinking" framework. Popularized by the design consulting firm IDEO in the late 20th century, the term describes the use of asking empathic questions, putting oneself in the "shoes of the user" and designing based on observed user interaction rather than associated survey questions [31]. This practice is something that can be refined and improved upon as an engineer or designer repeats the process and familiarizes themselves with common steps for improvement.

3. Examining Traditional Product Design Methodology

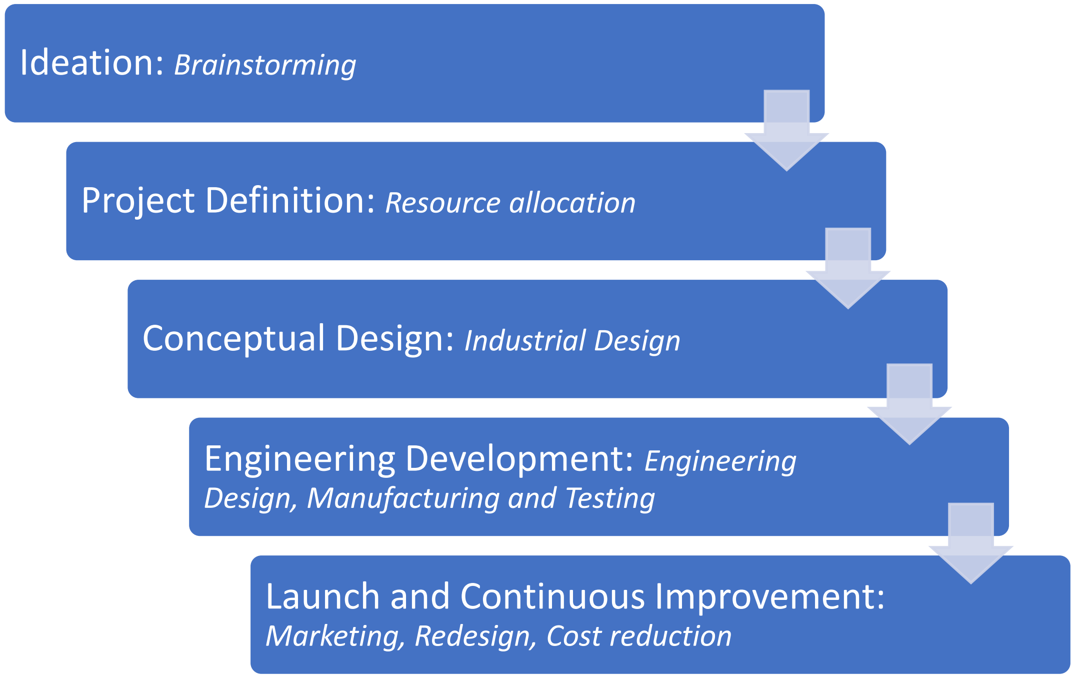


Figure 1: The above shows a view of an entire traditional product development process and each of the stages.

The focus of this thesis is in early stage design, which is contained within the areas of conceptual design and engineering development. Within these two areas of product development, there are subtasks and categories that are performed with the progressive intent to turn an idea into a functional product. For example, Figures 1 and 2 represent a widely-accepted conventional customer-centric product development process that is taught at Oregon State University, known commonly as the Ullman Method [32].

During the early stages of design, engineers and designers explore and refine ideas through brainstorming and ideation activities and evaluate concept models based on combination of physical and computational prototyping techniques. Early design stages of the product development have the highest impact on the final design language and the resources committed towards the end of the product development [33]. In Ullman's product development methodology illustrated in Figure 1, customer requirements are gathered through surveys, user-studies, and House-of-Qualities (HoQ) early in design (shown as *customer input*) and adapted into engineering requirements through the combination of numerous creative (brainstorming, C-sketches) and technical activities (Pugh charts, TRIZ). As the product progresses, the concept designs go through changes that shape the final product. It is important to note that in this traditional method, the customer only comes into contact with the product after the beta-prototypes become available or the final product is launched to market. During the beta-prototype evaluations, only a limited number of customers have a proxy interaction with the product development process in the form of representation in a focus group through human subject studies. A problem with focus groups is that they are not entirely reflective of all end consumers and their specific needs and preferences. This limited interaction between customer and product during the development phase can often result in an ill product-market fit and expensive product failures [34]. In addition, any human factors issues discovered on during focus group studies through full-scale prototypes require design rework and retrofitting which are costly and time consuming [35]. Product development processes that are based on the conventional method lack continuous user-product interaction because they consist of long periods of design, engineering, and refinement in isolation before the product reconnects with the market.

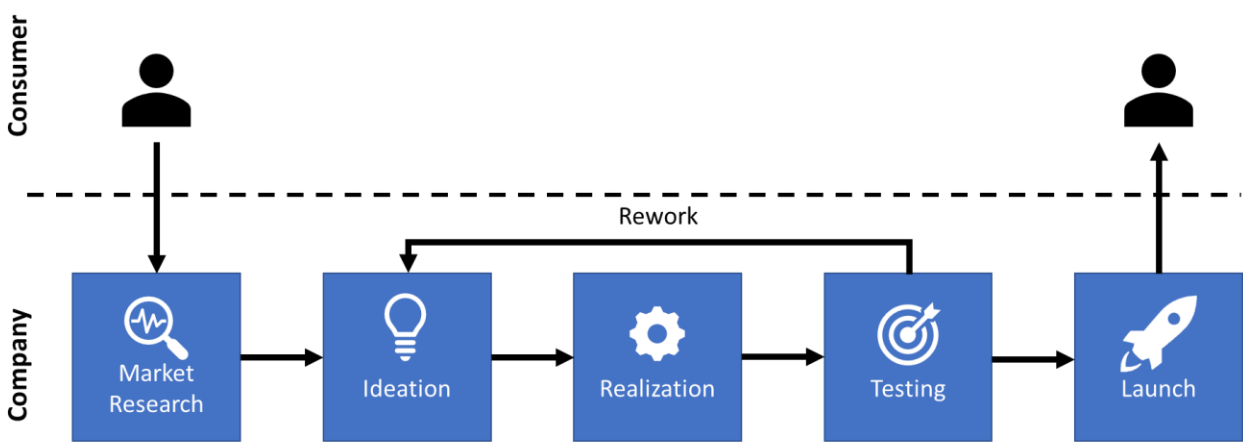


Figure 2: The above block diagram is a detailed account of what happens during the early stages of a traditional product development process. While there is only one arrow for rework in the above diagram it should be noted that numerous rework occurs in each stage and there is consistently communication and a feedback loop between each block of this stage.

The first stage in this process is Ideation. During this stage, designers or engineers conduct customer requirement gathering studies including one-on-one interviews, group interviews, questionnaires, and user observations. These studies focus on asking questions or observing about the ways in which the customer currently solves the problem and understand where the shortcomings of existing solutions lie. For example, IDEO, a global design consultancy, pioneered a “design-thinking” approach which focuses on user empathy studies to capture customer requirements. During these interview phases designers that utilize design thinking approach not only ask questions but also actively watch how customers use the products, noting potential human-product interaction issues [31]. Companies often aim to select a mix of archetypical and extreme users for these studies. For example, Nike and Adidas utilize elite athletes, Epic Systems interview Doctors and Nurses, OXO uses a mix of professional chefs and standard consumers [4]. This process is valuable for designers, but the initial meetings have long-term effects on how the product is developed which can be a double-edged sword. Incorrect findings, misleading assumptions or deceptive feedback at this stage could set the team down a path to failure as designers have interactions with the customer only for a limited amount of time. After the customer requirement gathering research is completed, the ideation stage moves on to potential solutions that address the problem at hand. The intention is to come up with rough ideas that could potentially be used as tools to address the problems discovered.

Through hand-sketching, industrial designers and engineers work together to express the rough concepts generated during ideation in a visual format. Hand-sketching can be done with traditional pen and paper or digitally in programs such as Sketchbook and Adobe Illustrator via digital sketchpads. Through hand-sketching, the initial form and functions of the product can be explored at little to no additional cost to the company. The sketches created during this stage will directly impact how the product is 3D-modeled.

The next phase comes in Realization of which the main activity is 3D-modeling. This can be done in varying fidelities and is used to explore form and function of the product in an interactive three-dimensional space. 3D modeling is a primary activity of a design engineer. A major value of 3D models is their ability to be transformed into physical and digital prototypes. 3D models can be converted into tool paths through computer-aided manufacturing (CAM), milled, 3D-printed, laser cut or manufactured via other methods. Alternatively, 3D models can also be used as communicatory pieces and used for running simulations in the simulation stage of product development.

After Realization is Testing, a stage that is focused around determining whether the product functions as intended. Simulation has taken much more of a leading role in this stage of product development where computer models are used to functionally test components of products in a computer environment. The types of simulations vary based on the product's end function. Possible simulations include computational fluid dynamics to test fluids, digital human modeling to test human interaction, finite element analysis to test structural strength. These digital simulations allow for early product analysis and error detection. By detecting errors and failures while the product is still a computer model, a significant amount of time and money can be saved [13].

Another portion of Testing is taking the product from computer into reality and it is called physical prototyping. This is a resource intensive stage of the product's development as it involves the physical manufacturing of initial prototypes to verify the digital design. Depending on the industry and the purpose of the product various tests are performed to ensure full functionality of the new design.

Finally, the Testing stage also contains human subject studies, the product is tested through usability studies - focus groups of humans to ensure that the product functions as intended. This test provides the first customer feedback in the product development process since ideation. The learnings from this test often inform the design team about the shortcomings with the form and function which often results in costly rework [35].

Upon in-depth examination, it is clear that product development is a complex multi-stage process that involves solving numerous problems in parallel. Today's modern development contains many new technologies (e.g. FEA, CFD), while still being littered with vestigial elements from the past. As a result, the modern development process leans heavily toward mass manufacturing of products and leaves significant room for improvement, especially as it relates to the design of personalized products.

4. **Proposed Design Framework**

The proposed methodology, called Digital Co-Creation, aims to address some of the shortcomings of the conventional product development method described in the previous section. These shortcomings include the lack of customer integration into the design process, expensive late-stage rework that can result after poor focus group feedback, and ill final product-market fit. Digital Co-Creation allows for a partnered design of products alongside customers to create an improved end-product market fit. The objective of the proposed approach is to create a medium which allows user feedback to be immediately integrated back into the product for rapid iterations and improvements. The type of product that emerges from the proposed methodology specifically focuses on "product personalization", which lies somewhere on the spectrum between bespoke products and mass customization (Figure 3). As explained in the Section I (Introduction), the goal of this methodology is to alleviate the challenges associated with mass customization by capturing customer needs and preferences early in design via a dual-way feedback mechanism.

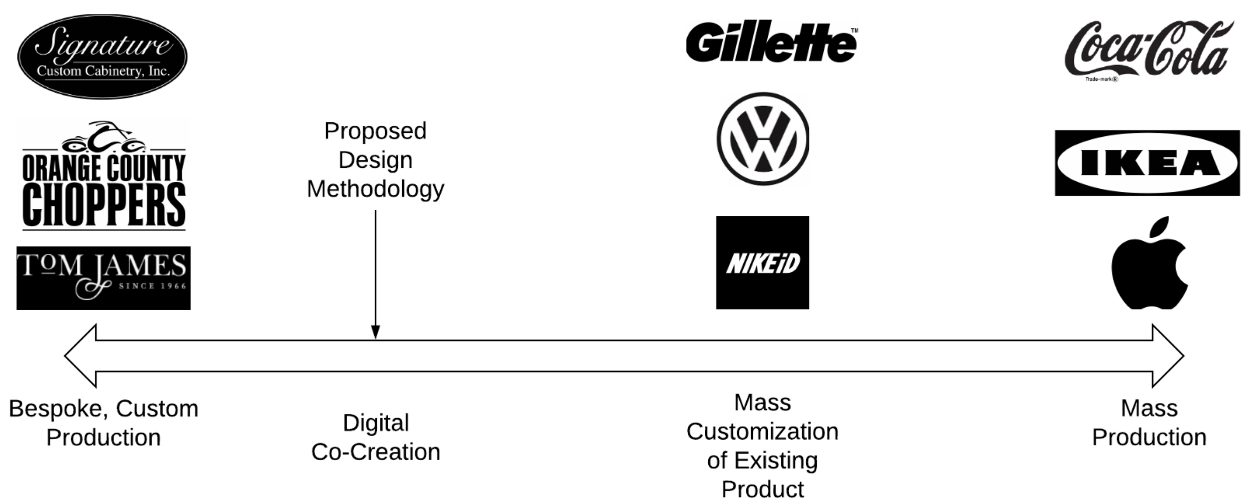


Figure 3: The above figure shows a traditional spectrum of products in scale of manufacturing. On the far right, mass produced items take full advantage of economies of scale by producing large quantities of identical parts. To the left of that is the mass customization sector which allows for color, material, and other changes to existing components to create custom scalable products. The far left contains bespoke or custom

production where the end product is built from the ground up specifically for the customer. The proposed methodology would create a product that falls between mass customization and bespoke production by utilizing common functional product bases with modular aesthetic additions.

Because of the current limitations of manufacturing techniques (e.g. high initial set-up cost of injection molding), many consumer products fall into the category of mass production. This typically results in a lower price point for the product due to the economies of scale. In contrast, because of the intense customization labor and craftmanship required in custom production market, which eventually reduces the total unit sales, bespoke products are sold at a premium which limits the market size. The proposed methodology aims to create a product design approach that leverages the benefits of both ends of the spectrum illustration in Figure 3 to deliver custom personalized products to end consumers. To ensure that the product meets the customers' actual needs and preferences, the customer requirements gathering activities will be injected into early design process, and customers will be kept in the loop, continually. The proposed methodology leverages state-of-the-art computational technologies such as digital sketching, digital human modeling, and augmented reality to bridge the user-designer gap. A theoretical illustration of the proposed methodology is provided in Figure 4 which outlines the interactions between the customer and designer as the product moves through the product development process.

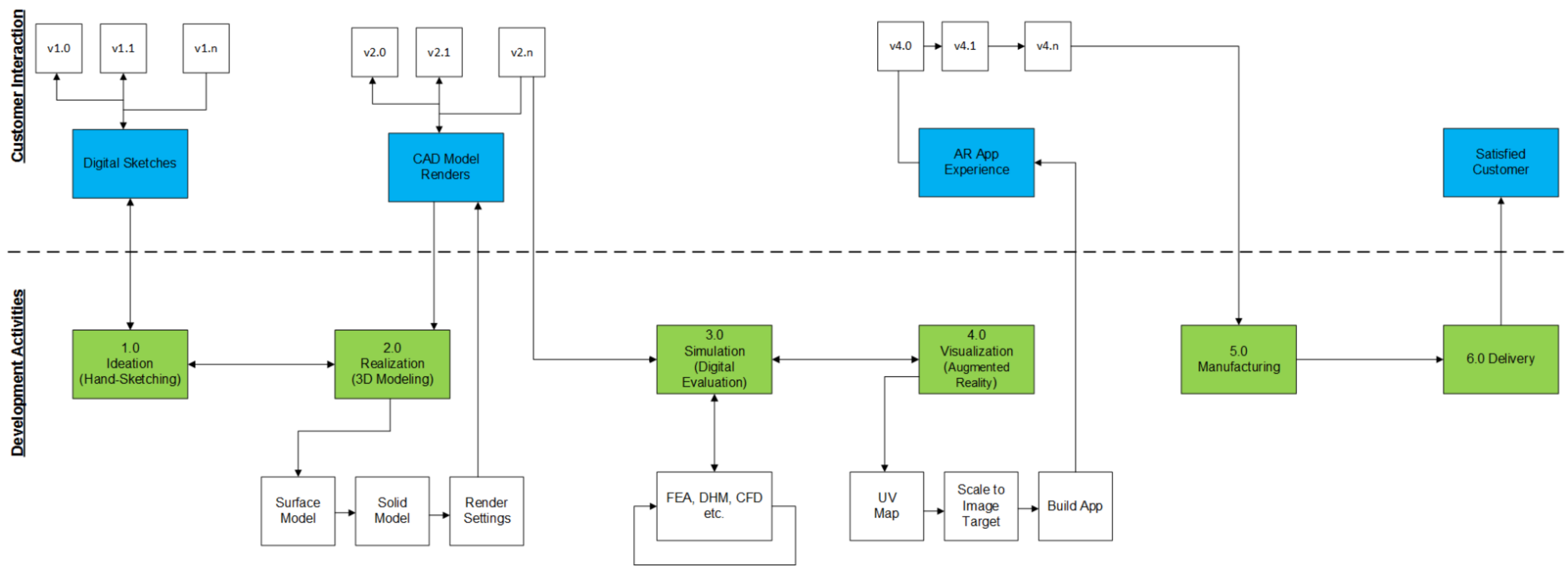


Figure 4: The above is a box diagram illustrating the proposed design process. Above the dotted line are customer interactions with the design of the product, below the line are internal development activities.

Before discussing each stage in detail is important to note that each of the stages in the proposed methodology would be able to be controlled over a single universal application. Either in the form of a mobile/tablet or web "app" the software program would help to contain the design process and ensure reliable, consistent collaboration that is straight forward and allows for customers of varying technological competencies to participate.

The proposed methodology starts with the Ideation stage. Ideation begins when a customer first goes to make a product inquiry from the company. The customer begins by describing their desired product and or needs over a phone/video call, or face-to-face at company offices. User needs and preferences are gathered through the standard customer requirement gathering techniques discussed in the previous section. The user's needs and preferences are then expressed in the form of a mood board. A mood board is a method that helps designers to express the style they are trying to evoke with the product. After the primary collection of information has occurred, the design team works to perform hand-sketches. These digital sketches are sent to the consumer via a PDF and opened in a PDF viewer (e.g. Apple Preview, Adobe Acrobat) that allows the user to mark them up with digital stylus, mouse, or keyboard. At this point, the user can point out the aspects such as shape, color, material and more. The digital mark-up provides immediate and instant feedback to the design team and allows for effective early stage communication. Upon receiving the marked-up copy, the design team will work to address the feedback and make changes. A similar iterative loop is something that is implemented in all stages throughout the proposed methodology and is what will help to ensure good product-market fit. After the customer is happy with the end sketch, the process will move forward into digital modeling.

The next stage in the proposed methodology is Realization. In this stage, 3D modeling begins by importing the digital sketches (coming from Ideation) into surface modeling software to be used as references for the shape and dimensions. This direct sketch-to-model integration allows for a reduction of rework because changes to either the model or sketches will carry through. The ability to easily tweak and make changes at low cost is one of the driving factors behind the widespread adoption of CAD [36]. With the introduction of surface modeling within CAD platforms (e.g., Autodesk Fusion 360), now digital sketches can be constructed in the form of simple digital sculpts or surfaces through using universal point and line manipulation techniques such as NURBS and S-splines. Through using digital sculpting and surface modeling, designers can quickly generate a low-fidelity representation of the desired custom product concept and attach material, texture, and color according to customer preferences. This process is called rendering, which transforms wire-frame or parametric models into photo-realistic images. Rendering allows users to effectively visualize the final product without manufacturing which results in saved time and money. A photorealistic rendering of the product is generated using a rendering engine which injects realistic texture, lighting, and shading and generates a raster graphics image or digital render. After the rendering is completed, a batch of final photorealistic renderings including varying material, texture, and color options with different texture, lighting, and shading that reflects the customer's intended use conditions (e.g., outdoors versus indoors) is shared with the customer via mark-up software to capture additional feedback on the digital sketches. At this stage, users can intuitively navigate in 3D space and visualize how the product looks like and write notes and callouts. Users are then sent back the annotated documents back to the designer, and the additional customer preferences and needs are integrated into the digital product model. This step provides another crucial customer touchpoint early in the product's design. This cycle proceeds until both parties are happy with the end result. While the Realization process might be slower than the traditional product design methodology, it is faster than bespoke design and ensures that all customer needs are met [37].

After the 3D modeling has been completed, the product moves out of the customer's eyes as internal simulations are performed to ensure that there are no functional issues arise with the product specifications that have been developed thus far. During this stage FEA, DHM, CFD, and more are performed to deliver insights to the engineers and designers. For these studies to be conducted, it is important to know what the product's extreme use-case scenarios are: this can be determined based on user weight, height, and planned intent for the product. With each of these in mind, the engineer can create scenarios that inform the functionality and failure modes of the designed product. During this stage, DHM is a valuable tool as it can provide you with accurate measurements of all parts of the body. The versatility of DHM to create accurate customer models based off of limited inputs allows for faster design and validation times. This combination of synthesizing intricate technical details into simulations to determine the functional behavior and performance of products, allows customer requirements to be converted into engineering requirements. As a result of the simulation findings, structural reinforcements, material changes, and additional computational performance tests can be conducted to refine and develop the product.

Next, the product moves forward into the penultimate customer-to-product interaction, augmented reality try-on. This is a unique and exciting opportunity that has arisen with the rapid growth in the augmented reality space. With the vast majority of mobile communication devices, such as smart phones and tablets manufactured in the last 5 to 10 years having access to platforms such as ARCore (Android) or ARKit (Apple), AR is now user-friendly for most users to visualize conceptual ideas in the physical space surrounding them [38]. From a user-try-out standpoint this is invaluable because it allows them to see size, scale, and materials in "real-world" setting. For example, within fashion design and the interior décor industries, the user can try on various clothing to see how it matches or place an item in a room to see if it will fit. As tracking technology continues to develop, market analysts predict that such applications will be an increasingly common part of the shopping experience for many customer goods [39–42]. By including this stage as part of the product development process, customers can "demo" the product, make suggestions and have their additional needs and preferences are integrated into the final product design before it undergoes manufacturing.

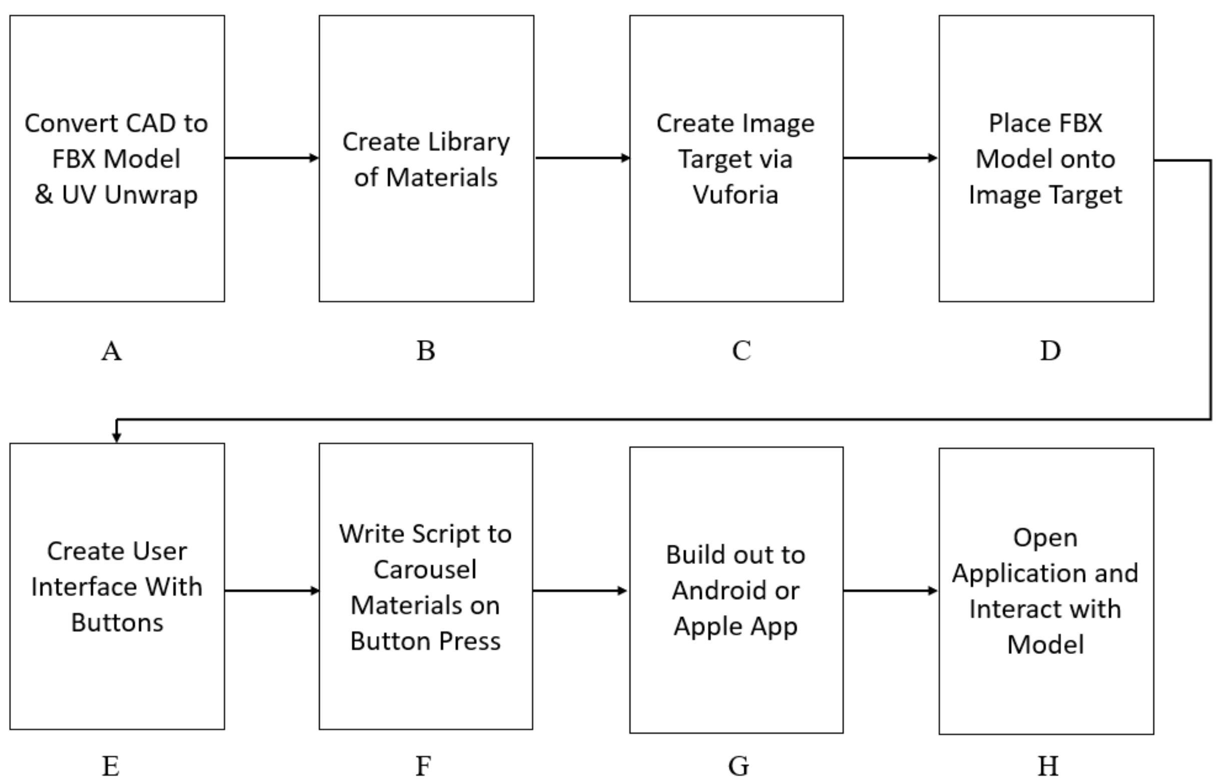


Figure 5: In order to visualize the 3D Model in Augmented Reality it is necessary to convert and manipulate the file in many ways. The above is an example of the workflow from CAD model to AR Application.

The next process that the customer doesn't see is the Manufacturing step. This process is beyond the scope of this research project since the proposed methodology described in this thesis is focusing on early design stages of the product development. In this step, traditional or additive manufacturing techniques such as 3D-printing can be utilized to convert 3D designs into products. The product will be manufactured according to the necessary requirements of material and function. Depending on the complexity of the product as well as the complexity of the user-product interactions, a human-subject trial or data collection with the actual user might still be needed before proceeding to Manufacturing. Even in cases where user trials or human-subject data collection are needed, the proposed methodology in this research captures the user needs and preferences and help to eliminate poor design decisions or resource commitments in the conceptualization process.

The final stage is customer Delivery. At this stage the product is shipped to the consumer and the product development process is complete. Throughout out the steps depicted in Figure 4, the product has been co-created alongside the customers with their input being considered wherever it impacts the user. Technical details have been effectively communicated when necessary; however, one can see that for the most part the customer is engaged only when it comes to aesthetics and high-level interactions with the product. In the proposed methodology, customers don't have direct input on the intricate technical details (e.g., electro-mechanical components) or system architecture. However, customers drive the design process by directing the designers/engineers on specific aesthetics and interaction related product attributes, which eventually builds personalization into the product. Because the customer's vested role in the creation of the product starts early in the design, unique customer needs and preferences are captured more systematically when compared to conventional product development strategies. In addition, the customer input is collected via a two-way feedback mechanism throughout the design process, it's likely that Digital Co-Creation will lead to personalized products and bridge the user-designer void found in mass-customization models.

5. Case Study

In order to evaluate the feasibility of the proposed framework a case study was performed. The case study aimed to explore the intricacies of the methodology through the design and digital evaluation of a lower-limb prosthetic casing. The prosthetic was selected as an area of focus because of the current pressing needs in personalization of biomedical products. Also, the medical product domain proposes a niche market to focus on creating individualized products tailored for specific users. In this study, the role of the prosthetic casing is defined as the exterior packaging unit or the frame that covers the internal electro-mechanical components. The prosthetic casing drives the function of the prosthetic lower limb assembly while also making the device more aesthetically pleasing and usable (fit for environmental conditions and provides protection from external forces) in alignment with the individual needs of the owner (marathon runner versus avid motorcyclist). Due to their everyday integration in the user's life, prosthetics possess an intimate relationship with the customer. This means that the user has clear, specific desires and needs from the product. These customer requirements help to drive the design partnership throughout the Digital Co-Creation process.

For the purpose of our case study, we will have two customers. The first of the two customers is Connor Goldberg, a 32-year-old American male living and working in Silicon Valley, California. He lost his lower right limb while serving in Afghanistan for the United States Army. Today, he works as a software engineer for a major technology company and is future-focused in his approach to life and product purchases. At approximately 6'2" Connor represents a 95th percentile male. Despite his disability, he is very active and enjoys his daily commute to work on his motorcycle. The second customer is Rio Nakamura, a 60-year-old woman from Japan, Rio is a professor of Forestry Management at the University of Tokyo. Her main physical activity consists of hiking and standing during lecture. She represents a 50th percentile Japanese female and stands approximately 5' 2".

	Connor Goldberg	Rio Nakamura
Height	6' 2"	5'2"
Age	32	60
Weight	213 lbs.	112 lbs.
Hometown	San Jose, California, USA	Tokyo, Japan
Profession	Software Engineer	Wood Science Professor
Physical Activities	Riding Motorcycle, Sailing	Hiking

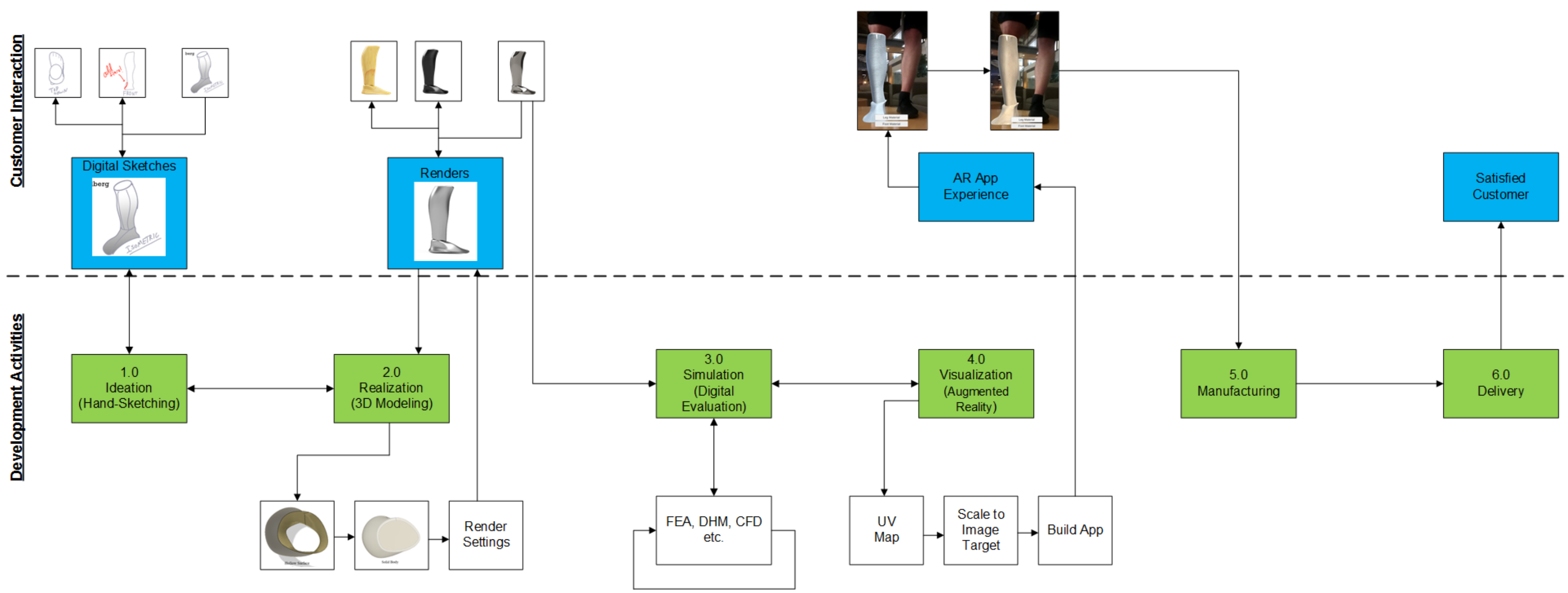


Figure 6: The above is a box diagram illustrating the case study as previously shown in Figure 4. Each of the images represents the activity that took place at that given time in the product development process.

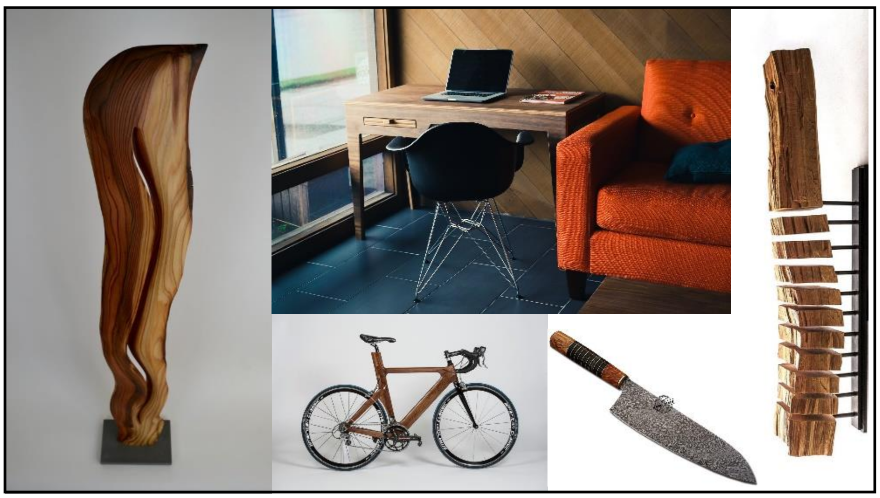
5.1 Ideation

This study starts first with customers selecting base electro-mechanical component architectures that is suitable for their needs. This stage is very similar to what is currently available in current mass-customization interfaces where customers select the desired components from a list of product variants or configurations. For example, an active runner may choose a dynamic electro-mechanical configuration with varying tuned-mass dampers and shock-absorbing mechanisms; whereas, a customer only needs a prosthetic limb for minimum mobility can proceed with static architecture without any special shock absorbing system. In either case, only product variants coming from off-the-shelf model configurations are provided to customers.

Figure 7: Electro-mechanical components that prosthetic casing will cover.

During the initial conversation, with Connor it was clear that he wanted his prosthetic casing to be metal, smooth, and minimalistic. The quote that he used during the initial video call was “let’s focus on maintaining a futuristic feel while preserving the traditional human form”. A challenge in this specific step of the design stage is that customer requirements are often vague or hard to convert into engineering requirements. Thus, designers use interviews, surveys, or video conferences to understand what customer needs and preferences. An example of this in practice was the designers work on a mood board of thematic images that were gathered from the Goldberg’s video call. The images clearly convey the notion of “maintaining a futuristic feel” and can be seen in the top mood board in Figure 8 below. In contrast to Goldberg, Nakamura wanted a dark finished wood aesthetic on her prosthetic and the images on her mood board reflected that.

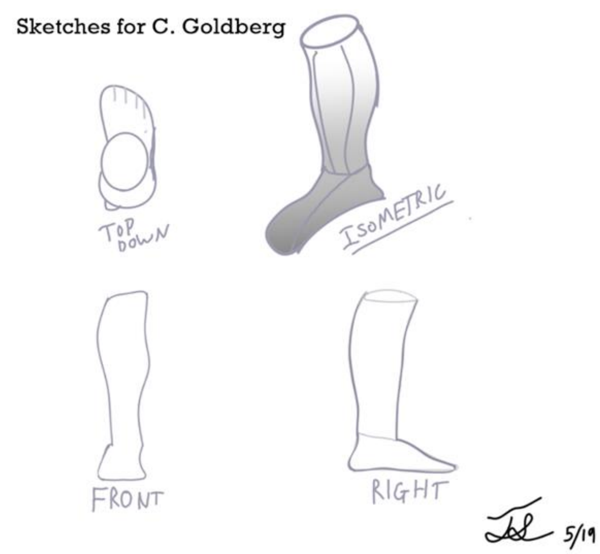
Connor Goldberg Mood Board



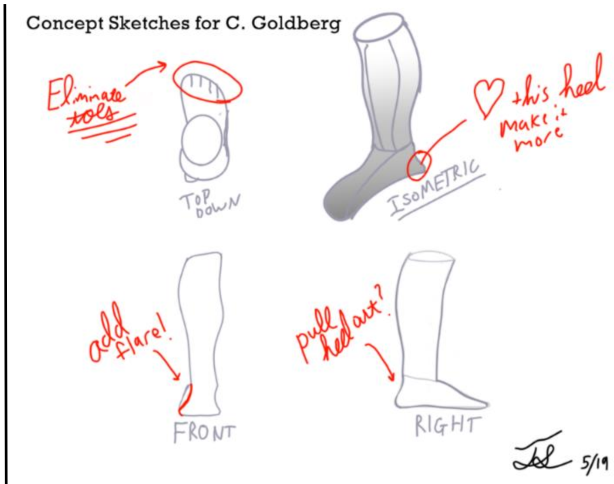
Rio Nakamura Mood Board

Figure 8: A mood board was constructed for each customer to identify their design ethos. This tool helps the designer and the customer to align their ideas and goals in an exploratory way. While Connor leaned toward metal, futuristic aesthetics, Rio opted for vibes of dark, contemporary wood.

After the two different customers agreed on "maintaining a futuristic feel" and "capturing the natural beauty of wood", the next step from the mood boards was to create initial sketches that could be sent to each customer for their review. The goal at this stage was to provide some rough or preliminary design ideas and let the customer refine them according to his/her needs. For example, sketches in Figures 9 and 10 include designers rough ideation and customers' feedback (annotations). These sketches were created using Autodesk Sketchbook and shared with the customer as PDF document. The advantages of this using a digital sketching software is that the interface allows designers to draw on multiple layers and use sdigital sketching tools such as predictive stroke to smooth your lines or create parametric point or line-cloud which enable rapid changes of the sketches.

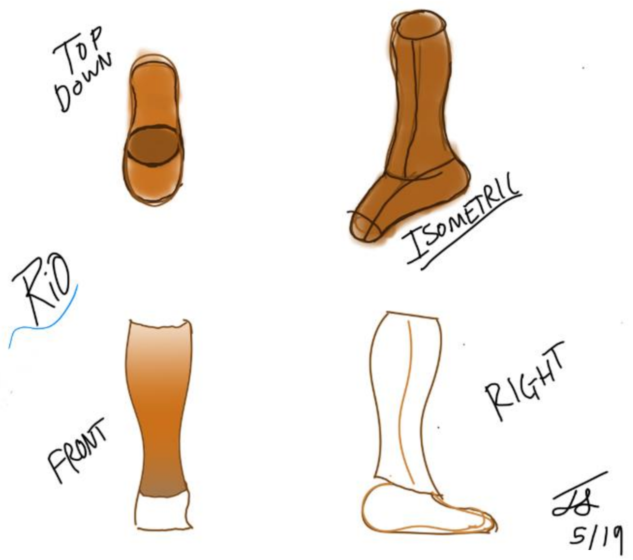


a) Sketches Sent to Connor

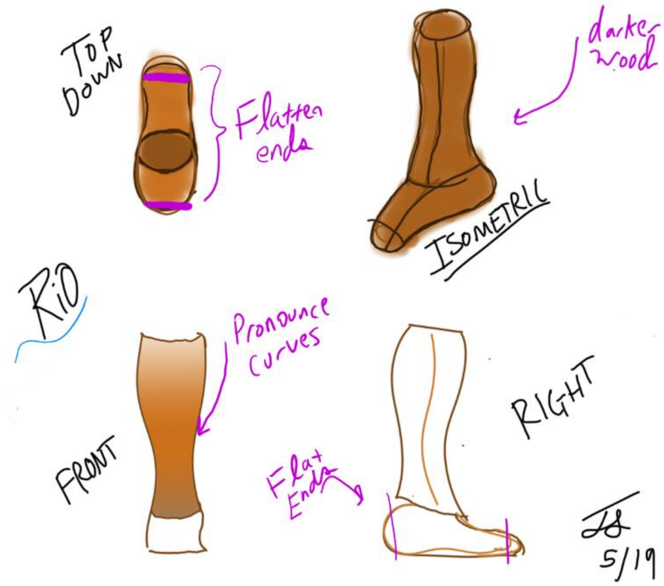


b) Feedback Received from Connor

Figure 9: The above figure is a representation of the digital sketches sent to Connor Goldberg during the Ideation stage of Digital Co-Creation. With the annotation, the customer puts emphases on eliminating toes and flaring out the mid-foot and heel to create a more artistic and futuristic feel.



c) Sketches Sent to Rio



b) Feedback Received from Rio

Figure 10: The above figure shows the communication through sketches that occurred with Rio during the Ideation stage.

These requests for change can be made directly on top of the sketches and can go back and forth for however many cycles are necessary until the user is satisfied. After the two parties have agreed to move forward with the design the sketches are exported by the designer to a CAD modeling software.

5.2 Realization

The next major step in the proposed methodology is CAD modeling. In this case study, Autodesk Fusion 360 software was used for 2D surface modeling and 3D parametric modeling. Fusion 360 brings the ability of turning surface models into solid bodies as well as generating photo-realistic rending and structural analysis. Most major software packages have surface modeling capabilities and could be used in place of Fusion if the design team desired.

Figure 11: Above shows a high-level overview of designing Connor Goldberg's prosthetic casing in CAD. Each of the steps are described in detail below.

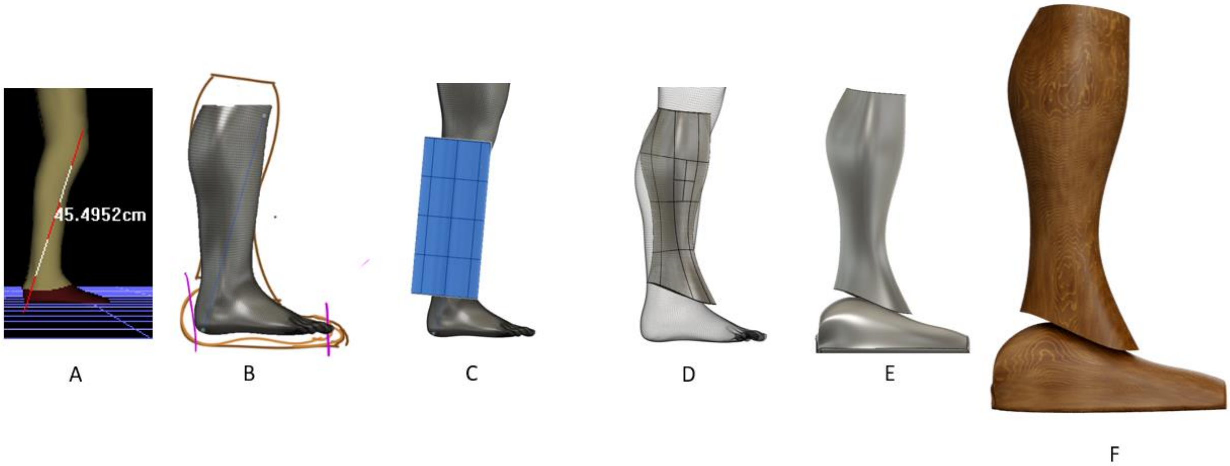


Figure 12: Above shows a high-level overview of designing Rio Nakamura's prosthetic casing in CAD.

The first step in this stage (step A in Figures 11 and 12) was measuring a model of a human leg retrieved from a Digital Human Modeling software which captured the individual anthropometric attributes of the customer. The leg model was generated based on the customer's geographic information, height, and weight data. In this case, Siemens JACK was used to generate a manikin model based on Connor's anthropometric attributes - 95% U.S. male by height and an average weight for his given height through the ANSUR anthropometric database (see Figure 13). For Rio, the Japanese database was used, and her anthropometry was set to 50% for both height and weight. These measurements could be also accomplished in other ways including scanning existing prosthetic for dimensions or taking a stock mesh from a database. For example, a mesh model from an online 3D modeling library (Grabcad.com) was the way that this specific CAD model was created. This model was scaled to Rio's height as known from prior measurements. In both customer cases, the mesh allowed for the prosthetic casing model to have a reference geometry that proved helpful in preserving some symmetry of the human leg and delivering the preservation of form that was established in the ideation stage of the project (Connor's input of "preserving the traditional human form").

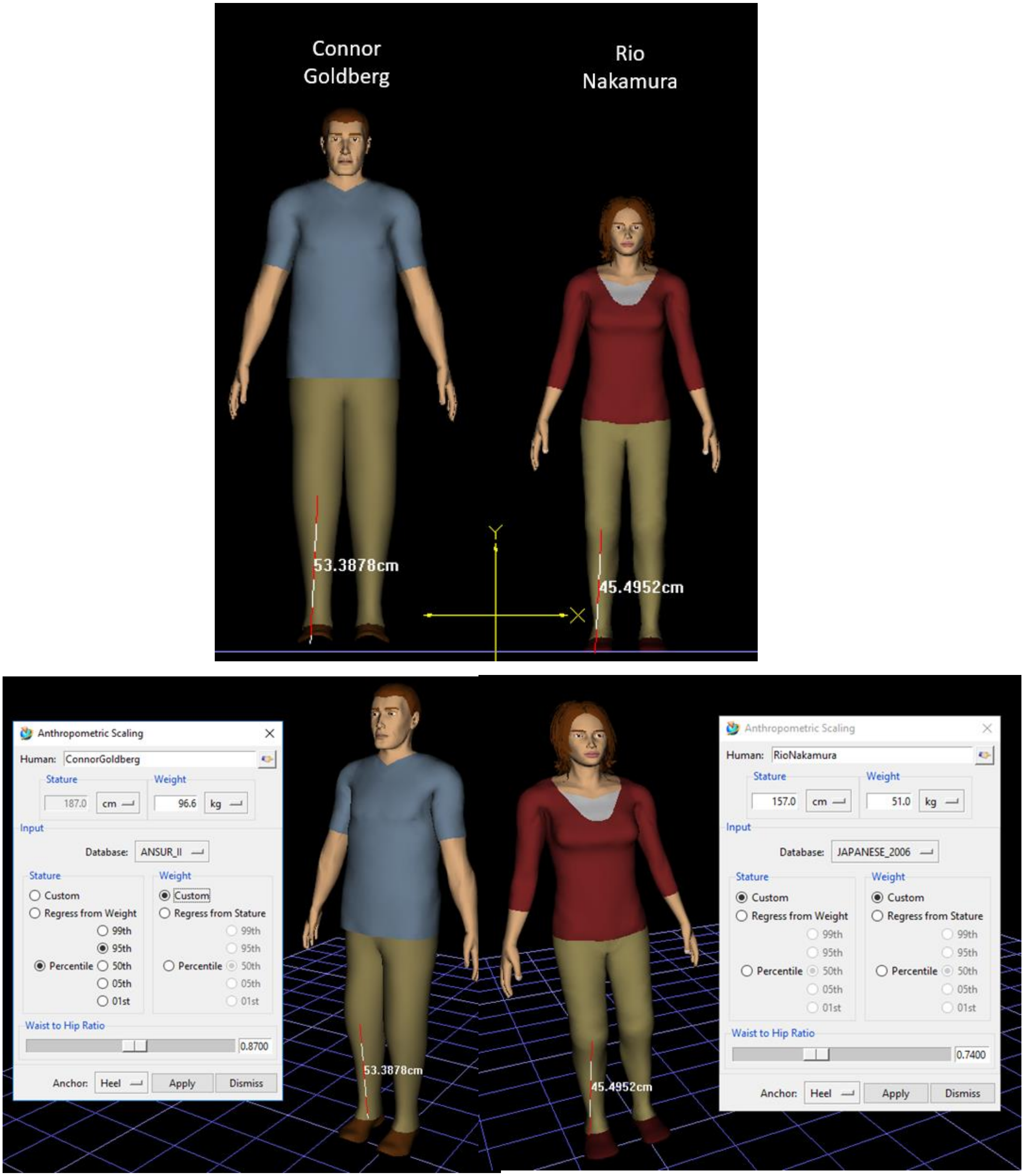


Figure 13: Digital Human Models of Rio and Connor were created using Siemens Jack. This yielded Anthropometric measurements that allowed for the proper scaling of the prosthetics.

Next, (Step B) the initial surfaces were created taking the mesh model as a reference. These surfaces were modeled by using digital sculpting command (e.g., push, pull, rotate) shown in Step C of Figures 11 and 14. For example, point clouds over the mesh were pulled tight on top of the mesh in desired areas. At this stage the prosthetic design was separated into two separate models, a foot and a lower-limb casing. This was necessary to ensure that there was capability for flexion in the ankle region of the prosthetic. When transforming the digital sculpture, the digital sketches imported during Step A were used as references for determining shape as shown in Step B of Figure 11.

Figure 14: Above is a series of screenshots that show the shaping process that takes place during surface modeling. This series is from the prosthetic casing for Connor, but a similar approach was taken when designing the casing for Rio.

The next stage of modeling (Step C) is shaping the surface model to match the desired shape. In order to do this each of the regions of the surface can be broken down into smaller grid meshes which can be individually transformed to alter the shape of the surface. After the surface matches the desired shape, it is patched on either end (with patch function) and converted into two solid bodies. This foot and leg models can then be used for the remaining steps in the design process. The solid bodies can finally be shelled to a desired thickness to achieve a lightweight and functional casing geometry.

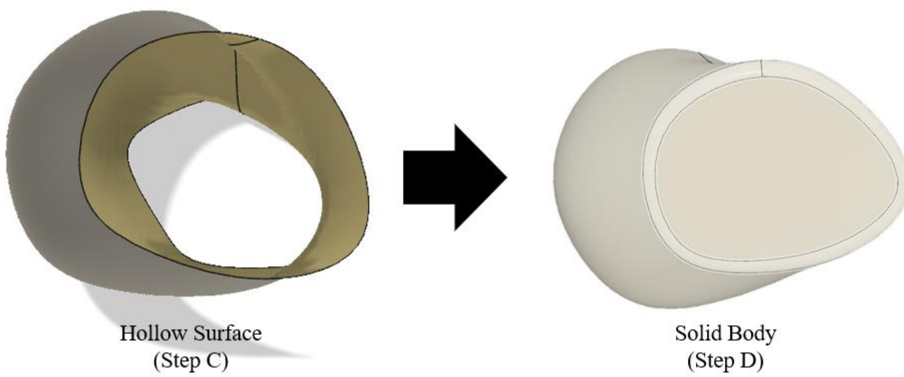


Figure 15: The image above shows the patching and stitching of a surface to solid body model. This is a necessary step in order to achieve a complete CAD model that is capable of being manufactured.

After the solid model was completed it was prepared for photo-realistic rendering by including a specific material, color, lighting, and environment attributes (Step E). For Connor, the initial material was stainless steel and for Rio, a stained maple was used. The rendering packages within modern CAD modeling platforms allows designers to quickly use edit materials, colors, and any other visual attribute to provide the customer with close-to-reality static image captures of the product which mirrors what the final product may look like. In addition to static images, renderings can also be captured as videos.

Figure 16: A variety of renders to show the capability of changing depth of field, texture, material, lighting and more within rendering package. These completed renders would be sent to customer for review.

After the photo-realistic renderings were completed, the designer sent the rendering outputs to the customers which helped to visualize the changes being made in the modeling due to different material options. The high-fidelity renders work best in 2D and can be sent as an image filed or embedded into a PDF for capturing further user feedback. The solid model can also be sent as an obj file which is widely accessible, especially with the inclusion of standard 3DViewers in modern operating systems [43]. Client feedback was quickly taken into consideration during the modeling process, suggestions were integrated into the current 3D model.

5.3 Simulation

The next stage of the design process was to simulate and validate the two designs. During this stage, the customer was not directly involved with the simulation activities; however, the needs and preferences collected in the previous stage (Realization) were integrated into the functional simulation model. The main objective of the simulation stage is to determine and ensure that the design is feasible and functional with the customer’s given design parameters.

Negative attributes of the current design were found during these simulation studies and corrective measures (updates on the design parameters) were made, and simulations were reperformed. In this study, FEA and DHM were performed. However, depending on the use case and product being designed, other multi-physical simulations must be conducted if necessary. Using the combined information of FEA and DHM, a maximum load study on the prosthetic casing was executed to measure the effects of different material scenarios. It is important to set up the loading in the proper orientation and create constraints for certain faces of the leg in place, so the results are meaningful. In Fusion 360, the FEA toolbox can also be used to measure the static stresses, buckling, modal analysis, and other varying types of information that could be helpful in determining viability of a given design.

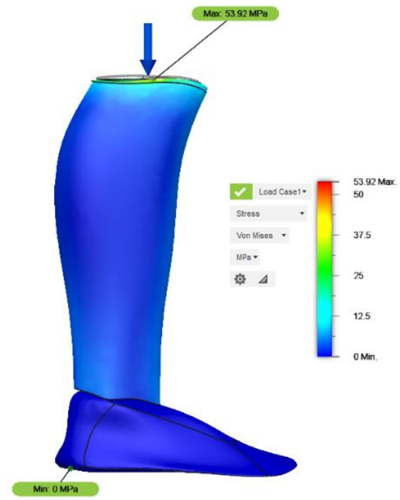


Figure 17: FEA is performed on the design with Stainless Steel as the material. Von Mises stress shown in the figure above.

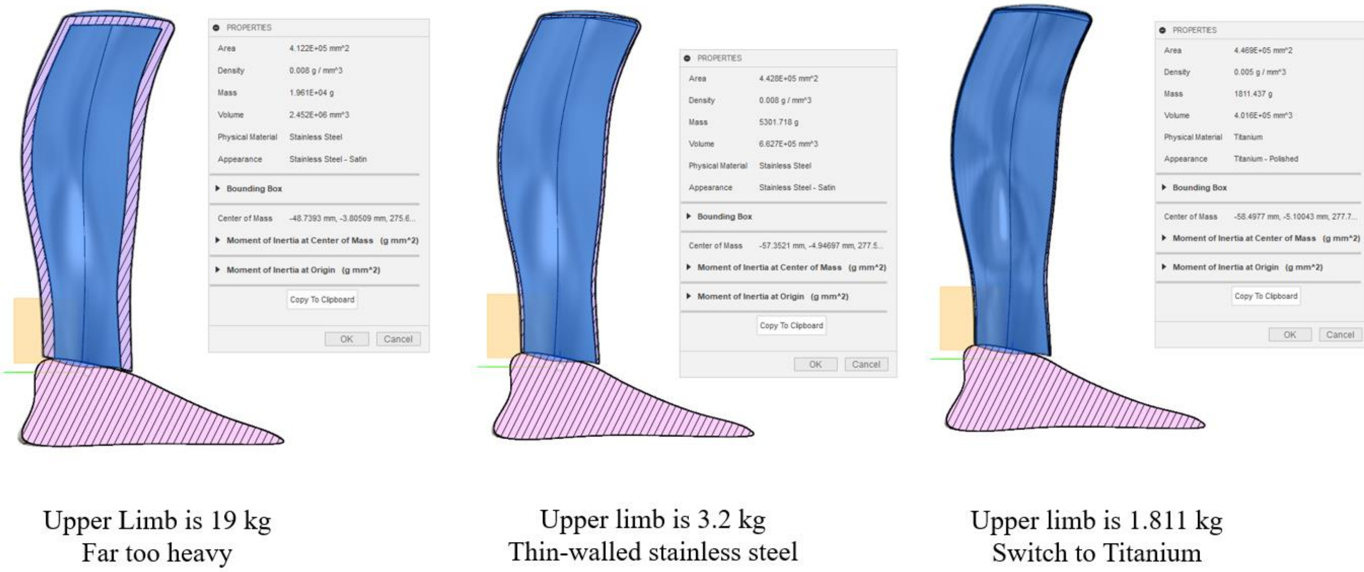


Figure 18: Another valuable tool that was accessible during simulation was a mass analysis in Fusion 360. By assigning varying thicknesses and materials an optimal form factor was determined.

In addition to FEA, the design was run through several material properties studies which quickly yielded results about the center of mass, the estimated overall weight, and the moment of inertia the leg possesses. These valuable insights were taken into consideration and the thickness was changed. Even after changing the wall thickness, the leg was still heavy, so a material swap from stainless steel to titanium was proposed to Connor. This decision to bring the customer in-the-loop is a great example of how this methodology helps to tune products specifically for the end-user and their needs. The titanium came at a premium price that was 3-times higher for raw material than that of stainless steel, but the weight savings was necessary, and Connor agreed to make the swap.

5.4 Visualization

The final and critical design stage in terms of user feedback is the AR Experience. With the AR model the customer was able see how the prosthetic looked in person. An AR interface was designed to show how different CAD product designs and variations look like when they're blended with the real environment. For example, using the AR interface, customers first imported the 3D prosthetics leg implant. Then, with help of the live tracking capabilities, the customer was able to spin the tracking image and in real-time can see the leg rotate in front of them. Through the touch of a button they were able to change the color and material of the prosthetic leg implant, and with varying the image targets they were able to see alternate versions of the casing. This visualization interface was made possible through the connection of multiple application programming interfaces (API) and file conversion methods, explained in detail below.

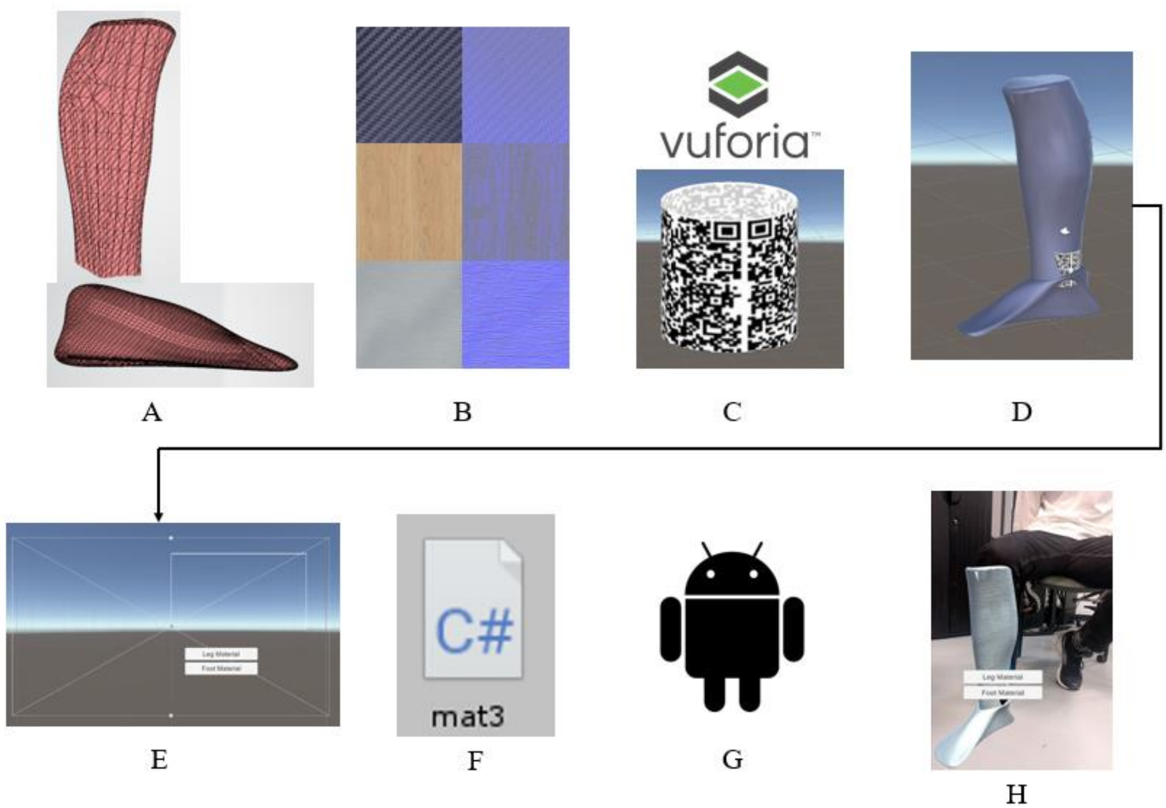


Figure 19: The above is a block diagram that shows the progression of CAD Model to AR app visualization.

The first process (Step A) that had to be completed was exporting the CAD file as an STL and converting file types to a Unity compatible model. For this, I used Autodesk Maya, an animation and graphics software. The file type was converted to a FBX file type and a basic cylindrical UV Map was applied. This UV Map will enable the material graphics to render in the final steps.

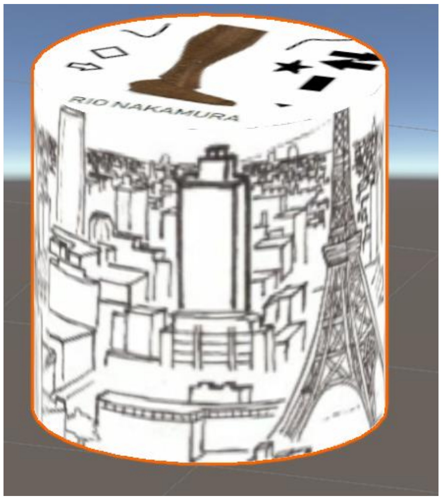


Figure 20: A cylindrical image target of Rio's image target shown in Unity screenshot. The target was created through Vuforia and was used to locate the prosthetic in the AR experience.

Next, a material library was created using seamless textured images from the internet (Step B). These images were put through a normal map generator which returned a map that the computer can process to create a 3D dimensional texture of the specific object. Several types of wood, brushed steel, polished titanium, carbon fiber and more were created to give customers the ability to make changes to the material if they were unhappy with their previous selection.

In order for the leg to be displayed in AR, it was necessary to have an image tracking and projection-based software package (Step C). In this project, Vuforia, which is capable of tracking and projecting onto a variety of shapes and sizes of image target was used as a software platform. An image target was created which the camera used the reference to determine where the model projection was going to be placed. To create an image target, the Vuforia development portal takes an uploaded image and processes it into a version that its camera will identify. When selecting an image, it is important for it to have a large amount of detail and contrast. This helps Vuforia's built-in image processing software to quickly and effectively recognize the target in a variety of environments. I chose to utilize a QR Code wrapped around a cylinder. The cylindrical image target is the ideal shape for this application due to the necessity of seeing the prosthetic casing from all angles.

For graphics and interaction with the on-screen leg it is necessary to have a mobile application programming platform (Step D). For this, I chose to use Unity, a well-known game development platform. Unity and Vuforia are well-integrated and while the combination is traditionally used to make AR-based video games the setup is sufficient for AR prosthetic limb try-on. After placing the cylindrical image target into the Unity environment, it is necessary to align the CAD model of the prosthetic with the image target. Note that in order to place a CAD model into Unity it must be saved as an OBJ file. Placement of the model is crucial to the success of the experience as this will be the location of the prosthetic in relation to the target in the final application.

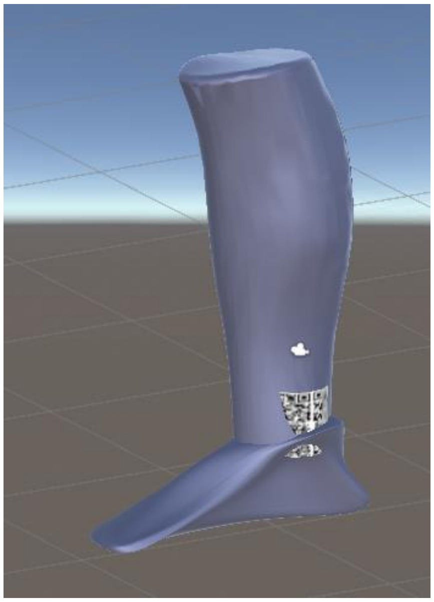


Figure 21: Connor Goldberg's modeled prosthetic is next placed on top of the cylindrical image target. This placement determines location in AR environment.

After placing the model into the environment, it is time to begin the process of creating a user interface (UI) for the consumer to interact with the files (Step E). To do this, a second camera element is created in Unity that will be a blank placeholder, but due to the Vuforia's use of an "ARCamera" it is necessary. By utilizing this second camera, the standard UI features that are built into Unity become available. With UI capability now enabled it is necessary to add two buttons: one to swap the material of the leg, and the other for the material of the foot. These are added as UI elements and their respective size, shape, color and features can be swapped in Unity at the programmer's discretion.

By assigning the onClick action to call a C# script (included in the appendix), the material can be "hard-coded" to change when a user presses the button (Step F). For simplicity's sake I chose to implement a carousel of materials. This allows the programmer to preset a stack of any number of Unity materials in the associated Game Object. As the user clicks through each of the materials the index will go up and reference the material in said Game Object.

In order for this to be accessible to the consumer, it is necessary to build the app out and export it from the Unity platform (Step G). This can be done via Unity's included Build feature. Android was selected as the desired platform and several minutes later an APK file was installable and ready for any consumer to install on their compatible Android device. If implemented at scale this would be as simple as any other mobile application download/update.

The final step is to open the application and point it at the cylindrical image target to view the prosthetic limb in the world around you (STEP H). At this point, Connor and Rio have the capability to naturally interact with the limb through the screen. For Connor, this is a great opportunity for him to experiment with seeing different titanium finishes that could be applied to the limb. Additionally, if he determines that Titanium is not aesthetically pleasing he has the capability to examine and explore different materials in an augmented reality setting. For Rio, she can not only analyze the look of different types of woods, she can also look into different stains and finishes and how they would impact the aesthetic.

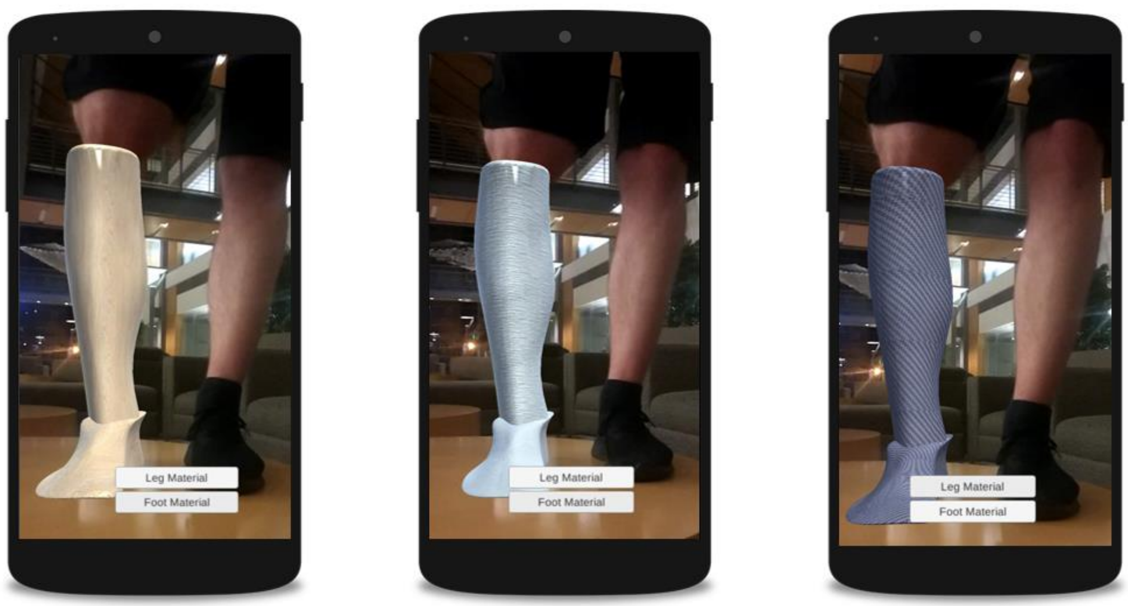


Figure 22: The above is a series of screen captures taken in the mobile application showing try-on of Connor's prosthetic casing aside my other leg. It fits well as we are similar anthropometries

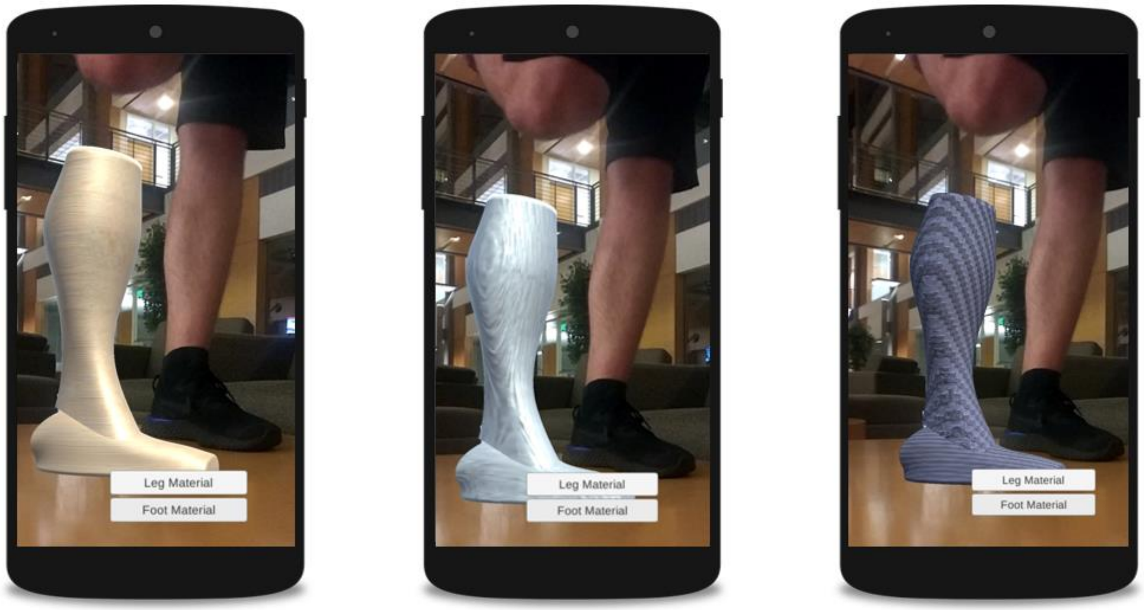


Figure 23: Here, the same materials and human is shown, but with the limb designed for Rio. Note that it is significantly too small for me as it was designed to match a 50th percentile Japanese woman.

6. Discussions and Conclusions

The Digital Co-Creation design framework discussed in this thesis synthesized computational design research (e.g., digital human modeling) and emerging technologies (e.g., augmented reality) to capture the voice of customer early in the design towards representing customer needs and preferences within a continuous feedback cycle. The notion of product personalization via co-creation was demonstrated as an alternative method to alleviate the challenges associated with the mass-customization. The case studies provided in Section X demonstrated how the Digital Co-Creation framework functions, including data flow from sketching to visualization through augmented reality. Through two conceptual case studies, I demonstrated how unique products can be created for multiple customers with contrasting needs and preferences. Although the case studies discussed in this thesis explored the design process and illustrated the potential benefit of Digital Co-Creation, this thesis only provided a proof-of-concept to the design methodology. The aim in this thesis was to provide an evidence of concept to designers who are interested in alternative methodologies to inject customer needs and preferences early in the design process.

As technology continues to drive economic commoditization, the proposed methodology could potentially serve as a major value-added service in a variety of industries. With the increasing accessibility of digital visualization tools (such as digital sketching, CAD, and AR), there are fewer barriers to long-distance communication between customer and designer. This thesis shows that there is room for the future of product design to become personalized (customizable, individualized, and interactive), and by doing so, companies can create additional value through the design process.

Throughout this thesis work, I was able to explore the various challenges and potential benefits of the methodology. For example, one of the potential positives came in the form of being able to quickly make changes to the digital sketching and CAD models, which reduced resource allocation (time and money) associated with traditional physical prototyping. Another significant positive of the design process was being able to visualize the prosthetic limb casing design within the actual use conditions. The integrated use of CAD models and AR technology through a smartphone interface generated new product evaluation capabilities such as visualizing, interacting, and navigating via digital models. I was able to demonstrate a proof-of-concept study, with an augmented prosthetic casing and examine it with different clothes, colors, and environments. This proved to be a major step up from the digital world of the CAD modeling ecosystem. I believe that in the hands of an archetypical customer this technology would have even larger implications.

Of special difficulty was the integration from CAD to AR. This process was much more arduous than I anticipated and involved numerous file conversions, Unity set-up, coding in a new programming language and more. As it currently stands there would be no way that this could be utilized at scale. In order for the proposed methodology to function well, it would be necessary to create a plug-in that can carry a single CAD model through the process. Another difficulty associated with this methodology is the delay in waiting to get feedback before advancing to the next design activity in the process. This fluctuation in works loads would be alleviated if the design company was working on many simultaneous products.

Limitations of the work include that there was no human data subject collection performed. Potential human subject data collection could include testing this specific case study with lower-limb amputees or examining a different product that was co-designed through the same process. This lack of human data leaves room for improvements that could be addressed in future work. Other future work could include a build-out of a mobile application that would allow a designer to virtually communicate and collaborate with the client. Another adjacent area that could be explored is how this might interface with artificial intelligence and the generative design of products.

Another interesting limitation of the work that is not addressable is how the customer's input will have a significant impact on the output of the end design. This is interesting because all users who participate in the process have direct shaping power over the end product, but some users may bring with them specific skill sets or abilities that will make the design process easier or more difficult to perform. In line with this a final challenge that arises with the proposed methodology is that of containing the user and the scope creep that could come with incorporating non-technical users into especially technical products or manufacturing processes.

Appendix:

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

//Code originally taken from ZakAlberda.WordPress.com

public class mat3 : MonoBehaviour
{

  public Material[] materials;//Allows input of material colors in a set size of array;
  public Renderer rend; //What are we rendering? Input object(Sphere,Cylinder,...) to render.


  private int index = 1;//Initialize at 1, otherwise you have to press the ball twice to change colors at first.

  public void buttonPressed()
  {
    if (materials.Length == 0)//If there are no materials nothing happens.
      return;

    index += 1;//When button is pressed down we increment up to the next index location

    if (index == materials.Length + 1)//When it reaches the end of the materials it starts over.
      index = 1;

    print(index);//used for debugging

    rend.sharedMaterial = materials[index - 1]; //This sets the material color values inside the index
  }
        }
```

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