ABSTRACT

JUNG, UIKYUNG. Exploring the Use of 3D Apparel Visualization Software through a Wildland Firefighting Protective Clothing Company's Design and Development Process. (Under the direction of Dr. Anne Porterfield and Dr. Cassandra Kwon).

Despite the rise of digital design practices, there continues to be a dearth of scholarly information and empirical research regarding the utilization of 3D apparel visualization software from the manufacturer's standpoint. While digital tools have the potential to enhance wearability and economic feasibility, the incorporation of new technologies in the development of firefighting gear has received insufficient attention in research. Therefore, this study aimed to explore the integration of 3D apparel visualization software into an industrial product design and development process, focusing on the manufacturer's perspective for wildland firefighting protective clothing. The research employed qualitative methods and consisted of two phases: action research with a wildland firefighting gear company and in-depth interviews with five additional firefighting gear companies.

The first phase, action research, examined the opportunities for integrating the software into the design and development process of a specific wildland firefighting protective clothing company. Over an eleven-month period, the primary investigator conducted six collaborative interviews with two representatives of the Company A, assuming the role of an instructor to demonstrate the software's capabilities and facilitate participants' understanding of its potential integration. The second phase involved in-depth interviews with ten experts in product development or technical design positions from five firefighting gear companies.

The results of this research offer valuable insights into the multifaceted perceptions and experiences of firefighting gear manufacturing companies in using 3D apparel visualization software. The findings consider not only the technological capabilities of the software but also

specific considerations related to firefighting gear, technology users, organizations, and the business environment. Moreover, the suggestions regarding software usage and improvement expressed by participants indicate avenues for further examination of this technology in the context of functional clothing design and production. These insights have practical implications for software providers and developers, firefighting gear designers, manufacturers, administrators, and the fire service community, providing valuable knowledge for harnessing the potential of 3D apparel visualization software in the development of functional clothing at a company level.

Exploring the Use of 3D Apparel Visualization Software through a Wildland Firefighting Protective Clothing Company's Design and Development Process

by
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DEDICATION

This dissertation is heartfully dedicated to my parents, parents-in-law, sister-in-law, and dear brother, whose unwavering support has been a guiding light throughout my doctoral journey. A special tribute goes to my remarkable husband, Wonkyung, whose exceptional encouragement and selfless sacrifices have been instrumental in propelling me through every step of this profound endeavor.

BIOGRAPHY

Uikyung Jung was born in South Korea and earned her bachelor's degrees in Clothing and Textiles, as well as Business Administration, from Ewha Womans University. She obtained her M.S. degree in Textiles from North Carolina State University in 2019. She continued her graduate studies and attained her Ph.D. degree in Textile Technology and Management at North Carolina State University. Her research interests encompass 3D apparel simulation and virtual fitting, inclusive and adaptive clothing design, and big data analytics for anthropometric data.

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CHAPTER 1 INTRODUCTION

Industry professionals predict that digitization will be the future of apparel sourcing (Berg et al., 2017; Fashionunited, 2019). Digital product creation and 3D assets are now regarded as key vehicles to streamline the product development process and achieve a leaner supply chain (McDowell, 2021; Weinswig, 2017). Nonetheless, there is still a lack of scholarly information and empirical research describing how 3D apparel visualization software can be used to develop functional clothing from the manufacturer's perspective. By means of action research and in-depth interviews, this research will explore the potential of introducing 3D apparel visualization software into an industrial product design and development process for one category of functional apparel: wildland firefighting protective clothing.

Background

Emerging 3D Apparel Visualization Software

Within the last decade, leading brands and retailers (e.g., Target, Nike, Under Armour, VF Corporation) have started adopting 3D apparel visualization software in long-term strategic planning to scale digital product creation throughout their supply chains (Papahristou & Bilalis, 2016). Even though 3D apparel visualization software was introduced in the 1990s (Sayem et al., 2010), the fashion and apparel industry is still undergoing an exploration phase regarding this technology for common utilization (Berg et al., 2017; Choi, 2015; Vanderploeg et al., 2017). While a small number of companies have successfully utilized 3D CAD, many have indicated that there is a long way to go before the technology can be fully integrated within the industry (Jefferson et al., 2012).

Even though fashion and apparel brands and retailers are significant CAD/CAM software clients, most of the previous literature on the usage of 3D apparel visualization software has focused on understanding users' perceptions and experiences at the individual level, with research participants or subjects being mostly general consumers or students rather than industry professionals (Absher, 2020; Algharabat & Shatnawi, 2014; Baytar, 2018; Bogović et al., 2019; Hartis, 2020; Hodges et al., 2020; Kim & Forsythe, 2008; Liu et al., 2016; Park, Kim & Sohn, 2011; Prather, 2017; Shim & Lee, 2011; Sohn et al., 2020). There is a lack of scholarly research addressing a company's process of 3D software adoption. Moreover, extant studies have overlooked a functional clothing company's perspective on this topic.

Introducing 3D Apparel Visualization Software for Wildland Firefighting Protective Clothing

In line with the rise of digital design practices, academic researchers have explored potential opportunities for adopting 3D apparel visualization software to develop functional clothing (Bogović et al., 2019; Cieśla et al., 2020; Haixia & Yongrong, 2020; Hong et al., 2017; Hudson & Hwang, 2020; Jin, 2016; Kozar et al., 2014; Liu et al., 2016; Mert et al., 2018; Rudolf et al., 2015; Rudolf et al., 2017). In general, adoption of new technologies for developing firefighting gear has been underrepresented in the research even though their integration might improve wearability and economic feasibility (Park et al., 2014), and no study has employed 3D apparel visualization software for firefighting gear research at the time of writing. Therefore, the current research will explore how 3D apparel visualization software can be embedded in wildland firefighting protective clothing's product design and development process from the company's perspective.

There are two types of firefighting gear: structural turnout gear and wildland firefighting gear (Duron, 2021; True North Gear, 2022). This research focused on wildland firefighting gear because wildland firefighting personal protective clothing is made of single-layered fabric (Jeffrey & Grace, 2021) and resembles ready-to-wear apparel, which can minimize the complexity of simulating multiple layered fabric construction in 3D virtual environments (Fontana et al., 2006; Lomov et al., 2011; Mageean, 2018). Therefore, this research was conducted based on the underlying assumption that the incorporation of 3D apparel visualization software would align seamlessly with the operational procedures of a wildland firefighting protective clothing company, given the distinctive attributes of the garments. Additionally, wildland firefighting gear has been underrepresented in the research compared to structural firefighting gear from both users' and manufacturers' perspectives in the current literature. The frequency and intensity of wildland fires and the resulting extent of the damage and firefighter injuries are increasing rapidly in the United States (McQuerry, 2020; Kennedy et al., 2021; United States Environmental Protection Agency, n.d.; Wibbenmeyer & McDarris, 2021). Research on design and manufacturing wildland firefighting personal protective clothing (PPC), and equipment (PPE) is more important than ever to address any needs or make improvements in the precedent practices of product design and development process.

Research Purpose and Objectives

Based on the gaps identified, the purpose of this research was to explore the potential of introducing 3D apparel visualization software into an industrial product design and development process of wildland firefighting protective clothing for a single company. To achieve the purpose of this study, the following research objectives were established.

Research Objective 1: Identify the potential opportunities to embed 3D apparel visualization software into the product design and development process of a wildland firefighting protective clothing company (Company A).

- Sub-objective 1-1: Understand the stages and activities of the current product design and development process of a wildland firefighting protective clothing company
- Sub-objective 1-2: Investigate key features and functions of 3D apparel visualization software that can be used for the stages and activities identified in sub-objective 1-1.
- Sub-objective 1-3: Identify drivers and barriers to adopting 3D apparel visualization software in the context of the features and functions established in sub-objective 1-2.

Research Objective 2: Capture the experiences of personnel from other firefighting personal protective clothing manufacturing companies in 3D apparel visualization software adoption and use to compare with the experiences of Company A.

Research Design

To fulfill the objectives, this research was carried out using qualitative methods in two phases: 1) action research and 2) in-depth interviews with multiple companies. To facilitate the implementation of the action research method, a preliminary interview was conducted to discover participants' initial views of the subject under study, identify participants' needs, and formulate goals (Merriam & Tisdell, 2015). In the phase one action research study, the primary investigator interacted closely with Company A. This involved conducting six collaborative interview sessions wherein two company representatives participated together in each interview. Collected data from the phase one action research sessions were analyzed to establish a framework to visualize where and how 3D apparel visualization software might fit into the wildland firefighting protective clothing design and development process. In phase two, representatives from five additional firefighting gear manufacturing companies were interviewed. The results obtained during phase two served to illuminate the similarities and disparities in the perspectives held by Company A in contrast to those of other companies, leading to a deeper understanding of the factors that influence decisions around implementation of 3D apparel visualization software.

Significance of the Study

This study will shed light on managerial issues related to integrating 3D apparel visualization software for an apparel manufacturing company to streamline current workflows and improve efficiency in design verification (Hwang Shin & Lee, 2020; Lee & Park, 2017; Porterfield & Lamar, 2017). It will provide industrial practitioners, including decision-makers and end-users, with a greater understanding of considerations and influential factors for firm-wide initiatives to adopt the software throughout the current supply chain (Davidson & Heslinga, 2006; Kocher et al., 2011; Lindgren et al., 2004). A framework presenting how 3D apparel visualization software might fit into the wildland firefighting protective clothing design and development process will be developed and could be used when functional clothing companies conduct strategic planning and evaluate the possibility of adopting 3D apparel visualization software (Papahristou & Bilalis, 2016; Porterfield & Lamar, 2021). The findings will benefit firefighters, firefighting gear designers, manufacturers, the fire service community, and apparel product development professionals with valuable knowledge of utilizing 3D apparel visualization software for dedicated-use functional clothing.

CHAPTER 2 LITERATURE REVIEW

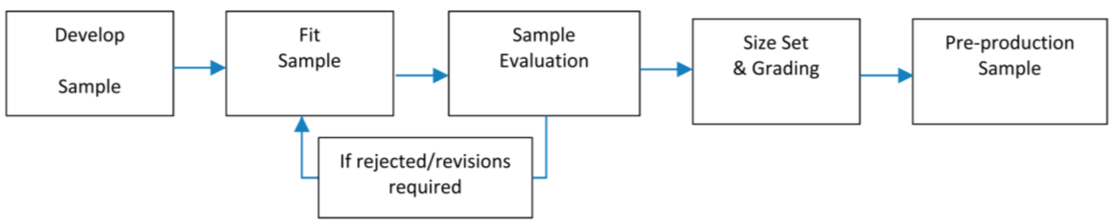
In this chapter, a review of the literature related to the purpose of the study is presented. An introduction to 3D apparel visualization software is provided, including an overview of the industrial 3D digital product creation process to offer insight into the current state of 3D apparel visualization software adoption. Next, industry professionals' experiences of adopting 3D apparel visualization software and its application for developing specific clothing functions are explored. Following that, wildland firefighting protective clothing and precedent studies on wildland firefighting protective clothing are described. Subsequently, an overview of action research design is provided. Finally, academic conceptual frameworks are elaborated upon to inform commonly employed approaches in organizing qualitative data analysis and visualization.

Three-dimensional (3D) Apparel Visualization Software

Three-dimensional (3D) apparel visualization software can be used to assemble 2D patterns into 3D garments on a virtual avatar to test and validate construction, silhouette, fit, and drape before an actual garment is manufactured (Lee & Park, 2017; Porterfield & Lamar, 2021). 3D allows users to visualize new ideas, and decide on color visualization, design details, and print placement at an early stage (Papahristou & Bilalis, 2016). In industry, 3D apparel visualization software can be used as an instrument for rapid prototyping streamlining the traditional apparel garment fitting process, and reducing the number of physical samples (Lee & Park, 2017; Papahristou & Bilalis, 2016). As shown in Figure 1, the traditional garment fitting process is an iterative optimization process that comprises trial-and-error cycles of sample preparation, trial fitting, and pattern change (Hwang Shin & Lee, 2020). According to previous studies, 94% of garments typically go through the fitting process at least two or three times to achieve the desired look (Bye & LaBat, 2005). Virtual fitting with an avatar can replace the number of iterations of developing physical prototypes and reduce the process of sending numerous samples back and forth between overseas manufacturers and clients to obtain feedback (Papahristou & Bilalis, 2016). Virtual prototyping reduces the number of physical samples and leads to faster prototype approval, alleviating environmental impact (Papahristou & Bilalis, 2016). One software company, CLO reported that one of their clients reduced the average product development lead time from 37 days to 27 hours after adopting their software because virtual fitting eliminated the need for redundant sample garment review processes (CLO, 2021).

Figure 1

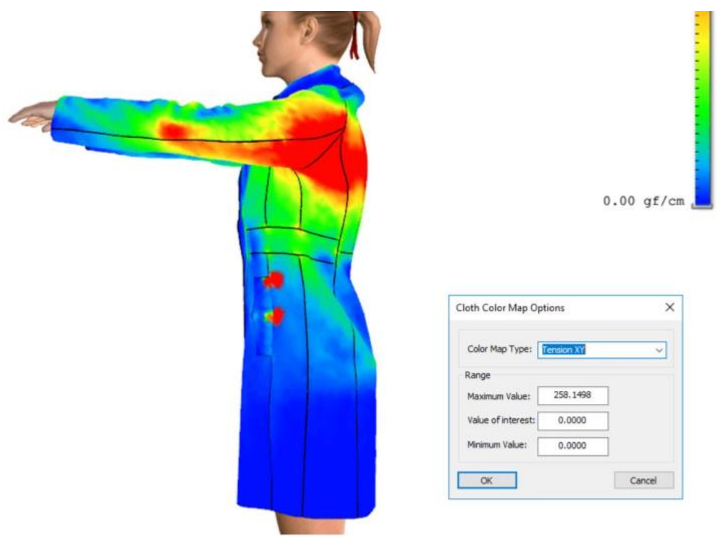
Traditional Garment Fitting Process (Hwang Shin & Lee, 2020, p. 302)



In addition, virtual fit assessment is achievable through use of strain/pressure map modes in conjunction with specifically sized avatars. Garment fitting is a process of evaluating garments on a body to check the fit, comfort, and appearance quality (Workman & Lentz, 2000). Optitex PDS, CLO, and Browzwear VStitcher 3D software systems provide strain and pressure map modes that provide a visualization of virtual garments' degree of stress, strain, and fit on an avatar through color variation (Figure 2) (Browzwear, 2021; CLO, 2021; Optitex, 2021). The color-coded maps on the garment depict the distribution of physical tension and pressure in various sections of the clothing, utilizing fabric characteristics as their basis. Designers and product developers can check the ease of virtual garments on avatars taking dynamic poses (such as bending and stretching). Based on the strain and pressure map modes, users can carry out pattern alterations using the features and functions in the software and these adjustments are reflected in both 2D block patterns and 3D virtual garments in real-time. Furthermore, sharing visualizations of virtual garments could improve communication efficiency and facilitate a lower rate of misinterpretation with other departments and between technical designers and manufacturers overseas (Hwang Shin & Lee, 2020; Lee & Park, 2017).

Figure 2

An Example of Virtual Tension Map of Optitex PDS (Optitex, 2021)



Industrial 3D Product Creation Process

In recent years, the landscape of digital technology has been evolving at an unprecedented pace, significantly impacting fashion and apparel industry. Among these transformative trends, the adoption of 3D apparel visualization software has emerged as a pivotal advancement for apparel product design and development. As is common in other rapidly developing technology sectors, users of 3D apparel visualization software present their approach to implementation at industry conferences, offering insight into how to approach adopting, implementing, and scaling the technology throughout a company. Presentations from an industry conference attended by the principal investigator were reviewed to add contemporary context for this rapidly changing industry trend of 3D apparel visualization software adoption. Presentations describing the 3D product creation process given at *PI Apparel*'s conference of 2020 in Los Angeles (Cekada & Crawley, 2020; Hansen & Joost, 2020) are described in the following paragraphs.

According to presenters, some fashion and apparel companies were already implementing 3D apparel visualization software and planning to leverage it for multiple activities throughout their product development process (Cekada & Crawley, 2020; Hansen & Joost, 2020). They reported that the 3D digital product creation process could be realized throughout the create/design, make, and sell stages, and each stage comprised several activities. In the create/design stage, conventional design sketches, pattern making, and production of sewn samples could be replaced with 3D digital product design and scalable 3D assets (Cekada & Crawley, 2020). Sharing scalable 3D assets allowed users to communicate and exchange accurate product data and visuals. Also, 3D digital product design facilitated pattern adaptation in real-time (Hansen & Joost, 2020). Additionally, material virtualization and photorealistic rendering could supplant the existing fabric swatch card (a visual representation of fabric) and provide realistic reproduction of the actual fabric drape (Cekada & Crawley, 2020). In the make phase (production phase), the fit of a sample could be validated virtually with an avatar instead of using a fit model, reducing physical samples and saving cost and time (Cekada & Crawley, 2020; Hansen & Joost, 2020). Furthermore, digital 3D assets could be utilized for marketing, selling, and retail by providing interactive merchandising and showroom tools and virtual fitting room platforms to maximize the engagement of buyers and customers (Cekada & Crawley, 2020; Hansen & Joost, 2020). Insights from these presentations suggested ways in which 3D apparel visualization software can be integrated into activities across design, make, and sell stages.

Industry Professionals' Perceptions of 3D Apparel Visualization Software

Academic articles discussing industry professionals' perceptions of 3D apparel visualization software were reviewed to identify considerations for integrating the software at the organizational level. Compared to other industries such as aerospace, architecture, and industrial design, adoption of 3D virtual prototyping in the apparel industry has been slow and complex due to the inherent properties of fabric and the complexity of fitting on the human body (Papahristou & Bilalis, 2015; Papahristou & Bilalis, 2017). At the initial stage, it is not always the case that potential users favor new technology (Nov & Ye, 2008). In industries, discordance often exists between a company's decision-makers for new technology adoption and the perspectives of the actual end-users within the company, therefore, unfavorable situations or frustrating cases associated with new technology are likely in early implementation phases (Park & DeLong, 2009). The following are details about studies investigating industry professionals' perceptions of implementing 3D apparel visualization software experienced by users in the global fashion and apparel industry.

Supply Chain Actors

Perceived drivers and barriers to using 3D apparel visualization software differ between supply chain actors of the fashion and apparel industry. Papahristou and Bilalis (2017) investigated challenges of utilizing 3D apparel visualization software experienced by early adopters to accelerate integration of digital prototyping in business processes. The researchers interviewed four different groups: software providers (n=11), professional 3D software users in apparel companies (n=13), independent entrepreneurs (n=8), and academics (n=8). Participants were asked about their experiences using 3D and its impact on the apparel product development process. The salient advantages mentioned by participants were faster decision-making, effective communication and reduction in time for design development and reduction in physical samples (Papahristou & Bilalis, 2017). However, participants' views on the challenges that impede the integration of digital prototyping for the whole industry were divergent depending on their interests and positions in the supply chain of the fashion and apparel industry.

Software providers interviewed by the researchers pointed out that manufacturing partners are not always equipped to create or use virtual prototypes and other 3D assets (Papahristou & Bilalis, 2017). The software providers stated that manufacturing partners do not dedicate time and effort to learning and implementing the new technology, and lack of commitment to learning new technology precludes the necessary change for integrating digital prototyping (Papahristou & Bilalis, 2017). Academics interviewed for the study reported that the lack of experienced users with technical knowledge impedes adoption (Papahristou & Bilalis, 2017). Their common concern was the amount of time it would take to learn this new technology (Papahristou & Bilalis, 2017). They also stated that many fashion courses in higher education ignore teaching the necessary 3D skills, which are ineffectively developed by inexperienced practitioners who are fearful of change (Papahristou & Bilalis, 2017). Some independent designers who participated in the research expressed concerns about the software's accuracy, which would limit its use to the concept and design stages (Papahristou & Bilalis, 2017). Participants who were software users from apparel companies maintained that establishing virtual trim and fabric libraries is a considerable workload, and incompatibility between different 3D software tools and file types is problematic (Papahristou & Bilalis, 2017).

The challenges of using 3D apparel visualization software reported by industry practitioners included lack of commitment to learning new technology, lack of skilled human resources, software accuracy and precision, the necessity of building a virtual fabric library, and interoperability of 3D virtual garment data. The roles and interests of supply chain actors were linked to barriers to implementing 3D apparel visualization software. However, the researchers did not provide details about their approach to data analysis.

Business Partnerships

Integration of 3D apparel visualization software is also proliferating to overseas manufacturers. Industry practitioners' perceptions of using 3D apparel visualization software have relevance to a company's local or foreign business partnerships. Hwang Shin and Lee (2020) conducted a survey to compare the perceptions toward using 3D virtual fitting technology between sourcing agents/contractors and domestic suppliers in South Korea. In the context of their study, sourcing agents/contractors manufacture garments in collaboration with U.S. apparel companies and export them, whereas domestic suppliers are domestic brands, domestic suppliers, and domestic manufacturers (Hwang Shin & Lee, 2020). A total of 213 participants from the garment industry in South Korea responded to the survey (Hwang Shin & Lee, 2020). They were asked about their current garment fitting process and perspectives on using virtual fitting technology through both closed and open-ended questions (Hwang Shin & Lee, 2020). One-way ANOVA and t-test were used to identify differences between sourcing agents/contractors and domestic suppliers (Hwang Shin & Lee, 2020).

According to the results, sourcing agents/contractors and domestic suppliers had different perspectives on the 3D virtual fitting technology (Hwang Shin & Lee, 2020). Two thirds of sourcing agents/contractors working with overseas apparel companies were using 3D virtual fitting technology, whereas domestic suppliers did not use it at all (Hwang Shin & Lee, 2020). Moreover, a greater number of sourcing agents/contactors reported that virtual fitting is important in the current industry in comparison with domestic suppliers (Hwang Shin & Lee, 2020). Both sourcing agents/contractors and domestic suppliers envisioned that 3D virtual fitting technology would be important in the future (Hwang Shin & Lee, 2020).

The majority of sourcing agents/contractors believed using 3D virtual fitting technology is useful for predicting a variety of fit issues from the virtual images, reducing production lead time, and increasing effectiveness of communication with overseas buyers (Hwang Shin & Lee, 2020). The findings implied that 3D virtual fitting technology could supplement the current communication practice of using technical packages with photos and web conference meetings (Hwang Shin & Lee, 2020). However, participants reported issues with software reliability, claiming that the software cannot accurately reflect different fabrics or sewing types and has limitations when checking body movements with a virtual model (Hwang Shin & Lee, 2020).

Domestic suppliers preferred the current practice of face-to-face meetings for domestic sourcing and production (Hwang Shin & Lee, 2020). They insisted conventional garment fitting on an actual person is less costly than acquiring and implementing 3D virtual fitting technology (Hwang Shin & Lee, 2020). However, they reported it would be inevitable to adopt virtual fitting technology if their foreign business partnerships expanded (Hwang Shin & Lee, 2020). This study added manufacturers' perspectives on industry professionals' perceptions of using 3D virtual fitting technology in the current literature. The communication methods and buyers' requests led to different opinions on industry practitioners' perceptions of 3D virtual fitting technology.

Technological, Organizational, and Environmental Factors

At the organizational level, multidimensional factors influence innovation adoption (Rogers, 1995). Henao-Ramirez and López-Zapata (2021) identified technological, organizational, and environmental factors influencing Columbian firms' perceptions of and intentions to adopt 3D digital design technologies. A conceptual framework was developed using technology-organization-environment (TOE) and technology acceptance model (TAM) theoretical frameworks (Henao-Ramirez & López-Zapata, 2021). An online survey was distributed to 227 manufacturing, construction, and services firms in Columbia (Henao-Ramirez & López-Zapata, 2021). One hundred thirty-eight respondents involved in product design, modeling, prototyping, and development processes participated in the survey (Henao-Ramirez & López-Zapata, 2021). A structural equation model with partial least squares (SEM-PLS) was used to test the influence of technological, organizational, and environmental factors on participants' perceptions and adoption intention of 3D design digital technologies (Henao-Ramirez & López-Zapata, 2021).

In the technological dimension of the structural model, it was found that the direct effect of perceived usefulness on intention to adopt 3D design digital technologies was significant (Henao-Ramirez & López-Zapata, 2021). In the organizational dimension, it was found that the relationship between technological competence and intention to adopt and the relationship between top management support and intention to adopt had significant effects (Henao-Ramirez & López-Zapata, 2021). In the environment dimension, it was found that the direct effect of competitive pressure on intention to adopt 3D design digital technologies was significant (Henao-Ramirez & López-Zapata, 2021). Concerning the impact of control variables, firm size was confirmed to be a significant driver of 3D digital design technologies adoption (Henao-Ramirez & López-Zapata, 2021).

The study identified significant factors for decision-making in adopting 3D digital design technologies in an organization and their causal relationships by testing an integrative theoretical model. However, data was collected from firms across different industries rather than focusing on the fashion and apparel industry. In addition, further empirical research is necessary to examine the applicability of identified decision factors in the different research contexts.

Social Groups in an Organization

Park and DeLong's (2009) study examined organizational factors such as the company's interdepartmental relationships and internal communications between employees to facilitate the diffusion of a virtual sampling system throughout a footwear company. The researchers assumed that social processes drive technological change (Park & DeLong, 2009). They proposed an integrated framework based on innovation diffusion theory (Rogers, 2003), social construction of technology theory (Pinch & Bijker, 1984), and the technology acceptance model (TAM) (Davis, 1986) to examine how relative social groups in an organization impact adoption and implementation of a virtual sampling system (Park & DeLong, 2009). The proposed framework was evaluated by administering a survey to employees of a footwear company located in the USA to explore reciprocal negotiation actions between users of a virtual sampling system in the company's adoption phase (Park & DeLong, 2009). General linear modeling (GLM) and principal component analysis (PCA) were employed to assess the relationships among the variables (Park & DeLong, 2009).

The results showed that frequency of use (every day, once a week, etc.) is the only X variable that has significant relationships with the participants' awareness of organizational changes, perceived usefulness and challenges of the technology, and company's performance with the use of the technology (Park & DeLong, 2009). Therefore, the researchers maintained that creating subgroups within the company based on the frequency of a virtual sampling system use would help the company increase the efficiency of inter-personal and inter-departmental communication and generate better performance with the technology (Park & DeLong, 2009). This study collected data from employees with diverse levels and roles of job positions by focusing on a single company. However, the study did not provide information about the current adoption and implementation of a virtual sampling system within the company's specific context.

Summary of Industry Professionals' Perceptions of 3D Apparel Visualization Software

The reviewed literature implied that industry professionals' perceptions of 3D apparel visualization software are subject to supply chain roles, and company's local or foreign business partnerships (Hwang Shin & Lee, 2020; Papahristou & Bilalis, 2017). A company's technological, organizational, and environmental factors that can present both constraints and opportunities for organizations' technology adoption decisions were also identified (Henao-Ramirez & López-Zapata, 2021; Park & DeLong, 2009). The reviewed research primarily focused on examining companies that had prior experience using and implementing 3D apparel visualization software for their business. Furthermore, most studies collected quantitative data to test the proposed model through a survey. While research has been carried out in using 3D visualization software to assist in functional clothing development, there is no research discussing a functional clothing company's potential 3D technology adoption.

Applications of 3D Apparel Visualization Software in Designing Functional Garments

Academic literature dealing with the use of 3D apparel visualization software to develop garments for specific functions was reviewed to explore the potential opportunities of introducing 3D apparel visualization software into an industrial functional clothing development process. 3D apparel visualization software has been examined for use in designing ergonomically fitted garments for specific functions such as cycling clothes, yoga outfits, protective overall for sport aircraft pilots, clothing for people with physical disabilities, costumes for performing arts, and plus size apparel (Bogović et al., 2019; Cieśla et al., 2020; Haixia & Yongrong, 2020; Hong et al., 2017; Hudson & Hwang, 2020; Jin, 2016; Kozar et al., 2014; Liu et al., 2016; Mert et al., 2018; Porterfield & Lamar, 2021; Rudolf et al., 2015; Rudolf et al., 2017). The literature review revealed functions and features of 3D apparel visualization software that can be used to optimize functional clothing design, such as custom avatars and pressure and tension maps. In addition, practices or approaches such as collaborative design and the 3D-to-2D design method were identified.

Custom Avatar

3D apparel visualization software can be used to simulate virtual garments on personalized avatars created using 3D body scanning technology. 3D body scanning technology extracts body measurement data (Istook & Hwang, 2001), and a generated personal avatar can be imported into 3D apparel visualization software (Kozar et al., 2014; Sayem et al., 2010). Employing personal avatars based on body measurement data could make it possible to provide customized apparel that accurately reflects an individual’s body size and shape (Griffey & Ashdown, 2006). Many researchers have used 3D apparel visualization software in conjunction with 3D body scanning technology for wearers with specific physical presentations such as body asymmetry (Annett-Hitchcock et al., 2020; Hong et al., 2017), wheelchair use (Jin, 2016; Rudolf et al., 2017; Rudolf et al., 2015), and pregnancy (Cieśla et al., 2020). These researchers focused on technical aspects of adjusting the avatar. Additional research is needed on how custom avatars can be used for specific product development settings.

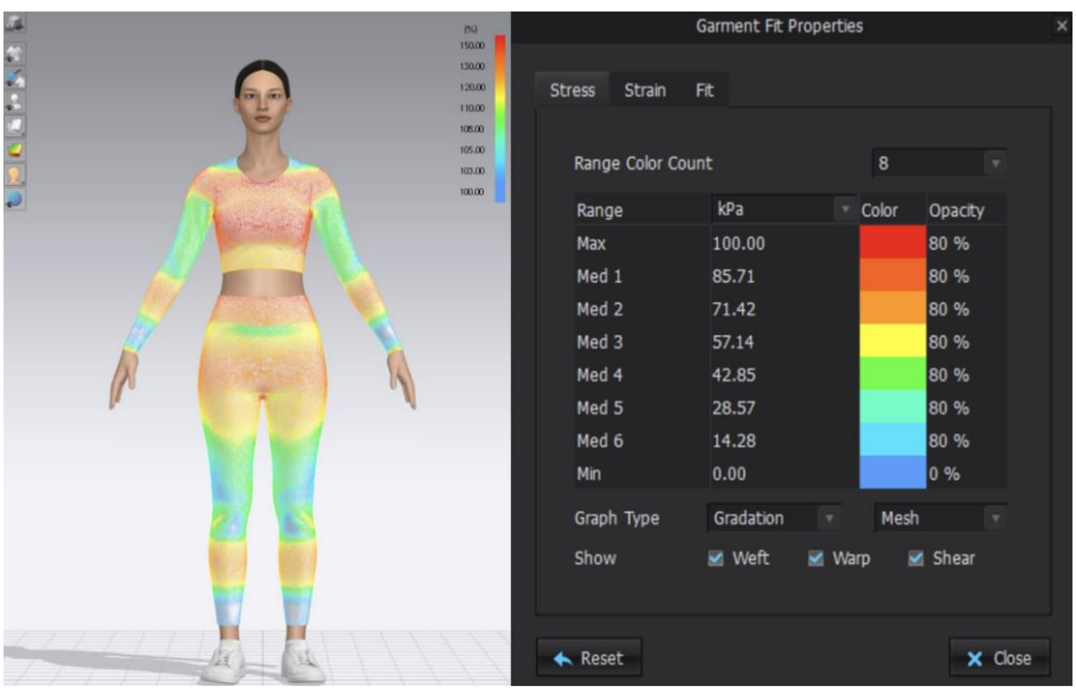
Users can select poses for an avatar provided in the software system or import third-party avatars from an external source (CLO, 2021; Optitex, 2021). Furthermore, virtual avatars can be given dynamic postures by integrating a kinematic skeleton consisting of bones and joints to mimic specific postures (CLO, 2021; Kozar et al., 2014; Optitex, 2021). Kozar et al. (2014) developed an adaptive 3D body model by scanning a subject and constructing a kinematic skeleton inside the polygonal mesh of the scanned surface using 3D computer graphics software. To assess the accuracy and reliability of the 3D body model's posture adaptations, the researchers measured virtual body dimensions and compared them to those of a physical model. Remarkably, the generalized adaptive 3D body model demonstrated the ability to assume various positions while maintaining true-to-life body measurements (Kozar et al., 2014). Researchers have compared variation of static and dynamic fit of 3D garments by changing postures and poses of a virtual avatar to identify which body points on garment patterns should be adjusted for wear comfort (Bogović et al., 2019; Haixia & Yongrong, 2020; Liu et al., 2016; Mert et al., 2018; Rudolf et al., 2017). Building upon previous findings demonstrating the capability to generate a personal avatar that accurately reflects an individual's body size and can adjust poses, it is crucial to conduct further investigation to explore the potential of integrating these capabilities into the industrial design and development of functional clothing.

Pressure Map/Tension Map

As shown in Figure 3, some 3D apparel visualization software systems provide tension and pressure maps, which are especially useful tools to review garments' fit (Gill, 2015). The maps display physical tension and pressure distribution in each part of the garment based on the fabric properties as a color-coded map on the garment. Depending on the software system, the level of tension is presented with a percentage value, or virtual pressure values in hPa, kPa, fg/cm, and gf/cm^2 units subject to software systems (Bogović et al., 2019; Haixia & Yongrong, 2020; Liu et al., 2016). The unit measures how much pressure is exerted on the surface area of the fabric (De Jong et al., 1986).

Figure 3

An Example of Garment Stress Map (Left) and Stress Properties (Right) in CLO3D (CLO, 2023)



Previous research has established that fabric properties can significantly influence garments' comfort and pressure distribution (Ancutiene et al., 2014; Dan et al., 2013; Varghese & Thilagavathi, 2015). Virtual pressure values of 3D simulated garments can provide reliable pressure comfort prediction to satisfy wearers' physiological and psychological needs (Wong et al., 2004). Construction of garment patterns and the design of apparel products can be optimized to improve pressure comfort based on evaluation of the pressure and tension maps in 3D software. Researchers have tested utilization of 3D pressure and tension maps for designing and developing yoga tops, upper cycling clothes, garments for people with paraplegia and scoliosis, tennis shirts for a wheelchair tennis player, climbing clothes, and protective coveralls for sport aircraft pilots (Bogović et al., 2019; Haixia & Yongrong, 2020; Hong et al., 2017; Jin, 2016; Liu et al., 2016; Rudolf et al., 2015; Rudolf et al., 2017; Viziteu & Curteza, 2021). These studies employed pressure and tension maps to estimate the fit of a virtual garment on 3D body models with static and dynamic body postures. Researchers optimized garment pattern design based on pressure and tension values and found that using pressure and tension maps could improve the wearer's comfort (Bogović et al., 2019; Haixia & Yongrong, 2020; Hong et al., 2017; Jin, 2016; Liu et al., 2016; Rudolf et al., 2015; Rudolf et al., 2017; Viziteu & Curteza, 2021).

Collaborative Design

Optimizing Design Solutions. 3D apparel visualization software can facilitate interaction among designers, pattern makers, and customers to achieve the desired garment fit effect. Hong et al. (2017)'s study introduced a co-design-based method by repeating the sequence of design, display, evaluation, and adjustment to develop customized clothes for people with scoliosis. The researchers designed 2D patterns based on the body points and curves of a personalized avatar of a person with scoliosis and a 3D virtual garment was created (Hong et al., 2017). Next, virtual garment images were shared with the wearer with scoliosis to obtain her feedback and fit preferences (Hong et al., 2017). Based on the wearer's responses, adjustments were made to the compositions of 2D patterns and technical parameters, including darts, folds, openings, wearing ease, fabric, and color (Hong et al., 2017). Following that, a group of fashion designers and pattern makers evaluated the fit appearance of the virtually simulated garments, considering the adjusted garment patterns to identify additional points that require extra adjustments in order to achieve the desired perception (Hong et al., 2017). This research found that the collaborative garment design process facilitated interactions among researchers, wearers, designers, and pattern makers, resulting in the generation of a design solution that addressed the specific needs of wearers with scoliosis while considering the technical requirements of product design (Hong et al., 2017).

Effective Communication. Porterfield and Lamar (2021) examined integration of 3D apparel visualization software into the process of designing and making costumes for the performing arts. The researchers developed virtual garments with paper patterns of costumes produced by the participating designers/maker teams (n=10) and interviewed participants online (Porterfield & Lamar, 2021). Designers and pattern makers viewed their simulated costumes and responded to questions about evaluating simulated costumes' fit, appearance, and functionality (Porterfield & Lamar, 2021). The study found the value of using 3D apparel visualization software to visually communicate and make design decisions in the early stage of the costume development process, optimizing the time with the performer for an actual fitting (Porterfield & Lamar, 2021).

Incorporating Consumer Needs. Hudson and Hwang's (2020) study used 3D apparel visualization software to explore ways to enhance plus-size apparel design. The researchers surveyed plus-size women (n= 57) to identify their clothing needs and perceived problems using the functional, expressive, and aesthetic consumer needs model (Hudson & Hwang, 2020; Lamb & Kallal, 1992). Based on their findings, a dress was designed by using style, design features, and garment measurements that can meet plus-size women's needs (Hudson & Hwang, 2020). A virtual prototype was developed in 3D virtual fitting software (Hudson & Hwang, 2020). For evaluation of the virtual prototype, eight academic and industry professionals reviewed a digital presentation describing the design process and the images of both virtual and physical prototypes (Hudson & Hwang, 2020). The participants were asked to assess the virtual fitting process's effectiveness, innovativeness, sustainability, and creativeness to satisfy the plus-size market's functional, expressive, and aesthetic needs (Hudson & Hwang, 2020).

The results indicated that the virtual prototyping process effectively incorporated plus-size women's functional needs and aesthetic preferences in consumer needs research (Hudson & Hwang, 2020). The academic and industry professionals stated that virtual prototyping helped them better understand the plus-size body, make effective decisions in planning design elements, and easily transfer files within the process compared to the traditional design process (Hudson & Hwang, 2020). The researchers implied that 3D apparel visualization software could be utilized as a tool for collaborative design to integrate users' needs and evaluate garments interactively to optimize prototypes. However, further research is necessary to apply 3D apparel visualization software to enhance and facilitate the product design and development process for an actual business.

3D-to-2D Design Method

Traditionally, 2D flat patterns are the beginning of the product development process (Zhang, 2015). An alternative, the 3D-to-2D design method, has been made possible since the advent of 3D apparel design software (Zhang, 2015). Researchers went through the following steps to accomplish the 3D-to-2D design method. First, researchers began drawing contours on a virtual avatar, and then 3D planes were generated around an avatar based on the contours in 3D apparel visualization software (Hong et al., 2017; Liu et al., 2016). Following that, researchers extracted 2D flat pattern pieces composing 3D planes using specific functions in the software system or by using another 3D computer graphics software (Hong et al., 2017; Liu et al., 2016). Lastly, researchers added seam lines, dart lines, notches, and grain lines to the generated 2D pattern pieces and modified the pattern pieces by virtually fitting the garment to an avatar in 3D apparel visualization software (Zhang, 2015).

Precedent studies have implied that the 3D-to-2D design method can be used for pattern making with relatively precise results (Jeong et al., 2006; Liu et al., 2016; Yunchu & Weiyuan, 2007; Yang et al., 2011). The 3D-to-2D design method could be effectively applied for wearers with atypical body shapes who cannot identify the most appropriate sizes with the existing standard basic garment patterns (Hong et al., 2017). Hong et al. (2017)'s study employed key performance indicators such as the total number of working hours, the total number of employees involved in the production process, etc., to evaluate the effectiveness of the 3D-to-2D virtual design method and 2D-to-3D virtual design method. A group of fashion designers and pattern makers were recruited to obtain a quantitative comparison while the two design methods were carried out in the same working environment (Hong et al., 2017). The assessment result indicated that the 3D-to-2D virtual design method could improve the effectiveness of the patternmaking process in terms of total working hours and the number of employees involved in the production process to achieve the desired garment fit (Hong et al., 2017). This method has only been used for experimental settings and needs to be examined in the typical product development process.

Summary of Applications of 3D Apparel Visualization Software in Designing Functional Garments

As the literature indicates, academic researchers have increasingly begun to investigate the use of 3D apparel visualization software as an evaluation method and a tool for designing ergonomically fitted garments for various functions in line with the rise of digital design practices. However, little is known about the use of 3D apparel visualization software in the digital product creation process for developing functional clothing. The following section will look into the features of wildland firefighting protective clothing and review previous studies in order to investigate potential opportunities for using 3D apparel visualization software to develop functional clothing in this category.

Wildland Firefighting Protective Clothing

Wildland firefighters risk their lives in the field of fire prevention, and suppression activities carried out in woodlands, forests, grasslands, and other vegetation regions outside of inhabited areas (Jeffrey & Grace, 2021). They wear personal protective clothing for thermal protection, such as shirts, trousers, jackets, and coveralls (Mandal et al., 2019). Key features of wildland protective clothing include loose fit, single-layer components, and uniform-like flame-resistance. These features ensure radiant heat and heat stress protection because ventilation is required to allow air and moisture to pass through the clothing microclimate to the external environment (Jeffrey & Grace, 2021; Smith & Petrilli, 2013). Wildland firefighters also use auxiliary equipment such as helmets, goggles, face and neck shrouds, gloves, boots, chainsaw protectors, and load-carrying equipment (Mandal et al., 2019).

In the United States, protective clothing and equipment certified by the National Fire Protection Association (NFPA) are widely used (Mandal et al., 2019). NFPA 1977: Standard on Protective Clothing and Equipment for Wildland Fire Fighting, 2016 Edition (Mandal et al., 2019) describes an established standard for wildland firefighting to regulate the design, size, performance requirements and protective properties of personal protective clothing and equipment. To be compliant with NFPA standards, firefighting protective clothing can only be altered to a limited extent by selecting different styles and types of pockets, trim, snaps, rivets, and closures (Boorady, 2015). According to the U.S. Forest Service, it costs about $2,700 to outfit a wildland firefighter from head to toe, as shown in Figure 4 (Edge, 2018).

Figure 4

Single Layer U.S. Forest Service Uniform (Edge, 2018)

Precedent Studies on Wildland Firefighting Protective Clothing

Evaluating Thermal Protection

Previous research on wildland firefighting gear noted the importance of balancing protection and heat stress of protective clothing (Budd et al., 1997; Carballo-Leyenda et al., 2017; Den Hartog et al., 2016). The studies compared physiological responses of firefighters during exercises while wearing protective clothing depending on thermal insulation levels (Budd et al., 1997) and thermal protection of product prototypes according to the fiber content, fabric type, fabric thickness, and fabric layer (Den Hartog et al., 2016; Carballo-Leyenda et al., 2017; Carballo-Leyenda et al., 2018). Researchers measured firefighters' heart rate, respiratory gas exchange, energy expenditure, evaporation of sweat, metabolic rate, and skin temperature during fire-suppression activities and exercise (Budd et al., 1997; Carballo-Leyenda et al., 2017; Carballo-Leyenda et al., 2018). Den Hartog et al. (2016)'s study evaluated the heat strain of the product prototypes on the sweating guarded hot plate and the sweating thermal manikin. Extant studies indicated that fabric construction and layers influenced wildland firefighting protective clothing's thermal protection performance and physiological responses.

Proposing Design Solutions

Researchers have proposed the design of a prototype for wildland firefighting protective clothing (Huck & Kim, 1997; Rucker et al., 2000). Huck & Kim (1997) designed individually sized coveralls for grass firefighting to solve improper fit. The ease in the crotch area was optimized based on the ease requirements specified by the wearers. In addition, stretch panels were inserted in the upper back, the back waist area, and the leg crotch area to facilitate movement. The developed prototype was evaluated via a range of motion measurements and firefighters' subjective assessment on the acceptability scale of fit and comfort.

Rucker et al. (2000) developed different prototypes to explore how design details and the fit of protective garments can affect the extent of burn injuries. The researchers modified the shirt collar and zipper, shortened the jacket, and reshaped the sleeve, pant legs, and shirt pockets to increase the wearer's range of motion. In addition, they compared the heat flux of single fabric and multilayer fabric garments in two different sizes (medium and large). The results indicated that differences in fit did not produce significant differences in burn injuries, but the two-layer systems were significantly more protective than the one-layer system. These studies implied that customization and alterations to patterns, design details, and garment layers could improve the fit, movement, and thermal protection of wildland firefighting protective clothing. None of the studies utilized 3D apparel design technology, and little is known about manufacturers' perspectives on improving product quality, design, and development through adopting new technology.

Action Research

The reviewed literature revealed that 3D apparel visualization software is an emerging technology and showed some of the potential opportunities for adopting the software to develop functional clothing. However, no research discusses a functional clothing company's potential 3D technology adoption. An action research approach can effectively introduce the software and facilitate identification of the potential opportunities to embed 3D apparel visualization software into the product design and development process in an industrial setting. In the following section, action research and the ways it has been applied in industrial settings are described.

What is Action Research

According to Reason & Bradbury (2008), action research “is a living, emergent process that cannot be predetermined but changes and develops as those who engage deepen their understanding of the issues to be addressed and develop their capacity as co-inquirers both individually and collectively (p.4).” Sadler and Barry (1968) also described action research as “the sociotherapeutic approach where the social scientist interested in organizations joins with managers in analyzing and attempting to solve human problems in the work situation (p. 316).” Action research has been considered a distinctive form of problem-solving since the early 1940s (Akdere, 2003). Kurt Lewin is generally regarded as one of the pioneers (Checkland, 1981; Argyris et al., 1989; Swanson & Holton, 2001) and the first person to use the term "action research" to refer to a specific problem-solving approach in which the practitioner generates new knowledge about a social system, while at the same time attempting to change it (Lewin, 1946; Peters & Robinson, 1984). Action research deals with social problems, intra-organizational and work-life problems in several fields, including management, education, sociology, agriculture, and community development (Akdere, 2003; Stringer, 1999).

Principles of Action Research

There are different types of action research, but they share several principles (Merriam & Tisdell, 2015). First, action research centers on resolving problematic situations or identifying methods to enhance practice (Mertler, 2019; Patton, 2002; Merriam & Tisdell, 2015). Bradbury et al. (2019) contend that action research serves as a transformative approach to learning, breaking free from a narrow reliance on factual information. The researchers emphasize the critical importance of recognizing and valuing personal experiences as integral to the learning process. By encouraging participants' active involvement, action research promotes the exploration and resolution of intricate issues within the local context. Second, action researchers engage participants as co-investigators to at least some extent (Merriam & Tisdell, 2015). A lead researcher can conduct an action research study as an insider to an organization, an outsider, or some configuration of the two that may emerge over time (Merriam & Tisdell, 2015). Third, the design of action research is emergent (Merriam & Tisdell, 2015). According to Herr and Anderson (2014), action research is directed towards a specific course of action or a series of actions that researchers and participants undertake with the aim of enhancing practice. Therefore, action research typically consists of a spiral cycle of planning, acting, observing, and reflecting (Kuhne & Quigley, 1997; Mertler, 2019). The action research cycle can continue, whether the action proved successful or not, to develop further knowledge about the organization and the validity of relevant theoretical frameworks (Merriam & Tisdell, 2015).

Action Research in Industrial Settings

Action research has been utilized in various industries and in educational research, and many examples of implementation are available (Sáez Bondía & Cortés Gracia, 2021; Shani & Coghlan, 2019). In this section, action research literature addressing the impact of adopting technology and the innovation process is explored.

Organizational Innovation Capability. Applying an action research approach allows the researchers to describe the innovation processes and establish appropriate structures to foster innovation in an organization. For example, Kocher et al. (2011) worked with a Swiss dairy food company to experiment with how action research can change and enhance small and medium-sized enterprises' (SMEs) innovation capability by performing three action research cycles for more than 18 months. First, researchers interviewed 15 top managers of other dairy food SMEs and compared their innovation experiences with that of a participating company to enable the participating company to identify their own "blind spots" (Kocher et al., 2011 p.26). Next, the participating company set up three different innovation project teams to generate product innovations in different product segments (Kocher et al., 2011). Finally, the company organized a workshop to increase employees' awareness of innovation, future opportunities, and internal production capabilities in an increasingly competitive market (Kocher et al., 2011). Consequently, the company developed an action plan including involvement in an innovation network for the food industry and participation in a nationally funded "Co-Innovation in the food chain" project (Kocher et al., 2011). This study shows how researchers' interventions led to a change and helped the participant company ameliorate their innovation capability and broaden organizational and individual understanding of innovation.

Refining an Extant Technology. Action research can be particularly appropriate for assessing and refining an extant technology to support the management of an organization. Lindgren et al. (2004) worked with six Swedish organizations to optimize the configuration and implementation of desk-top based competence management system (CMS) solutions. In a first action cycle, the researchers investigated the strengths and weaknesses of the current CMS solutions that participating organizations were using (Lindgren et al., 2004). New design principles were formulated based on the findings, and prototypes were built for a second action research cycle (Lindgren et al., 2004). The CMS solution prototypes were implemented and evaluated by participating organizations (Lindgren et al., 2004). This study showed how providing prototypes could synthesize insights and make an extant technology integrative for an organization.

Diffusion of Technology. Adopting new technologies into organizational practices poses significant technical and social challenges. At the implementation stage, planned interventions can effectively address barriers to adoption (Davidson & Heslinga, 2006). Davidson and Heslinga (2006) launched an action research project to study the social and organizational processes associated with adopting and assimilating electronic health records software into small physician practices. In phase one, researchers recruited 14 physicians in the local physician community to become part of the action research pilot group (Davidson & Heslinga, 2006). Moreover, they interviewed physicians to ascertain their level of awareness and interest in electronic health records software and perceived barriers to its adoption and assimilation (Davidson & Heslinga, 2006). The article reported the outcomes of phase one and the future plans for phases two and three of the action research project as the research team was transitioning to phase two at the time of writing. The study implies that collaboration within a professional community and providing IT implementation knowledge and technical support via the action research team may facilitate assimilation and diffusion of technology.

Summary of Action Research

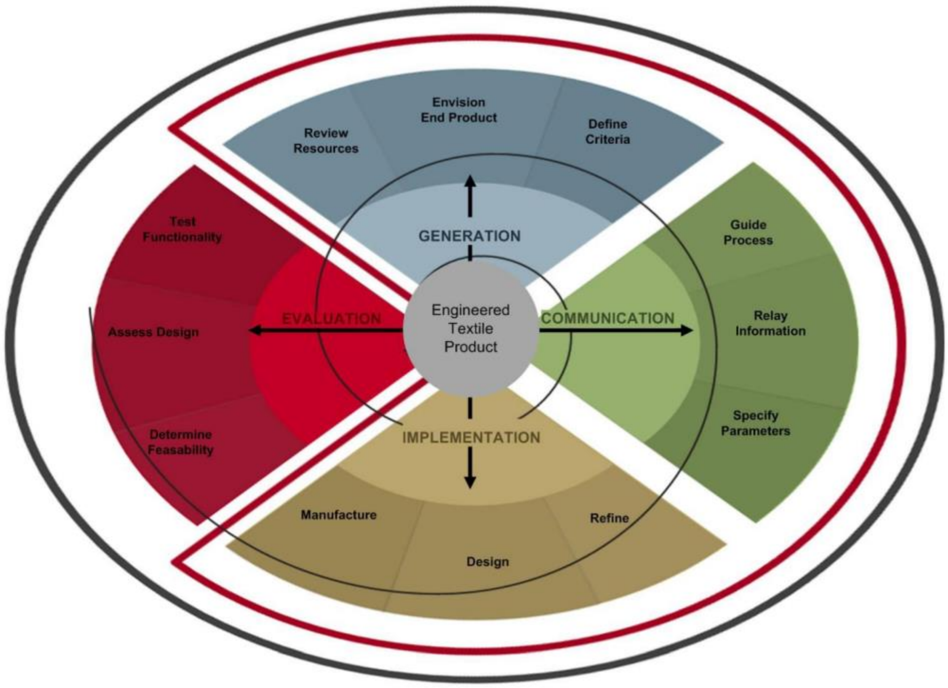
Action research seeks to understand an organization's problem and attempt to solve the problem by taking action. The action research literature indicated that action research allows researchers to influence an organization's technology adoption and innovation process in collaboration with participants in their work situations. Extant studies presented interventions of action researchers that contributed to forwarding companies' ability to transform knowledge and ideas into new technologies, broadening organizational and individual understanding of innovation, and facilitating innovation integrative for an organization.

Data Analysis and Visualization

Academic conceptual models and frameworks are frequently used to organize analyzed data into a visual format, and two examples from the textile industry are introduced here. Chapman (2008) built a comprehensive model of the process for textile design engineering within the shape of a product by integrating inkjet printing and integral knitting technologies (Figure 5). The researcher developed an initial model based on the literature review and her own professional experience. The model showed various points within the textile and apparel complex during which the coloration (dyeing and printing) of yarn and fabric could be specifically engineered within a product. Next, a Delphi survey was conducted with textile design experts in weaving, knitting, and printing to establish common terminology, communication procedures, and main product development phases for textile design engineering within the product shape. The results identified four main product development phases for textile design engineering within the product shape: i) idea generation, ii) idea communication, iii) idea implementation, and iv) idea assessment (Chapman, 2008). Finally, case studies consisting of interviewing and observing apparel manufacturers and firms allowed examination of an event in the engineering design process of printing and knitting onto their products. The results were organized to correspond with the process model to refine and validate the model. The process model provides a comprehensive overview of the entire engineering design process and allows the viewer to grasp the complex interaction of the main components of the process (Chapman, 2008).

Figure 5

Final High Level Process Model for Engineering Textile Design Properties within the Shape of a Product (Chapman, 2008, p. 185)

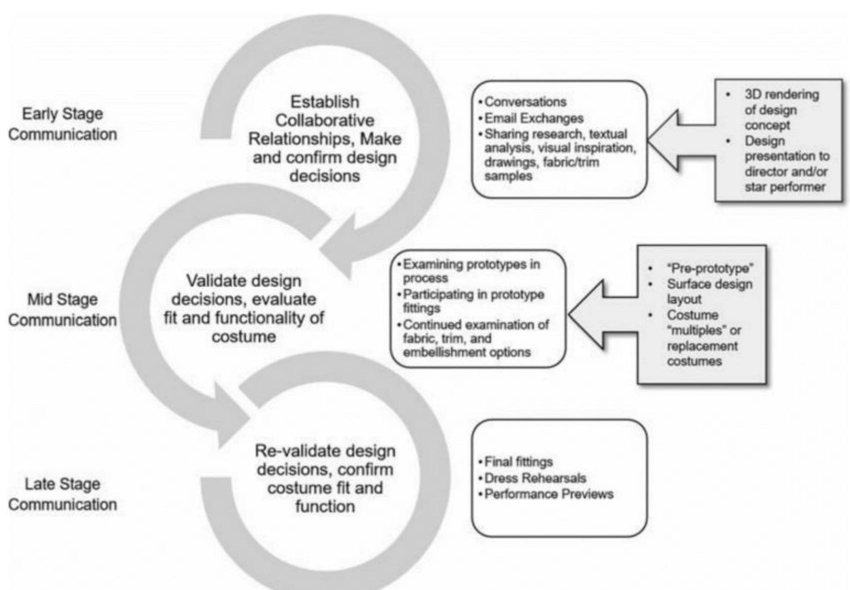


Porterfield and Lamar (2021) developed a framework organized with three communication stages showing how 3D apparel visualization software can fit into the costume design and production process to enhance communication and the quality and timing of communication and collaboration (Figure 6). The costume design and production process framework denoted the process through which designer and maker pass from making and confirming design decisions (early-stage communication), validating design decisions and evaluating fit and functionality of costume (mid-stage communication), re-validating design decisions, and confirming costume fit and function (late-stage communication) (Porterfield & Lamar, 2021). The study was conducted in two phases. Based on expert interviews, a framework of the basic costume design and production process was outlined, and additional findings from virtual fittings were added to the framework to reflect the potential incorporation of 3D apparel visualization software. For data analysis, interview transcripts were examined for themes pertaining to the process, such as preparation, sequencing of events, required personnel, activities, objectives, and results, were analyzed by reviewing transcripts of expert interviews (Porterfield & Lamar, 2021). Provisional coding themes related to the costume design and production process were predefined and confirmed through a constant comparative process. The study found the value of using 3D apparel visualization software to visually communicate and make design decisions in the early stage of the costume development process, optimizing the time with the performer for an actual fitting (Porterfield & Lamar, 2021).

The findings of these studies highlight the valuable contribution of academic conceptual frameworks and qualitative research methods to the comprehension and comprehensive examination of the integration and enhancement of processes in textile design engineering and costume design and production through the incorporation of new technologies.

Figure 6

Costume Design and Production Process Framework (Porterfield & Lamar, 2021, p. 96)



Summary of Literature Review

3D apparel visualization software is emerging as a disruptive technology that can streamline the fashion and apparel industry's traditional product development process and global supply chain. Many researchers have focused on users' perceptions toward 3D apparel visualization software at an individual level, yet there is a lack of literature addressing the decision-making factors of adopting 3D apparel visualization software as firm-wide initiatives at an organizational level. Furthermore, little is known about how 3D apparel visualization software can be used to develop functional clothing, especially in the firefighting gear sector. Therefore, this research will explore the potential opportunities to embed 3D apparel visualization software for the product design and development process of a wildland firefighting protective clothing company. An action research approach will facilitate examination of a wildland firefighting protective clothing company's understanding of 3D apparel visualization software and their perception of adopting the software for their business to improve the current practice. Action research is an interventionist method for studying technology in its natural context of everyday use (Susman & Evered, 1978). Utilizing this research method could effectively develop useful knowledge for both research and practice through the active participation of researchers and participants in the co-construction of knowledge. Moreover, two academic conceptual models illustrating textile design and engineering, as well as costume design production, present how data analysis and visualization can effectively facilitate a thorough exploration of technology integration within the process of product design and development.

CHAPTER 3 METHODOLOGY

As demonstrated in the literature review, 3D apparel visualization software is emerging as a disruptive technology that has the potential to streamline the traditional product development process of the fashion and apparel industry. Nonetheless, there is still a lack of scholarly information and empirical research addressing a company's perception of firm-level technology initiatives. Little is known about how 3D apparel visualization software can be used to develop functional clothing from the manufacturer's perspective, especially in the firefighting gear sector. This research was designed to explore how to introduce 3D apparel visualization software into an industrial wildland firefighting protective clothing development process. To achieve the purpose of this study, the following research objectives were established:

Research Objective 1: Identify the potential opportunities to embed 3D apparel visualization software for the product design and development process of a wildland firefighting protective clothing company (Company A).

- Sub-objective 1-1: Understand the stages and activities of the current product design and development process of a wildland firefighting uniform company
- Sub-objective 1-2: Investigate key features and functions of 3D apparel visualization software that can be used for the stages and activities identified in sub-objective 1-1.
- Sub-objective 1-3: Identify drivers and barriers to adopting 3D apparel visualization software in the context of the features and functions established in sub-objective 1-2.

Research Objective 2: Capture the experiences of personnel from other firefighting personal protective clothing manufacturing companies in 3D apparel visualization software adoption and use to compare them with the experiences of Company A.

Research Process

To fulfill the research objectives, this research was carried out using qualitative methods in two phases: 1) action research and 2) in-depth interviews with multiple companies. Table 1 shows an overview of the methodology. In phase one, which addressed Research Objective 1, researchers and participants jointly identified the company's situated problems, specified the plans for learning 3D apparel visualization software to improve the problem situations, assessed the result of each interactive interview session, and summed up the learning outcomes of the action research cycles. The cyclic action research model proposed by Susman & Evered (1978) frequently serves as a foundational framework for exploring the structures of action research (Øgland, 2007). Action research consists of cycles of diagnosing, action planning, action taking, evaluation, and reflective learning stages (Susman & Evered, 1978). Table 2 presents two action research cycles for the present phase one study and how each interview fell into each stage of the action research cycle.

Throughout the action taking and evaluation stages of the first action research cycle, the principal investigator entered the action research setting as an instructor to facilitate the participants' learning of 3D apparel visualization software so they could envision how the software could be integrated for their business to address any needs or make improvements in the precedent practices of the company. Each interview was transcribed, and categories were identified using a priori coding and emergent coding from the transcripts. The discovered categories were organized into a process-oriented diagram. The results were used to outline frameworks of (i) the basic wildland firefighting protective clothing design and development process, and (ii) how 3D apparel visualization software might fit into the wildland firefighting protective clothing design and development process (Chapman, 2008; Porterfield & Lamar, 2021).

Table 1

Research Methodology

	Research methods	Sample design	Data collection	Data analysis
RO1	Action research	Expert sampling	Audio & video recordings, transcripts, notes, 3D images, 2D patterns	Coding, Identifying categories based on both a priori and emerging coding
RO2	In-depth interviews	Expert sampling	Audio & video recordings, transcripts, notes	Coding, Identifying categories based on emerging coding

In phase two, which addressed Research Objective 2, five additional firefighting gear manufacturing companies were interviewed to explore multiple realities and different perspectives of the same technology. The experiences resulting from the phase one action research were compared with that of other firefighting gear manufacturing companies in the context of drivers and barriers to integrating 3D apparel visualization software for the product development process and for their business in general. The five interviews were recorded, transcribed, and coded to investigate participants' varying degrees of willingness to adopt or continue the technology. Thematic analysis was conducted on the transcriptions of the five interviews to identify patterns and themes within each company, as well as across the companies (Creswell & Clark, 2011; Heydarian, 2016). Results from in-depth interviews with multiple companies were used to gain insights into the integrative and multifaceted experiences of 3D apparel visualization software among firefighting gear manufacturing companies.

Table 2

Action Research Plan of Phase One Study by Research Cycle Stage

<table>
<tr><th></th><th>1st Action Research Cycle
(Preliminary interview and interviews 1 to 4)</th><th>2nd Action Research Cycle
(Interview 5)</th></tr>
<tr><td colspan="3">Research Objective 1: Identify the potential opportunities to embed 3D apparel visualization software for the product design and development process of a wildland firefighting protective clothing company.</td></tr>
<tr><td colspan="3">Susman and Evered's (1978) five stages of the action research cycle</td></tr>
<tr><td>Diagnosing
(Sub-Objective 1)</td><td>◆ A preliminary interview
- Identified potential needs or solving a problem in the current practice</td><td rowspan="2">◆ After completing the 1st cycle, detailed interview protocols and questions will be decided based on participants’ new needs and requests</td></tr>
<tr><td>Action Planning
(Sub-Objective 2)</td><td>◆ Establish action research plan in detail
◆ Decide features and functions of 3D apparel visualization software to introduce for each interview</td></tr>
<tr><td>Action Taking
(Sub-Objective 3)</td><td rowspan="2">◆ Conduct four interviews with given learning modules and 3D apparel visualization software demonstrations, asking
- Participants’ experiences of using 3D apparel visualization software for their product design and development process
- Participants’ new needs and possible revisions for future interview plans</td><td rowspan="3">◆ A one-time interview
- Evaluate the whole action research process and potential future action plan
- Validate rudimentary frameworks as part of member checking
◆ The frameworks were revised and refined based on participants' additional feedbacks and assessment</td></tr>
<tr><td>Evaluation
(Sub-Objective 3)</td></tr>
<tr><td>Reflective Learning
(Encompasses all sub-objectives)</td><td>◆ A principal investigator's reflection, data analysis, documentation, participants' member checking, and planning for the following interview content
◆ Establish frameworks for (i) the basic wildland firefighting protective clothing design and development process, and (ii) 3D product design and development process</td></tr>
</table>

Phase 1: Action Research

An action research approach involves the active participation of researchers and subjects in the co-construction of knowledge (McIntyre, 2007). Action research was chosen because an action research study provides the opportunity for both a principal investigator and participants (co-researchers) to focus on Company A's own practice and form an intention of improvement. Furthermore, action research allows for interactive learning sessions, as well as giving participants a voice in designing future action research plans and interviews based on their emerging needs (Rust & Clark, 2007). In the action research phase, the principal investigator closely interacted with Company A to investigate how their experiences with learning 3D apparel visualization software reveal the drivers and barriers to its adoption within their product design and development process. The findings from phase one addressed RO1: *identify the potential opportunities to embed 3D apparel visualization software for the product design and development process of a wildland firefighting protective clothing company.*

Sample Selection. An expert sampling approach was used in both phases of this research to recruit industry professionals working in the field of firefighting protective clothing. Expert sampling refers to selecting subjects who are experts in a particular field to be the subjects of the purposive sampling (Etikan et al., 2016). Sampling from experts can contribute to the acquisition of specialized knowledge and real-world experience related to firefighting gear. This, in turn, facilitates the collection of high-quality data necessary for investigating the potential of introducing 3D apparel visualization software into the industrial product design and development process of wildland firefighting protective clothing, with a particular focus on the manufacturer's perspective. In the phase one study, the participating company was a wildland firefighting protective clothing company located within the United States with less than ten years' history and with two employees. Selection criteria included the participants' willingness to participate in a series of interactive learning sessions for 3D apparel visualization software. The two employees of the selected wildland firefighting protective clothing company were participants and co-researchers of this phase one study. One participant is a garment designer who makes technical packages, sources materials, and works with manufacturers and pattern makers to ensure fit and sizing as needed. The other participant takes charge of accounting, marketing, customer relationship management, and communication with the company's distributors, retailers, and customers. Data in the form of interview quotes are used to support the findings, and participants were referred to as participant A1 for a garment designer and participant A2 for a business manager.

Action Research Plan Overview. The action research phase followed Susman and Evered's (1978) cyclical action research design, one of the most widely adopted in social sciences (Davison et al. 2004). The method formalizes five stages of the action research cycle: diagnosing, action planning, action taking, evaluation, and reflective learning. The preliminary interview conducted in May 2021 and the subsequent five interviews, divided into two cycles (1st cycle: interviews 1 to 4 and 2nd cycle: interview 5), aimed to explore the evolving perspective of a wildland firefighting protective clothing company regarding the adoption of 3D apparel visualization software. These interviews formed the basis of an interactive learning-based action research approach, as outlined in Table 1 (p. 42).

The First Action Research Cycle. The first action research cycle consisted of a preliminary interview and four interviews with given learning modules and 3D apparel visualization software demonstrations. The purpose of the first action research cycle was to establish rudimentary frameworks for (i) the basic wildland firefighting protective clothing design and development process, and (ii) 3D product design and development process to visualize where and how 3D apparel visualization software might fit into the wildland firefighting protective clothing design and development process. A preliminary interview was conducted as part of the diagnosing and action planning stages, and four separate interviews were conducted to execute the action taking and evaluation stages of the first research cycle.

Diagnosing and Action Planning Stages. A preliminary interview was conducted as part of the diagnosing and action planning stages. Many qualitative action research studies begin with in-depth interviews of participants as part of the planning process and then engage participants as co-researchers in a problem-solving process, and often conclude with individual or focus group interviews reflecting on the process (Merriam & Tisdell, 2015). The key purpose of the preliminary interview was to identify Company A's potential need to solve a problem in the current product design and development process. Moreover, participants' initial views or experiences of 3D apparel visualization software, participants' needs, and current practice were explored to formulate plans for the research process. On that basis, the action planning stage was followed by development of topics for features and functions of 3D apparel visualization software to introduce and design interview protocols and questions for each interview. The complete interview protocols and questions are in Appendix B.

Action Taking and Evaluation Stages. Action and evaluating stages were carried out through four interviews with participants A1 and A2. For each interview, the principal investigator served as an instructor to facilitate the participants' 3D apparel visualization software learning. Diverse learning modules (PowerPoint slides, recorded software videos, images, and live software demos) were provided to introduce different functions and features in each interview, and each interview session was an interactive learning process. Providing learning modules as a means of educational intervention was intended to broaden participants' understanding of 3D apparel visualization software and facilitate participants' contemplation of how it could improve Company A's product design and development process. A set of pattern pieces of a shirt and a pair of pants designed by the company were used to simulate 3D virtual garments to demonstrate in the interviews. Demonstrating features and functions of 3D apparel visualization software using Company A's pattern pieces assisted participants in generating insights on integrating the software for developing their wildland firefighting protective clothing. Figure 7 illustrates the virtual garment simulation images of wildland firefighting protective clothing made with the pattern pieces provided by the participating company.

Throughout the four interactive interviews, the principal investigator interviewed the participants about their experiences of demonstrated features and functions of 3D apparel visualization software. Each interview was designed based on the previous interview data but contained some interview questions about how the participants envisioned embedding the software into their current product design and development process and perceived drivers and barriers to adopting and implementing the technology. Each interview concluded with a comprehensive discussion encompassing participants' perspectives on learning, feedback, and assessment, potential adjustments for future interview plans, as well as their emerging needs. This permitted the participants and researchers to sum up the learning outcomes, make decisions and improve the interview process throughout implementation.

Figure 7

The Virtual Garment Images of the Participating Company's Wildland Firefighting Protective Clothing Created by the Researcher in CLO3D

Reflective Learning Stage. After completing each interview, the reflective learning stage was followed by the principal investigator's reflection, data analysis, documentation, participants' member checking, and planning for the following interview content. The resulting products of the first action research cycle were frameworks of (i) the basic wildland firefighting protective clothing design and development process, and (ii) how 3D apparel visualization software might fit into the wildland firefighting protective clothing design and development process. In the interpretation process for the cycle one data, any new questions that needed to be asked that were raised by the data were checked in the cycle two interview.

The Second Action Research Cycle. After completing the first action research cycle composed of four interviews and conducting data analysis, rudimentary frameworks for (i) the basic wildland firefighting protective clothing design and development process, and (ii) the 3D product design and development process were established. Subsequently, action taking, evaluation, and reflective learning stages of the second action research cycle were embarked on through a single interview with participants. Before conducting the interview, both participants and researchers discussed participants' new needs and decided on detailed interview topics and protocols by mutual consent as part of the diagnosing and action planning stages.

During the single interview for the second cycle, participants validated rudimentary frameworks for (i) the basic wildland firefighting protective clothing design and development process, and (ii) the 3D product design and development process developed by the principal investigastor as part of member checking. Thus, the frameworks were revised and refined based on participants' additional feedback and assessment. Moreover, the principal investigator and participants evaluated the whole action research process and discussed potential future action plans to apply the findings to their own practice. The principal investigator and participants outlined a strategy for documenting and disseminating the research results and findings, which involved presenting them at academic conferences and publishing articles (Mertler, 2019). During the reflective learning stage of the first and second action research cycles, the principal investigator engaged with dissertation advisors to assess the suitability of the collected data in addressing the research objective. Insights drawn from the research and identified implications for other situations and research contexts were documented. After the second action research cycle, the frameworks for (i) the basic wildland firefighting protective clothing design and development process, and (ii) the 3D product design and development process were confirmed and revised based on participants' additional feedback and assessment.

Preliminary Interview: The First Cycle's Diagnosing and Action Planning Stages. The findings from the preliminary interview were utilized to establish the direction of the action research plan and future interview topics. The preliminary interview was transcribed, and open coding was used to identify phrases related to the company's experience with 3D apparel visualization software and needs or problems in the current practice. The identified categories included 1) participants' experience in using 3D apparel visualization software, 2) curiosity about 3D apparel visualization software, 3) a need for solving a problem in the current practice, and 4) interoperability of 3D virtual garment data. Detailed findings of the interview are described in Chapter 4, where data in the form of interview quotes are used to support the design of subsequent interviews.

Four Interactive Interviews: The First Cycle's Action Taking and Evaluation Stages. The findings from the preliminary interview established the features and functions of 3D apparel visualization software to demonstrate for each interview. Each interview focused on a different topic: 1) 3D garment design, 2) virtual avatar, 3) virtual fit assessment, and 4) how to utilize 3D data across supply chain. Because it is easily accessible to the primary investigator, CLO 3D was mainly used throughout four interviews to create learning modules and answer participants' questions in real-time during each interview. Appendix C denotes plans for the demonstration sequence of 3D apparel visualization software for each interview based on types of learning modules.

Interviews focused on identifying at which stage and for which activity 3D apparel visualization software could be employed in the current product development process. In addition, participants' experiences of 3D apparel visualization software, drivers and barriers to adopting 3D apparel technology in the context of the features and functions, and decision factors related to implementing 3D apparel visualization software for their company were identified. Interview questions for the first interview were developed to validate the basic product design and development model and capture participants' first impressions of the general overview of 3D apparel visualization software. The remaining three interviews were designed based on the findings from the previous interview session.

Interview 1. The first interview session aimed to complete a rudimentary model of the basic wildland firefighting protective clothing design and development process and capture participants' first impressions of the general overview of 3D apparel visualization software. The principal investigator presented an initial model of the basic wildland firefighting protective clothing design and development process based on the findings of the preliminary interview. Participants reviewed the model and were asked to provide comments and suggestions. Regarding the learning modules of 3D apparel visualization software, the process of creating a 3D virtual garment with a set of 2D pattern pieces, garment fit map features, and 3D asset libraries such as virtual fabric, trim, and avatar in the software were introduced. Table 3 denotes the list of interview questions.

Table 3

First interview questions

Topic	Interview Question
Validate the basic product design and development model (Lou, 2020; Porterfield & Lamar, 2021)	*Tell me about your process for designing and developing wildland firefighting protective clothing.*
	Please check the stages and activities that are included in your design and development process of this model. Could you add or remove any activities as needed?
	Do you have any other comments or suggestions for this model?
	Please indicate the time and the resource loading needed for each activity.
	Do you have cyclic activities repeated within the design and development process?
Perceived Characteristics of Innovation (Lee, 2004; Dooley & Murphrey, 2000; Harting et al., 2009)	*What do you think about 3D apparel visualization software?*
	Where do you think using 3D apparel visualization software fits within your company's product design and development process?
	How will it affect your product design and development process?
	To what extent do you perceive 3D apparel visualization software as helpful or as a solution for any problems you probably encountered in the past?
	What suggestions would you offer for adopting or implementing the software?
	What do you think are the advantages/disadvantages of this software?
Influential factors and adoption intention (Cobos et al., 2016; Foster, 2017)	*What are the main factors which influence the adoption of 3D apparel visualization software?*
	Do you consider implementing 3D apparel visualization software for your business with the current understanding? Why?
Action research evaluation (Created by author)	*What other issues were not covered here that you believe are relevant to this study, and would you like to discuss them?*
	How was your experience learning 3D apparel visualization software from today's interview?
	How could learning modules be improved to enhance your learning and understanding of 3D apparel visualization software?
	Do you have any suggestions for designing the future interview and learning modules?
	Do you have any requests for me for the next interview?

Interview 2. The second interview session aimed to explore participants' experiences of using a virtual avatar and grading tools, how these features can be utilized in the current product design and development process, and drivers and barriers to adopting 3D apparel technology in the context of the features and functions. Regarding the learning modules of 3D apparel visualization software, the principal investigator demonstrated how to customize the avatar's size and posture and use avatar tape measurement, garment fit maps, and basic grading and auto-grading tools to perform a virtual fit assessment in the software.

Interview 3. The third interview session aimed to conduct a fit evaluation with a set of wildland firefighting protective clothing (shirts and pants) on a female live model and observe virtual garments on the model's personal avatar in 3D apparel visualization software. The third interview was conducted in person, and participants A1 and A2 and a fit model (female firefighter) visited a research lab at Wilson College of Textiles on January 12, 2023. Before the onsite interview, a female firefighter was recruited, and body scanned to create her avatar. A set of pattern pieces of garments manufactured by the participating company were virtually sewn on her personal avatar in 3D apparel visualization software. During the onsite interview, the fit model dressed in wildland firefighting protective clothing (shirts and pants) in her size and took multiple postures. During the fitting, the participants observed the fit appearance of their actual garments and checked the fit model's subjective fit and comfort judgments. Subsequently, the participants observed virtual garments on the fit model's generated avatar in 3D apparel visualization software and compared the fit appearance of actual and virtual garments to examine the accuracy of the software simulation.

Interview 4. The fourth interview session aimed to explore participants' experiences of sharing and utilizing 3D virtual garment data and information across the supply chain. Learning modules described how fashion and apparel brands and retailers adopt photorealistic rendered images and videos, 3D asset libraries (fabric, garment block, and avatar), and web-based collaborative platforms to scale 3D digital design practices throughout the industry's supply chain and collaborate with diverse stakeholders. Participants were asked how those 3D digital features and resources could be integrated into their workflow, assuming they are implementing 3D apparel visualization software for their company.

Data Analysis: The First Cycle's Reflective Learning Stage. In general, qualitative data analysis consists of three major steps: 1) preparing/organizing the data, 2) reduction of data into categories by coding, and 3) representing the data in figures, tables, and/or narrative (Creswell, 2007). Coding involves taking non-numerical data and extracting meaning from it (Hesse-Biber & Leavy, 2011, p. 309). Creswell states that the fundamentals of qualitative data analysis involve "coding the data into meaningful segments and assigning names to the segments, then combining the codes into broader categories or themes, and finally displaying and making comparisons in the data graphs, tables, charts, or discussion" (p. 148).

Coding. For this research, each interview was transcribed, and a combination of a priori coding and emergent coding was used to analyze the transcripts (Creswell, 2007). Essentially, a priori coding refers to the use of predetermined codes that are typically based on the literature, research questions, individual questions asked in the interviews, and preliminary method of data collection (Busetto et al., 2020; Creswell, 2007). Regarding a priori coding, the transcripts were coded for responses relating to addressing the needs or problems in Company A's current product development practice that had been identified from the preliminary interview. Sentences or phrases relating to potential opportunities to embed 3D apparel visualization software to 1) streamline company activities and better manage the time in the preproduction stage and 2) communicate the measurements, sizing, fit, and grading issues precisely with pattern makers and manufacturers were highlighted and labeled (Corbin & Strauss, 2008; Merriam & Tisdell, 2015). For example, responses showing *avatar*, *pattern alteration*, *virtual fitting process steps*, *prototyping*, *fit assessment*, *grading*, *measurement issues*, *pressure and tension maps, fit and sizing communication*, *fit appearance*, *virtual fabric*, *communication*, *and interoperability of 3D virtual garment* were searched from each interview. Furthermore, additional insights into the key features and functions of 3D apparel visualization software and perceived drivers and barriers to using those features and functions were also noted.

***Categorizing*.** The labeled sentences or phrases were sorted, and similar codes were assembled together into more general, higher-level, and more abstract categories reflecting stages and activities of product design and development process related to the preparation, the order of events, necessary resources, activities, goals, and expected outcomes (Porterfield & Lamar, 2021; Richards & Morse, 2013). The categories were supported by diverse quotations and ordered as a series of actions and graphically represented into a flow diagram of a 3D product design and development process (Creswell, 2018). The 3D product design and development process consisted of a series of diagrams depicting where 3D apparel visualization software can be integrated into activities and stages of the basic product development process of a wildland firefighting protective clothing company.

***Conceptual Frameworks*.** The current action research study drew upon previous studies and conceptual frameworks to guide its data collection and analysis. One aspect of the study involved converting qualitative research data into a visual framework. Inspired by Porterfield and Lamar's (2021) study, transcripts of interactive interviews were coded to identify themes related to the "preparation, the order of events, necessary personnel, activities, goals, and outcomes" (Porterfield & Lamar, 2021, p.94) of the participating company's current wildland firefighting protective clothing design and development process. Additionally, Chapman's (2008) study was referenced to represent the main stages and activities of product design and development using arrows and shapes, indicating activity order and listing inputs and outputs. Moreover, in the present research, Porterfield and Lamar's (2021) study served as a reference for delineating the elements (objectives, tasks, and software capabilities) and the procedure of constructing a framework for the potential utilization of 3D simulation in the existing product design and development process.

Additionally, the action research study employed multiple steps in data collection to refine the process-oriented visual frameworks. Both the introduced studies utilized various data sources, methods, and participants to establish the initial framework and develop the final framework for validation and completion (Chapman, 2008; Porterfield & Lamar, 2021). Although the participant group and data sources remained consistent in the current action research study, additional data collection was conducted after establishing the basic wildland firefighting protective clothing design and development process. This supplementary data collection led to the establishment of a framework illustrating the integration of 3D apparel visualization software within the basic product design and development process. Additionally, both visual frameworks of (i) the basic wildland firefighting protective clothing design and development process and (ii) the 3D product design and development process underwent refinement based on participant feedback and reviews to produce the final versions.

Single Interview: The Second Cycle's Action Taking, Evaluation, and Reflective Learning Stages. Action research is primarily focused on addressing practical problems or developing interventions, with the objective of examining their overall impact and understanding the unfolding process (Herr & Anderson, 2014). In the current study, initial frameworks of (i) the basic wildland firefighting protective clothing design and development process, and (ii) the 3D product design and development process were established from the first action research cycle findings. In the second action research cycle, one additional interview of participants was conducted to validate the established frameworks and reflect on the whole action research process. The primary investigator shared and explained what the two conceptual frameworks indicate, and participants were asked questions regarding whether they believe these frameworks effectively represent the potential usage of 3D apparel visualization software as they perceive it, what content should be modified or supplemented, and whether they agree with the content. Moreover, the participants shared their impressions of participating in a series of interviews to learn about different features and functions of 3D apparel visualization software, whether they were satisfied with the results, and how they would incorporate the findings into their business. The participants also discussed with the primary investigator what improvements could be made if they were to participate in this type of action research again. After the interview, the frameworks were completed based on participants' additional feedback and assessment.

Phase 2: Multiple In-depth Interviews

The phase two study addressed the RO2: *Capture the experiences in 3D apparel visualization software of other firefighting gear manufacturing companies to compare with the perceptions and experiences of Company A.* In the phase one study, data were obtained solely from a single company through action research. The results of action research are context-specific and, as such, cannot be generalized (Dosemagen & Schwalbach, 2019). Therefore, the findings from the phase one study cannot be extrapolated to make predictions or draw conclusions about other firefighting gear companies. Therefore, in phase two of the study, the research scope was broadened to include interviews with additional firefighting gear manufacturing companies. Although the size of the phase two sample still precluded generalization, this expansion aimed to examine different levels and perspectives of the same phenomenon and contribute to the validity of the study findings (Denzin, 2006; Denzin, 2009). By incorporating various companies, the study sought to explore variations within the company context, specifically in relation to different product sectors (structural turnout gear and wildland fire gear) and varying levels of prior experience with the adoption of 3D apparel visualization software in the respective roles of the participants. This method was employed to enable identification of distinct and recurring categories among the responses, allowing for the derivation of more comprehensive and dependable conclusions regarding firefighting gear manufacturers' experiences with 3D apparel visualization software.

In-depth interviews offer important information, especially when supplementing other data collection methods, even though the results are not generalizable due to the small sample size and lack of a random sampling method (Legard et al., 2003). Collecting data from multiple firefighting personal protective clothing and equipment companies can contribute to discovering multiple realities and generating richer knowledge under various organizational circumstances by adding insights from multiple respondents (Denzin, 2006; Denzin, 2009). The results of the action research were compared with results of the phase two interviews in the context of 3D apparel visualization software implementation and technology adoption in general. Moreover, organizational and environmental factors of firefighting protective clothing manufacturing companies that might influence the research findings were also identified.

Sample Selection. For the phase two interviews, an expert sampling approach was used to recruit industry professionals working in the field of structural turnout gear and wildland fire gear. There are numerous disputes over the appropriate sample size for an in-depth interview. Most scholars insist that the concept of saturation is an essential aspect to consider when deciding on sample size in qualitative research (Mason, 2010). Saturation occurs when the same stories, themes, issues, and topics emerge from respondents, so it no longer offers any new or relevant data (Dworkin, 2012). Many articles, book chapters, and books propose guidance and recommend 5 to 50 participants as acceptable (Dworkin, 2012). The phase two study recruited ten representatives from five different firefighting gear manufacturing companies, which is close to the minimum acceptable number of participants in qualitative research. Currently, the number of firefighting gear manufacturers within the United States is projected to be fewer than twenty based on a simple Google search. Moreover, sample sizes for qualitative research in feasibility studies are usually small in practice, typically between 5 and 20 individuals (O'Cathain et al., 2015). The principal investigator established a comprehensive list of manufacturing companies for both structural turnout gear and wildland fire gear and reached out to potential participants through a formal email and by contacting customer service, requesting their participation. In this study, experts in product development or technical design positions who were willing to participate in an in-depth interview were recruited.

Data Collection. In phase two, online interviews of representatives from five firefighting gear manufacturing companies lasting two hours each were conducted via Zoom from March 2023 to April 2023. Each interview included one to three representatives of a single company.

The research objective of the phase two study was to comprehensively explore and compare the experiences of participants from various manufacturing companies in adopting 3D apparel visualization software, contrasting these experiences with those of Company A. Consequently, the interview questions in the phase two study were tailored based on the insights derived from the phase one study. Given that the phase one study unveiled distinct categories related to perceived drivers and barriers concerning the utilization of 3D apparel visualization software in the product design and development process, the interview questions in the phase two study were specifically crafted to inquire about the technology utilization experiences of firefighting gear professionals. These questions aimed to explore their perceptions of the software's usefulness and the obstacles they had faced or anticipated encountering when using it for their roles. Furthermore, the interview questions sought to identify the drivers and barriers specific to the firefighting gear industry in adopting this software. The interview questions were adapted and customized based on the studies of Cobos et al. (2016) and Foster (2017). The complete interview questions are listed in Appendix E. Prior to the interview, the principal investigator offered a concise overview of CLO3D fashion design software's features and functionalities, especially for individuals lacking prior familiarity with any form of 3D apparel visualization software. The primary investigator and participants began the interview by collectively looking at the website of CLO3D fashion design software provider.

Data Analysis. After collecting data from all respondents from five participating companies, thematic analysis of the interview transcripts was carried out to identify patterns and themes at two levels, within each company and across the companies (Coffey & Atkinson, 1996; Creswell & Clark, 2011; Heydarian, 2016). To provide a comprehensive perspective of the investigated phenomenon, both inductive and deductive data analysis approaches were utilized

(Blackstone, 2018; Hyde, 2000). The data was initially organized inductively into increasingly abstract units of information. Then, the primary investigator revisited the transcript data in relation to the identified themes to determine whether more evidence could support each theme or if additional information needed to be gathered. The researcher moved back and forth among the data, gradually advancing from coding to conceptual categories (Lichtman, 2012), and subsequently gaining an understanding of the realities of firefighting gear manufacturing companies' thoughts and experiences in using 3D apparel visualization software for their product design and development process. Emerging themes and findings were distinguished and contrasted with the responses of Company A from the phase one study.

Minimizing Bias

The potential for researcher bias in the phase one action research study was minimized by actively involving the research participants in checking and confirming the results (Merriam & Tisdell, 2015). After each interview, they were provided with opportunities to review the summarized analyses and examine rudimentary frameworks and final reports throughout the second action research cycle (Mills, 2011; Stringer, 2007). This can enhance the rigor of the research by allowing participants to verify that various aspects of the research process adequately and accurately represent their beliefs, perspectives, and experiences (Mertler, 2019). It also allows them to explain further or extend the information they have already provided and create opportunities to add data (Harvey, 2015; Mertler, 2019).

The potential for bias in the phase two in-depth interview study was minimized through several strategies. An interview protocol was developed and followed, which consisted of an introduction, a set of open-ended questions, follow-up questions, and a conclusion. This standardized protocol ensured that the primary investigator's approach remained consistent across different researchers (Gibbs, 2007). To enhance the trustworthiness of the findings, data were collected from diverse participants recruited from different companies, allowing for a comparison of different approaches to the same phenomenon (Bilgili, 2005).

In qualitative research, the principal investigator often serves as both the data collector and data analyst, giving potential for researcher bias by imposing personal beliefs and interests on the research process (Mason, 2002; Miles & Huberman, 1994). In order to mitigate bias, a detailed description was provided to assess the appropriateness of the collected data in addressing the research objectives (Yin, 2009). In addition, a thorough peer examination was carried out through a review of findings by dissertation advisors (Merriam & Tisdell, 2015).

Summary of Methodology

Qualitative methods were used for this research. The research was conducted in two phases, each informing the next. First, action research was conducted with Company A, focusing on their experience and insights. The text data gathered from five interviews with two representatives was organized, coded, and analyzed. A framework was developed to depict where and how 3D apparel visualization software might fit into the wildland firefighting protective clothing design and development process. Second, five additional firefighting protective clothing companies were interviewed to add multiple realities and richer knowledge. The 3D product design and development process for wildland firefighting protective clothing companies will be expanded, refined, and completed as the final result of this research. The experiences of other firefighting protective clothing manufacturing companies in adopting 3D apparel visualization software were compared with those of Company A to gain insights into the integrative and multifaceted perceptions among firefighting gear manufacturing companies.

CHAPTER 4 RESULTS

Introduction

This chapter presents the results of analyses that addressed the research objectives through the utilization of qualitative methods conducted in two distinct phases: 1) action research and 2) in-depth interviews conducted with multiple companies. First, the results of the preliminary interview in the phase one action research study are presented as categories derived from the data, focusing on the themes of Company A's current wildland firefighting protective clothing design and development process. Moreover, the categories identified in the preliminary interview data pertaining to Company A's needs for problem-solving within their existing practices are presented. Secondly, the findings from the four interactive interviews conducted during the action research study with Company A are presented as categories derived from the data, focusing on the themes of perceived drivers and barriers regarding the utilization of 3D apparel visualization software in their product design and development process. Thirdly, an analysis of the action research participatory process is provided. Fourthly, the participants' reflection on taking part in action research through one additional interview is described. Lastly, the results of phase two's in-depth interviews with participants from five firefighting gear manufacturing companies are presented as categories, focusing on the perceived drivers and barriers to adoption and utilization of 3D apparel visualization software.

Phase 1: Action Research

An action research approach was employed in the phase one study to address *research objective #1* (Identify the potential opportunities to embed 3D apparel visualization software into the product design and development process of a wildland firefighting protective clothing company (Company A)). The two action research cycles for the action research study included a preliminary interview (diagnosing stage of 1st cycle), four interactive interviews (action taking and evaluation stages of 1st cycle), and a single follow-up interview (action taking and evaluation stages of 2nd cycle). The data analysis and documentation of findings presented in this chapter functioned as a reflective learning stage within the two action research cycles. Data in the form of interview quotes are used to support the findings, and participants were referred to as participant A1 for a garment designer and participant A2 for a business manager. The six interviews were recorded, transcribed, and coded to document outcomes and evaluate whether the learning intervention proceeded as planned (Davison et al., 2004). The data analysis and documentation of findings presented in this chapter functioned as a reflective learning stage within the two action research cycles.

Preliminary Interview Findings

The findings from the preliminary interview were utilized to establish the initial framework portraying Company A's current product design and development process. Three main stages emerged from the data, describing the participating company's product design and development workflow: 1) design ideation, 2) product development, and 3) business development. The initial framework provided a fundamental basis for the subsequent conceptual frameworks that illustrate the integration of 3D apparel visualization software into the product design and development process of a wildland firefighting protective clothing company. Moreover, the preliminary interview confirmed potential needs or problems in the participating company's current product design and development process. The findings became the foundation for developing plans for the action research cycles and topics for a series of interactive learning interviews that completed phase one of the research.

Wildland Firefighting Protective Clothing Company's Current Product Design and Development Process. In this section, the findings from the preliminary interview of participants A1 and A2 were analyzed to address *sub-objective #1-1* (Understand the stages and activities of the current product design and development process of a wildland firefighting protective clothing company (Company A). Sentences or phrases relating to the product design and development process such as inputs, order of events, necessary personnel, activities, goals, and outcomes were highlighted and labeled from each interview (Merriam & Tisdell, 2015; Porterfield & Lamar, 2021). Three main stages emerged describing the participating company's product design and development workflow: 1) design ideation, 2) product development and 3) business development. Data in the form of interview quotes are used to support the findings, and participants were referred to as participant A1 for Company A's garment designer and participant A2 for Company A's business manager.

Design Ideation. The participants stated that their goal in the design ideation stage is to establish a new baseline design for wildland firefighting protective clothing. Interview responses indicated that internal organizational communication and communication with firefighters are important for making design decisions at this stage. The participants' responses revealed that the design ideation stage comprises two primary activities: 1) conducting end user research, and 2) analyzing existing outdoor clothing designs.

End user research. Participants reported conducting surveys with firefighters to investigate end users' needs, preferences, and areas for improvement in order to enhance comfort with their current protective clothing. Moreover, the company collects anthropometric data of firefighters by asking them to send their body measurements. The timeline to collect consumer research data varies with fire seasons and firefighters' working shifts. Participant A2 commented:

> If it's during the fire season, we have to consider that the response time may be impacted as firefighters are in and out of their stations. If we do it in the offseason, we may not reach all individuals who will be working during fire season since some may be seasonal or laid off.

The participants' responses indicated the need for a solution capable of facilitating time savings and enhancing the accuracy of body measurements performed on firefighters.

Based on the measurement data provided by firefighters, the company gets an average of body measurments on the different sizes and creates their own sizing and grading rules charts. Participant A1 stated, "*We have noticed that a woman's thigh will be slightly bigger than the average in this field. Because they do intense physical labor and hiking, they typically need that little extra room.*" The company also conducts focus group interviews by recruiting firefighters for wear trials of their products. Getting feedback from firefighters through firsthand wear trials enables designers to confirm and refine design decisions. Participant A1 mentioned:

> We initially designed the cargo flap on the top of the pocket to fold over. However, during the firefighters' live fitting session, we observed that the pocket stretched to its maximum capacity when we added extra items, and the hook and loop tape did not secure as firmly as desired. To address this, we decided to increase the length and width of the hook and loop tape.

In this manner, designers establish a new baseline product while incorporating minor alterations in the positioning, dimensions, and orientation of shirt and pants pockets as well as fasteners, guided by the findings of consumer research.

Analyzing existing clothing designed for outdoor use. In addition, the participants reported that they research different types of outdoor clothing to identify novel sewing techniques and design details available for reference. Participant A2 said, "*We bought many different outdoor pants and shirts and tried them on during hiking to see if they had the feel of the direction we wanted to go with the diverse attributes we put on our products.*" By synthesizing all information, the company excogitates a baseline design that complies with the design and sizing requirements of National Fire Protection Association (NFPA) standards. Based on the results of consumer research and existing outdoor clothing analysis, the team discuss and finalize design decisions for the new baseline product.

Product Development. The participants emphasized that their goal during the product development stage is to maintain consistent fit and quality standards. This involves overseeing the ordering of fabric and trims, manufacturing products based on specifications, and reviewing and validating prototype samples across a complete size range to facilitate quality assurance. Effective communication with manufacturing factories was highlighted as a crucial aspect during this stage. The participants reported that they rely on contract manufacturing and collaborate with pattern makers who are affiliated with the contracted manufacturers, rather than operating their own facilities. The participants' feedback revealed that the product development stage encompasses four primary activities: 1) technical package development, 2) sourcing and prototyping, 3) fit evaluation, and 4) grading.

Technical package development. Participant A1 reported that, after establishing a baseline design, she develops the technical package (tech pack) consisting of flat drawings (front, back, and detail views). After receiving a tech pack, the manufacturing factories develop prototyping samples of the base size. Participant A1 described,

> I make technical packages to send to manufacturing factories and work with pattern makers to make the design happen and make sure they are made the way we want them to be. Before we have a garment, we make a flat drawing in Illustrator to develop the tech pack, and then if we need to tweak something, we take a picture of the actual garment

> and then show and tell them what needs to be done to request another prototyping sample.

In this way, the tech pack is the primary means of communication between the Company A and manufacturing factories which is typical of communication in the product development process (Lee & Steen, 2019).

Sourcing and prototyping. Participants reported that production of prototyping samples and ordering fabrics and trims are handled simultaneously, as final fabrics and trims should be input for the preproduction sample. In terms of sourcing, they explained that every material used for firefighting protective clothing must be certified by the NFPA 1977 standard. Participant A2 described, "*Our sourcing options are limited, so we don't have a wide variety of fabrics to choose from. Even just a few good options would be really nice – we don't necessarily need hundreds of choices*." When selecting an option, the company considers minimum order quantity, price, breathability, and hand of fabric. Participant A1 explained:

> Since we faced difficulty in obtaining the required amount of fabric initially, we used a similar fabric for our first few rounds of prototyping. This alternative fabric closely resembles the final product, so it has no impact on the sizing and fit.

Depending on the price and inventory status, substitute fabrics may also be used in the initial sample production.

Fit Evaluation. Participants reported that the manufacturing factories develop prototyping samples of the base size after receiving a tech pack. When a sample is produced, the garment fit is evaluated to check whether the design specs need to be adjusted or the factory's interpretation of the specs needs to be corrected. The company conducts fit evaluation sessions of a base size sample using live models whose measurements fall within the average range of the base size group. Participants noted that any feedback regarding fit issues, ease of movement, donning/doffing, and utility provided by the fit models during the fitting session should be taken into account to make adjustments to the design specifications or rectify any misinterpretation of the specifications by the factory.

Grading. According to participants, once the sample of a base size is approved, the grade rules (increments) are applied to the perfected base size pattern for larger or smaller sizes. The graded set of samples is then reviewed to ensure that the sizing and details are proportionate across all sizes. The company conducts several different fit evaluation sessions with the fit models with measurements representing each uniform size group. They communicate grading rules with manufacturing factories by sharing hand graded paper patterns with a grading chart. Interview responses implied that the manufacturing factories' interpretation of grading rules could be inconsistent with the designer's intent, and this inconsistency can lead to spending extra time and expenses. Participant A1 said, "*We had to go through several versions because the manufacturer wasn't following the instructions properly. Correcting their mistakes, which included incorrect grading, caused a delay and some additional expenses for adjustments and alterations*." She added, "*They're not following the tech pack, or when I tell them to fix something, they don't do it, and they've changed the sizing on our patterns*." The participants also mentioned that the inclusion of visual aids could potentially enhance ongoing communication between them and the manufacturing company.

Business Development. In the business development stage, participants reported that the company distributes its products via online and offline channels and networks with the firefighting gear community to raise awareness of the brand and its products. Therefore, building collaborative relationships with distributors, firefighters, and NFPA committees is important at this stage. The participants' responses revealed that the business development stage comprises three primary activities: 1) product distribution, 2) public relations, and 3) size recommendation for customers.

Product distribution. The company's products are sold to consumers through their own online website and fire distributors (companies that sell, distribute, and service fire equipment) and wholesalers. Participant A2 stated, "*We could keep the wholesalers and fire distributors separate. For example, there's an outdoor store nearby that sells a wide range of outdoor gear, as well as military and workwear items.*" Fire distributors and wholesalers create their own product catalogs and distribute them to their customers. Company A provides product images for these catalogs, adhering to its own brand guidelines.

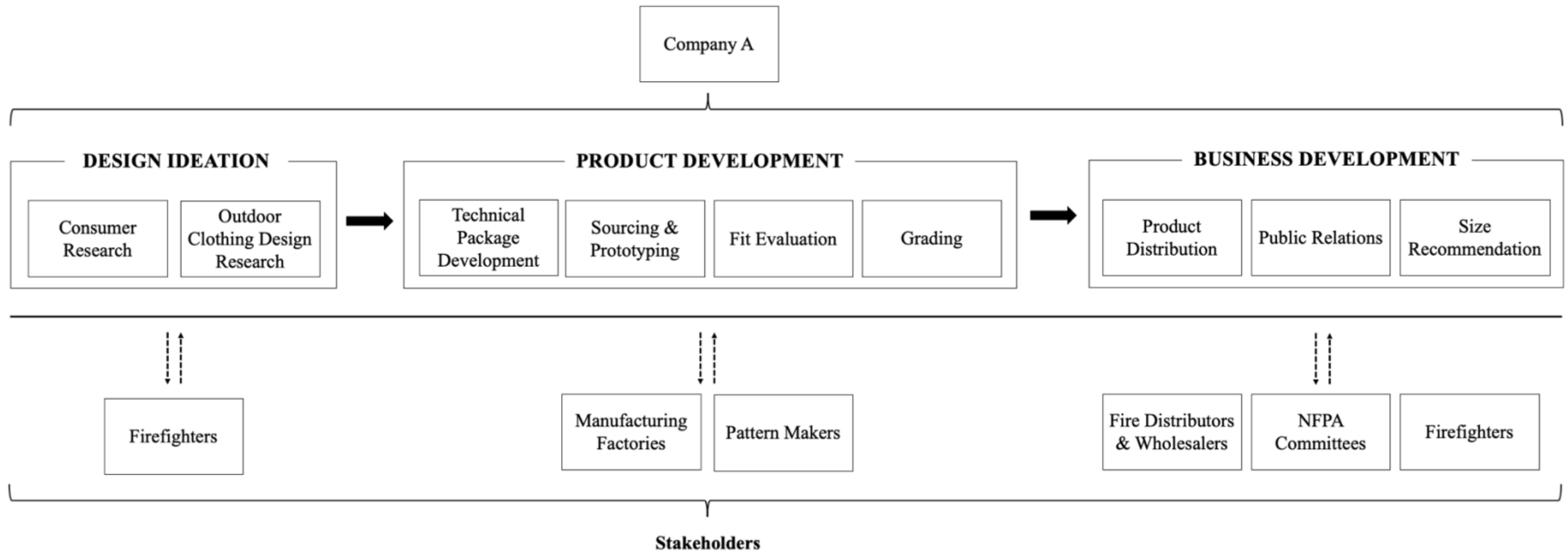
Public relations. The company also tries to raise awareness of their brand and products among distributors and the public by seeking crowdfunding, arranging sales meetings, attending NFPA committee meetings and fire service leadership conferences, and promoting marketing campaigns via social media. Participants A1 and A2 serve as NFPA technical committee members and are responsible for regularly attending meetings to discuss developing and revising standards on protective clothing and equipment for wildland firefighting. Company A also holds a sales meeting with the aim of educating distributors about the company's products and their features.

Size recommendation for customers. Moreover, the company helps customers and end users find their correct sizes by getting their measurements. The participants clarified that they currently provide detailed measurement instructions to their customers, specifying the exact points to measure and the appropriate methods for measurement. *Participant A1 said, "People have to take their measurements, which requires an unbelievable amount of time and effort, to determine their correct size to wear." She also added, "In some cases, there may be a slight* *delay in obtaining measurements from certain individuals due to their fieldwork or travel commitments. Moreover, not everyone possesses a tape measure, particularly the specific type required for accurate measurements*." The participants suggested that there is a potential opportunity to integrate advanced technology for the purpose of streamlining the process of finding an appropriate size for end users.

An Initial Framework. The preliminary interview was transcribed, and sentences or phrases pertaining to the product design and development process, including inputs, order of events, necessary personnel, activities, goals, and outcomes, were identified and annotated to establish an initial framework (Merriam & Tisdell, 2015; Porterfield & Lamar, 2021). The initial framework shows the current product design and development workflow of Company A, which encompasses three primary stages (design ideation, product development, and business development) along with their corresponding activities and participants. These activities represent the essential steps required to achieve the objectives of each stage, with participants identifying the supply chain stakeholders involved in each stage, as discussed in the preceding section. The identified stages and activities were then arranged in a process-oriented visual frameworks as illustrated in Figure 8. These results aided in identifying potential areas where 3D apparel visualization software could be integrated to address Company A's problem-solving needs in the current product design and development process. The findings related to these areas are reported in the following section.

Figure 8

The Current Product Design and Development Process of A Wildland Firefighting Protective Clothing Company (Company A)



Assessing the Company A's Needs for Problem-solving. The preliminary interview additionally served to confirm participants' prior experience in technology usage and identify any needs or challenges within the Company A's current product design and development process that could be potentially met by 3D apparel visualization software implementation. The preliminary findings became the foundation for developing plans for the action research cycles and topics for a series of interactive learning interviews. The identified categories included 1) curiosity about 3D apparel visualization software, 2) a need for solving a problem, and 3) concerns regarding the interoperability of 3D virtual garment data. The findings of the interview are described in the following sections.

Curiosity about 3D Apparel Visualization Software. The preliminary interview confirmed that the two representatives from the participating wildland firefighting protective clothing company have never used three-dimensional apparel design software before, and they were not exactly sure what the 3D apparel visualization software involves, although they had attended a webinar on the subject. Participant A2 said, "*Maybe 3D CAD hasn't been available because the manufacturers and prototypes we've been working with hadn't used it…, so it's just nothing that's been in our repertoire.*" Both participants showed interest in learning about this unfamiliar technology and believed that the use of 3D apparel visualization software could improve their work performance based on their webinar experience. Participant A1 said, "*It seems like you can see the patterns on the different body types so you can see how it's fitting…I think that sounds like gold to me, and it could definitely help to save tons of time*." Participant A2 added, "*It was really intriguing and eye-opening for us...We hear and see a lot of this stuff and put it on our bucket list...*" Thus, in order to address their curiosity regarding the technology, the decision was made to structure the interview sessions as interactive learning sessions, aimed at facilitating the process of learning and discovery.

A Need for Solving a Problem. When asked about their present product design and development practices, participants expressed a desire to streamline company activities and enhance time management, specifically focusing on the product development stage. Typically, the participants engage in reviewing two to three physical samples to make design and construction decisions for final approval, while also conducting multiple fit sessions with models of different sizes. Participant A1 highlighted the impact of sample approval on production timelines, stating, "*Now we can't start production until sample approval is done, and so that's why we got put back an extra six months because manufacturers had to do everything again, then we'd be another couple months out for sampling*." The production of physical samples involves numerous activities and steps, often necessitating multiple reviews and revision rounds (Lee & Steen, 2019).

Furthermore, the participants conveyed their goal to pinpoint and address sizing and fit issues directly with pattern makers and manufacturers in order to ensure precise fit accuracy. Company A collaborates with multiple manufacturers across the United States, but has encountered challenges related to miscommunication and misinformation in pattern making and grading. Participant A1 shared her experience, stating, "*Sometimes I tell pattern makers and manufacturers to fix something, but they don't fix it but change the sizing on our patterns...With the same pattern, they might miss an articulation or interpret it differently*." She further explained, "*I typically do hand grading and provide that to the manufacturer...We had to go through several iterations of grading because the manufacturer wasn't fully adhering to it*."

Consequently, the integration of 3D apparel visualization software emerged as a potential avenue to expedite the production process with improved accuracy by digitally creating grading rules and providing visual aids. Based on the participants' feedback gathered during the preliminary interview, it was inferred that exploring the use of 3D apparel visualization software held promise for addressing the specific needs of the participating company, particularly in streamlining the prototyping process and facilitating effective communication regarding fit and sizing concerns with pattern makers and manufacturing facilities.

***Concerns Regarding the Interoperability of 3D Virtual Garment Data*.** Even though the participants envisioned that using 3D apparel visualization software would be beneficial, they were worried about the interoperability of 3D virtual garment data and information with manufacturers. The participants realized that manufacturing partners might have difficulty viewing and interpreting files generated from 3D software unless they have a license to use that specific software. Participant A2 said, "*One of the biggest issues that I can foresee without knowing exactly about the software is taking virtual prototype information and getting it conveyed to the manufacturers*..." The participants were curious about how information is conveyed through virtual prototypes and how manufacturers are able to use the information. These questions and concerns contributed to selection of topics for the interviews that would make up theaction research cycles which are described below.

Action Research Planning. The participants' curiosity toward 3D apparel visualization software and the potential for employing the software for virtually fitting wildland firefighting protective clothing provided a basis for planning learning modules for participants throughout the action research. Throughout a series of interviews, interactive learning was carried out with participants through prepared learning modules and question-and-answer sessions. The learning modules became the medium to advance participants' knowledge about 3D apparel visualization software and explore how the software can improve the current product design and development practice.

The problems or needs identified through the preliminary interview data in the current product development practice were to 1) streamline company activities and better manage the time in the preproduction stage and 2) communicate the measurements, sizing, fit, and grading issues precisely with pattern makers and manufacturers. Furthermore, the participants exhibited a curiosity regarding the exchange and utilization of 3D assets across the entirety of the supply chain. Therefore, different functions and features of 3D apparel visualization software that could improve the current practice and satisfy the participants’ curiosity were introduced in each subsequent interview as part of action research, with interactive interview sessions that assisted in facilitating learning and discovery. Each interview covered different topics: 1) 3D garment design, 2) virtual avatars, 3) virtual fit assessment and grading, and 4) how to share 3D data across supply chain. The findings from the preliminary interview established the features and functions of 3D apparel visualization software to be demonstrated during each interview. Additionally, initial ideas were presented on how the existing practices of the participating wildland firefighting protective clothing company (Company A) could potentially benefit from the utilization of 3D apparel visualization software (refer to Table 4).

Table 4

The Current Practice of the Participating Wildland Firefighting Protective Clothing Company and Counteracting Functions/Features of 3D Apparel Visualization Software

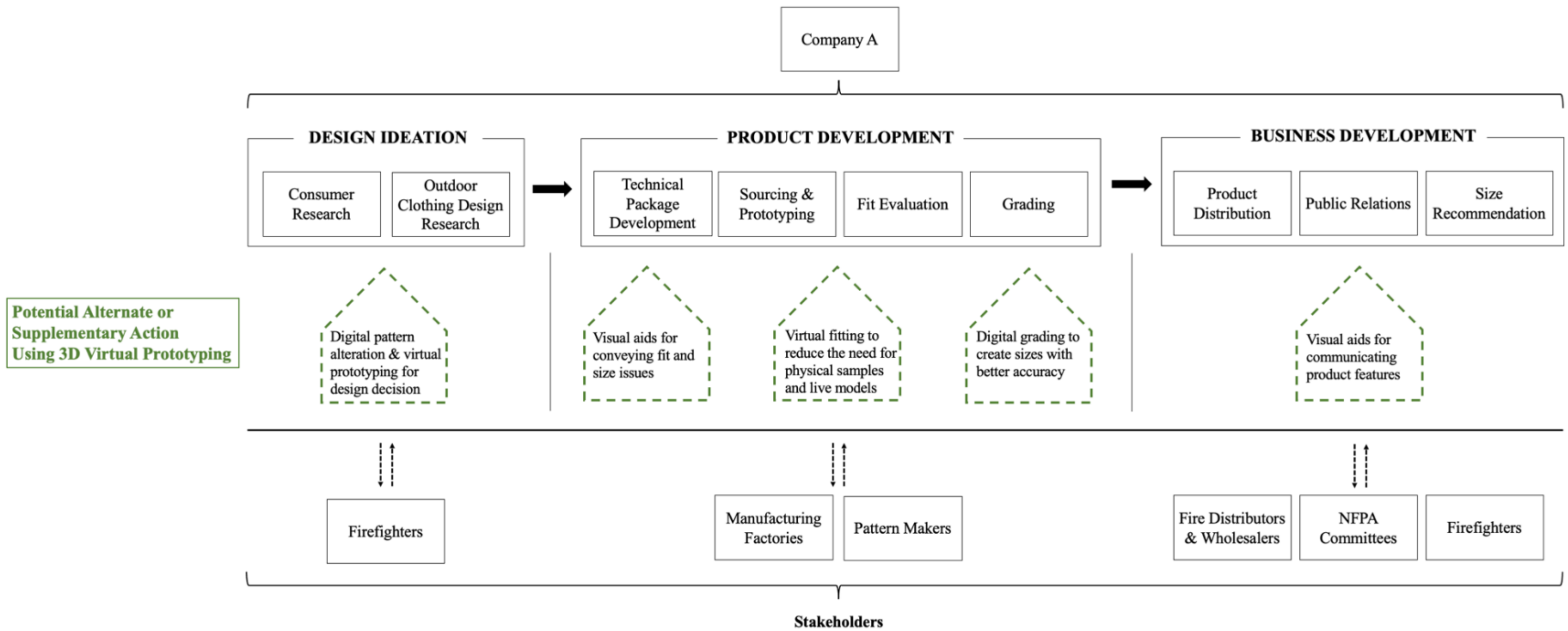
Current Practice	Corresponding features of 3D apparel visualization software	Potential impact
◆ **Reiterate two to three physical samples**	Virtual fitting on avatar before producing physical samples	Reduce the number of physical samples; Faster decision making for any changes in the design
◆ **Pattern alterations by hand**	Correct and modify 2D patterns as needed and visualize them into 3D garments with a few clicks in real-time	Save time by replacing hand-correcting updated 2D patterns; Faster decision making for any changes in the design
◆ **Several fit sessions with models of different sizes**	Virtual fitting on customized avatars based on anthropometric data with different postures; Refer to pressure map and tension map modes to check physical tension and pressure distribution	Fitting on personalized avatars of different sizes and body types faster without extra sampling reduces the need for actual fit models
◆ **Communicate sizing and fit issues through explanation with tech pack and pattern block**	Share digital images of 2D patterns and 3D virtual garments to visualize the desirable appearance of a garment; Pinpoint the location and amount of inches to fix to make sure the fit is going to be what need it to be exactly	Reduce the possibility of misinterpretation and miscommunication; Speed up designing by trial and error
◆ **The same pattern is not interpreted consistently and exactly as per pattern makers**	Share digital images of 2D patterns and 3D virtual garments to visualize the desirable appearance of the garment clearly; Pinpoint the location and amount of inches to fix to make sure the fit is going to be what need it to be exactly	Reduce the possibility of misinterpretation and miscommunication; Speed up designing by trial and error
◆ **Hand grading**	Creating multiple sizes for patterns by adding size groups; Automated grading	Create consistent grading rules across different manufacturers; Speed up production process with better accuracy
◆ **Concerns on exchanging and communicating digital information with manufacturers**	Save 3D virtual garment assets in high-rendered images, animation videos, and a turntable; Export grade rules and 2D patterns	Share 3D virtual garment images; Import/export convertible file types of 2D patterns, and grade rules across different software systems

Potential Integration Points for 3D Apparel Visualization Software. Prior to commencing the interactive interviews, a framework (Figure 9) was developed to delineate potential integration points of 3D apparel visualization software within Company A's product design and development process. This framework was formulated based on the identified problems and needs elucidated by the participants from the preliminary interview. It encompasses a range of potential integration points spanning the three stages of the process, with the overarching goal of streamlining company activities and enhancing communication pertaining to product features, fit, and sizing with supply chain stakeholders. The framework specifically emphasizes the potential for alternative or supplementary actions that could be facilitated through the use of 3D apparel visualization software.

The purpose of this framework is to illustrate the initial ideas outlining how the adoption of 3D apparel visualization software can offer benefits to existing practices. Particularly during the design ideation stage, the software enables designers to efficiently modify pattern blocks and instantly visualize them as 3D garments through a simple software interface. This functionality has the potential to expedite the design process, foster informed decision-making regarding design and fit, and facilitate swifter inter-organizational communication. Within the product development stage, utilizing 3D virtual garment images could serve as valuable visual aids for conveying fit and sizing concerns to manufacturing factories. Furthermore, when live fit models are unavailable, digitally fitting virtual garments on an avatar in a fit model's size could potentially expedite the fitting process and reduce the need for physical samples. Additionally, replacing the current manual grading process with digital grading could accelerate the creation of multiple pattern sizes while enhancing accuracy. In the business development stage, 3D virtual garment images could serve as visual aids for elucidating and promoting product features effectively during interactions with product distributors, NFPA boards, and firefighters. The subsequent section will delve into the analysis of data collected from four interactive interviews within the context of this framework. The focus will be on whether the participants perceived the utilization of 3D apparel visualization software as having the potential to benefit the identified existing practices, aligning with the initial ideas posited by the primary investigator. Distinct categories that shed light on the perceived drivers and barriers associated with the utilization of 3D apparel visualization software in Company A's product design and development process will be provided.

Figure 9

Potential Integration Points for 3D Virtual Prototyping within Company A's Product Design and Development Process



Perceived Drivers and Barriers to Adoption of 3D Apparel Visualization Software established through Action Research Cycles

In this section, action research interviews with participants are analyzed to address *sub-objective #1-2* ("Investigate key features and functions of 3D apparel visualization software that can be used for the stages and activities in the current product design and development process of Company A") and *sub-objective #1-3* ("Identify drivers and barriers to adopting 3D apparel technology in the context of the identified key features and functions").

Three out of four interactive interview sessions were conducted using Zoom, providing participants with the opportunity to view the 3D apparel visualization software on their computer screens. The third interview was conducted in person to conduct a fit evaluation with a set of wildland firefighting protective clothing (shirts and pants) on a female live model and observe virtual garments on the model's personal avatar in 3D apparel visualization software. Each interview covered different topics: 1) 3D garment design, 2) virtual avatar, 3) virtual fit assessment and grading, and 4) how to share 3D data across supply chain. During each interview, the researcher demonstrated the software's capabilities and acted as an instructor to facilitate the participants' learning of 3D apparel visualization software. In general, the conversations with participants focused on their opinions of demonstrated features and functions of 3D apparel visualization software, how they envisioned embedding the software into their current product design and development process, and the decision factors involved in implementing the technology for their company.

Through the interactive interviews conducted with Company A, distinct categories emerged, highlighting perceived drivers and barriers in the utilization of 3D apparel visualization software within their product design and development process. In this study, perceived drivers and barriers are factors believed or perceived by participants to either positively or negatively influence the usage or adoption of 3D apparel visualization software. These categories highlighting perceived driver and barriers, pertaining to software features and stakeholder-related features, played a significant role in shaping the company's perspective on adopting 3D software. Software features identified in the data encompass utilitarian capabilities and technical performance of the 3D apparel visualization software, while stakeholder-related features encompass considerations relevant to the participating company's organizational characteristics, industrial characteristics, as well as the various stakeholders involved in the firefighting gear supply chain, including firefighters, manufacturing facilities, fire distributors and wholesalers, and NFPA committees. Data in the form of interview quotes are used to support the findings, and participants will be referred to as participant A1 for the garment designer and participant A2 for the business manager. Instead of presenting the findings chronologically, interview by interview, the categories related to perceived drivers and barriers that emerged across the course of the four interactive interviews are described.

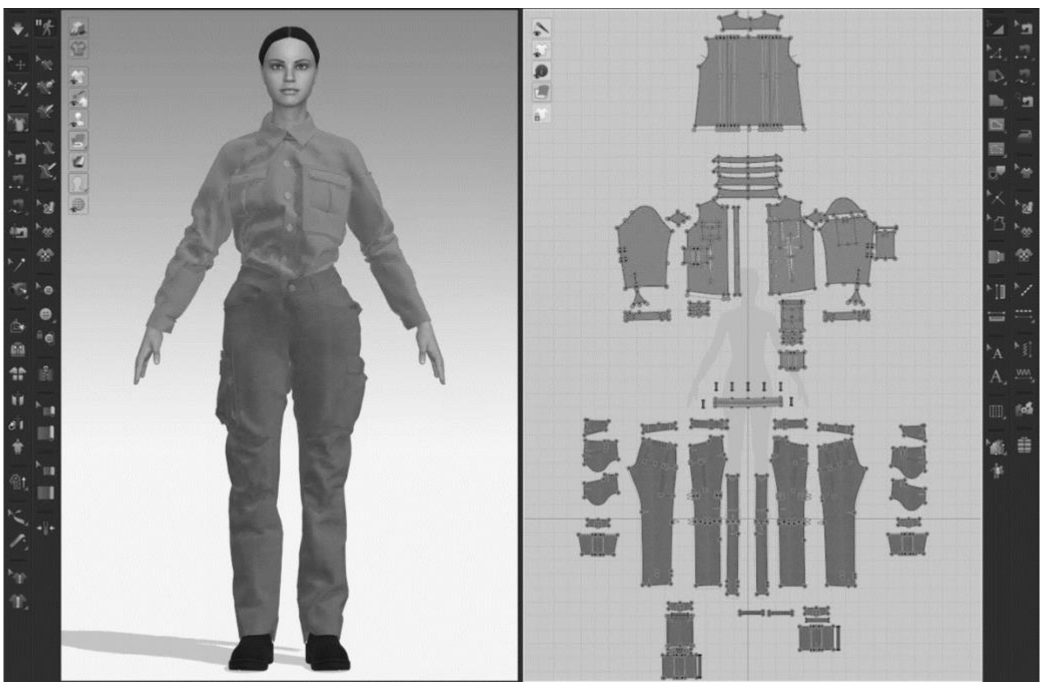
Perceived Drivers. This section presents the identified categories related to perceived drivers of incorporating 3D apparel visualization software into Company A's product design and development process.

Software Features. The analysis revealed five distinct categories related to perceived drivers of integrating 3D apparel visualization software, specifically focusing on software features. These categories are as follows: 1) informing design decisions, 2) customizing avatar sizes and postures, 3) visual aids for technical package, 4) digital grading and multi-size review, and 5) virtual fit assessment using garment fit maps.

Informing Design Decisions. In this study, 3D virtual garment simulation refers to the software's capability to visualize 2D block patterns as sewn garments. Figure 10 shows the 2D and 3D workspaces within CLO3D fashion design software, where users can adjust the 2D block patterns and observe how these adjustments are reflected in real-time in the 3D virtual garment simulation. After looking at a demonstration, participants suggested that 3D virtual garment simulation would be also useful for making decisions on design attributes in the early design stage.

Figure 10

2D Block Patterns and 3D Virtual Garment Simulation in CLO3D



The participants expressed the view that the utilization of 3D virtual garment simulation, which enables users to promptly adjust patterns and simulate them into a sewn product, could accelerate decision-making processes within the internal organizational design context.

Participant A2 suggested that adjusting garment details such as lengths and proportions could be more easily worked out in virtual simulation.

> Despite spending five years on research and development to achieve the best fit, we make annual design adjustments based on customer feedback. This includes altering the types, dimensions, and locations of pockets, plackets, and fasteners. Furthermore, to visualize the impact of adjusting hip or thigh measurements for end users on the sewn pants, it is more efficient to use virtual garments and avatar than creating physical samples.

In a similar vein, participant A1 saw the value in 3D virtual garment simulation being able to save time for prototyping various styles. "*Even when we extend the pocket size, we either have it sewn on or make a makeshift pocket by cutting them out and laying them all next to each other to see how they would look at the body*." Moreover, as shown in Figure 11, participants suggested that the ability to view virtual garments in transparent and mesh fabric surface settings could enable them to see the distance between the avatar's body and virtual garments, as well as how the virtual garments lay on the body, which would be helpful in making fit decisions. Throughout multiple interviews, they repeatedly expressed their interest in utilizing the transparent and mesh fabric surface setting of the virtual garment.

Figure 11

Transparent (Top) and Mesh (Bottom) Fabric Surface Settings of Virtual Garments in CLO 3D

Customizing Avatar Sizes and Postures. A parametric avatar is an editable avatar that allows adjustments to its size, pose, texture settings, and accessories (such as hair and shoes) to showcase fit and design of virtual garments. In relation to the parametric avatar capability, the participants expressed a strong inclination to customize sizing and postures to align avatars effectively with their product design. They expressed a belief that the customization of avatar sizes would be the most effective approach for leveraging virtual garment simulation as a reference for pattern making, particularly in situations where live fit models are not readily available or in-person collaboration is not feasible, as opposed to relying on default avatars in ASTM sizing standards or the digital version of the Alvanon body form provided by the software. The ASTM size standards consist of US-specific sizing tables of body measurements for women, missy, men, children, and plus, which have been developed by the American Society for Testing & Materials (Armstrong, 2006). Alvanon is a fashion technology company, focused on the body and its application within the apparel industry (Alvanon, n.d.).

Participant A2 said, "*Firefighters often possess a muscular hourglass shape resulting from the demanding physical labor and hiking tasks associated with their work*." The participants emphasized that their size chart is based on their own sizing research and incorporates average body shapes for different sizes of firefighters, setting it apart from the general population. In addition, the participants stated that checking how everything fits on the fit model and assessing the mobility of the fabric when taking various movements is one of the crucial factors to consider when designing wildland firefighting protective clothing, as the fabric used in such clothing typically has low stretchability. Participant A1 stated,

> The first thing I do with everything is assume the A-pose to assess the basic fit without any movement. After that, it is important to see how garments fit on models when they step up, hike, squat, and reach out, as they engage in what's called cold training. They often assume a downward position and run their hands through the ash. Therefore, I prefer to observe virtual garments on avatars in these positions from front, side, back, and overhead views.

The inclusion of diverse avatar poses within 3D apparel visualization software, illustrating firefighters engaged in various job tasks, would prove advantageous in the design process of wildland firefighting protective clothing.

Visual Aids for Technical Package. Participants perceived that the integration of 3D virtual simulation images into a technical package (tech pack) could facilitate the communication of design specifications with contract manufacturing factories. Participant A1 has experienced miscommunication when working with contract manufacturing factories, saying, "*having all information in a tech pack doesn't mean that it would be correctly interpreted and understood as it was meant to be by a pattern maker at manufacturing factories.*" She suggested that 3D virtual garment simulation images could potentially be used to present how the end product will look to contract manufacturing factories, in cases where they may not fully understand the tech pack. Participant A1 also stated that having an avatar in a fit model's size with multiple postures can allow her to pinpoint areas that needed to be adjusted: "*I can show them images of virtual garments in customized scales and angles, and say, 'The shirt rises too high when they lift their arms, so it needs to be a little lower.'*" Both participants preferred displaying the fabric surface as a transparent or mesh view. They both felt that this would allow manufacturing parties to better understand garment layers, and design details, and identify areas where the garment fits tightly to the body.

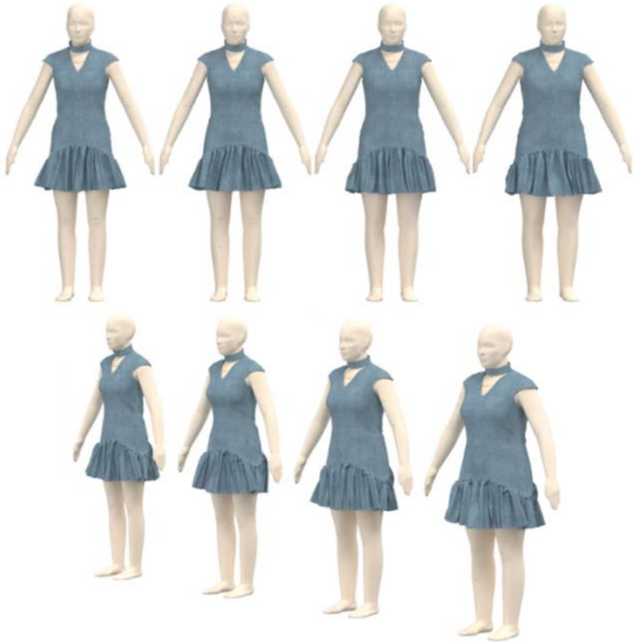
Digital Grading and Multi-size Review. Participants perceived that the digital grading tool and grading review mode could potentially speed up their current hand grading practice and iterations of grade rule reviews. A digital grading tool is a function that allows users to input grading values for points that make up the outlines of 2D block patterns or to set the offset between each size (Figure 12). Moreover, grading review mode displays all grading sizes of virtual garments and their counterpart avatars on a single screen. Figure 13 illustrates how users can simultaneously observe a comprehensive collection of virtual garments, graded in various sizes and displayed on differently proportioned avatars.

Figure 12

Digital grading tool in CLO 3D

Figure 13

Grading Review Mode in CLO 3D



By utilizing both digital grading and grading review mode, users can visually verify whether the distance from the point of the base size between multiple sizes is correctly set and, if necessary, edit the grading rule values appropriately. Participant A1 said that grading is one of the trickiest parts of her job, and the software feature could lessen her workload: "*Being able to see to make sure grading is working on each body type before you do a full draft run would be beneficial.*" She stated that the grade review mode could serve as a visual aid to communicate which parts need to be fixed when the grading is off and digital grading tool could reduce human error in grading, such as inputting incorrect numbers or swapping numbers by mistake.

Virtual Fit Assessment using Garment Fit Maps. The "Garment fit maps" feature presents predictive color-coded maps of garment fit properties (such as stress, strain, and fit) distributed on the created virtual garments. In CLO3D, there are four different types of garment fit maps: stress map, strain map, fit map, and pressure points map. Each map displays a different fit property and unit. Figure 14 illustrates the stress map mode provided in CLO 3D. Participants showed the greatest interest in the garment fit maps feature among all the capabilities of the 3D apparel visualization software.

Figure 14

Stress Map Mode in CLO 3D

Regarding garment fit maps, the participants were impressed with the software's ability to provide information, which displays a colored map depicting external stress and tightness applied to virtual garments. They proposed that the utilization of the garment fit maps feature is advantageous for identifying and addressing fit issues during the pattern optimization process. Specifically, participant A2 had ideas of utilizing garment fit maps in conjunction with feedback from firefighters obtained during fit evaluation sessions.

> It has to be a compilation of not only this but also the end-users' feedback to ensure that the data matches. We can still obtain that information from individuals, but combining anecdotal data with statistical data is one of the most significant challenges we face.

Moreover, participant A2 remarked that if the functionality of garment fit maps was improved to suggest expected reasons behind the pressure points, apart from predicting the stress applied on garment fabric, it would prove extremely beneficial. After observing the primary researcher demonstrate the activation of the garment fit maps feature in the software, she remarked, "*We have multiple pressure issues placed here and there in the simulation. Could it be because the shirts are tucked into the pants? I believe there may still be some factors that haven't been accounted for, which could cause discrepancies*." Likewise, participants suggested enhancing the garment fit maps feature by providing users with information on the specific deficits such as garment segments and design details that need to be corrected in the existing pattern block for better fitting and the extent to which measurements should be adjusted.

Stakeholder-Related Features. The participants explained the importance of considering not only the technical features of a technology, but also the organizational and environmental factors when contemplating its implementation at a firm level. The analysis revealed four distinct categories related to perceived drivers of integrating 3D apparel visualization software, specifically focusing on stakeholder-related features. These categories are as follows: 1) visual presentation for consumer research, 2) visual presentation to communicate with manufacturing factories, 3) visual presentation to communicate with NFPA committees, and 4) visual presentation to communicate at sales meetings.

Visual Presentation for Consumer Research. Both participants noted that 3D virtual garment simulation images could facilitate conversations with firefighters to investigate their needs and fit preferences. Participant A2 considered using virtual garment images as part of surveys and focus group interviews, allowing firefighters to verbally identify areas of improvement for greater comfort in their current protective clothing. She preferred gathering both subjective feedback from end users and objective data generated by the software, utilizing the software's capability as supplementary materials for effective communication in consumer research.

Visual Presentation to Communicate with Manufacturing Factories. The participants shared their ideas on how to incorporate 3D virtual garment simulation into communication with manufacturing factories. Participant A1 proposed the use of virtual garment images to identify fit issues, allowing pattern makers to understand specific adjustments needed to modify garment details. Participants were also interested in using the digital grading tool and grading review mode as visual aids when collaborating with manufacturing factories in order to communicate grading rules and review samples in all sizes. Participant A1 hoped that the grading tool and grading review mode could facilitate the communication process with manufacturing factories to correctly fix such errors and minimize room for error. "*I could sit down and input all the exact numbers. If I organize them like this, they will form the pattern pieces, which they would have to follow instead of me just telling them and then not adhering to them*." However, both participants mentioned that no matter how honed the grading rule and sizing chart are, the quality results of the product is ultimately determined by the manufacturing process.

Visual Presentation to Communicate with NFPA Committees. Participants A1 and A2 serve as NFPA technical committee members, responsible for developing and revising standards on protective clothing and equipment for wildland firefighting. The participants suggested using virtual simulations and garment fit maps as persuasive tools when discussing design and sizing regulations of wildland fire gear with NFPA committees, whose members often do not have an apparel design background. Participant A1 mentioned,

> One of the biggest points we've stressed at the NFPA committee meetings is that we can't apply the same increments across the board. I suggest using the consistent increments across the board, and then visualizing the results in both 2D and 3D workspace to show them how it affects the design. I believe this approach could be helpful in adjusting and fine-tuning the numbers.

In this manner, the participants acknowledged the potential of integrating the digital grading tool and grading review mode capability to significantly facilitate discussions on design and sizing regulations with NFPA committee members who possess limited knowledge in apparel design. *The* participants also paid attention to transparent and mesh fabric surface settings of simulation images, which make it possible to visualize the air gap between an avatar and virtual clothing, as illustrated in Figure 15. Participant A1 stated, "*They think you make a garment detail a little bit smaller, and the uniform gets instantly skin tight, and they don't quite understand the concept of design, and what you can do*." Participants expressed interest in exploring the utilization of 3D virtual garment simulation, specifically in the context of transparent and mesh fabric surface settings, to enable the NFPA audience to visually identify areas where the garment does not conform closely when making adjustments to garment measurements. However, at the same time, both participants mentioned that in order to convince the NFPA committee that this tool is useful, the accuracy and validity of the numeric data (stress force per unit area, distortion rate, etc.) and software simulation should be significantly improved.

Figure 15

The Transparent Fabric Surface Setting of Virtual Garment Simulation in CLO3D

Visual Presentation to Communicate at Sales Meetings. The participants shared their ideas on how to incorporate 3D virtual garment simulation into communication with customers at sales meetings. Participant A2 suggested leveraging virtual garment simulation to facilitate discussions with new customers regarding design details and options, stating that "*If we collaborate with a partner with specific pocket requirements, we can present our clients with a visual representation before creating physical samples*." Other suggestions involved using images of virtual garment simulation and grading review mode during business meetings with fire distributors, and wholesalers. Participant A2 stated,

> We do not operate on a large scale, making it difficult to keep a full size run. There have been times when I couldn't conduct a meeting because I didn't have anything to show.

> Having a fabric swatch with a graded set of virtual garments in all sizes would be beneficial for understanding product features. Because if it's not being sold at retail, they don't necessarily need to try the garment on. If we had something like this in the past, it could have really helped me move forward on the business development side.

Moreover, participant A2 emphasized the value of employing virtual garment simulation images when educating fire distributors and wholesalers about the company's products, especially in situations where full-sized prototyping samples are not yet accessible. By leveraging these visual aids, participants proposed the utilization of the grading review mode capability to enable fire distributors and wholesalers to preview and comprehend the product features of the participating company in situations where physical samples are unavailable during a sales meeting.

Efficient Size Selection for Consumers. Participants proposed that the future integration of 3D virtual simulation with a mobile body scanning application could potentially provide firefighters with the ability to swiftly and accurately find the most suitable sizes for their purchases. Currently, the participants are asking consumers to send their measurements and find an appropriate size that will best fit their customers, which takes a significant amount of time and work. Participant A1 said,

> Firefighters don’t know what size they need to be in and they are not going to fit. So I'm kind of thinking something like this would be super helpful, just for those purposes as well. If they could take a picture or scan their own body with their own phones and then receive information about their exact measurements, it would be incredibly useful. This would pair beautifully with what we're doing.

The participants explained how a mobile body scanning application could potentially reduce the considerable time and expertise required for manual tape measures, which could ultimately benefit their business. Participant A2 stated, “*Everybody has a smartphone, so if they could take a picture and scan their own body, the application could help them pick the best size*.” They also expected that this would be a great opportunity for them to build a wildland firefighter's body size database and refine size charts. Moreover, participant A2 suggested that creating a personal avatar based on the customer's body dimensions and embedding virtual fitting simulations as visual aids in such an application could be an attractive point, saying, "*If you can see how uniforms fit on your avatar, that's a whole different story*." With the help of such technology, participants felt they would be able to streamline the size recommendation task and enable consumers to properly understand and choose their own size and product.

Perceived Barriers. This section presents the identified categories related to perceived barriers of incorporating 3D apparel visualization software into Company A's product design and development process.

Software Features. The analysis of the interview transcripts revealed three distinct categories related to perceived barriers of integrating 3D apparel visualization software, specifically focusing on software features. These categories are as follows: 1) accuracy of 3D virtual garment simulation, 2) indispensable nature of wearer feedback, and 3) validity of garment fit maps.

Accuracy of 3D Virtual Garment Simulation. Despite participants acknowledging several perceived drivers of utilizing 3D apparel visualization software to inform design decisions, they expressed reservations regarding the reliability of 3D virtual garment simulation for making fit-related decisions. In an in-person interview, participants observed the fit appearance of a set of wildland fire protective clothing (a shirt tucked in pants) on a fit model and virtual garments in the same size on the fit model's body scanned avatar in 3D apparel visualization software. After viewing both the actual garment and the virtual representation, participant A1 stated that the accuracy of the simulation would not be at a level that could be solely relied upon to make fit decisions based on the software.

> For the most part, I feel like virtual garments represent how uniforms looked on her. The bust, waist, and hips look similar to how they did on the fit model. I would say that the thigh and seat look close as well. But the sizes were a little off. The shirt is pulling off to the left, the shoulder is a little low, and the sleeve length is longer. Also, it is hard for me to know if it's fitting right. I would still have physical prototypes. I don't think it could stand alone and support everything holistically that we would need.

Participants A1 and A2 suggested that more accurate representation of software simulation might increase their confidence in using 3D apparel visualization software. Participant A1 expressed her skepticism regarding the simulation's precision, suggesting that it would not be sufficiently dependable to make fit-related judgments solely through the software. Participant A2 also stated that she was not confident that the garment fit map feature was accurately indicative of the stress, strain and fit appearance of counterpart actual garments.

Indispensable Nature of Wearer Feedback. The participants' responses indicated that examining virtual garments on an avatar could serve as an initial step, facilitating the identification of certain garment details for discussion in situations where a fit model is unavailable. However, their responses indicated that they felt this approach cannot replace the essential practice of conducting live fitting sessions and obtaining feedback from real models to evaluate garment fit accurately. Participant A2 argued that they still prefer a live model and actual fitting, pointing out that there is still a lot of interpretation involved in using virtual simulation: "*Getting feedback from firefighters is integral to ensuring it's functioning in real life because they possess firsthand knowledge of the job requirements and working environment.*" To better understand movement comfort in the stressful work environment of wildland firefighters, participants wanted to hear evaluations from those who wear the clothing while performing job tasks.

Validity of Garment Fit Maps. For fit evaluation purposes, the participants believed that virtual simulation and garment fit maps could be supplementary tools when they cannot access resources in person and a fit model is not readily available. However, both participants were dissatisfied with the garment fit maps' validity in comparison to the fit appearance of actual garments. They emphasized that such a capability is a reference tool and that a human model is still needed to perform certain tasks. Participant A1 stated, "*I don't see the software being able to stand alone and completely rely on that. We can use software like this to support what an actual human can do*." Similar to the virtual garment simulation capability, it is imperative to enhance the reliability and accuracy of the garment fit maps feature through the incorporation of feedback from real end users.

Stakeholder-Related Features. The participants explained the importance of considering not only the technical features of a technology, but also the organizational and environmental factors when contemplating its implementation at a firm level. The data analysis revealed five distinct categories related to perceived barriers of integrating 3D apparel visualization software, specifically focusing on stakeholder-related features. These categories are as follows: 1) financial capability, 2) effortfulness and necessity for additional resources, 3) preparedness among contract manufacturers, 4) unchanging garment style requirements, and 5) concerns surrounding product promotion through virtual stimuli.

Financial Capability. Regarding the feasibility of adopting 3D apparel visualization software, it was mentioned that the company's financial capability to invest in the costs needed for installation, maintenance of the software, as well as relevant accessories such as fabric testing devices and texture scanners, and for hiring and training workers to upskill in the required area is important as a small-sized enterprise. Participant A2 commented, "*The most important thing to figure out is the cost versus payoff*." The participants explained that the company should consider whether it is worth paying the cost of introducing technology.

Effortfulness and Necessity for Additional Resources. Moreover, the participants conveyed a feeling of being overwhelmed by the expected additional effort and time required for tasks beyond their regular duties and roles. This would entail acquiring proficiency in new software and establishing comprehensive company-wide workflows to facilitate the complete integration of the new technology. As a result, they anticipated that hiring additional personnel specifically dedicated to tasks related to 3D apparel visualization software would be necessary, and seeking assistance or advice from software providers and third-party agencies specializing in creating digital fabric and avatar libraries would be a practical approach if they do decide to adopt the technology.

Preparedness among Contract Manufacturers. Due to other external factors, participants were worried that manufacturers might not be ready to access and interpret 3D virtual garment data. Participants A1 and A2 pointed out that their company's reliance on contract manufacturing may pose limitations to their ability to adopt 3D apparel visualization software. Participant A2 stated, "*We realized that no matter how precise everything is, the outcome is determined by the manufacturing factories and their choices of how to cut and sew the garments.*" Moreover, participant A2 expressed that this technology is unfamiliar and novel to the firefighting gear industry, leading to anticipated challenges and potential issues.

> Unfortunately, change has not been well-received across the board in this industry. There are certain manufacturers, who are part of NFPA 1977 standards, that we are supposed to work with. The manufacturers we have worked with thus far have not used anything like this. It remains to be seen how this will translate over if we continue working with them in the future. It will be necessary to train these manufacturers, but first and foremost, they have to be open to these changes.

Overall, participants expressed that lack of awareness, innovativeness, and technological infrastructure and competence among their manufacturing partners could impede their adoption of such technology.

Unchanging Garment Style Requirements. Both participants acknowledged the crucial capability of 3D apparel visualization software in providing them with unhindered ability to explore and experiment with different garment details and new designs. However, considering the unique nature of the wildland fire gear industry, the participants remained uncertain about the extent to which adopting such software could truly contribute to their practical work. Participant A1 said,

> We don't offer lots of different styles and redesign new styles every season. So, for the past twenty plus years, manufacturers have been making the same thing. You don't necessarily need the speed once you establish a good fitting shirt and pants. Our product should stay within the NFPA regulations on design, sizing and thermal protective performance. There is not a lot of freedom. Every variation that you are going to do is changing the fit slightly or adjusting placements, shapes, sizes, and types of pockets.

Furthermore, the participants highlighted the limited availability of suppliers and product options for fabric and subsidiary materials specifically certified by NFPA for wildland fire gear. The participants thought that this restriction may potentially limit their ability to assess the fit and drapability of garments by utilizing different virtual fabrics within the software.

Concerns Surrounding Product Promotion through Virtual Stimuli. Neither participant had a positive view of using virtual simulation images for marketing purposes on their website, social networking services, and product catalogs aimed at end users. Despite the potential time and cost savings, the participants did not think it was an effective approach. Their responses showed how important feedback and testimonials of actual firefighters are in their business. Participant A1 mentioned, "*For our industry, a fake model wouldn't go over very well. Other competitors use pictures of products for product catalogs and pages on their websites*." Participant A2 underlined that the company's marketing strategy specifically targets wildland firefighters as it aligns with their personal connection to the firefighting community.

> It's essential for us to have real models to establish relationships with firefighters. For our

> brand, I believe that portraying real-life situations with actual garments on live models and creating an environment like that would be more effective and better perceived by our community. Therefore, we prefer to use wildland firefighters specifically because they know firsthand how the clothing they wear feels when completing their job tasks, and their testimony is more credible to other firefighters.

Participants' responses indicated that the utilization of virtual garment images for marketing purposes would be constrained, as the company's marketing strategy primarily centers on fostering a personal connection with the wildland firefighter community.

Participants' Thoughts on Taking Part in the Action Research Study

After the completion of four interactive interviews (first-cycle of action research), an additional interview was conducted as part of the second-cycle of action research. This collaborative effort allowed both participants and the primary investigator to thoroughly examine a framework that depicted the integration of 3D apparel visualization software into the design and development process of wildland firefighting protective clothing. This interview also provided an opportunity to reflect on the entire action research process. The participants expressed that their curiosity about 3D apparel visualization software had been heightened and discussing with the researcher had been helpful. They mentioned that this opportunity has provided them with a chance to consider whether adopting the technology within their company would be a good fit and to prepare for the future of their business. Although both participants were already aware of the existence of such technology due to their previous participation in a webinar on the software, participating in the learning modules allowed them to intensively review the software's key capabilities in a short period of time. Participant A2 mentioned,

> If we had never done this, we would still be stuck at this point, wondering if we should sit down and try to figure it out ourselves, and what that would even look like. Your assistance was particularly helpful because you are familiar with the program

> and we don’t have the time to learn a new one. So, it was beneficial for us to have someone take the wheel and guide us in the right direction by telling us what we need to look for and try to do. We have a tendency to get carried away and go down rabbit holes that are not necessarily helpful and now we won't have to wander anymore.

Moreover, the participants expressed their confidence in effectively representing their company and articulating their knowledge regarding 3D virtual garment simulation and its implementation. They conveyed their readiness to engage in discussions concerning these pertinent topics at future meetings with other manufacturers or NFPA committees. However, both participants expressed regret that, aside from a brief trial of the software's free version, they were unable to dedicate enough time and effort to fully study its features and functions. Participant A1 also expressed a desire to attend offline classes on specific dates and times if given the opportunity to receive training on the software in the future. After reviewing the first action research cycle findings, both the participants and the primary investigator agreed that it would be premature to partially introduce 3D apparel visualization software to Company A. Therefore, the participants and researcher decided not to proceed with additional action research cycles. However, participants did recommend that in the event that the wildland fire gear industry adopts this technology in the future, the company should collaborate with software developers to develop a new software system specialized for this industry.

Summary of Phase One Study Findings

This action research study aimed to explore the potential opportunities for integrating 3D apparel visualization software into the product design and development process of a wildland firefighting protective clothing company. Through the learning interventions, participants were able to identify multiple perceived drivers and barriers associated with the application of the software within their specific businesses. In terms of the basic design and development process for wildland firefighting protective clothing, participants' responses revealed that input from various stakeholders is required across three key stages: design ideation, product development, and business development. These stakeholders included firefighters, designers, pattern makers, manufacturing factories, distributors, wholesalers, and NFPA committees. Their collaboration is crucial in completing the necessary steps for each stage. Therefore, this study elucidates the identified factors that could influence the adoption of 3D apparel visualization software, encompassing both software attributes and stakeholder-related considerations.

The participants' comments on the evaluation of the virtual fitting experience through a series of interactive interviews showed perceived drivers of using 3D apparel visualization software as a tool for visual communication and decision making in all stages of product design and development. Having access to 3D virtual garment simulation images would enable them to pinpoint fit and sizing issues accurately and mitigate misinterpretation when producing prototype samples and explaining product design features to a diverse audience without a design background. The utilitarian advantages and software functionalities encompassed various aspects such as informing design choices, enabling avatar customization in terms of size and postures, facilitating technical package development, enabling digital grading review, offering garment fit maps, and supporting product customization. The perceived benefits associated with Company A's attributes, industry-specific characteristics, and diverse stakeholders encompassed visual presentation for effective communication with manufacturing factories, NFPA committees, and fire distributors and wholesalers. Additionally, participants A1 and A2 projected that virtual fitting might facilitate an efficient size selection process tailored to the needs of firefighters.

The participants of the study recognized the potential usefulness of virtual fitting in situations where a firefighter may not be available for an in-person fitting, and physical resources are inaccessible. Nonetheless, neither participant saw 3D apparel visualization software as a replacement for the conventional tools they use. They acknowledged that the involvement of the end user is still indispensable in wildland firefighting protective design and development. The input of wildland firefighters on aspects such as fit, functionality, and safety was deemed essential for a successful outcome in understanding the job requirements and addressing their needs. Additionally, the participants emphasized that manufacturers of the wildland firefighting gear industry typically establish a baseline design and produce the same style for several years. In addition, NFPA regulations limit the freedom to design various styles of wildland firefighting protective clothing, and the availability of raw materials is severely limited. Hence there is less incentive to streamline the prototyping process and reduce the number of physical samples, as compared to the apparel industry, which designs hundreds of styles each season.

In general, the participants did not show a high level of assurance in the precision of the 3D virtual garment simulation. This undoubtedly contributed to their unwillingness to propose that virtual fitting and garment fit map features of the software could replace physical prototypes and actual fitting. Furthermore, participants' responses indicated that the technological competency of manufacturing factories and the lack of innovativeness of the firefighting gear industry community were also factors to be considered. The forthcoming discussion and conclusion chapter will elucidate the process by which the perceived drivers and barriers of integrating 3D apparel visualization software within the product design and development process, as identified from the series of interactive interview responses of the action research study, were utilized to construct a refined conceptual framework.

Phase 2: Multiple In-depth Interviews

The multiple in-depth interviews conducted for the phase two study involved interviewing industry professionals working in the field of structural firefighting gear or wildland firefighting gear to address *research objective #2* ("Capture the experiences of personnel from other firefighting personal protective clothing manufacturing companies in 3D apparel visualization software adoption and use to compare with the experiences of Company A"). In the study, most of the participating companies focused on manufacturing structural turnout gear, which consists of a 3-layered composite material. Figure 16 provides visual representations of the appearance of structural turnout gear and wildland fire gear. The interviews were recorded, transcribed, and coded to investigate the perceptions and experiences of personnel from other firefighting gear manufacturing companies regarding the adoption and use of 3D apparel visualization software. Thematic analysis was conducted on the transcriptions of the five interviews to identify patterns and themes within each company as well as across the companies (Creswell & Clark, 2011; Heydarian, 2016). In line with the phase one action research study, notable categories have emerged, highlighting participants' perceived drivers and barriers regarding the adoption and use of 3D apparel visualization software. Characteristics of the five participating companies that are particularly relevant to the study are elucidated in the following sections.

Figure 16

Structural Turnout Gear Versus Wildland Fire Gear (The Public Safety Store, n.d.)

Characteristics of the Participating Companies

Five additional firefighting gear manufacturing companies were recruited, and one-time in-depth interviews were conducted with one to four representatives from each company. Ten experts in product development or technical design positions from five firefighting gear manufacturing companies participated and details about the experts are listed in Table 5. Data in the form of interview quotes are utilized to substantiate the findings, and participants were referenced in an alphanumeric manner (e.g., B1, B2), similar to the approach employed in the phase one study.

Table 5

Expert Interview Subjects (n=10)

Company Label	Number of Participants	Type of Company	Technology Adoption (Y/N)	Position	Participant Label
Company B	2	Structural turnout gear	Y	Pattern Maker	B1
				Pattern Maker	B2
Company C	2	Structural turnout gear	N	Pattern Maker	C1
				Product Innovation Manager	C2
Company D	1	Wildland fire gear	Y	Designer	D1
Company E	4	Structural turnout gear/ Wildland fire gear	N	Designer	E1
				Technical Designer	E2
				Glove Designer	E3
				Technical Designer	E4
Company F	1	Structural turnout gear	N	Technical Designer	F1

Companies using 3D apparel visualization software. Two out of the five participating companies have implemented 3D apparel visualization software. One company was a structural turnout gear manufacturer (Company B), and the other was a wildland fire gear manufacturer (Company D). Both companies used the technology partially in the design ideation and pattern making stages rather than throughout the product design and development process. Participants from both companies reported that the introduction of the software was initiated by one or two managers in the design team who convinced higher decision-makers to purchase software licenses and subscriptions once they became aware of the technology. The participants stated that the driver behind the software's adoption was that they expected it would be useful for showing new styles, addressing fit issues in pattern making, and also had potential for use in the marketing team. According to the participants, the criteria for selecting the software were the licensing cost, grading and marker alteration features, and perceived user-friendliness.

Companies not using 3D apparel visualization software. Participants representing companies that had not adopted the technology (Companies C, E and F) mentioned that they had never been exposed to the technology and that their existing systems were working well, so the companies did not want to take the risk of introducing unproven technology from a business perspective. Some participants from Company E have prior experience of learning and using 3D apparel visualization software in university, but they are not currently utilizing the software in their careers. A participant from Company F reported that his design team is in the exploration stage of the software and mentioned that some designers have received training on a specific supplier's software. To assist participants without prior experience, the primary investigator spent approximately ten minutes at the beginning of each interview browsing websites of CLO 3D and Optitex 3D design software and explaining key capabilities of 3D apparel visualization software, as well as its applications in the apparel industry.

Perceived Drivers and Barriers to Adoption and Usage of 3D Apparel Visualization Software

In line with the phase one action research study, participants' perceived drivers and barriers regarding the adoption and use of 3D apparel visualization software were classified and explicated with respect to both software features and stakeholder-related aspects. In the phase two study, it became evident that factors originating from the distinctive attributes of structural turnout gear exerted an influence on participants' perceptions of 3D apparel visualization software. Consequently, these pertinent categories were duly organized and delineated under the designation of 'structural turnout gear features.'

Perceived Drivers. This section outlines the categories that have been identified in relation to the perceived drivers of adoption or usage of 3D apparel visualization software for participants' professional roles. All the participants stated that the safety of firefighters is the most important factor to consider in the firefighting gear industry. The participants also mentioned that the biggest driver for introducing new innovations in this industry is to find ways to improve the design, fit, and thermal protection of garments, so that they can perform at a higher level in terms of safety.

Structural Turnout Gear Features. This section describes specific categories driven by the distinctive attributes of structural turnout gear that motivate participants to try using or expanding the functionality of 3D apparel visualization software for their jobs. The analysis revealed two distinct categories pertaining to perceived drivers of integrating 3D apparel visualization software, with a focus on structural turnout gear features: 1) visualizing air gap volume, and 2) predicting thermal protection and water penetration.

Visualizing Air Gap Volume. Some participants recognized the potential of 3D virtual garment simulation in visualizing the volume and location of the air gap between the wearer and their structural turnout gear. The air gap serves the purpose of keeping firefighters thermally protected, allowing for the evaporation of sweat, facilitating heat loss, and enabling breathability. Participant E1 mentioned that finding an optimal air gap that can balance thermal protection and movement comfort is still being discussed at the NFPA committee meeting. E1 said,

> The use of 3D modeling would be particularly useful in visualizing the location of the air gap between the garment and the skin, in order to observe and discuss the balance between allowing sufficient air gap for the garment to perform the necessary movements for the job, and ensuring the functionality of the garment. For instance, when a firefighter

> wears an SCBA tank, any air gap that was previously present in their shoulders and around their back neck is compressed by the tank. This raises the question of how much air gap is actually necessary.

The participants stated that 3D virtual modeling has the potential to facilitate deepening discussions and facilitate consensus in this field as visual aids.

Predicting Thermal Protection and Water Penetration. Some participants argued that using 3D apparel visualization software for the purpose of pattern making or virtual fit assessment alone is not enough motivation for them to adopt such technology. Instead, they said that if the software could predict thermal protection performance indices (such as breathability and total heat loss) and provide them as data, it would be a game changer. Participant C1 said, "*It would be incredible if the software could tell us how pattern alterations affect thermal protective performance on a composite in 3D simulation. We spend a lot of money on product testing by third-party labs to obtain certification from NFPA.*" Participant F1 stated, "*We conduct shower tests for our new product, and being able to predict where exactly the water goes in the garments would be helpful to change the pattern design as needed*." He aspired to utilize these types of indices while designing structural turnout gear, experimenting with vent creation, and employing creative pattern engineering while considering the relationships between garment construction and actual fireground conditions.

Software Features. Analysis of the interview transcripts revealed six distinct categories related to perceived drivers of adopting or using 3D apparel visualization software specifically focusing on software features. These categories are as follows: 1) assistive tool for pattern optimization, 2) enhancing pattern design through body movement considerations, 3) integrating firefighters' postures into avatars, 4) expanding the functionality of garment fit maps, 5) streamlining sample iterations through virtual fitting, and 6) facilitation of on-demand production.

Assistive Tool for Pattern Optimization. Participants commonly appreciated how 3D apparel visualization software could be beneficial in the early stages of designing and developing a new pattern and determining if the fit is satisfactory before making samples, regardless of their previous experience with such software. Participants who have tried using 3D apparel visualization software for designing structural turnout gear expressed their resounding endorsement of the software's effectiveness specifically in the domain of pattern making. Participant B2 described how using software was helpful in getting what they wanted out of the three layers of pattern pieces when developing a new turnout coat:

> We could look at where the armscye was, where the sleeves were, and where the end of that sleeve segment finished and determine whether the alignment is satisfactory. We could also determine whether it was advantageous to skew one layer in another direction, back and forth.

Participant B2 highlighted the ability to visually assess the alignment of garment segments of the three layers of materials to make informed decisions on potential adjustment. Participant D1 from a wildland fire gear manufacturing company also uses 3D apparel visualization software in her job and illustrated,

> I created a pattern for pants that I believed was good. However, when I put it on an avatar, there were some draglines on the back of virtual garments. I adjusted the pattern and fitted it again, and the draglines disappeared.

Participant F1 expressed a hope that the software could alert users whether their pattern blocks and garment designs comply with NFPA standard sizing and design requirements. The participants suggested that the software's visual feedback and pattern making and alteration capabilities could allow users to identify and rectify potential fit issues before producing physical samples.

Enhancing Pattern Design through Body Movement Considerations. Some participants expressed interest in making avatars mimic specific poses when designing patterns that prioritize the body movement comfort of firefighters.Participant E1 said, "*We have to consider the ability to do the moves that they need to perform the job, and how the material is going to, possibly compress to the body in certain areas or certain positions*." As part of the phase two study interview, the participants had the opportunity to view the software website, which included parametric hand avatar images. After looking at the image, participant E3 expected that the parametric hand avatar and modification of finger joints would be applicable to the glove design, as she could trace the hand to draft and engineer patterns by predicting how a firefighter would grip, hold, or carry things. Participant C2 commented on the potential utility of employing garment fit maps in the design of protective hood coverings, "*Particulate blocking and proper fit, as well as the consideration of movements and stress points. Scanning digital head models and visually representing stress patterns that diverge from the software would be very useful*."

Furthermore, participant E1 emphasized that the software could greatly benefit from a collection of poses and animations representing the daily work and fire suppression process of firefighters.

> I personally have had the opportunity to go out to a firehouse and observe the firefighters performing some of their typical movements and actions when entering an active scene. They don't crawl on their hands and knees as one might expect. Instead, they use a technique called a 'three-point pose,' where they progress with one knee up and one leg dragged out behind them. They use different poses than what one might expect. Being able to model these movements on an avatar during the development stage would be really useful, I think.

Additionally, she emphasized the importance of the avatar's capability to assume specific poses in order to ensure compliance with the design regulations.

> There's a rule within the NFPA Standard that states when you lean forward, your coat must cover the top of your trousers by at least 2 inches. This can be tested by designing the garment length on an avatar in a forward position. I think it would be really cool to try out some of those motion features.

These responses showed that some participants were interested in utilizing garment fit maps with avatars in various poses to aid in designing patterns to enhance functionality required for firefighting operational environments and NFPA standards.

Expanding the Functionality of Garment Fit Maps. Some participants suggested that the software would be useful if it could improve the stress maps feature to not only indicate the current tension or stretchability applied to the fabrics of virtual garments but also predict how modifying a specific garment segment's measurement would affect the result. Participant C2 expressed, "*Sometimes we have anywhere from 8 to 12 layers of fabric. If a computer could tell me how adding 2 more 8-inch layers of foam affects the stress distribution. We are eager to have a model that can provide us with such information.*" Additionally, participant C1 recommended the representation of inter-garment tension, which would assist users in identifying any competing elements between the shell, moisture barrier, and thermal liner layers. He thought such software capability would enable them to address any sewing issues and engineer patterns to alleviate the tension.

Streamlining Sample Iterations through Virtual Fitting. Some participants believed that virtual fitting with an avatar could save costs and time for producing physical samples. Participant C1 described that the company spends a lot of money on structural gear samples: "*If we make a garment with the wrong sizes or specifications, it can be very expensive. These garments cost between $3,000 and $4,000, so a lot of time is spent making sure we have* *everything right before cutting the fabric*." Participants were considering that the high costs associated with fabric or sample production for structural turnout gear might be the reason for the greater potential of 3D apparel visualization in contributing to the product validation process, compared to wildland fire gear. Participant B1 mentioned:

> Making a single-layered garment, such as wildland fire gear and stationwear, is nowhere near the cost of sampling the structural turnout gear. I'm not saying it wouldn't be great, and I'm not saying that those businesses may not want to explore that, but there are different complexities and needs involved.

The participant emphasized the importance of virtual fitting capabilities as a major factor in her company's decision to acquire the software license. She argued that modifying the grading rules of base size pattern blocks and avatar sizes could potentially streamline current grading practice.

> Checking the fit of all the components on multiple sizes is started by making the base size because the garments are very expensive. Sometimes you do a small size run, but you never know until it gets out in the industry, and we've had coat sizes ranging from 30 all the way up to size 82. Sampling that range is impossible, and we do have a visual room where we have the base pattern printed on a grid, and we can put all these magnetic parts to see if they'll fit. But again, that's a base size. So, then you have to look at the grid and go, okay, if this was a size 30, now we only have this much room, so we can do that manually and then take a picture and send it to a customer. But it would be nice, in this day and age, to be able to do it digitally.

Participant D1 also reported that the use of software helped them eliminate a fitting step for developing wildland fire gear, which previously took a couple of hours, if not a couple of days or a week. Furthermore, participant F1 expressed hope that the software would aid in time and cost savings associated with conducting actual trial fitting tests of physical samples during their product customization process.

> When the product is 90 percent finalized, we go to a fire station for a customer trial fitting and to receive feedback. After the visit, the design might change to incorporate all the feedback, and the time required to make the changes and put them into production is typically between 8 months to a year, involving at least twenty engineers. The cost of going through this process is very expensive. Although fit satisfaction is subjective and the software may not perfectly satisfy end-users, there is still a way to gain confidence in a newly designed garment's fit quality before conducting an actual trial test.

Overall, the participants recognized the potential of 3D apparel visualization software to enhance efficiency, reduce time and costs, and gain confidence in fit accuracy for sample iterations.

Facilitation of On-demand Production. Among the participating companies, company C was beta testing an on-demand production system to improve speed-to-market and facilitate mass customization. Therefore, participants C1 and C2 noted that virtual fitting on the end user's personal avatar could potentially enhance performance and outcomes of their on-demand production system. Participant C1 said that they are exploring a process of allowing customers to build their own product specifications and creating markers and fabric cutters automatically from order reception to address the multifarious needs of every fire department and reduce manual errors. He stated,

> Obtaining body measurement data and having a 3D digital form of end users allows us to pick the best option among existing pattern blocks and make modifications to the pattern block to ensure the requested specification before producing actual garments. The current approach of providing kits of all sizes and letting people try them on is inefficient. But that's the only way we've been able to be successful. Now, I think we're headed towards virtual fitting technologies, and it is very interesting.

The participants paid attention to the potential of 3D apparel visualization software for seamlessly incorporating visual presentation into their on-demand production system.

Stakeholder-related Features. Analysis of interview transcripts revealed three distinct categories related to perceived drivers of integrating 3D apparel visualization software, specifically focusing on software features. These categories are as follows: 1) visual presentation to communicate with municipalities, 2) visual presentation to customers for product customization, and 3) enhancing consumers' size selection through virtual fitting.

Visual Presentation to Communicate with Municipalities. Some participants suggested utilizing 3D virtual simulation images to facilitate discussions about product features when meeting with decision-makers at municipalities, fire departments, and counties. Participant B1 believed that virtual fitting enables their salespeople to present visual aids to their customers without incurring fabric and labor costs. She said,

> There is no true visual representation of the gear until the department makes a purchase decision and writes the purchase specifications. The hope with virtual prototyping is that once the specifications are available, ordered products can be rendered and presented to the department, saying, 'Here is a 3D virtual view of what your gear will look like.' This may help solve some issues, as often stakeholders request physical samples to see the gear's features and details, which can be a costly and time-consuming process.

The participant envisioned that the dealers and salespeople would benefit from having their 3D virtual garment images, as they could easily access and present them on their phones or computers during meetings with decision-makers. Participant B1 commented, "*My hope is to one day provide our marketing team with 3D renderings for advertising, but we are not at that point yet.*" In a similar vein, participant D1 stated, "*I'm driven to show virtual simulation images to people who don't have an eye for looking at a drawing, to demonstrate how it fits on a valuable body. This is crucial for selling the idea to the decision makers*."

Visual Presentation to Customers for Product Customization. Some participants emphasized that the virtual fitting capability offered by 3D apparel visualization software holds considerable potential in significantly enhancing their ability to comprehend the unique requirements of individual firefighters. Of the five participating companies, companies E and F were offering customized firefighting gear to their clients. Participant E1 explained:

> Our customers communicate with our sales representatives through written or verbal instructions, and they often send reference pictures of dimensions and design options via email. However, we have experienced misinterpretation in this process. To address this issue, we have created a technical illustration spec sheet that shows all the available options and the placement of various elements. We are currently in the beta testing phase of this product and have not yet introduced it fully to the market. Going forward, we plan to offer this tool online so that customers can build their own gear. Ultimately, we hope to move to a 3D platform where customers can fully customize their gear and then send their design to us for a quote.

Participant F1 emphasized that the end user's fit satisfaction is subjective, and mentioned that software usage could potentially help receive customer feedback to finalize product design.

> During trial fitting sessions, some firefighters explain what they want well, but some don't even know how to express themselves. So we have to extract information from them, and it is a very difficult process. In such situations, garment fit maps and virtual garments can be visual aids that predict which body parts have less tension and compare them with feedback from actual wearers. We can also discuss and record in real-time whether adding or subtracting ease is appropriate by garment parts.

Both participants recognized that 3D apparel visualization software has the potential to serve as an effective visual confirmation tool for customization services to address customers' unique requirements and needs.

Enhancing Consumers' Size Selection through Virtual Fitting. Some participants predicted that virtual fitting on body-scanned personal avatars could be utilized as visual aids to help end users find their optimal sizes among existing products. Participant D1 stated, "*I think the primary use might actually be for the customer base, where they could use it to see what size they are and decide what size they are going to fit into what is available*." Participant F1 expected that this feature could reduce the time required for firefighters to decide on the most suitable size.

> For example, when you visit a fashion brand's store, they may take a photograph of you to generate your body measurements and recommend sizes for different product categories. This would be helpful for customers to make decisions such as choosing a size one bigger or smaller when they try on the recommended sizes in the fitting room.

The participants believed that integrating technologies such as body measurement taking and personal avatar generation could enable customers to make informed decisions when finding their optimal sizes.

Perceived Barriers. This section provides an overview of the identified categories associated with perceived barriers to adopting or using 3D apparel visualization software in participants' professional roles and companies, as well as their suggestions for enhancing the software's performance to optimize its utilization.

Structural Turnout Gear Features. The majority of participants in the field of structural turnout gear commonly described important product features that should be considered significant for the technical capabilities and simulation performance of 3D apparel visualization software. The interview transcript analysis revealed three distinct categories related to perceived drivers of integrating 3D apparel visualization software, specifically focusing on structural turnout gear features. These categories are as follows: 1) three layered composite material, 2) inherent necessity for a substantial air gap, and 3) donning multilayered garments.

Three Layered Composite Material. Structural turnout gear, which consists of three layers comprising an outer shell, a moisture barrier, and a thermal liner, serves specific functions (McQuerry et al., 2017) as shown in Figure 17. Some participants noted that software simulation needs to be able to realistically reproduce the three-layered composite material of structural turnout gear and its impact on garment construction. Participant C2 explained how the thickness of three layers of composite material can affect seams, seam allowances, and sewing techniques, resulting in complex garment construction and production quality.

> We talked about three layers of fabric, and as a pattern maker in this industry, overcoming this challenge is unique. For instance, an 18-inch armhole in ready-to-wear apparel needs a sleeve cap that is pretty close to 18 inches to fit properly. However, this is not possible in firefighting apparel due to the fabric thickness and 5-thread serges we use. Moreover, every curve reacts differently to the curve it's plugging into, causing the seam allowances to not line up on each hole differently. You can only truly understand these challenges when you experience them firsthand on the production floor.

Participant B2 also mentioned that he tried to achieve three protective layers of the coat by individually sewing three pattern blocks and overlaying them, but visualizing this process was quite cumbersome.

> To simulate a single layer, you should establish sewing relationships between pattern pieces and place each one around the avatar. To connect three layers, each individual layer has to be assigned a placement on the body and on the garment, and so building that, just in the avatar face, gets complex. Unfortunately, sometimes the same technical problem occurs repeatedly, and at other times, new issues arise, and the program may crash. The biggest challenge is that we can put the pattern together in a single product and see that the patterns fit together, but we can't truly see the representation of how they hang on the body because of the layers. As of now, we haven't been able to render a true three-layered garment.

The complexity of garment construction and production quality of structural turnout gear arises from factors such as the thickness of the layers, sewing techniques, and the challenges posed by fabric thickness and seam allowances. The participants reported that technical issues and limitations in software performance are hindering the simulation of a true three-layered virtual garment.

Figure 17

Graphic of the Outer Shell, Moisture Barrier, and Thermal Barrier Layers Opening of a Fire Suit, Each with Different Protective Qualities (MSA Safety, n.d.)

Inherent Necessity for a Substantial Air Gap. Another important product characteristic is that air gaps must exist between the coat and the wearer in structural turnout coat and pants for thermal protection and heat dissipation. Participant C2 commented, “*As you get closer to the body, you improve your breathability but you reduce your thermal protection*.” He added, “*My chest circumference is 44 inches, and I want my coat to measure 52 inches around me so that a nice cushion of air between the coat and my body keeps me safe*.” The participant’s responses revealed that the inherent requirement of big looseness in structural turnout gear makes it difficult to assess the appropriate fit characteristics within the software. Participant C2 stated, “*The stress map cannot be valid unless you can accurately get the three-layered fabric. Moreover, I am unsure how much those maps would benefit us as our product is quite boxy and requires a lot of ease*.” He also explained that in the field of firefighting gear, evaluating heat stress performance is considered more important than fit. “*For the majority of our production, we are interested in total heat loss (THL) and thermal protective performance (TPP). These numbers are not even close to what the software can provide. While it's interesting, this would be a huge hurdle*.” Participant C1 added, “*We're such a niche industry that focusing a lot of time on fire or other very specialized areas may not make business sense for them*.”

Donning Multilayered Garments. Some participants suggested that giving consideration to replicating the interaction between multilayer garments would be beneficial in enhancing the software's performance and simulation accuracy. Firefighters wear undergarments, station wear, t-shirts, and jeans in combination with structural gear coat and pants. Participant E1 stated:

> For example, in the elbow area, you won't have the full range of motion that you would have with a bare arm. Adding layers in those areas is similar to having four layers of clothing. I'm also considering the layers of the structural coat and trousers worn together.

Additionally, depending on the application of trimming and design details on coats or pants, as well as the use of additional items such as fire hoods, suspenders, and aluminized gear, garment layers can be added. Participant D1 expressed her hope that the simulation capability would be improved to enable stable multi-layer modeling of accessories worn by firefighters in addition to fire coats and pants.

Software Features. While most participants agreed that virtual fitting on an avatar would help with their pattern optimization process, they expressed concern about bridging the gap between the quality of virtual simulations and the actual appearance of garments. The interview transcript analysis revealed two distinct categories related to perceived drivers of integrating 3D apparel visualization software, specifically focusing on software features. These categories are as follows: 1) imperative need for complementing a digital material library, and 2) technical difficulties in configuring intended garment design.

Imperative Need for Complementing a Digital Material Library. Participant responses indicated that digital fabrics and subsidiary materials used to construct virtual garments should reflect their physical and mechanical properties, precisely configuring these characteristics within the simulation. Some participants highlighted that the digital fabric library provided by the software provider lacks the inclusion of fabric types used in the outer shell, moisture barriers, and thermal liners of structural turnout gear, as well as various design details such as trims, edge treatments, stitches, seams, and fasteners across garment segments and layers. Participant B2 explained:

> We have many things that add weight and thickness to the garment, such as reinforcement cuff trim, lining, knee pads, nickel metal hooks, bellowed pockets, triple trim, and ankle trim. However, they are not simulated to add any weight but are rendered as picture elements by loading JPEG images. This skews the product so much that I'm losing any kind of data that could be collected from it.

He expressed concerns that lack of digital assets of different types of fabrics and trims used in firefighting gear could lead to inaccuracies in fabric simulation and a lack of realism in fit evaluation from the software. Some participants expressed their interest in collaborating with material suppliers to establish a precise digital material library for integration into 3D apparel visualization software. Participant E1 commented, "*It would be nice if some textile manufacturers purchased physical testing devices to gather fabric data and scanned the texture surface to create a digital fabric library*." These responses showed that some participants felt that the seamless integration and precise configuration of material properties in the software would contribute to accurately simulating the fit and drape of intended designs of structural turnout gear.

Technical Difficulties in Configuring Intended Garment Design. Some participants who have used 3D apparel visualization software for their jobs reported there is a bit of a gap in information for users trying to input garment details into the software, and they reported their findings, indicating that they were unable to achieve certain garment details due to the current limitations of the software capability. Participant B2 explained that he couldn't simulate some design details and insisted that the software's capability of allowing users to edit and adjust components by components should be dramatically enhanced to simulate complex parts. He stated,

> The program was stunted while trying to get the military tucks on fire coat to go down either side and be thrown on the back. I couldn't figure out how to fix it, so they had to be turned into a picture on the garment. Our fire coat also features a bi-swing back to help the shoulders move more freely, and it's quite a challenge to get the pleats to work as they should.

Participant B1 also reported experiencing technical difficulties, such as encountering simulation errors when trying to achieve design details for unclear reasons from time to time. The participants expressed a desire for the software's functionality and performance to be enhanced, allowing users to precisely translate their intended designs.

Stakeholder-related Features. Participants highlighted that the usage and adoption of 3D apparel visualization software may significantly rely on the technology user, organizational characteristics, specific circumstances and market context within the firefighting gear industry. The interview transcript analysis revealed seven distinct categories related to perceived drivers of integrating 3D apparel visualization software, specifically focusing on stakeholder-related features. These categories are as follows: 1) perceived effortfulness in learning and using software, 2) financial capacity and return on investment, 3) unique and manifold nature of the manufacturing business, 4) unchanging garment style requirements, 5) restricted availability of customized firefighting gear in the market, 6) insufficient focus on design and product innovation, and 7) limited receptiveness to innovation.

Financial Capacity and Return on Investment. All participants unanimously agreed that implementation cost is the most critical decision factor for adopting 3D apparel visualization software, regardless of current status of software adoption. Responses suggested that return on investment should be proven from the decision makers' perspective. Participant D1 works at a company that has used 3D apparel visualization software over the past year, and she mentioned,

> Our existing system is working fine, and it is hard to justify the cost of a yearly software license. The last time I inquired about it, it was $13,000. Although virtual fitting and simulation were very nice, it was not worth the thousands of dollars it cost. We create ten new styles a year so the cost-benefit wasn't good enough. If we were ten times our current size, it might make sense to spend that kind of money. However, for a small company, and given that our current process is already working well, I don't know if it is really worth the cost of it. Therefore, we will let it expire.

For most small-sized manufacturers with limited funds, management had no option but to allocate investments based on priorities other than 3D apparel visualization software. Participant

E1 stated that their current priority is investing in innovative solutions that could potentially address the shortage of labor for their sewing operation rather than design or product innovation.

> I think our particular boss would have maybe an issue with investing money in the design side up front. Because he's mostly focused on can we produce the product efficiently? Can we get the product to the customer in a reasonable amount of time? Can we cut costs by making it more efficient, using less material, those kinds of things. We're still trying to figure out how to manufacture our gear efficiently and secure enough labor to keep our company running smoothly every day. Therefore, I think we would face difficulties investing in this type of software since it's less relevant to our daily operations compared to the pre-development stage of design.

Some participants also illustrated that an immense expense is required to train employees and have an entire team to facilitate the digital product creation process by building digital material and pattern block libraries. Participant E1 stated, "*If any software provider can offer an intensive week-long training at the location of your choice, that would be a huge advantage when considering purchasing new software*."

On the other hand, participants suggested that companies belonging to larger-scale firms would be willing to bear the cost if it was proven that using the software could improve the product quality. Participant F1 mentioned,

> I believe that the software license fee is easily affordable for our company, and they are willing to invest heavily in proving that our product is the safest option available. We have already spent a significant amount of money obtaining certifications from NFPA regulations and UL labs. Therefore, as long as we can get reliable metrics to enhance the safety of our gear, our company will be willing to pay for it.

However, at the same time, he expected it would be challenging to communicate and prove the effectiveness of the software to the company decision-makers. In general, participants reported that firefighting gear manufacturing companies primarily considered the overall value-to-cost ratio of implementing 3D apparel visualization software when making adoption decisions.

Perceived Effortfulness in Learning and Using Software. Interestingly, all participants who are currently using the software for their work reported that it is not easy to use. Participant D1 said, "*Despite my age, I am tech savvy, but it was really heavy input and difficult to use. It was not user friendly. I used it with some help from my coworkers*." Some participants also had concerns about the time and effort required to use the software. Participant B2 commented:

> It's time intensive and everything you brought up just getting one layer. Then you should repeat sewing pattern pieces for the other two layers, and each layer is unique. Sometimes the same problem will happen every time. So each render is like another go around the carousel. Sometimes something new pops up and sometimes it does crash.

Moreover, the participants perceived the use of 3D apparel visualization software as extra work on top of their existing tasks. Participant B1 said, "*We're trying to keep up with the daily minutia of business while trying to use this new software. That's not actually part of our daily routine*." Moreover, Participant D1 was concerned that creating the pattern to make virtual garments in software before selling the product is out of sync with their normal workflow, and it is like putting the cart before the horse. "*It is extra work. If it did help make pattern adjustments, I was able to see that it wasn't fit correctly. I would still make samples. I think they're more reliable than virtual fitting*." Some participants even preferred the conventional method of pattern drafting and physical prototyping. Participant C2 said, "*My process doesn't involve computer. It's more about hands on brown paper, and cutting out fabric, old school fashion design*." Participant D1 who is using 3D apparel visualization software as part of her work explained,

> I was accustomed to using the traditional methodology, which seemed easier and more time-efficient to me. While making adjustments in the layers of pockets assembly, I found it more helpful to switch from the software to hard patterns. This allowed me to visualize how all the layers were working together, how they interacted with each other, and where the seam lines needed to be. Sometimes, working physically with something can be more beneficial than working digitally.

In this regard, the participants raised challenges and expressed concerns about the software's lack of user-friendliness and its time-consuming nature. Moreover, they showed a preference for adhering to the existing method and perceived the software as an additional burden.

Unique and Manifold Nature of the Manufacturing Business. Some participants pointed out that although the firefighting gear industry is small, it seems difficult to create a specialized 3D digital design platform or a unified digital product creation process for this industry. This is because each manufacturing company has different product design and development processes and systems. Participant C1 commented,

> We have evolved our manufacturing processes internally and while things are similar, there are a lot of differences in the way we all implement and the technology we use. So it’s almost like a custom application for every specific company. I don't know that there's a one-size-fits-all solution. If I were developing this program, understanding everybody's manufacturing systems would be a challenge.

Participant C2 added, “*Even the way we sew is very different from company to company, so the process itself varies.*” In this regard, the participants were concerned that the uniqueness of manufacturers might impede the development of an integrated 3D ecosystem across the supply chain, connecting suppliers, manufacturers, and clients. Participant F1 stated, “*Understanding our design process and integrating it into the software would make more sense for users and motivate us to try using it*.” He suggested that software engineers should design software after listening to what functionalities each company needs through conversations with their representatives, considering the specificity of each company's situation.

Unchanging Garment Style Requirements. According to the participants, firefighting gear manufacturers not only refrain from changing the design of their patterns for years, but also utilize a limited range of fabrics. As a result, the frequency and value of using virtual fitting to modify patterns of various styles or apply virtual fabrics with different properties to observe drapability or fit are restricted. Participant C1 stated, "*Our patterns have been 30 years old. Although we have newer patterns for new products, they possess similar properties*." Participant F1 said, "*our existing customers only come to us once every 5 or 10 years and request the same product as their previous order*." Participant D1 explained, "*We introduce around 10 new styles per year, including some reduced styles that have been in our line for a while and require an update*." Moreover, a participant stated that the business style of the fire distributor also acts as a strong driver that repeatedly produces the same product over and over again. D1 stated:

> A major distributor of fire products is very particular about not changing the style number of our products over the years. They want to ensure that they sell the exact same thing to individual users at fire companies or utilities, as they send out product information. Even a minor change on a garment would require changing the connections, which they don't prefer. On the other hand, when we introduce something new, they can easily add it to their product offering. We have styles in our line that are over 25 years old and are still popular.

The persistence of unchanged garment styles over extended periods, combined with a limited range of fabrics, poses limitations on the frequency and potential benefits derived from utilizing virtual fitting to modify patterns or explore different styles, according to participants.

Restricted Availability of Customized Firefighting Gear in the Market. Some participants claimed that the software is more suitable for the custom market that is not related to the majority of manufacturers in the firefighting gear market. Participant D1 stated, "*Right now, for our industry, all the companies that we deal with work on a larger scale and they do not fit individual people*." Also, the participants emphasized that they have to cover an immense range of body types with limited style and size options of firefighting gear, so the software's value is limited for them. Participant B1 said, "*It's not like the fashion world where you offer, and they get what they want or they don't buy it*." Also, participant D1 commented, "*We're fitting* *everyone. So we have to think about just one somebody in the middle of all the different shapes of end users*."

Insufficient Focus on Design and Product Research. Some participants mentioned that the firefighting gear industry tends to pay less attention to design and product research and innovation. Participant E1 explained,

> I think a barrier is convincing the people in power that innovative design is worth investing in. The design isn't just an aesthetic choice, but also designing for functionality, designing technically so that it will perform as needed. To ensure proper thermal protection and safety, correct sizing and fit are essential. Without them, the protective gear will not function properly and may not provide the necessary protection.

Participant E2 added, "*I don't even think there are a whole lot of designers for firefighter gear specifically because that's a very niche market*." Participant E1 further elaborated on the diverse design preferences of firefighters. "*Some firefighters prefer the classic appearance of firefighters, while others argue for more fitted garments with athletic cuts and trimming to address safety and performance features*." As designers or pattern makers in the firefighting gear industry, some participants expressed their hopes that digital design technology could contribute to achieving ergonomic firefighting gear designs capable of addressing diverse user needs in the future.

Limited Receptiveness to Innovation. Some participants also pointed out that decision-makers in this industry tend to have lower levels of innovation openness compared to other industries. Participant F1 mentioned, "*A challenge in implementing this type of technology in this industry is overcoming the conservative mindset*. *Since safety is paramount, they tend to have a conservative mindset and are less receptive to new technology*." Participant E1 expressed concern that the performance of the computer-aided design software for the firefighting gear industry was lagging behind that of other manufacturing industries.

> I work with a lot of people who have been involved in other types of manufacturing like aerospace, automobile, and cannabis industries. They see the software that we are using for just two-dimensional designs and said the software seems so far behind what they were using in their industry.

The participants recognized that the firefighting gear industry tends to have a conservative attitude towards adopting change and embracing new innovations, especially when compared to other manufacturing industries.

Summary of Phase Two Study Findings

According to participants, the degree of willingness of firefighting gear manufacturing companies to use or adopt 3D apparel visualization software is influenced by three contributing factors: structural turnout gear features, software features, and stakeholder-related features. For each of these categories, the perceived drivers and perceived barriers reported by participants from five firefighting gear manufacturing companies were identified.

Structural Turnout Gear Features. In the phase two study, the majority of participating companies specialized in the production of structural turnout gear and the primary concern of these manufacturers was whether the 3D apparel visualization software could accurately simulate the properties of their 3-layered composite material. This concern was paramount before exploring the potential applications of the software in their product design and development processes. Participant B2 clarified that despite their utilization of software, they were unable to simulate an entirely accurate representation of the final product. This constraint stemmed from their methodology involving the creation of distinct pattern blocks for each layer of the 3-layer composite material, followed by the stacking of these blocks around an avatar to simulate the virtual garments. Moreover, participants were concerned with the software's capability to replicate various garment construction techniques such as seams, seam allowances, and sewing methods, which can vary across different sections of the garment. They believed that the software's ability to accurately simulate these factors could significantly impact the quality of virtual garments.

Software Features. Due to the novelty of 3D apparel visualization software in the industry, participants from only two companies (Company B and Company D) were utilizing the technology, specifically emphasizing its application during the design ideation and pattern making stages. Similarly, participants from other companies (Company C, Company E, and Company F), which were not currently employing this technology, recognized the potential benefits of adopting such software to enhance design decision and pattern optimization. Their main anticipated utilitarian benefits were to ensure an ideal fit, proper air gap, and optimal functionality by utilizing the software's capability to model these key factors, which were identified as the potential motivators for its adoption. Furthermore, some participants suggested that the software can contribute to reducing both the time and cost associated with sample iterations. Additionally, participants who use it suggested that the software offers visual aids that effectively facilitate the communication of product specifications and garment details with various stakeholders within the supply chain. Furthermore, participants reported that there is potential for integration with body scanning technology, enabling the creation of personalized avatars and simulating the fit of virtual garments on these avatars. Participants who made this suggestion felt that this capability would open up the possibility of recommending optimal sizes for end users. These utilitarian benefits emerged as perceived drivers for the use and adoption of 3D apparel visualization software, particularly in relation to software features commonly suggested by participants from all participating companies of the phase two study.

Most participants in the phase two study picked the following software capabilities as key features and functions to meet those operational benefits through the utilization of 3D apparel visualization software: 3D virtual garment simulation, customizing the sizes and poses of parametric avatars, and garment fit maps. In particular, the participants had a vision of utilizing 3D virtual garment simulation as a visual aid to facilitate discussions on product features, garment details, fit and quality standards, and design and sizing regulations. This would involve engaging with inter-organizational communication, manufacturing factories, sales meetings with municipalities, fire departments, and distributors, as well as NFPA committee meetings. Besides, most participants expressed a keen interest in enhancing the capabilities and expanding the usage of garment fit maps. The participants expressed a strong interest in utilizing the garment fit maps capability during the pattern making process. This would go beyond predicting the pressure or tension of the virtual garment, as it would also involve identifying problematic areas of the garment, determining the underlying causes, and proposing modifications to improve the fit and comfort of the wearer during movement. Ultimately, the participants anticipated reaching a stage where the garment fit maps could provide scientifically reliable numeric data that would serve as a credible foundation for discussions on sizing regulations. Participants also expressed interest in using garment fit maps to show optimal amount of air gap and garment in structural turnout gear when discussing at NFPA committee meetings.

On the other hand, all companies agreed that the lack of accuracy in virtual garment simulation and the reliability of garment fit maps features are the biggest technological risks associated with adopting 3D apparel visualization software. For example, participant B2, who uses 3D apparel visualization software in the pattern making stage, highlighted the deficiency in the realistic representation of mechanical and physical attributes of trims, seams, bindings, reinforcements, and fasteners when simulating virtual garments they created. The participant emphasized that even if there are improvements in technological performance in the future, the intention behind utilizing this technology is not to replace existing methods but rather to serve as a supplementary tool. Moreover, most participants stressed that in an industry where safety is paramount, the production of actual samples, as well as obtaining trial fittings and feedback from real users, remain crucial and indispensable practices. Participant E1 said, "*In the firefighting gear industry, our highest priority is designing something that will not only keep firefighters safe but also ensure their functionality*."

Stakeholder-Related Features. Responses indicated that the learning curve and psychological resilience of users present obstacles to the adoption of 3D apparel visualization software. All participants acknowledged that incorporating the new software and adapting to a new workflow, alongside their regular responsibilities within designated work hours, would result in a steep learning curve when it comes to understanding new technology. Participants appeared to not be motivated to adopt new technology when the superiority of the new technology had not been confirmed compared to its predecessor. Participant D1 said that her company made the decision not to renew their 3D software license, while participant C1 found that their current operating system was functioning effectively and that some of the benefits offered by the technology could be fulfilled using their existing systems. Even participants B1 and B2 who are already using 3D apparel visualization software for their work find it difficult to comprehend and use the software as intended.

Another factor mentioned by participants that might hinder the implementation of 3D apparel visualization software was the fiancial capacity. The magnitude of this financial obstacle was closely linked to the company's size. With the exception of participant F1, who is from a dominant player in the firefighting gear market, all participants emphasized that the costs associated with adopting new technologies can place a considerable financial burden on their operations. This underscores the importance of evaluating the return on investment before committing to technological advancements. Most participants asserted that the costs associated with adopting new technologies can exert a substantial financial strain on their operations, highlighting the significance of evaluating the return on investment before committing to technological advancements. Participant D1, who is using 3D apparel visualization software, acknowledged its usefulness during the initial stages of product design but cast doubt on whether its benefits justify the annual cost of approximately $15,000. Consequently, her company has chosen not to renew the license, even upon its expiration. In addition to the software license expenses, participants anticipated incurring supplementary costs such as purchasing fabric testing devices and texture capturing scanners, recruiting skilled personnel, providing training and upskilling for existing employees, and availing services such as consulting from software providers or third-party agencies for the construction of digital fabric and pattern block libraries. As employees of small-scale enterprises, the majority of participants emphasized that their companies tend to prioritize investing in managing administrative tasks, supply chain operations, and production-related issues over investing in design or product development due to financial constraints.

Moreover, the findings indicated that the level of technological awareness and innovativeness among managers significantly influences the adoption of 3D apparel visualization software within the organization. Specifically, in the instances where this technology has been implemented, it was reported that both Company B and Company D had mid-level managers who possessed a comprehensive understanding of the technology's existence and associated benefits. These managers effectively persuaded higher-level decision makers to introduce the software to the design team, emphasizing its potential contributions to product design related tasks and projects. Interestingly, even among companies that have not yet integrated the 3D apparel visualization software, participants who recognized a pressing need for investment in design and product development, despite the software's current limitations and lack of validation, exhibited a more positive attitude towards the feasibility of adopting such technology. Furthermore, participants who had previous exposure to the technology through education or training showed a more positive attitude and curiosity towards the potential of adopting such technology.

From a broader perspective, participants highlighted the anticipated challenges in adopting and implementing 3D apparel visualization software, which stem from the unique characteristics of the firefighting gear industry. These characteristics undermine the efficacy of the software and devalue its capabilities in firefighting gear design and development from the point of view of participants. The primary concern in the firefighting gear industry expressed by participants is ensuring the safety and thermal protection of the wearers and this crucial factor takes precedence over any other consideration in product design and development. Additionally, participants pointed out that, unlike fashion and apparel industry, the firefighting gear industry does not introduce different styles each season. Instead, manufacturing companies rely on a proven baseline design that remains consistent for decades. Moreover, due to the strict regulations imposed by NFPA regarding design, sizing, and protective performance, the scope for alterations in firefighting gear design is limited. These unique characteristics of the industry expressed by participants pose challenges in fully utilizing the virtual fitting capability of 3D apparel visualization software. Consequently, participants did not view this technology as a means to experiment with various styles or to replace the current practices of physical prototyping and actual trial fitting. Instead, they prioritized gathering feedback from end users, particularly firefighters, to ensure the functionality and safety of the designed and produced gear during real-world fire prevention, suppression, and rescue operations, when worn in conjunction with other equipment.

Additionally, the participants highlighted that another major hindrance to the adoption and implementation of 3D apparel visualization software is the inadequate understanding and awareness of technology existence as well as capabilities among NFPA boards, administrators, engineers, and decision-makers. Furthermore, they pointed out that there is a significant lack of openness to innovation and recognition regarding the importance of investing in design and product innovation. This challenge extends beyond individual employee and permeates the entire firefighting gear industry. Moreover, the participants emphasized the crucial need to develop a digital material library that precisely represents the mechanical and physical properties to establish effective 3D design practices. They underscored the imperative cooperation of software providers and material suppliers in achieving this objective. Based on the findings, the next chapter will introduce a comprehensive model that examines the perceived drivers and barriers of using 3D apparel visualization software for designing and developing firefighting gear from the manufacturer's perspective.

The findings from both phase one and phase two studies revealed the manufacturers' perspective regarding the adoption and usage of 3D apparel visualization software for designing and developing firefighting gear. Through the identification of distinct and recurring categories about perceived drivers and perceived barriers of using or adopting 3D apparel visualization software across different companies, richer knowledge under various organizational circumstances and multiple realities were discovered. The categories pertaining to perceived drivers and barriers, identified through the phase one and phase two studies, have been consolidated into a comprehensive single chart (Table 6).

Table 6

Perceived Drivers and Barriers of Using Virtual Fitting for Designing and Developing Firefighting Gear from Manufacturer's Perspective

<table>
<tr><th rowspan="2"></th><th rowspan="2">Software Feature</th><th colspan="2">Firefighting Gear Type</th><th colspan="2">Stakeholder-related Feature</th></tr>
<tr><th>Wildland Fire Gear</th><th>Structural Turnout Gear</th><th>Organization Characteristics</th><th>Industry Characteristics</th></tr>
<tr><td rowspan="2">Perceived Drivers</td><td rowspan="2">▪ Informing design decision
▪ Pattern making and optimization
▪ Considering body movement in design with customized avatars
▪ Digital grading and multi-size review
▪ Virtual fit assessment using garment fit maps
▪ Streamlining sample iterations through virtual fitting
▪ Facilitation of on-demand production and customization</td><td></td><td>▪ Visualizing air gap volume
▪ Predicting thermal protection and water penetration</td><td rowspan="2">▪ Visual presentation to communicate with
- Manufacturing factories
- Municipalities and fire departments
- Distributors and retailers
- NFPA committees

▪ Facilitating consumers' efficient size selection</td><td rowspan="2"></td></tr>
<tr><td colspan="2">▪ Enhancing the design, fit, and thermal protection of garments to elevate their performance in terms of safety and functionality</td></tr>
<tr><td>Perceived Barriers</td><td>▪ Inaccuracy of 3D virtual garment simulation
▪ Validity of garment fit maps
▪ Need for complementing digital material assets
▪ Technical difficulties in configuring intended garment design
▪ Indispensable nature of wearer feedback</td><td></td><td>▪ Three layered composite material
▪ A considerable amount of air gap
▪ Donning multilayered garments</td><td>▪ Financial capacity and return on investment
▪ Learning curve and effortfulness in using software
▪ Psychological resilience
▪ Technological awareness and innovativeness among managers
▪ Unique and manifold nature of the manufacturing business
▪ Preparedness among contract manufacturers</td><td>▪ Enduring practice of maintaining a consistent garment style
▪ NFPA regulations on design and sizing requirements
▪ Restricted availability of customized firefighting gear in the market
▪ Concerns surrounding product promotion through virtual stimuli
▪ Insufficient focus on design and product innovation
▪ Lack of technology awareness
▪ Limited receptiveness to innovation</td></tr>
</table>

CHAPTER 5 DISCUSSION AND CONCLUSION

This research investigated the potential of introducing 3D apparel visualization software into the industrial product design and development process of wildland firefighting protective clothing from the manufacturer's perspective. In this chapter, the findings from the phase one action research study are visualized as a framework illustrating potential applications of 3D apparel visualization software in Company A's wildland firefighting protective clothing design and development process. Next, an analysis of the action research participatory process is provided. Moreover, congruencies and disparities in the perceptions and experiences of multiple firefighting gear manufacturing companies are explored. Subsequently, the academic and practical implications of the findings are discussed. Lastly, limitations and suggestions for future research are described.

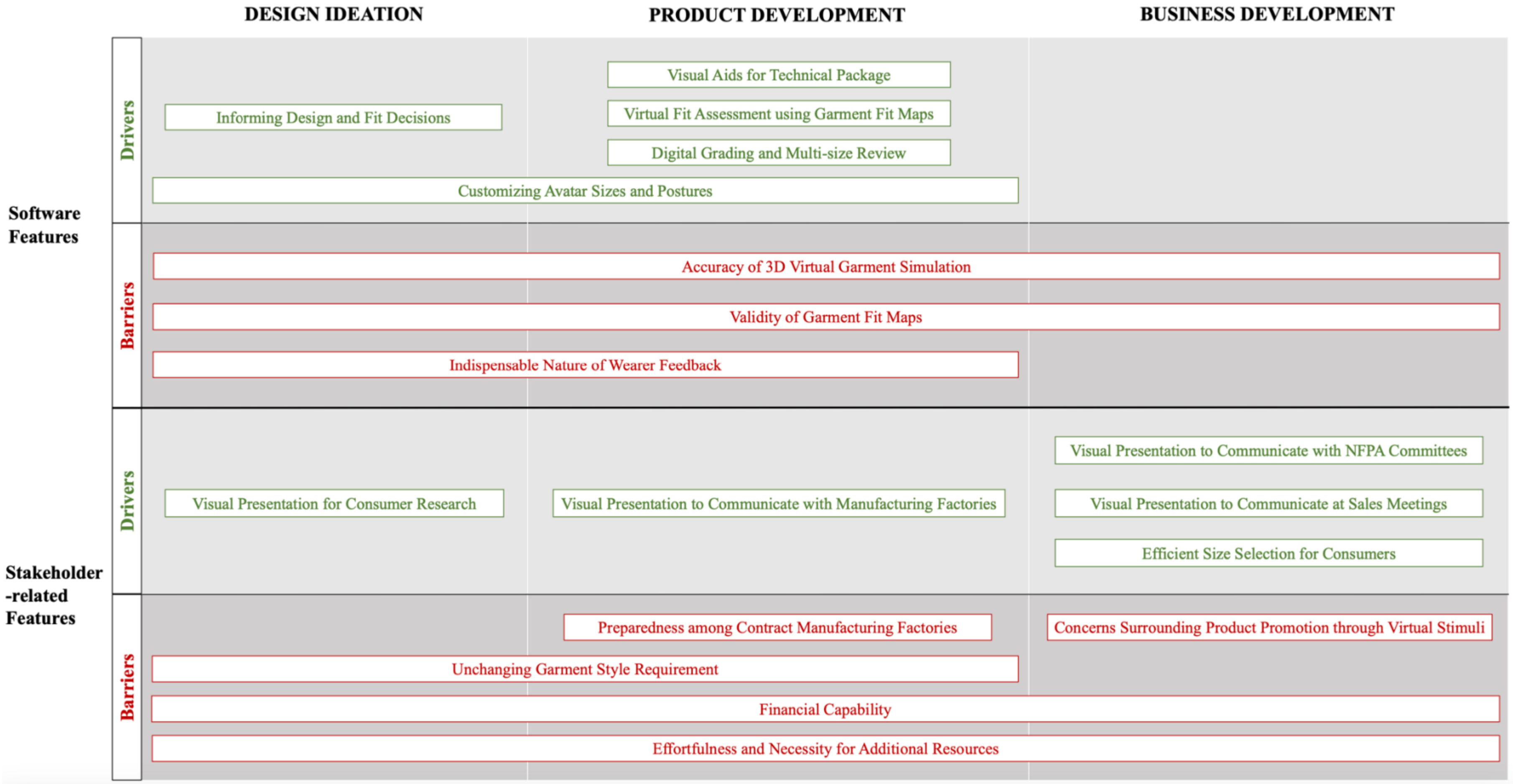
Revised Wildland Firefighting Protective Clothing Design and Development Framework

The phase one action research study aimed to explore the potential opportunities for integrating 3D apparel visualization software into the industrial product design and development process of wildland firefighting protective clothing, focusing specifically on the manufacturer's perspective. The "Potential Integration Points for 3D Virtual Prototyping within Company A's Product Design and Development Process" (Figure 9) provided an overview of the activities involved in the three main stages of the process, the supply chain stakeholders engaged in each stage, and the potential alternate or supplementary actions that could be facilitated through the utilization of 3D apparel visualization software. Through the preliminary interview, the identified challenges and needs within the current product design and development practices were primarily focused on the product development stage. These challenges included the need for streamlining and improving time management, as well as the precise communication of sizing and fit issues with manufacturing factories.

However, following the learning intervention through the four interactive interviews of phase one action research study, the responses of participants A1 and A2 demonstrated an appreciation for the utilitarian benefits that 3D apparel visualization software could provide across all stages of Company A's product design and development process. Nonetheless, they acknowledged that, at least for the present, the software could not completely replace their existing practices due to technological, organizational, and industrial challenges. As a result, the final framework for the Incorporating Virtual Prototyping into Wildland Firefighting Protective Clothing Design and Development Process (Figure 18) illustrates potential applications of 3D apparel visualization software, taking into account both perceived drivers and barriers. The potential applications of 3D apparel visualization software are classified as perceived drivers in green, while anticipated challenges in utilizing software capabilities or implementing it are classified as perceived barriers in red. The identified factors that could influence the Company A's adoption of 3D apparel visualization software, encompassed both software attributes and stakeholder-related considerations. Within the framework, the identified categories of software features (top two rows) and stakeholder-related features (bottom two rows) are labeled to signify the software's capabilities. These drivers and barriers are then positioned within their respective stages among the three main stages of the product development process.

Figure 18

Incorporating Virtual Prototyping into Wildland Firefighting Protective Clothing Design and Development Process



Software Features

Perceived Drivers. Throughout the phase one interviews, responses from participants A1 and A2 underscored the significance of specific software features that are anticipated to yield utilitarian benefits in the design and development of wildland firefighting protective clothing. These features encompassed 3D virtual garment simulation, parametric avatars, garment fit maps, and digital grading tools with a multisize review mode. Participants perceived that the incorporation of these software features holds the potential to streamline and enhance the internal workflow, encompassing design and fit decisions, pattern optimization, fit evaluation, and the application of grading rules. Furthermore, participants recommended utilizing the software as visual aids to facilitate effective communication pertaining to product features, specifications, and garment details. This aspect assumes particular importance in identifying consumer needs and preferences, ensuring product quality assurance and refinement, as well as managing distribution, promotion, and public relations involving various stakeholders within the firefighter gear supply chain across all three stages.

The anticipated utilitarian benefits identified by participants A1 and A2 in this study align with the advantages highlighted in the existing literature concerning the utilization of 3D apparel visualization software in diverse domains of functional clothing. Previous research has reported its usefulness in optimizing patterns for improved fit, integrating consumer needs, supporting design decision-making, and enhancing visual communication (Haixia & Yongrong, 2020; Hong et al., 2017; Hudson & Hwang, 2020; Jin, 2016; Porterfield & Lamar, 2021; Rudolf et al., 2019; Viziteu & Curteza, 2021). Moreover, the literature pertaining to the adoption of 3D apparel visualization software in the fashion and apparel industry also recognizes its value in streamlining the conventional garment fitting process, facilitating rapid prototyping, enabling early-stage design decisions, improving communication efficiency, and reducing misinterpretation between departments, technical designers, and manufacturers (Hwang Shin & Lee, 2020; Lee & Park, 2017; Papahristou & Bilalis, 2016).

Perceived Barriers. The action research study also highlighted technological concerns held by participants A1 and A2 regarding the use of 3D apparel visualization software for designing and developing wildland firefighting protective clothing. These concerns included the lack of accuracy in virtual garment simulation and the reliability of garment fit maps features. Initially, responses by participants A1 and A2 regarding the potential use of 3D virtual garment simulation for interactive fit decisions were positive at the beginning of the interview series. However, their perspectives on the software's suitability for fit decision purposes evolved over the course of the action research interviews, particularly as they became aware of the limitations in simulation accuracy through observing the fit appearance and making comparisons between virtual and actual garments. These findings align with existing literature, which has shown that comparing the fit of real and simulated garments reveals limitations in terms of accurate fit and visualization (Ancutienea et al., 2014; Apeagyei & Otieno, 2007; Kim & Labat, 2012; Lim, 2009; Lim & Istook, 2011). Additionally, apparel industry practitioners have identified software accuracy and precision as major challenges that hinder the integration of virtual prototyping (Lee & Park, 2017; Papahristou & Bilalis, 2017). Participants A1 and A2 highlighted two specific areas for improvement that they would like to see in the software: enhancing the accuracy of software simulations and increasing the validity of garment fit maps, making them reliable enough for making fit decisions. By improving the performance and precision of software simulation to a level where it can verify the designs of functional clothing, we can begin exploring how this technology can enhance the wearability and economic feasibility of producing wildland firefighting protective clothing.

Stakeholder-related Features

Perceived Barriers. At the organizational level, the adoption of innovation is influenced by various factors (Rogers, 1995). These factors encompass the characteristics of technology users, organizations, and the business environment, all of which have been recognized as contributors to companies' willingness to adopt technology (Rogers, 1995; Tornatzky & Fleischer, 1990). In the specific context of stakeholder-related features associated with perceived barriers to using 3D apparel visualization software, the responses of participants A1 and A2 in the action research study revealed that limitations in Company A's financial capability, the time and effort required for learning, additional resources required, and the preparedness of contract manufacturing factories may also hinder their potential adoption intentions of this technology. These concerns voiced by the participants align with findings from previous studies investigating the perceptions and adoption intentions of apparel firms regarding 3D apparel visualization software. These studies highlighted concerns such as the time and effort required for learning and internal integration (Papachristou, 2016; Papahristou & Bilalis, 2017; Park & DeLong, 2009), organizational resources (Henao-Ramirez & López-Zapata, 2021; Papachristou, 2016), high investment costs (Hwang Shin & Lee, 2020; Papachristou, 2016), a lack of skilled employees and technological competence (Henao-Ramirez & López-Zapata, 2021; Papachristou, 2016; Papahristou & Bilalis, 2017), and the technological readiness of suppliers (Papahristou & Bilalis, 2017). Furthermore, participants A1 and A2 indicated that certain characteristics specific to the firefighting gear industry may contribute to the limited utilization of 3D apparel visualization software in the design and development of wildland firefighting protective clothing. These characteristics included the unchanging garment style requirements and concerns related to promoting products using virtual garment stimuli. The responses of participants A1 and A2 also highlighted the need to address the conservative mindset of stakeholders in the firefighting gear industry overall by providing industry members with sufficient information and resources, as well as presenting application cases from other manufacturing sectors. This can be the first step in spurring the preliminary exploration of 3D apparel visualization software in the firefighting gear industry.

Perceived Drivers. Despite several concerns, participants A1 and A2 communicated that the adoption of such technology in the future could bring new lenses to a roadblock encountered by the wildland firefighting gear industry: the establishment of safe sizing standards. They highlighted the need for NFPA committees to have substantial data to make informed decisions in this area. In the end, there is a possibility of creating a new platform that has significantly improved accuracy by carefully choosing only the necessary key features that can be utilized for the design and development of wildland firefighting protective clothing and maximizing the potential of the software to achieve cost-effectiveness in all aspects. The platform could provide an integrated material library by digitizing all fabrics and trims certified by the NFPA standards so users can use any options without experiencing any digital disconnections. An approach for melding 3D body scanning technology with virtual fitting could be considered as mobile body scanning applications are readily available in the market which can capture the size and shape of end users to create individualized avatars. It also seems promising to add a feature that recommends suitable uniform sizes for consumers by collaborating with such application developers.

Action Research Participatory Process

Morales (2016) and Datta et al. (2015) highlighted crucial aspects of action research, including participant collaboration, co-learning, shared research efforts, group reflections, and the generation of new knowledge and meaning. In this action research study, participants' involvement in the series of interviews aimed at learning the capabilities of 3D apparel visualization software manifested itself in three distinct ways: 1) overall action research design, 2) collaborative planning and preparation for each interview, and 3) collaborative deliberation on data analysis.

Overall Action Research Design

The initial impact of participant involvement in the action research study was primarily observed in the overall research design. A preliminary interview conducted with the participants at the outset of the study served as the foundation for determining the purpose, direction, and data collection method of the action research study. During the preliminary interview, it was established that neither of the participants had prior experience with 3D apparel visualization software. However, the participants expressed a keen interest in acquiring knowledge about this unfamiliar technology. Consequently, the primary investigator made the decision to conduct a series of interactive learning interviews, taking on the role of an instructor to facilitate the participants' understanding of capabilities of 3D apparel visualization software. The aim was to help the participants envision how the software could be integrated into their product design and development process.

Additionally, through collaborative efforts between the primary investigator and the participants, the preliminary interview also served to identify the company's specific needs and areas for improvement in their current practices. The participants expressed two primary needs or problems: 1) streamlining company activities and improving time management during the preproduction stage, and 2) enhancing communication regarding measurements, sizing, fit, and grading with pattern makers and manufacturers. Accordingly, various functions and features of the 3D apparel visualization software that could address these needs and satisfy the participants' curiosity were demonstrated. As the four interactive interviews progressed, the participants' evolving needs and requirements were discovered, leading to revisions in the content and protocol of each subsequent interview based on their feedback.

Collaborative Planning and Preparation for Each Interview

The second aspect of participants' involvement revolved around the planning and preparing for each interview. After every interview session, participants engaged in discussions with the primary investigator to provide feedback on the day's setup, express new requirements, and suggest potential revisions for future interviews. These discussions empowered participants to make meaningful choices and actively contribute as co-planners.

Reconstruction of interview content and protocol. Firstly, the interviews and learning modules were restructured based on participants' opinions, and relevant resources were incorporated to maximize their acquisition of knowledge about the software, allowing them to judge its suitability for their business practices more effectively. For instance, participants expressed concerns about the accuracy and validity of virtual garment simulations, saying, "*Accuracy is key, so we aim to compare the virtual garment with the actual garment, at least one size, to enhance our confidence in utilizing the software for determining fit appearance and garment measurements.*" To alleviate these doubts, the participants wanted to directly compare the fit appearance of virtual garments with their real-life conterparts. Additionally, the participants showed great interest in utilizing 3D body scanning technology to create a personal avatar for a fit model. To experience this firsthand, participants insisted on conducting the third interview in person, leading them to visit the campus directly. During this process, they actively raised the need for a female firefighter to serve as a fit model and showed enthusiasm in recommending specific individuals during the recruitment.

Providing materials and resources for creating learning modules. Moreover, participants provided materials and resources that were utilized in preparing the interview content and learning module. These materials and resources included digital files of pattern pieces for shirts and pants designed by their company, actual samples of their products, and example photos illustrating how fit models wear the garments and pose during their live fit evaluation session. The provision of such materials and resources by the participants proved instrumental in aligning the learning module with their company's actual work setting, thereby maximizing deriving the potential opportunities for embedding software capabilities in their product design and development process.

Attempts to utilize the software. Furthermore, participants went beyond just observing the primary investigator's software capabilities demonstration through their responses, as they downloaded the free trial version of CLO3D fashion design software and browsed and tried out some features in the software to have actual interaction with the software. As a result of the collaborative planning and preparation for each interview, participants remained engaged and active learners throughout the entire series of interviews. This process enabled the primary investigator to gain a better understanding of the participants' needs and facilitated the co-construction of knowledge, leading to valuable findings that addressed the research objectives.

Collaborative Deliberation on Data Analysis

The third impact on participant involvement in the action research interviews was the collaborative discussion and elaboration of summarized findings, resulting products, and action research procedures. Participants actively engaged in member checking and reflecting on the primary investigator's data analysis, which shaped the design of the interview content. To illustrate, the primary investigator documented the preliminary interview findings and developed a basic model of the existing design and development process for wildland firefighting protective clothing in the participating company. During the initial interview session of a series of interactive interviews, the participants were presented with the initial model and summarized findings. They thoroughly reviewed and provided valuable comments and suggestions to refine the model. Following a series of interviews in the first cycle, the primary investigator conducted data analysis as part of the reflective learning stage. This led to the creation of an initial model that explored how 3D apparel visualization software could be integrated into the design and development process of wildland firefighting protective clothing. Subsequently, the summarized findings from the interactive interviews and the rudimentary 3D product design development process model were validated in the second cycle of interview.

Participants' feedback and assessment regarding the 3D product design and development process model were utilized to refine and enhance the model during the subsequent reflective learning stage. This iterative process ensured the research's rigor by allowing participants to verify that various aspects of the research process effectively represented their beliefs, perspectives, and experiences (Mertler, 2019). As a result, the credibility of the research findings was strengthened through active discussions with participants throughout the research process and through meticulous analysis and reflection on the research outcomes.

Congruencies and Disparities in the Perceptions and Experiences of Participants from Multiple Firefighting Gear Manufacturing Companies

The following analysis sheds light on the shared and diverse perceptions and experiences of participants from six firefighting gear companies (from both phases of this study), offering valuable insights into the specific requirements and considerations for effectively integrating this technology at the organizational level during the decision-making and early adoption phases. Three factors emerged from the data analysis that could influence the perceived drivers and barriers of using 3D apparel visualization software as well as the participants' willingness to use of adopt the software: 1) firefighting gear type, 2) unique and manifold nature of manufacturing business, and 3) prior experience with technology usage. These factors were found to possess a dual nature, functioning in some cases as drivers and in other cases as barriers.

Firefighting Gear Type

Participants' expectations and attitudes towards 3D apparel visualization software were shaped by the specific product categories their respective companies produce. Participants from companies specializing in wildland fire gear with a single-layer fabric and less complex construction and style, displayed lower skepticism towards the accuracy and performance of the simulation software. For instance, participants A1 and A2 acknowledged the software's effectiveness in aiding design decisions but expressed reservations about its accuracy in fit decisions. At the same time, the responses revealed that these participants, influenced by the less complex nature of wildland fire gear, also perceived a decreased need or inclination to depend on 3D software in their current product design and development processes. Participants from companies manufacturing structural turnout gear also expressed concerns about the software's precision in translating and configuring their products at the garment level. Furthermore, they worried about the software’s capacity to accurately replicate three-layered composite materials, subsidiary materials, and intricate garment construction details, especially those that can vary across different sections of the garment. Some participants who are from companies specialized in structural turnout gear expressed that the complexity of garment composition, intricate details, and the high cost associated with sample and product production presented opportunities for cost and time savings, as well as workflow streamlining through the adoption of such technology.

Additionally, all the participants from companies specializing in structural turnout gear expressed high expectations for the garment fit map feature’s potential utilization and expansion. Participants B2, C1, E1, and F1 particularly emphasized the desire to use 3D simulation to reference estimated values, such as inter-garment tension, total heat loss, water penetration, and wearer's fit satisfaction, during the pattern design process, even if the software cannot be flawless. Furthermore, participant E1 envisioned the software’s capability to predict the effects of garment pressure and movement comfort on different body parts when wearing structural turnout gear along with additional accessories like fire hoods, suspenders, SCBA, gloves and boots. However, the participants stipulated that they could only justify this investment provided that significant improvements in software performance and clear validation of return on investment are achieved. In this regard the share similarities with participants in the wildland firefighting gear sector.

Another notable distinction between wildland fire gear and structural turnout gear is that the latter requires firefighters to wear additional layers of station wear, shirts, and pants along with specific undergarments. Consequently, the proponents of the software's utilization for virtual fit evaluation purposes argued that the software should also be capable of accommodating these multilayered garments within a simulation. Furthermore, participants C1 and C2 emphasized that the existing functionality of garment fit maps within 3D apparel visualization software, primarily designed for ready-to-wear garments and based on generic garment ease measurements, might yield negligible results when applied to the design of structural turnout gear. This is due to the importance of accounting for the presence of air gaps between the wearer and the garments in structural turnout gear, which are crucial factors for thermal protection.

The Unique and Manifold Nature of the Manufacturing Business

Phase two participants reported that willingness to use or adopt 3D apparel visualization software varied among companies due to their unique business operations and internal situations. Participants from smaller-scale companies anticipated a potential financial risk associated with implementing this technology. Participants A2, D1 and E1 emphasized the pressing management and operational issues they faced, which necessitated immediate investment that should take precedence over product design or R&D within their limited funds. These challenges encompassed factors such as inadequate human resources at production facilities and the need to streamline the customer order-to-delivery timeline. Conversely, participant F1 from a larger company exhibited a willingness to absorb the costs if the software could be proven to enhance the safety of their products.

Notably, Company A, unlike its counterparts with in-house production facilities, employs a contract manufacturing approach, collaborating with pattern makers at the factory site for product manufacturing. Consequently, participants A1 and A2 expressed concerns regarding potential hindrances in software utilization due to the lack of technological infrastructure and competence among their manufacturing partners. Furthermore, participants A1 and A2 explored ideas for integrating 3D virtual garment simulation into their communication with manufacturing factories to ensure adherence to fit and quality standards. In contrast, other participants did not mention factories or production facilities when discussing the potential usage of 3D apparel visualization software for their companies.

Previous studies have indicated that stakeholder pressure and competitive pressure are the primary environmental factors that can influence a firm's decision to adopt 3D digital design technologies (Henao-Ramirez & López-Zapata, 2021; Papahristou & Bilalis, 2017). It is worth noting that the use of 3D apparel visualization software is still in its early exploratory stage in this industry, with only a few firefighting gear manufacturing companies utilizing it partially for design ideation and pattern making. Moreover, a significant portion of the participants either had no prior experience with the software or were unaware of its existence. Furthermore, participants E2 and F1, who are from companies offer product customization services, expressed significant interest in utilizing 3D virtual simulation as a visual confirmation tool. The participants aimed to establish a platform where clients could customize their own gear and submit their designs for quotation.

Prior Experience with Technology Usage

The participants' perceptions of the utilitarian benefits, ease of use, and technical limitations of 3D apparel visualization software were influenced by their level of knowledge about technology, previous learning experiences, and current usage status. For instance, participants from firefighting gear manufacturing companies that had already adopted the software highlighted specific cases that revealed disparities between users' intentions and the performance and accuracy of virtual simulations. Participants B1 and B2 pointed out simulation errors and technical difficulties, such as the software's inability to incorporate certain design details. Participants A1 and A2, who were involved in the phase one action research study, did not report any technical challenges apart from concerns about the accuracy of the software simulation and the garment fit maps feature. This observation could be attributed to their limited utilization of the software in performing tasks or integrating it into their daily workflow, which may have constrained their responses. In other words, those participants who had used the software previously were better able to evaluate the return on investment, enabling them to form clear intentions regarding the adoption, continuation, or discontinuation of its use. Furthermore, the two firefighting gear manufacturing companies in phase two that reported adopting a 3D software use a different software than the one demonstrated by the researcher in the phase one interviews. This difference in software providers may have influenced participants' responses regarding the technological characteristics of the software. Different 3D apparel visualization software varies in capabilities, including interface, simulation engines, representation of layers and materials, editing tools, features, and more.

Academic and Practical Implications

The results of this research provide valuable insights for researchers, decision-makers, and technology users in the firefighting gear industry regarding the adoption of 3D apparel visualization software for product design and development process. The findings stand out from previous studies by investigating the potential integration of software capabilities into the industrial design and development of functional clothing, from a manufacturer perspective. Notably, this research reveals unforeseen discoveries that pave the way for new opportunities in terms of applications and advancements within the firefighting gear sector. Specifically, in the context of this study, the participants anticipated achieving enhanced design, fit, and ease of movement of firefighting gear by leveraging the capabilities of 3D apparel visualization software. This, in turn, would enable the protective garments to perform at a higher level in terms of safety and functionality.

The study contributes to the academic understanding of the complex nature of firefighting gear manufacturers' perceptions and experiences with 3D apparel visualization software. The established conceptual framework, "Incorporating Virtual Prototyping into Wildland Firefighting Protective Clothing Design and Development Process," and the comprehensive chart, "Perceived Drivers and Barriers of Using Virtual Fitting for Designing and Developing Firefighting Gear from the Manufacturer's Perspective," extend the existing literature on digital design technology adoption by firefighting gear manufacturers, considering not only the technological capabilities of the software but also the specific characteristics of the firefighting gear product category, technology users, companies, and the business environment. By elucidating the company-level reasons behind varying perceptions and experiences of 3D apparel visualization software, these findings offer guidance to decision-makers and end-users alike, enabling them to gain a comprehensive understanding of the key considerations and influential factors necessary for implementing the software across the existing supply chain.

Additionally, the research results can assist 3D apparel visualization software providers in improving the simulation performance and effectiveness of their software. By gaining insight into the implications of enhancing specific features and functions, software providers can make their offerings more applicable for designing and developing firefighting gear. Furthermore, software developers and providers should possess a prior understanding of specific industries and product characteristics to expand the market for such software, not only in the fashion and apparel industry but also in functional clothing sectors like firefighting gear. In the case of the firefighting gear industry, the utilization of software aims to enhance the design, fit, and thermal protection of garments, enabling them to perform at a higher level in terms of safety. Additionally, due to the diverse and unique nature of manufacturing businesses, it would be beneficial to collaborate with officials from manufacturing companies to gain insights into their workflow and provide customized software tailored to their specific needs.

Limitations and Suggestions for Further Research

Despite the meaningful implications, the results of both phase one and phase two studies have several limitations. Firstly, the focus on firm-level research and the reliance on a single data source (interviews) with a small sample size limits the generalizability of the findings. This limited sample size resulted in a lack of diversity in participants’ thoughts and experiences during data collection. Additionally, another limitation arises from the fact that some participants’ responses were based on their limited interaction with 3D apparel visualization software. Although the primary investigator provided explanations of different software capabilities by exploring materials on software provider websites together during the interviews, participants without previous experience with the software may have had limited perceptions rather than hands-on experience using it in their business operations. Therefore, practical training experiences in participants' jobs are necessary to mitigate limited interaction and perception-based responses and enhance the research results. Furthermore, since all participants were primarily designers, technical designers, and pattern makers, their perspectives may differ from those in other roles within the company, such as production facility staff, marketing and sales personnel, and business administrators.

Future research in this field can be categorized into different areas: further clarification of the functional requirements for designing and developing virtual fitting for firefighting gear, exploration of the actual integration of virtual fitting into the workflow of functional clothing companies, and investigation of the validity and accuracy of current virtual simulation technology. To effectively utilize 3D apparel visualization software in firefighting gear design and development, substantial enhancements are needed in the accuracy of virtual simulation and the validity of garment fit maps. Prior to improving the software's performance, several preliminary studies must be conducted. Firstly, it is essential to determine the optimal air gap, considering both thermal protection and functionality, to establish a suitable fit for firefighting gear. Once this is established, the appropriate amount of garment ease can be determined, and the software can provide suggestions on modifying garment details to achieve a good fit for the pattern block of firefighting gear. Furthermore, garment fit map features can predict garment tension and stress by considering the optimal amount of air gap for firefighting gear. Additionally, to maximize the software's usefulness, it is imperative to establish a body measurement database specifically for firefighters. During phase one and phase two studies, participants commonly highlighted the lack of a body survey of firefighters, necessitating internal research at the company level due to spatial and temporal limitations. They also emphasized the need for an accurate and effective method of taking body measurements to enable manufacturers to refine the current sizing system and pattern block, and to assist firefighters in finding the correct size to wear. The accuracy of virtual fit depends on the measurements input for the avatar and digital pattern making. Combining 3D apparel visualization software with body scanning technology raises questions about how they can synergize to address fit and sizing issues in firefighting gear. Finally, research should be conducted in parallel to improve simulation accuracy on a standardized method for accurately digitizing the properties of the 3-layered composite material, trim, and components used in structural turnout gear.

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APPENDICES

Appendix A

Adult Consent Form

Title of Study: Exploring Personal Protective Clothing Company's Perceptions toward the Use of 3D Apparel Visualization Software in the Product Design and Development Process **(eIRB # 23872)**
Principal Investigator(s): Uikyung Jung (Email: ujung@ncsu.edu, Phone: 919-360-3293)
Funding Source: None
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<u>What are some general things you should know about research studies?</u>
You are invited to take part in a research study. Your participation in this study is voluntary. You have the right to be a part of this study, to choose not to participate, and to stop participating at any time without penalty. The purpose of this research study is to gain a better understanding of a personal protective clothing company's perceptions toward the use of 3D apparel visualization software in the product design and development process. We will do this through a series of interviews.

You are not guaranteed any personal benefits from being in this study. Research studies also may pose risks to those who participate. You may want to participate in this research because you can contribute to the advancement of knowledge on managerial strategies on adopting 3D apparel visualization software for a personal protective clothing company. You may not want to participate in this research because of a time restriction.

Specific details about the research in which you are invited to participate are contained below. If you do not understand something in this form, please ask the researcher for clarification or more information. A copy of this consent form will be provided to you via email before starting an interview. If, at any time, you have questions about your participation in this research, do not hesitate to contact the researcher(s) named above or the NC State IRB office. The IRB office's contact information is listed in the *<u>What if you have questions about your rights as a research participant?</u>* section of this form.

<u>What is the purpose of this study?</u>
The purpose of the study is to explore the perceptions toward the use of 3D apparel visualization software for the apparel design and development process, the potential impacts of adopting 3D apparel visualization software in the current workflow, and the decision-making process of adopting 3D apparel visualization software.

<u>Am I eligible to be a participant in this study?</u>
There will be approximately 2 participants in this study. In order to be a participant in this study, you have to be employees of Green Buffalow and agree to be in the study.

<u>What will happen if you take part in the study?</u>

If you agree to participate in this study, you will participate in a series of online interviews via Zoom. The interviews will be led by a primary researcher, Uikyung Jung, a graduate student in Wilson College of Textiles at NC State University. Before starting the first interview, you will receive some open-ended questions along with the informed consent form.

The topics that will be discussed during the interviews include the motivations and perceptions toward the use of 3D apparel visualization software for your business. There will be five separate interviews, and each interview will last about one and half-hours. As a part of the interview protocol, a primary investigator will demonstrate using 3D apparel visualization software.

Participants will be interviewed together for the first interview, and subsequent interviews may be conducted with individual participants, depending on the interview topic. The interviews will be video recorded in order to capture what is said accurately. If you participate in the study, you may request that the recording be paused at any time. You may also choose to leave the interview at any time.

After an interview, recorded videos will be transcribed, and participants will review a summary of the data for a quality control process to improve the accuracy, credibility, and validity of the data analysis.

To facilitate 3D apparel visualization software implementation, we ask that you share a set of pattern pieces of garment(s) manufactured by your company for this research. These patterns will be considered as secondary data and, as such, will not be shared or reported. The research team will agree in writing to non-disclosure of this data if needed. Images of 3D simulations from these patterns may be shared with the consent of research participants.

Based on the findings from interviews, the primary investigator will establish conceptual frameworks of 3D product design and prototyping process and technology adoption decision process. Subsequently, the established conceptual frameworks will be refined through interviews with other firefighting uniform manufacturers. Participants will have a chance to review the frameworks before they are shared. The identity of the company will not be revealed in these phase two interviews.

The total amount of time you will be participating in this study is five times ninety-minute interviews over seven months.

Recording and images

If you want to participate in this research, you must agree to be video recorded. If you do not agree to be video recorded, you cannot participate in this research. The recorded videos will be saved in NCSU Google Drive. Only the research team (principal investigator and faculty point of contact) will have access to recorded videos. After transcription, the recorded videos will be deleted from NCSU Google Drive.

Risks and benefits

There are minimal risks associated with participation in this research. There are no direct benefits to your participation in the research. However, your response may help us learn how personal protective clothing company envisions adopting 3D apparel visualization software for their company. Also, knowledge may be gained to help fashion and apparel companies understand considerations and managerial strategies on adopting and implementing 3D apparel visualization software throughout an organization.

Right to withdraw your participation

You can stop participating in this study at any time for any reason. In order to stop your participation, please contact the researcher, Uikyung Jung, via phone at 919-360-3293 or via email at ujung@ncsu.edu and the faculty advisors, Anne Porterfield, via phone at 919-515-5181 or via email at japorter@ncsu.edu and Cassandra Kwon, via phone at 919-807-1355 or via email at chkwon@ncsu.edu. If you choose to withdraw your consent and to stop participating in this research, you can expect that the researcher(s) will redact your data from their data set, securely destroy your data, and prevent future uses of your data for research purposes wherever possible. This is possible in some, but not all, cases.

Confidentiality, personal privacy, and data management

Trust is the foundation of the participant/researcher relationship. Much of that principle of trust is tied to keeping your information private and in the manner that we have described to you in this form. The information that you share with us will be held in confidence to the fullest extent allowed by law.

Protecting your privacy as related to this research is of utmost importance to us. There are very rare circumstances related to confidentiality where we may have to share information about you. Your information collected in this research study could be reviewed by representatives of the University, research sponsors, or government agencies (for example, the FDA) for purposes such as quality control or safety. In other cases, we must report instances in which imminent harm could come to you or others.

How we manage, protect, and share your data are the principal ways that we protect your personal privacy. Data that will be shared with others about you will be re-identifiable.

> **Re-identifiable**. Re-identifiable data is information that we can identify you indirectly because of our access to information, role, skills, combination of information, and/or use of technology. This may also mean that in published reports others could identify you from what is reported, for example, if a story you tell us is very specific. If your data is re-identifiable, we will report it in such a way that you are not directly identified in reports. Based on how we need to share the data, we cannot remove details from the report that would protect your identity from ever being figured out. This means that others may be able to re-identify from the information reported from this research.

Future use of your research data

The transcribed data will only be accessible to the research team composed of a primary investigator, Uikyung Jung, and associated two advisors, Dr. Anne Porterfield and Dr. Cassandra Kwon. The re-identifiable data will be accessible to the research team and may be shared with others if participants agree to the broad consent.

Compensation

For your participation in this study, there is no compensation for participating.

What if you have questions about this study?

If you have questions at any time about the study itself or the procedures implemented in this study, you may contact the researcher, Uikyung Jung, via phone at 919-360-3293 or via email at ujung@ncsu.edu and the faculty advisors, Anne Porterfield, via phone at 919-515-5181 or via email at japorter@ncsu.edu and Cassandra Kwon, via phone at 919-807-1355 or via email at chkwon@ncsu.edu.

What if you have questions about your rights as a research participant?

If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact the NC State IRB (Institutional Review Board) Office. An IRB office helps participants if they have any issues regarding research activities. You can contact the NC State IRB Office via email at irb-director@ncsu.edu or via phone at (919) 515-8754.

Consent To Participate (Electronic Consent)

By signing this consent form, I am affirming that I have read and understood the above information. All of the questions that I had about this research have been answered. I have chosen to participate in this study with the understanding that I may stop participating at any time without penalty or loss of benefits to which I am otherwise entitled. I am aware that I may revoke my consent at any time.

Appendix B

Preliminary Interview Protocol

First, let me thank you for being willing to participate in this interview. As you know, our study seeks to explore manufacturer's perceptions toward the use of 3D apparel visualization software in the apparel design and development process for their business. The interview today will last approximately one hour. As a reminder, I will be recording this conversation.

Before we start, do you have any questions? [Discuss any questions from the participant]

One reminder, this process is completely voluntary, so if at any time you want to stop the interview or recording, please let me know.

Interview Questions

1. First, I want to focus on you and your role in the company. Could you tell me about your role in the company?
    - If not mentioned, prompt for information about this list of things
        - What are your typical responsibilities?
        - What are the tools that you use?
2. Tell me about the current product design and development workflow of your company.
    - If not mentioned, prompt for information about this list of things
        - What are the activities that are included in your design and development process? Please explain the activity of material selection/prototyping/fit testing/sample approval/create marker/pattern grading/production/source production and its sequence in the overall workflow.
        - How long is your company's current design and development cycle?
        - When do you use CAD software?
        - Which CAD software do you use?
        - Could you come up with a need or solving a problem in the current practice setting of product design and development?
3. Would you describe your experience with 3D CAD software?
    - If not mentioned, prompt for information about this list of things
        - What is your understanding of 3D CAD software?

- Have you ever used any 3D CAD software?
- What was it like for you when you used 3D CAD software?
- Could you come up with any 3D CAD software and its provider that you are interested in?

4. Suppose your company adopted 3D apparel visualization software. What would it be like?
    - If not mentioned, prompt for information about this list of things
        - Where do you see 3D fit in your workflow?
        - What you intend to adopt the software?
        - Would you explain what you think the ideal change would be like after implementing 3D apparel visualization software?
        - Could you come up with a need or solving a problem in the current practice setting of product design and development by employing 3D apparel visualization software?
        - What would be the challenges and concerns of implementing 3D apparel visualization software?
        - Does any supply chain actor use 3D CAD software for their business?

5. Tell me about any ongoing discussion on the digital transformation of product design and manufacturing among the firefighting uniform community.
    - If not mentioned, prompt for information about this list of things
        - Does any company explore the 3D CAD software for designing and developing personal protective clothing?
        - What would be the challenges and concerns of implementing 3D CAD software for the firefighting uniform business?

Appendix C

3D apparel visualization software learning modules and demos for each interview

	Interview 1	**Interview 2**	**Interview 3**	**Interview 4**
Topic	3D garment design (General overview of 3D apparel visualization software)	Virtual avatar (Available options and functions for customizing avatars)	Virtual fit assessment (Grade evaluation and performing the fit assessment)	How to share 3D assets (File formats and web-based platforms to share)
Types of Learning Modules				
PowerPoint Slides	**1)** Introductory concepts on 3D apparel visualization software and its digital assets (Virtual fabric, trim, avatar, sewing, runway, turntable, and rendered images) **2)** The same set of 2D pattern pieces virtually sewn into a 3D garment(s) in both CLO 3D and Optitex 3D	**1)** Avatar type **2)** Pose and posture adjustment **3)** Avatar measurement **4)** Avatar style edits **5)** Virtual AlvaForms **6)** Stationary 3D body scanner and a mobile 3D body scanning application **7)** Personal avatar development **8)** Virtual garment versus physical garment	**1)** Implementing grade evaluation on virtual AlvaForms and validating the fit of a virtual garment on an avatar with different poses **2)** Virtual garments on a personal avatar and physical garments on a live-fitting model with different poses	**1)** High quality rendered images and animation **2)** compatible file type for each digital design asset **3)** virtual fabric swatch and material platforms **4)** communication platforms to upload and share 3D assets and create line sheets
Software Demo Videos	**1)** Process of creating a 3D virtual garment with a set of 2D pattern pieces of garment(s) manufactured by participants' company **2)** How to use the 'flattening' function in CLO 3D for the 3D-to-2D virtual design method	**1)** Selecting avatars of ASTM standards and Alvanon series **2)** Changing the avatar size **3)** Adjusting the avatar's posture and taking different poses **4)** Using avatar tape measurement function	**1)** Import dxf file with a grade rule file **2)** Grade base size patterns validate fit using a transparent map, mesh pattern, pressure points, and strain/stress map **3)** Measure 2D pattern and 3D garment for the fit check	

Appendix D

Consent Form

Title of Study: Exploring Personal Protective Clothing Company's Perceptions toward the Use of 3D Apparel Visualization Software in the Product Design and Development Process **(eIRB # 23872)**
Principal Investigator(s): Uikyung Jung (Email: ujung@ncsu.edu, Phone: 919-360-3293)
Funding Source: None
NC State Faculty Point of Contact: Anne Porterfield (Email: japorter@ncsu.edu, Phone: 919-515-5181), Cassandra Kwon (Email: chkwon@ncsu.edu, Phone: 919-807-1355)

<u>What are some general things you should know about research studies?</u>
You are invited to take part in a research study*.* Your participation in this study is voluntary. You have the right to be a part of this study, to choose not to participate, and to stop participating at any time without penalty. The purpose of this research study is to gain a better understanding of personal protective clothing companies' perceptions toward the use of 3D apparel visualization software in the product design and development process. We will do this through an in-depth interview.

You are not guaranteed any personal benefits from being in this study. Research studies also may pose risks to those who participate. You may want to participate in this research because you can contribute to the advancement of knowledge on managerial strategies on adopting 3D apparel visualization software for a personal protective clothing company. You may not want to participate in this research because of a time restriction.

Specific details about the research in which you are invited to participate are contained below. If you do not understand something in this form, please ask the researcher for clarification or more information. A copy of this consent form will be provided to you. If, at any time, you have questions about your participation in this research, do not hesitate to contact the researcher(s) named above or the NC State IRB office. The IRB office's contact information is listed in the *<u>What if you have questions about your rights as a research participant?</u>* section of this form.

<u>What is the purpose of this study?</u>
The purpose of the study is to explore the perceptions toward the use of 3D apparel visualization software for the firefighting gear development process.

<u>How many people will be in the study?</u>
There will be approximately 5 participating companies and 1 to 3 participants from each company will be interviewed in this study.

Am I eligible to be a participant in this study?
In order to be a participant in this study, you must agree to be in the study and you have to be an employee of firefighting gear manufacturing companies. You cannot participate in this study if you do not meet the inclusion criteria.

What will happen if you take part in the study?
If you agree to participate in this study, you will participate in an online interview via Zoom. The interview will be led by a primary researcher, Uikyung Jung, a graduate student in Wilson College of Textiles at NC State University. Before starting the interview, you will receive the informed consent form.

The topics that will be discussed during the interviews include the motivations and perceptions toward the use of 3D apparel visualization software for your business. The interviews will be video recorded in order to capture what is said accurately. If you participate in the study, you may request that the recording be paused at any time. You may also choose to leave the interview at any time.

The total amount of time that you will be participating in this study is one time ninety-minute interviews.

Recording and images

If you want to participate in this research, you must agree to be video recorded. If you do not agree to be video recorded, you cannot participate in this research. The recorded videos will be saved in NCSU Google Drive. Only the research team (principal investigator and faculty point of contact) will have access to recorded videos. After transcription, the recorded videos will be deleted from NCSU Google Drive.

______I consent to be video recorded.

______I do not consent to be video recorded.

Risks and benefits

There are minimal risks associated with participation in this research. There are minimal risks associated with participation in this research. There are no direct benefits to your participation in the research. However, your response may help us learn how firefighting gear company envisions adopting 3D apparel visualization software for their company. Also, knowledge may be gained to help personal protective clothing companies understand considerations and managerial strategies on adopting and implementing 3D apparel visualization software throughout an organization.

Right to withdraw your participation

You can stop participating in this study at any time for any reason. To do so, just stop any research activity that you are doing or contact the researcher, Uikyung Jung, via phone at 919-360-3293 or via email at ujung@ncsu.edu. You can also contact the faculty advisors for this research, Anne Porterfield, via phone at 919-515-5181 or via email at japorter@ncsu.edu and Cassandra Kwon, via phone at 919-807-1355 or via email at chkwon@ncsu.edu If you choose to withdraw your consent and to stop participating in this research, you can expect that the researcher(s) will redact your data from their data set, securely destroy your data, and prevent future uses of your data for research purposes wherever possible. This is possible in some, but not all, cases.

Confidentiality, personal privacy, and data management

Trust is the foundation of the participant/researcher relationship. Much of that principle of trust is tied to keeping your information private and in the manner that we have described to you in this form. The information that you share with us will be held in confidence to the fullest extent allowed by law.

Protecting your privacy as related to this research is of utmost importance to us. There are very rare circumstances related to confidentiality where we may have to share information about you. Your information collected in this research study could be reviewed by representatives of the University, research sponsors, or government agencies (for example, the FDA) for purposes such as quality control or safety. In other cases, we must report instances in which imminent harm could come to you or others.

How we manage, protect, and share your data are the principal ways that we protect your personal privacy. Data that will be shared with others about you will be re-identifiable.

> **Re-identifiable**. Re-identifiable data is information that we can identify you indirectly because of our access to information, role, skills, combination of information, and/or use of technology. This may also mean that in published reports others could identify you from what is reported, for example, if a story you tell us is very specific. If your data is re-identifiable, we will report it in such a way that you are not directly identified in reports. Based on how we need to share the data, we cannot remove details from the report that would protect your identity from ever being figured out. This means that others may be able to re-identify from the information reported from this research.

Future use of your research data

To help maximize the benefits of your participation in this project, by further contributing to science and our community, your re-identifiable information will be stored for future research if you agree to the terms of the broad consent form.

Compensation

There is no compensation for participating in this study.

What if you are an employee?
Your participation in this study is not a requirement of your employment, and your participation or lack thereof, will not affect your job.

What if you have questions about this study?

If you have questions at any time about the study itself or the procedures implemented in this study, you may contact the researcher, Uikyung Jung, via phone at 919-360-3293 or via email at ujung@ncsu.edu and the faculty advisors, Anne Porterfield, via phone at 919-515-5181 or via email at japorter@ncsu.edu and Cassandra Kwon, via phone at 919-807-1355 or via email at chkwon@ncsu.edu.

What if you have questions about your rights as a research participant?
If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact the NC State IRB (Institutional Review Board) office. An IRB office helps participants if they have any issues regarding research activities. You can contact the NC State University IRB office at IRB-Director@ncsu.edu, 919-515-8754, or fill out a confidential form online at https://research.ncsu.edu/administration/compliance/research-compliance/irb/irb-forms-and-templates/participant-concern-and-complaint-form/

Consent to participate (Electronic Consent)

By signing this consent form, I am affirming that I have read and understand the above information. All of the questions that I had about this research have been answered. I have chosen to participate in this study with the understanding that I may stop participating at any time without penalty or loss of benefits to which I am otherwise entitled. I am aware that I may revoke my consent at any time.

Appendix E

Interview Questions for Manufacturers Using 3D Apparel Visualization Software

1. What is your role, and could you explain how you use 3D apparel visualization software in your role?

2. Tell me about your company's software adoption journey. [Who was involved, how did you test the software capabilities]

3. What does your company use 3D apparel visualization software for? Does it meet your company's needs?

4. Do you consider using 3D apparel visualization software as an effective tool for designing and developing firefighting gear? Why or why not?

5. To what extent do you feel firefighting gear companies and stakeholders are aware of and use 3D virtual prototyping?
    - Do you think there are opportunities for further adoption of 3D technology in the industry?

6. What needs to be added or improved to current software capabilities that you see are needed for the firefighting gear industry?

7. What would be the drivers of implementing 3D apparel visualization software for the firefighting gear industry?

8. What do you think are the challenges and concerns of implementing 3D apparel visualization software for the firefighting gear industry?

Interview Questions for Manufacturers that Have Not Adopted 3D Apparel Visualization Software

1. Are you familiar with 3D apparel visualization software?
    - Have you ever tried using 3D apparel visualization software before?

2. Are there any particular reasons that hold your company back from using 3D apparel visualization software?

3. *This question will depend on the level of understanding of the software:* After reviewing software supplier websites and some companies' software using experience stories, what do you think of 3D apparel visualization software?

4. Do you think 3D apparel visualization software is applicable for designing and developing firefighting personal protective clothing and equipment?

5. Based on your current understanding, how do you think the technology could meet the needs of you and your company?

6. In your opinion, what are the factors that need to be considered when adopting 3D apparel visualization software for firefighting gear manufacturing companies?

7. What is your impression of how widely this software has been adopted in the firefighting gear PPC/PPE industry?
    - Do you think there are opportunities for further adoption of 3D technology in the industry?

8. Do you foresee integrating 3D apparel visualization software for developing firefighting gear for your job or company? Could you explain why?

9. What would be the drivers of implementing 3D apparel visualization software for the firefighting gear industry?
    - What are the barriers or challenges?