Universidade do Minho
Escola de Engenharia

Sara Luísa Ribeiro Oleiro

Development of fashion products using 3D digital technology to enhance the presentation of fashion collections - Case Studies

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Dissertação de Mestrado
Mestrado em Design e Inovação de Produtos Têxtil e Acessórios

Trabalho efetuado sob a orientação da
Professora Doutora Maria da Graça Pinto Ribeiro Guedes

janeiro de 2024

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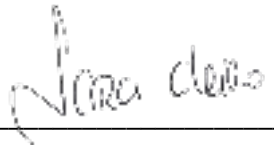

(Assinatura)

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Resumo

Esta dissertação de mestrado examina a transformação dinâmica da indústria da moda, desde as práticas tradicionais até a combinação de tecnologias digitais avançadas. O foco principal está na reinvenção da moda através da adoção de programas digitais inovadores em 3D, que são cada vez mais proeminentes no cenário da moda atual.

Esta pesquisa apresenta uma análise abrangente no papel do design de moda, com vertente no 3D, na indústria da moda contemporânea, particularmente no desenvolvimento e apresentação de coleções de moda. O contraste entre as apresentações físicas tradicionais de moda e a abordagem moderna é orientada para a tecnologia que destaca os benefícios da tecnologia 3D no aumento da acessibilidade, da relação custo-benefício e da liberdade criativa.

O estudo aborda o design 3D que integra sistemas de simulação virtual para oferecer um novo *upgrade* na apresentação de coleções de moda no processo de desenvolvimento de design e na vertente comercial. A autenticidade da representação material e a criação de gémeos digitais realistas também são exploradas, com foco em plataformas que melhoram a fidelidade visual dos ativos digitais.

A pesquisa inclui uma revisão ampliada da literatura e um estudo das marcas de moda que adotaram esta inovação tecnológica, selecionando 3 casos de estudos proeminentes para análise detalhada. O estudo sugere que para que as empresas de moda prosperem nas vendas e cativar novos clientes, é imperativo o investimento estratégico na tecnologia 3D e na integração digital. Esses avanços são fundamentais para promover uma indústria da moda inclusiva, sustentável e inovadora.

Concluindo, esta dissertação serve como um recurso essencial para profissionais e entusiastas da moda, oferecendo *insights* sobre o potencial transformador da tecnologia digital 3D no futuro das apresentações de moda.

Palavras-chave: Simulação virtual vestuário; Design de moda; Coleções de moda; Tecnologia digital 3D; 3D prototipagem virtual

Abstract

This master's dissertation examines the fashion industry's dynamic transformation, tracing its transition from traditional practices to the combined use of advanced digital technologies to develop fashion products and enhance collections. The core focus is the reinvention of fashion by adopting innovative 3D digital programs, which are increasingly prominent in today's fashion landscape.

This research presents a comprehensive analysis of the role of 3D design in the contemporary fashion industry, particularly in developing and showcasing fashion collections. The contrast between traditional physical fashion presentations and the modern technology-driven approach highlights the benefits of 3D technology in enhancing accessibility, cost-effectiveness, and creative freedom.

The study approaches 3D design that integrates virtual simulation systems to offer a new upgrade in showcasing fashion collections in the design development process and commercial proposals. It also explores the authenticity of material representation and the creation of realistic digital twins, focusing on platforms that enhance the visual loyalty of digital assets.

The research includes a thorough literature review and examination of fashion brands that have embraced this technological innovation, selecting three case studies for detailed analysis. The study suggests that for fashion companies to thrive in sales and customer attraction, strategic investment in 3D technology and digital integration is imperative. Such advancements are key to fostering an inclusive, sustainable, innovative fashion industry.

Conclusively, this dissertation serves as an essential resource for fashion professionals and enthusiasts, offering insights into the transformative potential of 3D digital technology in the future of fashion presentation.

Keywords: virtual garment simulation; fashion design; fashion collections; 3D digital technology; 3D virtual prototyping

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List of Abbreviations

3DVD - 3-Dimensional Virtual and Digital

AI - Artificial Intelligence

ANN - Artificial Neural Network

BCT - Block-chain Technology

BDA - Big Data Analytics

BOM - Bill of Materials

BPR - Business Process Re-engineering

BTF - Bidirectional Texture Function

CAD - Computer-Aided Design

CAM - Computer-Aided Manufacturing

CC - Cloud Computing

CDSCI - Critical Digital Supply Chain Integration

CE - Circular Economy

CGI - Computer-generated Imagery

CIM - Computer Integrated Manufacture

CMF - Colour, Materials, Finish

CNC - Computer Numerical Control

CPS - Cyber-Physical Systems

DAM - Digital Asset Management

DES - Discrete Event Simulation

DL – Deep Learning

DML - Digital Material Library

DPC - Digital Product Creation

DSC - Digital Supply Chain

DSCC - Digital Supply Chain Capacities

DT - Digital Twin

DTC – Direct-to-consumer

DTT - Digital Transformation Team

EoL - End-of-Life

ERP - Enterprise Resource Planning

FAST - Fabric Assurance by Simple Testing

FMS - Flexible Manufacturing System

GHG - Greenhouse Gases

GVC - Global Value Chains

HDRI - High Dynamic Range Images

I4.0 - Industry 4.0

ICT - Information and Communications Technology

IIoT - Industrial Internet of Things

Industrie 4.0 - Fourth Stage of Industrialisation

IoT - Internet of Things

IoTaa - IoT as-a-Service

IT - Information Technology

KES - Kawabata Evaluation System

KPIs - Key Performance Measures

LCA - Life Cycle Assessment

ML - Machine Learning

MoL - Mid-of-Life

MOQs - Minimum Order Quantities

NC - Numerical Control

NFTs - Non-fungible Tokens

NPI - New Product Introduction

NVA - Non-Value-Added

PBS - Process Breakdown Structure

PCA - Principal Component Analysis

PDS - Pattern Design System

PIM - Product Information Management

PLC - Programmable Logic Controllers

PLM - Product Lifecycle Management

POD - Print-on-demand

POS - Point-of-sale

RFID - Radio Frequency Identification

ROI - Return on Investment

RTFS - Real-time Fashion System

SaaS - Software as a Service

SCM - Supply Chain Management

SeCSs - Smart Electro-clothing Systems

SME - Small-and-medium Enterprises

SF - Sustainable Fashion

T&C - Textiles & Clothing

TCI - Textile and Clothing industry

VA - Value-Added

VF - Virtual Factory

VP - Virtual Prototype

VR - Virtual Reality

VT - Virtual Prototyping

XR - Extended Reality

Glossary

3D design: Computer software creates and manipulates a mathematical representation of any three-dimensional object or shape for various applications across industries like architecture, gaming, and film. In fashion, it is represented in a 3D mesh that creates a virtual visualisation of products with the object of substituting for physical prototypes (McKinsey & Company & BOF, 2021).

3D virtual and digital (3DVD): Includes technologies from 3D modelling, virtual and augmented reality (VR/AR), 2D/3D scanning, and digital twin (DT) (Casciani et al., 2022).

3D modelling: Computer graphics technique of creating a three-dimensional digital copy of any object or surface (Vrljanac et al., 2023).

Cloth simulation: Specialised area of computer graphics with complex calculations and computational physics that deals with creating realistic models and animations of cloth and fabric. It involves physics-based modelling that replicates the physical properties of real-world fabrics, including how cloth folds, drapes, and wrinkles and interacts with external forces like wind or gravity and other objects, such as the human body. It needs to pay attention to collision detection (cloth meets other objects), particle systems and meshes (vertices particles in triangular or square shape) to simulate the movement and behaviour of the cloth and interactive applications to users' inputs between digital environment. Cloth simulation is applied in various fields, including video games, animation, and fashion design. In fashion, the rendering must be more efficient than the animation or video game field because it can take time to simulate (Volino et al., 2005).

Digital asset: Content in digital form that comes with data rights, including multimedia, documents, digital art, software, websites, cryptocurrencies, and NFTs (Heim & Hopper, 2022).

Digital fashion: Integrates technology and fashion in creating, developing, and marketing fashionable clothing and services. It involves using computer technologies and software, such as 3D modelling and virtual reality, to design clothing and accessories. Digital fashion allows the sharing of virtual designs through social platforms, websites, and virtual fashion shows (Geršak, 2022).

Digital samples: Virtual representations of fashion products created using 3D modelling software, used for design visualisation, modification, and presentation before physical production (Särmäkari, 2023).

Digital twin: Duplicate a physical item, system, or methodology used for simulation, analysis, and optimisation purposes in various industries (M. Liu et al., 2021).

Garment model: This is an essential component for designing digital garments. It includes general and sewing information, grading data, and multiple garment options for various designs. The model comprises data information, geometric shapes, and appearance. Appearance consists of a texture map for surface texture expression and pattern combinations for different designs (Geršak, 2022).

Internet of Things (IoT): Electronically connecting interconnected devices and objects equipped with inputs, systems and other technologies to exchange data and interact with each other and the environment over the Internet (Fernández-Caramés & Fraga-Lamas, 2018).

Non-fungible tokens (NFTs): Digital assets verified using blockchain technology that represent the proprietary rights of a particular content unit, such as digital art, music, videos, or other types of digital files. They cannot be exchanged directly like cryptocurrencies (Joy et al., 2022).

Phygital fashion: Physical and digital worlds merged to provide unique interactive experiences for consumers (Pangarkar et al., 2022).

Product Lifecycle Management (PLM): Strategic approach to managing the entire journey of an item from foundation through engineering design and production to service and disposal, integrating people, data, processes, and business systems (Conlon, 2020).

Rendering: The process of transforming 3D scenes into 2D images using cameras, objects, materials, and light (Makryniotis, 2015).

Simulation software: Program used to create a virtual environment to imitate, analyse, and visualise real-world processes, systems, or events for purposes like training, visualisation, or entertainment, using advanced computer graphics technology (Nuraliyev et al., 2019).

Sustainable fashion (SF): Approach to designing, manufacturing, and consuming clothing that maximises environmental protection and social responsibility, minimising the industry's ecological footprint and ethical impact (Z. Wang et al., 2023).

Texture maps: Contain texture image data for realistic texture expression (Geršak, 2022).

Virtual clothing: Digital garments designed based on virtual garment information and models. The virtual clothing is categorised into information (name, type, colour), clothing product type (2D & 3D, physical properties, surface appearance), simulation (spatial arrangement, sewing information, layers), and fitting data (surface strain, balance, colour map, and air gap) (Geršak, 2022).

Virtual fabric: Virtual attributes like tensile modulus, bending rigidity, shear resistance, thickness, and weight (Geršak, 2022).

Virtual sampling: Specifically for the fashion industry, is a digital creation of a 3D sample of a garment, accessory, or footwear developed by a patternmaker/fashion designer/3D designer and shared with value-chain partners and "sell-in processes" (McKinsey & Company & BOF, 2021).

Virtual garment simulation: Involves creating a virtual garment on a virtual human body using a pattern, sewing, and bounding volume. This is a crucial part of CAD systems and has immense business potential (Geršak, 2022).

CHAPTER - I

Introduction

1.1. Contextualization

The fashion sector is one of the most important industry sectors in the world, with a revenue value of $1.7 billion in 2023 (Smith, 2023). However, it is also one of the most polluting, representing 4% of greenhouses (GHG) globally (Berg et al., 2020). In 2023, only 1% of clothes were recycled from 100 billion garments produced globally, and 92 million tonnes ended up in landfills, meaning that each second, the equivalent of a rubbish truck full of clothes ends up in either incinerators or landfills (Fashion Revolution, 2023; Ruiz, 2023). Additionally, toxic chemicals released during the textile processes flushed into rivers and seas caused 20% of global water pollution (Igini, 2023). Therefore, there is an urgency to reduce the fashion industry's carbon footprint on the planet. World Economic Forum (2021) reported that reducing at least 15% of all emissions in the fashion industry is possible if companies increase their process efficiency. Companies from the fashion industry are taking steps to reduce their environmental impact by implementing more sustainable practices and investing in new sustainable technologies and methods to minimise these problems. It includes using organic and recycled fabrics, reducing water and energy consumption, and adopting circular economy models to minimise waste and extend the lifetime of clothing.

Moreover, in the past decade, there have been significant changes in the behaviour of consumers and fashion companies. One example highlighted is the recent Covid-19 pandemic, which forced the worldwide population into lockdown and increased the demand for digital solutions from 2020. With the increasing demand for more sustainable practices in the fashion industry, digital solutions have been developed throughout the fashion industry's supplier chain. This dissertation allows the industry to reduce the waste of resources and production time by creating digital twins, reducing the number of physical samples, and improving efficiency, profitability, and sustainability for fashion brands and suppliers.

Subsequently, in the Textile and clothing (T&C) industry, fashion brands and suppliers are interested in digital solutions. Mid-high and luxury brands are investing in 3D virtual simulation systems such as Clo3D and DC Suite (Choi, 2022). These 3D software allow companies to decrease physical sampling manufacturing, reduce stock accumulation, enable real-time changes, and provide more direct customer feedback, which turns into economic and environmental

advantages. Furthermore, it demands an investment in hiring people specialised in 3D design tools. Nevertheless, these costs are minimal compared to traditional methods (X. Chen et al., 2020).

To stay competitive in the market, fashion companies must adopt green practices and embrace digital transformation with the help of new tools such as 3D technology. This technology can streamline and enhance the design process for fashion collections, making it more efficient. Their workers are crucial in bringing fashion products to life and implementing sustainable practices (Huynh, 2022). Each team has specific functions: design, marketing, patternmaking, production, and sales. Fashion designers develop clothing, accessories, and footwear based on the type of segment they are working on, such as womenswear, menswear, or childrenswear. They research fashion trends, create mood boards and sketches, conceptualise designs with fabrics and colours, and oversee production by working closely with manufacturers or producers. Depending on the size of the brand or segment, fashion designers may also engage in marketing, participate in fashion shows, and manage photoshoots. Other professionals are also involved in the product development cycle, such as pattern makers, textile designers, producers, quality control specialists, buyers, merchandisers, marketers or PR personnel, sellers, photographers, stylists, HR, finance, and legal teams who reinforce the brand's operations. All these teams must work together with cohesion and harmony to increase the company's success.

According to reports by McKinsey, the fashion industry has undergone several changes between 2021 and 2024 to keep up with fashion companies and invest in the latest technologies. In 2021, it was predicted that virtual sampling would be a crucial area for fashion brands to invest in, allowing them to source fabrics and generate digital samples (McKinsey & Company & BOF, 2021). In 2022, the focus shifted to metaverse and e-commerce sales, investing in NFTs, gaming, and virtual fashion through product passports that keep and share product information with clients and stakeholders (McKinsey & Company & BOF, 2022). By 2023, fashion companies were advised to adopt mixed channels to their direct-to-consumer (DTC) model, such as wholesale and marketplaces. Additionally, textile manufacturers were encouraged to invest in vertical integration in their supply chain models to enhance digitalisation (McKinsey & Company & BOF, 2023). In 2024, 73% of executives are investing in generative AI to explore its combination with human creatives, while 5% are already using it to improve creativity, design, and product development. Finally, fashion companies must also consider sustainability regulations set by governments (McKinsey & Company & BOF, 2024).

With all these changes occurring in the fashion industry, there is a need to understand how fashion brands integrate 3D technology into their collection processes and how its use has impacted the industry. Therefore, the main aim of this study is to understand the benefits of 3D digital technology, especially in creating digital products to incorporate into fashion collections and present to customers.

1.2. Objective of the research

This dissertation seeks to identify the benefits of 3D technology applications in the fashion industry while highlighting areas that can be improved in the product development of fashion collections. This study examines the intersection between technology and the textile industry, exploring the role of 3D computer programs in fashion clothing prototyping and collection development. Traditional methods of material selection, mood board creation and sketching are also considered. These will remain important despite technological advances. The project will also analyse three fashion brands, study their background, and determine which 3D technologies they use to improve fashion collection presentation and reduce physical sampling. Moreover, this dissertation will evaluate how 3D technology can promote innovation in fashion design, which could change industry practices and customer experiences. Finally, the project offers insights into the challenges encountered during the research phase and proposes recommendations for future exploration in this dynamic field.

1.3. Research methodology and structure

This dissertation aspires to explore the role of 3D technology in the fashion industry for modelling, visualisation, and immersion to enhance digital products in fashion brands' fashion collections. A thorough literature review used several search engines and databases to identify relevant sources. The search was based on keywords such as "Digital fashion", "3D virtual simulation system fashion", "Fashion design processes", "Digital design", "3D-technology", "3D CAD", "Virtual clothing prototyping", "Digital transformation", and "Industry 4.0". The research focused on identifying how 3D technology is helping fashion brands to enhance their collections.

Case study research focused on the most relevant fashion companies that use 3D technology. The research started with the identification of twenty fashion companies/brands. Three of those twenty companies were selected for further analysis on using 3D software in their design processes. A bibliographical review of each brand was carried out and summarised in Appendix A. The selection criteria for case studies included identifying the pioneer companies that invested in 3D technology, the percentage of usage of the type of technology to improve digital products added to fashion collections, and the reasons why they invested in this technology. The objective of this study was to explore real cases of fashion brands using 3D software to improve performance and create sustainable responsibility on the planet. The literature review and case studies provide insights into how 3D technology transforms the fashion industry.

The present study is structured in five chapters covering the research and analysis process. The first chapter introduces the study's themes, objectives, and methodology. In chapter two, virtual simulation technology in the fashion industry is explored, including using Industry 4.0 technologies such as prototyping and digital twin technology. Chapter three covers the development of digital clothing simulation for fashion design using 3D software, focusing on three

case studies. After that, chapter four presents the research and final selection of three fashion brands presented in the case study. Finally, chapter five presents the analysis, conclusion, and future perspectives.

CHAPTER - II

Virtual Simulation in the fashion system

2.1. Virtual simulation of clothing in the Textile Industry

2.1.1. Contextualization: concepts and milestones of IT on textile value chain system

The T&C value chain is one of the world's most complex and longest processes (Jacometti, 2019), divided in different stages in production (Alves et al., 2022), to customer engagement influenced by the integration of information technology (IT). This integration of digital technologies in textile value chain systems has been distinct by milestones such as 3D Virtual prototyping (VT), Computer-Aided Design (CAD) / Computer-Aided Manufacturing (CAM) systems, improved Product lifecycle management (PLM), connected Internet of Things (IoT) manufacturing, e-commerce platforms, blockchain, big data analysis, AI (artificial intelligence) and Radio Frequency Identification (RFID) management (Akram et al., 2022). All these options bring sustainability, efficiency, transparency, revolutionising processes in the value chain, and more refined operation efficiency and product quality (Fernández-Caramés & Fraga-Lamas, 2018). Also, creating a trace platform to discover information about each item stored in a digital twin (DT) is necessary to store and share information with suppliers using Blockchain technology (BCT) (da Cruz & Cruz, 2020) and IoT technology along the supply chain to improve Circular economy (CE) (Akram et al., 2022).

For cohesive ecosystem fashion companies, investing in digital solutions that contain Product lifecycle management (PLM), Product information management (PIM) and Digital asset management (DAM) functions is necessary, enabling them to manage the process, workflow, and team collaboration (Lectra Group, 2023). PLM is designed to manage and control all divisions of the product life cycle, from concept design collaboration, trend analysis, cost, supplier, inventory, and sample management, as in quality control, time and end-of-life management and integration with other systems (Fashion United, 2023). It advances digital technology and 3D design throughout the product life cycle to significantly increase performance, product quality, cost savings, and profit. Integrating 3D digital product development (called e-fashion) across the digital value chain permits brands to manufacture merchandising. As a result, there will be no overproduction or dead stocks. One of the most difficult challenges is integrating 3D digital product creation across the entire supply chain, connecting manufacturer systems to offer complete control over the

product lifecycle (Souza, 2021). Implementing all these advanced technologies (AI, big data analyses, cloud computing) is part of Industry 4.0 that enables the evolution of virtual simulation technology (Spahiu et al., 2021).

2.1.2. Industry 4.0: Beyond digitalization of the textile industry

The textile industry is deeply integrated into the history of human life, which evolved with the advancement of society during four different periods during the Industrial Revolution. The first Industrial Revolution occurred in the first half of the 18th century until the end of the 19th century, with the emergence of industrial mechanisms for controlling water and steam. Around 1870, with the expansion of electrification, a second industrial revolution occurred, leading to mass production. Then came the third revolution, the development of electronic devices - computers- in the '70s (Bertola & Teunissen, 2018) – Figure 2.1. The 4th Industrial Revolution began around 2011 when the German government launched a program to renew the country's production system, which focused on intelligent production, becoming the central point of digitalisation (Geršak, 2022).

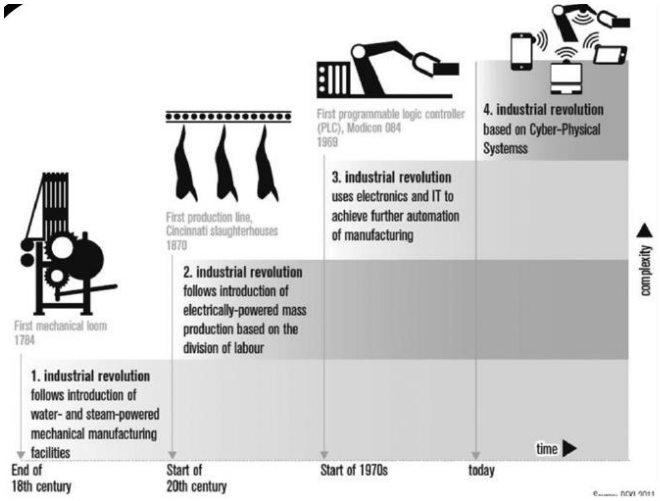

Figure II.1. The four stages of industrial revolution (Bertola, 2018).

According to Särmäkari (2023), the fashion industry has transformed digitally, resulting in "Fashion 4.0". This process requires using smart technologies such as 3D software in fashion design to blur the boundaries between the digital and physical worlds. The integration of digital technology has disrupted traditional industrial sectors, including fashion. As a result, companies need to rethink their business models to leverage internet-based distribution channels and platforms (Behr, 2018). Fashion 4.0 entails the integration of smart technologies, networks, and the digital and physical worlds. Designers must enhance their technical skills and learn new software such as 3D computer-aided design (CAD) to communicate effectively with engineers (Särmäkari & Vänskä, 2022).

2.1.3. Definition of virtual simulation

Virtual simulation is a computer-based technology that creates a realistic, interactive, and immersive representation of a real-world environment, process, or system, creating partial immersion (Brey, 2014). The goal was to replicate real-life conditions accurately, incorporating visual, auditory, and sometimes tactile elements for an immersive experience using Artificial reality (AR) or Virtual reality (VR) (Lee et al., 2022). This computerised simulation is a complex and advanced method that can be applied in many areas, fashion is no exception (Volino & Magnenat-Thalmann, 2005) and purposes, including training, education, research, design testing and entertainment (Elfeky & Elbyaly, 2021). Online simulation involves sophisticated software and hardware, such as VR headsets and tactic devices, to ensure realistic scenarios (Herz & Rauschnabel, 2019). Offering customisation, a safe and cost-effective alternative for situations where real-life training, ranging from simple computer models to complex ones, multi-user setups, provides a versatile tool for understanding and analysing complicated systems and methodologies in a controlled virtual setting (Ahmed & Sutton, 2017).

In the fashion industry, the virtual simulation industry is a key element in studying fabric behaviour, improving fitting and sizing, optimising supply chain processes, increasing training of professionals and improving customer experience in marketing and retail. It allows designers to create and prototype clothing in a 3D digital environment. Also, fashion designers can utilise computer systems to view and modify their designs without being limited by the physical properties of traditional design methods, allowing for greater convenience and practicality in the fashion design process (Cugini et al., 2007). Additionally, projects can be saved in a database, making it easier to consult and adapt them for future projects without starting from scratch. It offers a fast, effective, and controlled atmosphere for experimentation without physical prototypes (J. Zhang, 2022).

2.1.4. Virtual prototyping on the fashion value chain: pros and cons

Virtual prototyping in the fashion industry involves using digital tools and technologies to create and test new designs before producing physical samples. This approach significantly shifts from traditional fashion design and production methods (Papahristou, 2016). This technology has advantages and challenges related to adoption, sensory limitations, skill requirements, and security concerns. The main aspects of this innovation include the 3D design software, the digital fabric simulator and virtual fit/sizing (Mihai et al., 2023). All this can be applied to design, development, marketing, sales, and customer engagement (Tih et al., 2016).

The study of general virtual simulation in software-hardware creation started with the study of a geometric mesh of cloth material in the late 1980s with Terzopoulos' study about the shape of a flag and rectangular cloth (Terzopoulost et al., 1987) and Weil method improved performance of the simulation cloth (Weil, 1989). After this, the transition to

developing flexible objects for digital garments, reducing collision surfaces in a body, began in the early '90s (Carignan et al., 1992; Lafleur et al., 1991).

Particularly in the clothing industry, CAD/CAM tools have been used since 1970 for patternmaking, development, grading, and cutting (Goldstein et al., 2009). Initially, (Wang et al., 2003) used CAD software to create a 3D sketch input method for designing garment patterns to fit 3D human models but found it unproductive for design transformations.

Afterwards, (Luo & Yuen, 2005) showed a 3D fitting simulation for apparel that can efficiently and rapidly react to 2D pattern changes without repeating the simulation. To create a virtual simulation garment design, combining extended techniques such as collision detection, user interface, and mechanical properties of cloth is necessary because it interferes with geometric contact between the avatar and cloth mesh (Volino & Magnenat-Thalmann, 2005).

However, two major problems were identified in garment representation: the difficulty in creating digital avatars that accurately represent the human body correctly and the challenge of garment drapes simulation on a body (Goldstein et al., 2009).

Table 1 presents the advantages and disadvantages of virtual prototyping in the fashion value chain:

Table 1. Pros and Cons of virtual prototyping on fashion value chain

Pros	Cons
Increase cost efficiency and save time	The complexity of this type of technology and its cost
Increase sustainability by minimising the need for physical samples	Investing in specific training and time-consuming in developing digital skills
Speed up the design and development process, enabling quick decision-making	Lack of sensory experience cannot replace the tactile touch and feel of fabrics for designers
Fashion designers have more time to dedicated to experimenting with new designs, allowing for enhanced creativity	Teams can be resistance to chances and innovations
Facilities collaboration between multiple stakeholders like fashion designers, manufacturers, and producers	Technical limitations, like accuracy in representing clothes through digital fabrics
Upgrade accuracy and fitting using 3D design software, reducing errors, and improving quality	Sensitive data can be compromised if data is not secure methods (Wagner & Kabalska, 2023a)
Use body scanning in design to improve garment fit. Retailers can use this data to understand female body types and improve advertising	

Note. Table made by own author

2.1.5. Virtual simulation technologies for prototyping

Simulation is one of the pillars of Industry 4.0, playing a pivotal role at the centre of Industry 4.0 (Gunal, 2019). Traditional garment construction is time-consuming and costly. Virtual garment construction using software tools simplifies the process, making it more reliable. Garment simulation creates virtual replicas of models, allowing garment fit tests before completing the physical sample. This simulation is done on personalised body models (Spahiu et al., 2021).

Advanced technologies are being integrated into fashion for around 50 years. Over time, new inventions were adopted to improve products and systems in the textile industry. Previous studies before 2020 focused on integrating technology with fabric fibres to transform them into smart fibres that can adapt to the environment using conductive materials and thermochromic inks to change colours, surfaces, or shapes (Berzowska, 2005), and also replace rigid electronic parts, making them easier and lighter to incorporate into a garment (de Mulatier et al., 2018). Moreover, the microscale/macroscale integration of mobile devices and sensors shows the potential of smart clothing (Fernández-Caramés & Fraga-Lamas, 2018; Pailes-Friedman, 2018). Wearable technology took centre stage, with designers Hussein Chalayan, Moritz Waldemeye, and Mary Huang incorporating LEDs and woven fibre optics in their fashion collections (Mostafa & Demerdash, 2018).

Since the Covid-19 pandemic, fashion industries have been forced to accelerate toward digitalization and virtualization, driving brands to redefine business models using immersive technologies to adapt to this shift. The advance of the internet has created a space where the real and virtual can be transformed through interacted devices, allowing the testing of fashion design and body images in virtual social environments through digital garments (Choi, 2022). Digital technology has given fashion and textile designers access to computer graphic software and 3D virtual simulation systems (Makryniotis, 2018).

3D modelling is time-consuming and expensive, but it worsens the investment because the creation of 3D assets can be systematically modified in multiple ways without needing to make new ones again. The 3D assets are digital samples that sellers, retailers, and consumers can share in marketing campaigns without making physical prototypes or photo shoots, saving time, money, materials, and travel (Souza, 2020).

Apparel manufacturing has four pillars: Product Development, Pre-Production, Production, and Post-Production. To establish a diversified digital product development, teams in all departments involved in the product life cycle can shift product conceptualisation and production (Souza, 2020). So, companies implementing 3D software for product development can increase speed and accuracy, reduce the number of physical samples, and improve design and visualisation decisions. Also, it is essential to collaborate between companies, software vendors, and internal teams, such as designers, patternmakers, product manufacturers, marketing, and sales (Prahl, 2017). Moreover, this technology has more advantages for fashion brands like they can use virtual simulations for marketing purposes, creating engaging digital experiences for customers, including virtual fashion shows, interactive digital catalogues, and

immersive advertising campaigns. Additionally, virtual simulation enhances students' training by simulating several outfits, saving resources and time (Siersema, 2015).

Technology provides better solutions for fashion companies that give more efficiency and captivate other audiences and consumers to buy their products. 3D design improves the value chain for the fashion industry because it boosts designers' creativity and optimises production, retailers, and distribution. Digital sampling is helping fashion brands reduce the product development life cycle of fashion products because it improves the speed to faster production and optimises all phases of the end-to-end fashion cycle. This automation simplifies the sampling process, reducing sampling stages (Tessone, 2022).

Virtual fashion simulation has revolutionised traditional fashion design methods by employing computer-generated simulations to create digital prototypes of garments, giving a realistic representation, and improving the accuracy of garments, like structure, colour, and fabric behaviour. Learning any 3D fashion design software for beginners may take a few weeks to several months, depending on the learning motivation and tools practice. Learning the user interface, creating basic garment designs, simulating fabric behaviour, and working with patterns and textures are important. It does not require knowledge of patternmaking, but it is a plus because this software is intuitive for any user (Särmäkari, 2023).

Digital prototypes are crucial for modern design processes, through CAD software with virtual try-on technology and 3D body scans that can reduce time to market and costs. These technologies provide advanced computer-supported garment simulation and accurate fitting (Papachristou & Bilalis, 2015).

Digital technologies like 3D modelling, virtual and augmented reality (VR and AR), 2D/3D scanning, and digital twinning (DT) are continuously advancing. The fashion industry is progressing towards virtual try-ons, immersive experiences (AR/VR), and mixed reality, transforming all aspects of 3D fashion design value chains (Casciani et al., 2022), shown in Figure 2.2.

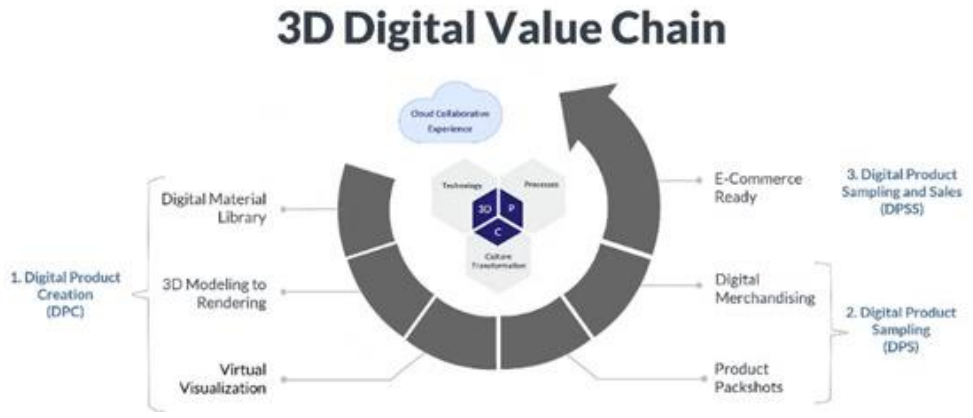

Figure II.2. 3D digital value chain (Melo, 2021).

Digitalisation transforms the fashion industry using 3D design value chains incorporating 3-dimensional virtual and digital technologies. These technologies have the potential to revolutionise the traditional fashion supply chains. By adopting these technologies, fashion companies can innovate, streamline processes, reduce lead times, and encourage artistic transformation. This leads to changes in organisational culture and a shift towards self-expression and diversity in consumer behaviour. 3D technology also promotes creative design, enhances skills and knowledge, and fosters a change in corporate culture towards digital transformation (Casciani et al., 2022).

2.1.5.1. Traditional vs Digital sampling process using 3D CAD software

The sample is a prototype to test a garment's comfort, fit, construction, and details until the final garment is completed (Successful Fashion Designer, 2023). The sampling process is normally long, slow, and costly because it has several stages depending on the the garment's complexity and can take many months to reach the final product. In garment manufacturing, the sampling process for product development is essential because it reduces mistakes, risks, and extra costs (Online Textile Academy, 2019). Furthermore, several authors provide several different results regarding the number of samples that are needed to develop a physical prototype conventionally, for example, using three to five development stages (Bertasiute, 2019) or seven stages of sample making (H&M Group, 2018), while others mention using up to 11 stages (Crista, 2022) or even 20 samples (3DLook, 2023; Cho, 2021).

For this study, it has decided to use describe eight stages of conventional sampling process, show in Table 2 which describe each step and their definition:

Table 2. Traditional sampling process

	Stages sampling process	
1º	**Proto Sample**	First sample made with woven raw cloth based in tech pack
2º	**Fit sample**	Check fitting with final fabric. Normally, women in size M and men in size S
3º	**Showroom sample / SMS Sample**	Buyers Sample used for showcases
4º	**GPT sample**	"Garment Performance Test" for chemicals and physical tests (shrinkage, colour fastness, seam performance)
5º	**Size-Set sample**	All sizes are made to the client's approval
6º	**Pre-production sample / PP Sample / Bulk Sample**	Last stage for approval production
7º	**Top Production Sample**	First samples are analysed for the client to give ok
8º	**Shipment sample**	Some samples are randomly selected to send to the client to check quality

Note. Table made by own author

The initial step for a brand to create its merchandise collection is sampling, which can take several weeks or months to receive final approval. Virtual environments provide a cost-effective way to carry out the sampling process without incurring expenses associated with physical prototyping. However, due to flaws in landmarking, physical prototyping is often needed in digital product creation (Scott et al., 2023).

Rapid prototyping processes and three-dimensional product creation have revolutionised the consumer market. New technological approaches allow the production of a small series of customised products without extensive costs (Santos et al., 2020). A prototype goes through several stages of development, taking time, resources, and travel to produce (Huynh, 2022).

One of the problems in traditional sampling is that fabric waste in the prototype development process can change depending on various factors, such as the complexity of the garment, type of fabric, and material width. Some studies show the percentage of fabric waste: around 15% cutting fabric (Cho, 2021), between 15% to 20% pre-production fabric (Tukatech Inc, 2023), 30% sample-making process (Seemsay, 2021), and annually four to five million tonnes of cutting scraps (H&M Group, 2018). Another example is using Browzwear software. On average, fashion brands can produce less than 35% of samples (Binnis, 2019). For unsold clothes and end in deadstock, some authors report 30% H&M clothing (Matevosyan, 2016), $4.3 billion unsold stock in 2018 by H&M, and $37 million burning products by Burberry (Metail, 2020). 3D sampling saves 90% waste than traditional sampling (FlixStock, 2023).

Another area for improvement is the waste of time involved in the traditional process. Making a physical sample takes 60% more time than a virtual one. It can be reduced to hours (Garza, 2023). 3D software and virtual patterns are up to 30% more accurate and effective than traditional pattern-making methods, reducing time and cost (Habib et al., 2023). Digital sampling can shorten this time through the reduction of manual labour, as well as physical samples - brands like Hugo Boss, Coach, Nike, Abercrombie & Fitch, Victoria's Secret (FlixStock, 2023) Under Armour and Cordeiro Campos (Papahristou, 2016).

Some studies compare traditional time production samples vs digital sampling from 15 to 25 days, reduced to 12 hours (Parker, 2022). On average, 3D is 6x more cost-effective than the on-body tailoring process, which can take one to four days (Crista, 2022). Other show a reduction of three months to 30 days (Varshney, 2023), other reports that can short seven to ten days compared with traditional timelines (FlixStock, 2023), increase 40% efficiency communication between teams (Première Vision, 2023) and 40% to 50% reduction fitting sessions and 35% reducing development and design time (Moda Circolare, 2023). For example, F&F, the clothing brand of Tesco, utilised 3D technology to reduce their product samples from 1.8 to 1.2 (Papahristou, 2016). The time to make products from supply chain to retail can range from 30 to 40 weeks. Conventionally, product sampling takes several stages that take time and resources. The technology of 3D Software can eliminate intermediary layers of these processes through virtual sampling. The solution is a 3D design to reduce the number of samples. Also, fabric sourcing takes at least three months to narrow a material prototype stage, with fabric digital twins shortened from six months to seven days

(Varshney, 2023). Hugo's boss reported that using 3D models reduces the timeline from six months to eight weeks, also reducing physical samples per collection by more than 30% (Adobe, 2023). In the context of global warming, 3D has the potential to significantly reduce the brand's carbon footprint by 10% to 30% (Bertasiute, 2019; Metail, 2020).

Another factor to consider is the cost of fabric sampling. Generally, the sample creation cost can range from a lower price to several hundred dollars. This cost varies based on the material's quality, the design's complexity, labour cost, and production location. Some studies show the cost of sampling per style is $1548 (Bryant, 2022), between $1000 to $2000 (Warren, 2021). Compared with the production of a 3D sample, it can vary between $50 to $600, depending on the complexity and how many pieces are in the look (Brown, 2023), compared with the traditional process, it can save 70% of the cost (FlixStock, 2023).

Figure 3 compares the different steps of creating a prototype using traditional methods and compares it with the digital process. The author shows in Figure 2.3 a simplified way in which the digital process can reduce the number of physical samples needed and save time and resources, such as travel between the customer and the factory, drawing inspiration from the authors' work (Casciani et al., 2022; Hoi et al., 2023); Papahristou, 2016; Parung & Waluyo, 2022):

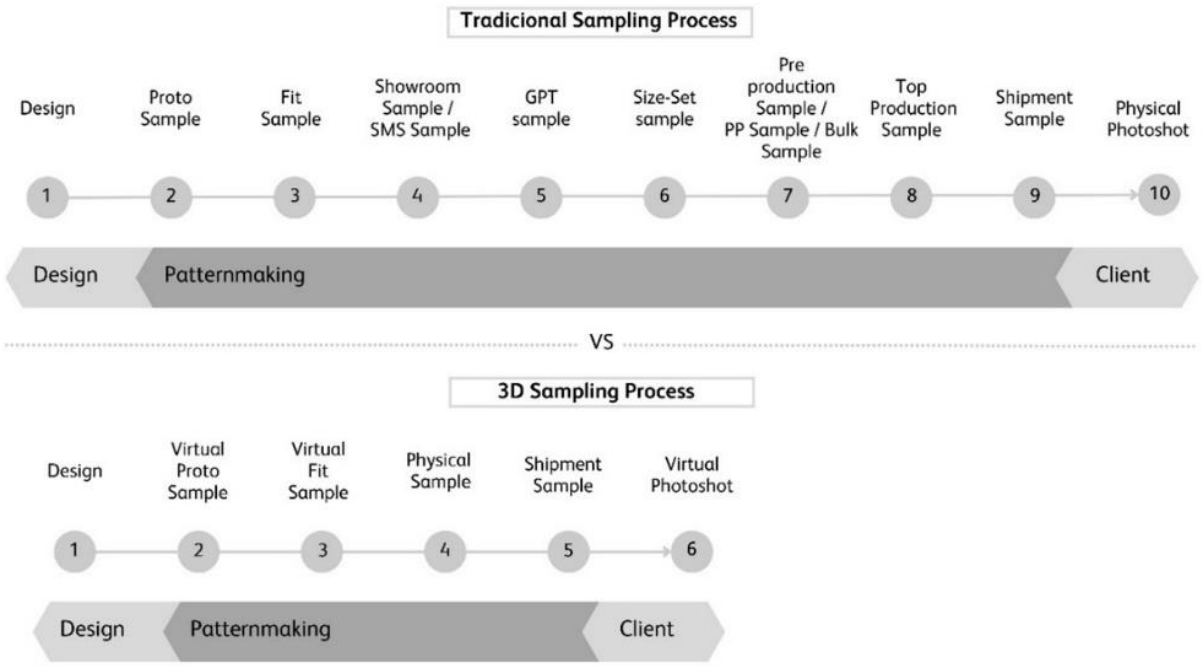

Figure II.3. Traditional sampling process vs Digital sampling process.

Using digital sampling in the fashion industry offers numerous benefits. Based on several studies, it significantly reduces fabric waste, saving up to 50% compared to traditional methods. It also lowers sampling costs, ranging from $50 to $600, and reduces sampling process time remarkably, from weeks to hours, which leads to increased efficiency. Additionally, it promotes environmental sustainability by cutting carbon footprints by 10% to 30%, significantly reducing water usage and greenhouse gas emissions.

According to a study by DressX, digital clothing production saves water and reduces CO2 emissions. Compared to the 2,700 liters required for a physical t-shirt, only 8 cups of water are needed for a digital garment (Igini, 2023; More et al, 2023) – Figure 2.4. This results in a 97% reduction in CO2 emissions, as calculated by Carbon.fyi in DressX's 2022 report (More et al, 2023).

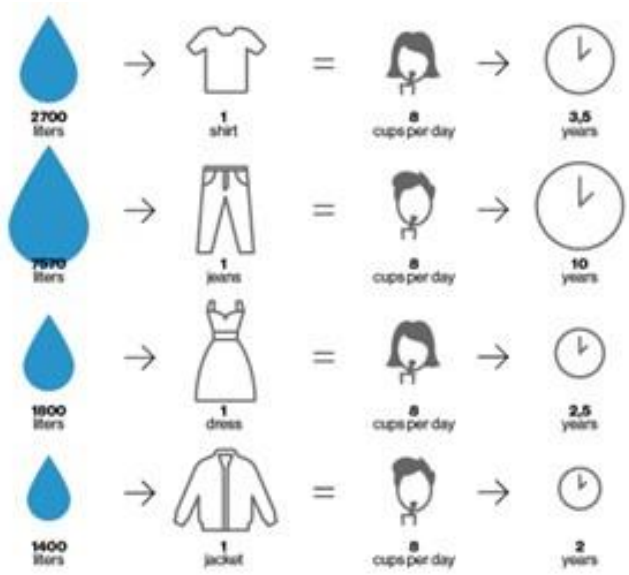

Figure II.4. Representation of the cost of producing a physical vs digital clothing (More Dash Inc., 2023).

2.1.5.2. Scan and fit technology

Also, 3D body scanning technology advancements, automatic pattern generation, and virtual simulation have transformed the design process from conception to fabrication (Greder et al., 2020). The digital fittings system includes virtual fabric, garment patterns, sewing lines, and human body simulation for fit assessment (Geršak, 2022).

In the fashion case, the 3D body allows fashion designers and product developers to understand the fitting and sizing of body forms, supporting the comprehension of human movement and pressure areas of the body. Avatars allow inclusivity and representation of uniqueness because they can create various body types, skin tones, and styles. They allow us to change traditional beauty standards, inspiring self-expression, and diversity (Larocheski, 2023).

Subsequently, the fashion supply chain started to adopt RFID technology in 2000, which has been used in tags to track inventory, improve logistics, and reduce overstock (Landt, 2005). Follow up with wearable technology by designer Hussein Chalayan, who has incorporated this technology into his garments since 2000. The technology ranges from solar panels and LED lights to microcontrollers, which add movement to the clothes (Toussaint & Smelik, 2017). With the emergence of 3D printing in fashion runways, Iris van Herpen combines traditional craftsmanship with modern technology to create innovative collections (Smelik, 2018). Moreover, improvements were being made to 3D body scanning technology, which emerged from new tools to measure the human body and enhance fitting, sizing, and visualization (Gill, 2015). Iris van Herpen, the Dutch fashion designer, is a perfect example of combining traditional tailoring techniques with the CAD system using 3D body scan data that rely on parametric data (Greder et al., 2020).

Digital fashion, virtual reality, and augmented reality have infiltrated the fashion and retail industry. Augmented reality has improved the customer experience with virtual fitting and dressing rooms. However, emerging technologies like CAD, 3D body scanning, 3D virtual garment design, and interactive mirrors require skilled personnel to create new scenarios for the future of digital fashion (Geršak, 2022).

2.1.5.3. AR / VR technology - Immersive experience & Smart mirrors

Immersive technology, such as AR or VR, can be added to explore virtual try-ons, such as smart mirrors, virtual style assistants, trend forecasts, generative images for designing and deep learning to optimize supply chains (Luce, 2018). They allow customers to experiment and increase interactions and conversion rates for fashion brands. 3D technology also improves sustainability and efficiency in all supply chain processes, such as manufacturing and distribution. Fashion brands like Gucci, Zara, H&M, and Nike use this technology (Y. F. Wu & Kim, 2022).

Smart mirrors and applications like AR mirrors are becoming more popular in fashion stores worldwide. Modern stores like H&M, Zara, Ralph Lauren, and Burberry have installed smart mirrors. These mirrors use radio frequency identification with AR technology to create a virtual model of the user wearing the scanned clothing. Uniqlo was the first fashion brand to use smart mirrors in 2012. Likewise, Neiman Marcus used a "Memory Mirror", displaying outfits in 360 degrees with different colours and allowing customers to share on social media (Vrljanac et al., 2023).

Louis Vuitton generated skins for League of Legends characters. Ralph Lauren partnered with Bitmoji so customers could dress their avatars in Polo outfits. Tommy Hilfiger's 2015 Autumn/ Winter fashion show used a 360-degree experience, and in 2017, Coach used VR in stores for fashion shows. Oasis used VR to promote collaboration with the London Zoological Society (Vrljanac et al., 2023).

Other fashion brands have invested in AR or VR technologies to enhance their consumer experience and create digital replicas of their fashion collections with digital twins. For instance, Alexandra Moura has incorporated AR filters

for virtual try-ons, while Martina Spetlova has implemented QR tags that contain store data and product information (Macit, 2023).

2.1.5.4. AI technology

Luxury brands now offer virtual consultants on their websites using AI as the first point of contact for customer concerns. These include Louis Vuitton, Burberry, Tommy Hilfiger, Dior, and Estée Lauder (Joy et al., 2022). Another example highlighted is AI used by the luxury brand Bulgari, which ordered the Serpenti Metamorphosis multimedia installation designed by Refik Anadol and later sold as an NFT at an auction (Joy et al., 2022).

2.2. Digital twin technology

2.2.1. Digital twin in fashion

A digital twin is a duplicate of a real-life object or process. The concept originated in 2010 by Michael Grieves (Wagner & Kabalska, 2023). It involves collecting data from the physical environment and creating a digital representation that can be used to simulate and validate the behaviour of the physical twin both now and in the future. This technology allows for data-driven decision-making, monitoring of complex systems, product validation, simulation, and management of an object's entire lifecycle (Botín-Sanabria et al., 2022). The first representation of DT was NASA's Apollo 13 program, which used twin spacecraft to simulate and predict conditions in space (M. Liu et al., 2021). The digital twin can visualise a product's quality, authenticity, origin, and location (Alves, Cruz, et al., 2022). The Information and Communications Technology (ICT) and BITKOM predict digital twins in manufacturing will exceed 78 billion euros by 2025 (J. Wu et al., 2020).

Creating DT in fashion accelerates the speed of products sent to markets, spending less time developing physical samples and reducing errors and waste. DT involves a complex ecosystem incorporating different departments of the supply chain: designers, pattern makers, developers and manufacturing and sales teams that work with brands and manufacturers to leverage all the steps from concept to commerce (Prahl, 2017). Designers use DT to virtually test their fashion collections without using raw materials, simulating materials, reducing labour hours, and only producing physical fashion items when only after an accurate simulation of the product (Wagner & Kabalska, 2023).

Working with 3D assets allows clear communication and collaboration between all stakeholders during the sampling and production processes: product information sent to suppliers is clear and consistent, as the digital twin perfectly matches the product information physics. They found some case studies where the required number of samples during product development was reduced by 80% (Portugal Têxtil, 2023).

Traditional product production methods, such as design, originality, visuals, and practical components, will not be replaced with technology. However, digital twins can improve efficiency, reduce resources, optimise product quality, and adapt to customer preferences (Wagner & Kabalska, 2023). DT reduces the gap by creating a Digital Product Twin at the Mid-of-Life (MoL) and End-of-Life (EoL) stages, improving transparency and interconnection between the product, company, and consumer (Riedelsheimer et al., 2020).

3D technologies can create digital twins with sub-divisions such as 3D modelling, AI, IoT, Blockchain, Big Data (World Economic Forum et al., 2023), Machine learning (ML), VR and NFTs (Joy et al., 2022) derive from Industry 4.0 (dos Santos et al., 2021).

Product lifecycle management (PLM) was developed as a strategic tool for fashion and textile organizations during the rise of CAD systems. Its purpose is to help achieve operational excellence and innovation in products and services. PLM enables suppliers, partners, and enterprises to create, organize, and manage product-related knowledge (Conlon, 2020).

Integrating 3D technology in supply chains has transformed the fashion industry, allowing for better product lifecycle management (PLM), shorter lead times, and faster time-to-market (TTM). With 3D modelling directly incorporated in PLM, designers can create realistic models, plan collections using IT solutions, and easily collaborate with the development team on material and colour choices (Vezzetti et al., 2015).

2.2.2. Pros & cons

Digital Twin technology has been gaining popularity in the fashion industry due to its benefits, but it also has some challenges that must be addressed. The advantages of using DT in fashion include sustainability, efficiency, and stakeholder collaboration. However, some initial limitations must be overcome, such as cost, collaboration, and industry-wide standardisation.

Additionally, there are concerns about data security and the potential impact on traditional fashion design and production (Kuzmichev & Yan, 2022; Wagner & Kabalska, 2023). Table 3 shows in more detail the pros and cons of DT in the fashion space:

Table 3. *Digital Twin pros and cons*

Pros	Cons
Improve design and innovation	Compromise ethics, privacy, and security information (Rasheed et al., 2020)
Improves garment sustainability: providing technical info on product history, resource use, emissions, materials, and maintenance/repair, and reduces energy (Wagner & Kabalska, 2023a)	Reduce real time modelling, continuous updates systems, lower interaction and representing inferior physical assets (Rasheed et al., 2020)
Decrease waste, physical prototypes, and clothing transportation while increasing flexibility and shortening manufacturing times (Wagner & Kabalska, 2023a)	Expensive investment can require advanced technology, software, and skilled collaborators
Asset performance boost, life longevity, anticipation errors and a backup plan (Rasheed et al., 2020)	Have complex and technical amounts of data, advanced analytics, and systems integration
Better decision-making	
Increase efficiency and optimise processes	
Reduce risks by testing/analysis	
Increase training and education methods	
Help to predict the potential failure of products	

Note. Table made by own author

2.2.3. Development of digital fabric texture simulation

For the construction of garment simulation, it is necessary to understand that it includes digital fabric to create a more realistic fabric look. Over the years, adding texture to give more accuracy to the images was necessary to create realistic-looking fabrics. To get to the current point, we must go back to the beginning when we first began to study fabric behaviour from their physical and mechanical properties. CAD systems for virtual textile simulation use complex parameters are used based on real physical behaviour using The Kawabata Evaluation System (KES) and Fabric Assurance by Simple Testing (FAST) measurements have been used to measure cloth mechanical draping behaviour for analysing tensile, shear, bending, compression, and surface properties since 1972. All these characteristics help to represent a digital fabric, but this process is more complex because of geometric computer systems (X. Wu & Kuzmichev, 2020). The system has elasticity parameters that allow the creation of materials with different appearances in two directions - weft and warp (Cugini et al., 2007). One of the challenges in virtual garment design is the representation of mechanical properties of cloth, such as folds and wrinkles. This problem occurs because of collision detection between the digital body and cloth. To facilitate the process, the spring-mass scheme of the particle system

represents vertices of polygonal mesh that move according to the forces applied in virtual cloth to simulate fabric mechanical behaviour in complete garments on avatars (Volino et al., 2005). To create realistic 3D garments, you need excellent 3D materials, and for that must adjust the material parameters, and the software will generate a photorealistic material with the desired consistency (Adobe, 2023).

In Figure 2.5, it can see the process of included a digital fabric in a blouse giving a realistic look.

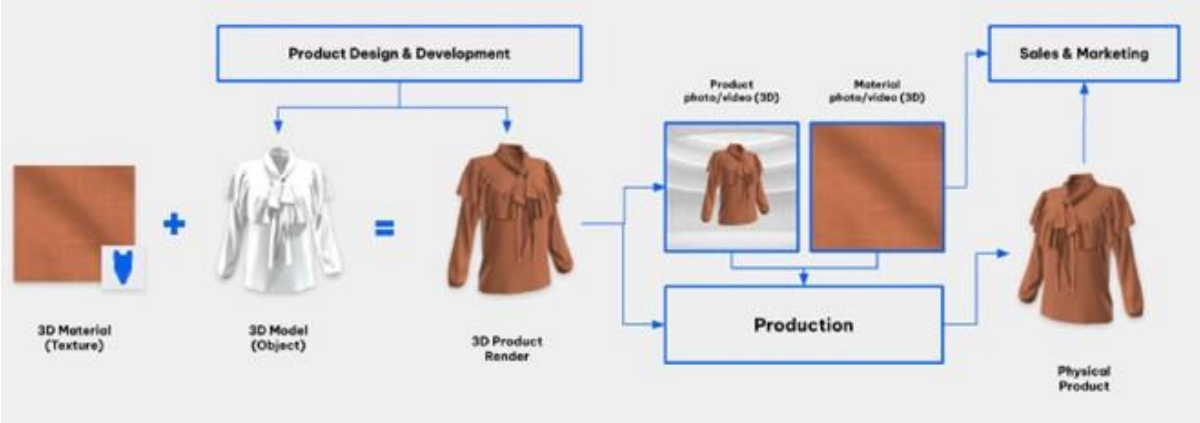

Figure II.5. Digital material incorporated in blouse (Interline, 2022).

Developing 3D fabric textures involves researching fabric properties, creating texture maps, generating detailed texture content, developing shaders, testing, iterating for realistic visual effects, and optimising performance in digital environments (Jang & Ha, 2023). A virtual simulation for modelling and simulation is already available for creating photorealistic renders of fabrics, surroundings, and lighting. Professionals, clients, and buyers use this technology. Advanced technologies have made distinguishing between a rendered image and a photograph difficult due to the high level of realism achieved (Cugini et al., 2007).

Realistic virtual textile simulation in visualisation can only be achieved through complex computer equations that use numerical algorithms (Volino et al., 2005). In the try-on process, the cloth patterns are manually placed on the avatar, known as the pre-positioning step. Next, the patterns are placed in the desired zone and sewn together using a system. Then, the garment is simulated on the avatar, and the computer calculates the behaviour of the draping of the garment at six-degree angle. During this step, the program detects collisions between the garment and the computer-generated body. Two methods are available to solve collision response in computer simulations: constraint-based collision response and force-based collision response. Constraint-based collision response is primarily used to prevent collisions between extremities' vertices.

Figure 2.6 give an idea how it works the parametric material software:

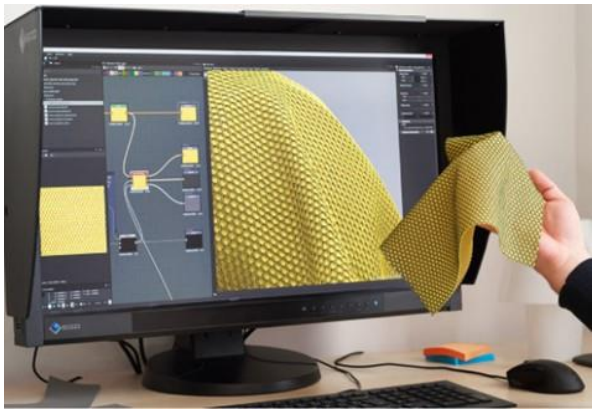

Figure II.6. Representation of a virtually simulated fabric (Interline, 2022).

In contrast, force-based collision response involves repulsing unit fields to prevent parts of the cloth from intersecting. In case they have already collided, a force-based collision response can also be used to separate them (X. Dai & Hong, 2024). To achieve a more realistic appearance of materials in 3D rendering, Dana developed a technique called BTF in 1999, which involves inclining a flat sample of the material in different directions depending on the brightness and shadows in the textile. The sample has a resolution of 800x800 pixels that can be repeated and blended for bigger objects. Adding PCA to make it lighter to create simulations and advanced multi-texturing algorithms are used to create material structure and quality requirements. This process allows fast decompression to suit modern graphics hardware for rendering, depending on texture size to reduce the files' size. Finally, the garment is checked for self-collisions in a 3D environment using HDRI to create a realistic surrounding environment, calculating the lighting and shadow of objects (Cugini et al., 2007).

Nowadays, the invention is the creation of fabrics represented digitally, called fabric digital twins. With the advancement of technology, several software and applications can help improve the realistic appearance of virtual fabrics. Digital materials consist of two components: physics and texture, being compatible with 3D apparel design software (Clo3D, Browzwear, Optitex or Style 3D) (X. Dai & Hong, 2024). Physics refers to a collection of measurements that detail the physical characteristics of fabric that are conducted by testing kits through pre-configured 3D design software or creating a new one using platforms designed for this purpose (Cotton Incorporated, 2023). Figure 2.7 represents the two digital materials components.

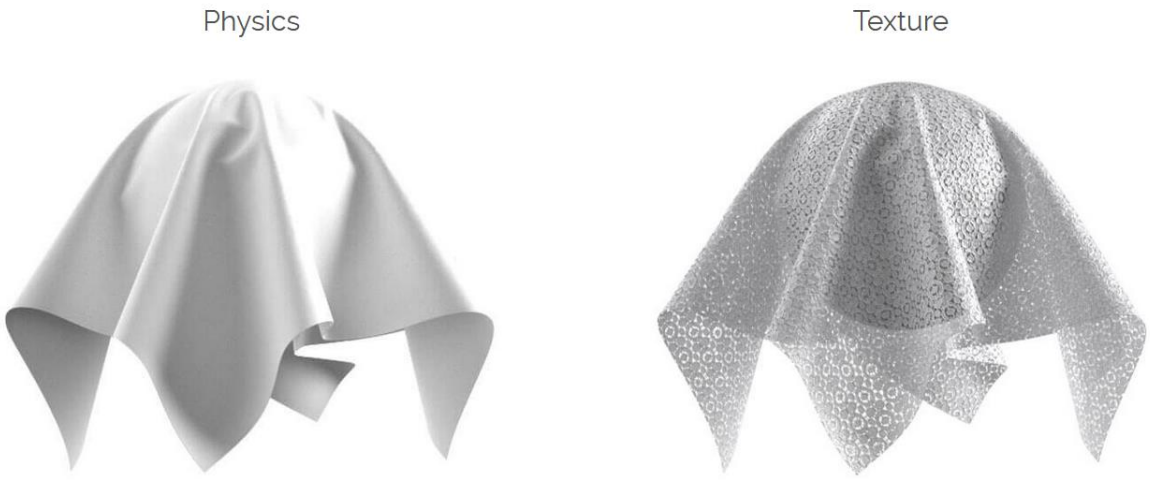

Figure II.7. Digital materials components (Cotton Incorporated, 2023).

In detail, the physics references to the physical properties of fabric like:

- High-quality texture image (which simulates visual and tactile characteristics like bend, weight, stretch, and thickness) obtained through scanned photos.
- Fabric physics (ensuring realistic behaviour under light and motion, like how it drapes and moves).
- Data (providing details like weight, fibre content, and functionality): This information is added to the simulation.

The Cotton Incorporated (2023) describes that after creating a digital fabric, a collection of images showcasing the fabric's surface, commonly known as texture, is obtained from a high-resolution fabric scan. Furthermore, it is necessary to improve 3D fabric simulation (based on computing with engine algorithms) through six maps that create a set of image layers, represented in Figure 2.8:

- 3D Model (plain colour),
- Base/Diffuse Map (pattern and print),
- Normal Map (lighting),
- Roughness Map (shine properties),
- Transparency Map (opacity).

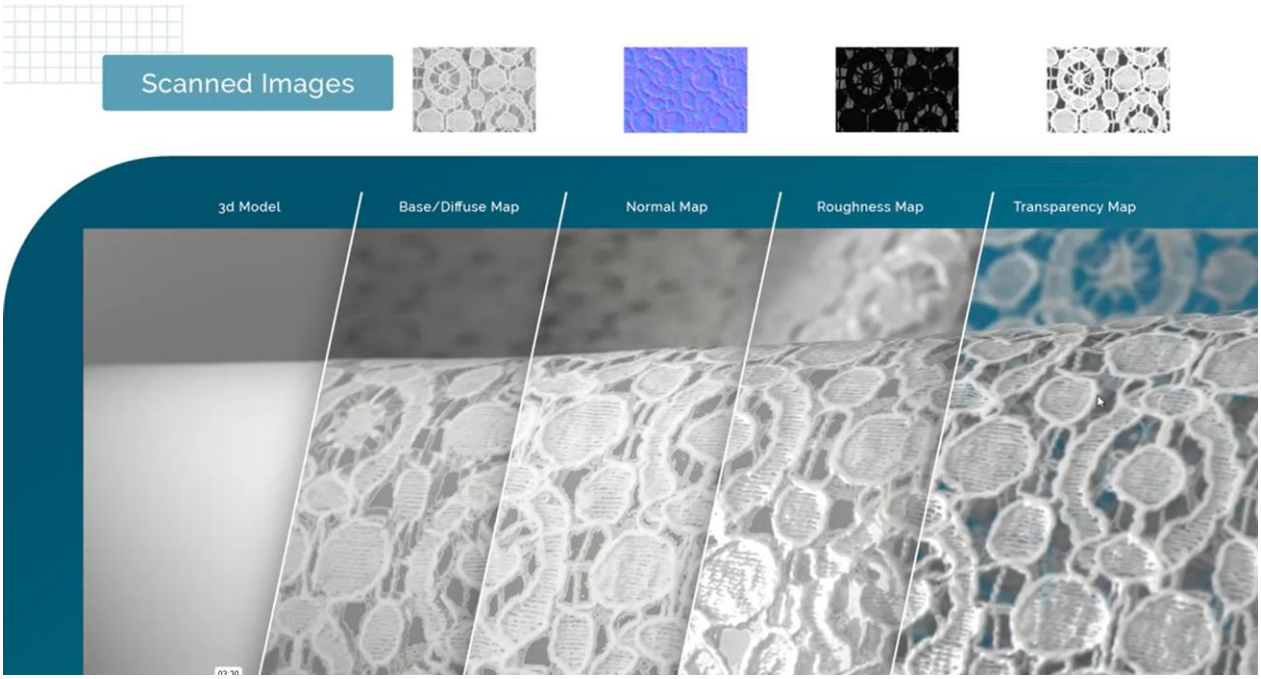

Figure II.8. Texture digital maps (Cotton Incorporated, 2023).

Use 3D materials to test any idea with printed designs on garments, including embroidery, flocking, glitter, and plastic injection, and it is possible to have complete control over colour, gloss, thickness, and metallicity (Adobe, 2023).

It is not 100% accurate but can reach about 90% depending on the complexity of the material (Varshney, 2023) and depending on the fabric's complexity this process can take a few minutes to several days, depending on the complexity of the material (Bosset, 2023).

An analysis of the most commonly used software for texturing fabrics was conducted based on information shared with online fashion companies. The analysis reveals which fashion brands are utilising these platforms to enhance the realism of their digital garments. Table 4 displays the various types of commercial texture software.

Table 4. Types of commercial texture software

Commercial Texture Software				
Company	**Type of Software**	**About**	**3D technology characteristics**	**Fashion Brand Collaboration**
Adobe Inc.	Adobe Substance with 5 platforms: Substance 3D Stager (create 3D scenes), Sampler (transforms photos to 3D materials/models), Designer (design parametric 3D	SaaS platform for 3D design that create GCI images for eCommerce	Virtual footshots reduce carbon emissions by 98% (Adobe, 2023d) compatible 3D design software and 3D	Prada Group, Hugo Boss, Amazon, Louis Vuitton, Burberry, Puma, Yves Saint Laurent, New Era Cap,

	assets), Painter (texture 3D models) and Modeler (sculpt 3D models) (Adobe, 2023).	photoshoots (Shaw, 2021).	computer graphics (Shaw, 2021)	Crocs, Pink Shirtmaker, Lowe's Home Improvement and H&M (Shaw, 2021)
Frontier. cool	TextileCloud™ (platform); Design Hub™(cloud), FabriSelect™; Eco-Impactor™ (fabric's environmental impact); Frontier 3D Fabric Creator (scanner); (Frontier.cool, 2023) (The Interline, 2023)	AI plataform to construct maps with fabric specs into images (Frontier.cool, 2023)	Convert fabric materials photos into 3D & 4D digital twin materials using scanner (Frontier.cool, 2023)	Under Armour; Adidas; (Frontier.cool, 2023)
Seddi Inc	SEDDI Textura Cloud-native platform (Seddi Inc, 2023)	AI texture maps creating fabric images (Seddi Inc, 2023)	Generate maps from scan images (Seddi Inc, 2023)	Bestseller, Under Armour (Seddi Inc, 2023)
Shima Seiki	Shima's SDS-ONE APEX series design system (Hunter, 2020)	Flat knitting software (Inside Textiles Ltd, 2020a)	3D flat knitting high-quality using yarn and thread details (Hunter, 2020)	Decathlon; H&M (Inside Textiles Ltd, 2020a)
Vizoo GmbH	xTex™ (Software or Hardware); physX™ (Platform and Digitalization) (Vizoo 3D, 2023)	Material scanning & digitization software (Vizoo 3D, 2023)	High-resolution scanner based PBR texture maps (Vizoo 3D, 2023)	Adidas, Avery Dennison, Diesel, H&M, Hugo Boss, Under Armour, Triumph, Ralph Lauren, PVH, Puma, Nike (Vizoo 3D, 2023)
Z-emotion Co., Ltd.	Z-weave (e-commerce, simulation, and gaming platform)	3D garment technology company (Z-emotion Co. Lda, 2023)	Reduce time to market, compatible 3D computer graphics and Vizoo (Z-emotion Co. Lda, 2023)	Nike, Louis Vuitton (Z-emotion Co. Lda, 2023)

Note. Table made by own author

Fashion companies that have invested in 3D design and digital fabric libraries will have a competitive advantage over other companies in the long run because adopting new 3D technologies has been proven to be a game changer for increasing efficiency and speed and reducing costs and materials. It also leads to a more sustainable way of creating products.

Figure 2.9 demonstrates that using different parameters can improve the appearance of a digital fabric, making it more similar to a physical fabric swatch.

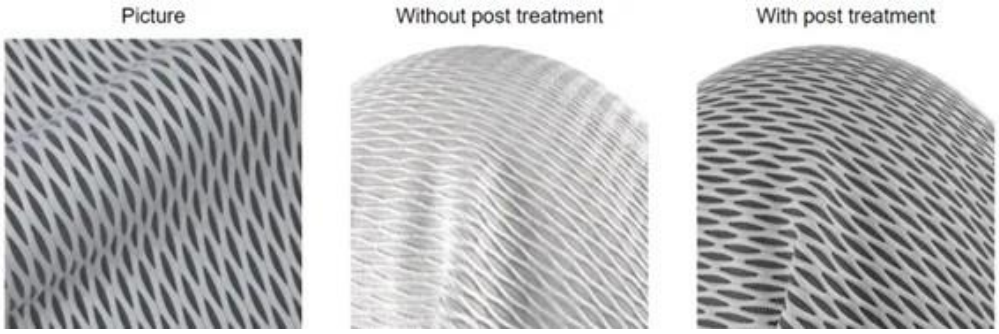

Figure II.9. Digital material with different parameters (Bosset, 2023).

As part of the research on digital twin materials, it was discovered that certain fabric companies have begun compiling digital libraries of their fabric samples. These libraries are then available for fashion designers on 3D design software platforms.

Table 5 displays the fabric supply companies that have already established virtual showrooms:

Table 5. Examples of virtual fabric library

Fabric platform compatible 3D software's			
Company	**About**	**3D technology characteristics**	**Fashion Brand Collaboration**
Lycra Company	Global textile industry spandex (elastane) fibre (Braun, 2022)	3D digital collection using own fabric digital twin "Lycra Brand Materials Library" in Browzwear (Braun, 2022a)	Intimate wear; Sportwear; (Braun, 2022)
Chargeurs PCC Fashion Technologies	Interlining & underlining company (Business Wire Inc, 2021)	Virtual showroom incorporating Clo3D (own fabric digital twin) (McDowell, 2021)	Balenciaga Gucci, Chanel, Hugo Boss, Dior (McDowell, 2021)
Polartec®, LLC	Textile technology company (Polartec, 2023)	Virtual showroom with 14 digital twin of sportswear technical fabrics compatible Browzwear (Inside Textiles Ltd, 2021)	Adidas, Nike, Moncler, O'Neill, Patagonia, Prada, Supreme, The North Face, Timberland, Under Armour (Polartec, 2023)
Cotton Incorporated	Non-profit organisation promotes cotton fabric	Virtual showroom Fabricast™ compatible with Clo3D and	All brand using cotton fabric for Casualwear and Denimwear (Varshney, 2023)

	(physically/virtually) (The Interline, 2022)	Browzwear and Adobe Substance (The Interline, 2022)	
SwatchOn Co. Ltd	Wholesale fabric trading service (SwatchOn Co. Ltd, 2023)	Virtual showroom VMOD 3D with 200k fabrics compatible Vizoo, Clo, Marvelous Designer, Adobe Substance, Blender, Cinema 4D and Maya (SwatchOn Co. Ltd, 2023)	Nikolaj Storm, Amy Parris, Altar, Pocket Square Clothing (SwatchOn Co. Ltd, 2023)
Avevy Dennison	Labelling manufacturer company (Avery Dennison, 2023)	Virtual showroom with 4 types of labelling compatible Browzwear (Warren, 2021)	All types of clients in fashion, automobile, medical (Avery Dennison, 2023)

Note. Table made by own author

2.2.4. Phygital fashion brands

In context, the term "Phygital" was first used in 2004 by WIRED magazine (RLTY, 2023). 2007, Chris Weil coined this term generally worldwide (Dagnino & Minin, 2022). In the early 2010s, this term was focused on personalised, customisable experiences. However, with the Covid-19 epidemic that led to physical retail stores struggling, brands focused on virtual fashion shows and digital interactions (RLTY, 2023). It also improves the performance of fashion brands by creating a better experience in retail, adding value to the brand by featuring new content like 3D images/videos of realistic or hyper-virtual models to showcase clothing from different angles (Audaces, 2023).

In the case of luxury fashion, brands are leading the way in "phygital fashion", which creates experimental journeys in online and physical stores to increase exclusivity (Lawry, 2022) and improve brand equality (Hyun et al., 2022). In the case of blockchain, technology gives transparency and expands supply chain evolution by creating traces of the garment life cycle, from materials passed to production and finished in selling. It also secures consumers from transactions along supply chains (Dash, 2023).

Fashion brands, such as Burberry, Gucci, and Louis Vuitton, were the first to pioneer this ecosystem (Armstrong & Rutter, 2017), investing in omnichannel retail to improve consumer experiences, merging the physical and virtual worlds to create "phygital" experiences to create personalised fashion experiences using immersive technologies like VR and AR in fashion shows, wearable tech, and merging online and offline fashion consumption (Macit, 2023), bringing a new way to rethink design, produce and merchandise new products, and bring a new circular perspective

(The Interline Group Limited, 2023). Currently, fashion brands can integrate technologies to reshape the fashion industry (RLTY, 2023).

Figure 2.10 shows an example of collaboration between the fashion house Balmain and the Altava agency.

Figure II.10. 3D collection display for Balmain (Altava, 2023).

According to a study conducted by Kang & Chun (2022) during 2021/2022, many fashion brands invested in experimental digital fashion shows to present their collections (SS21 and FW21) because human contact was not possible, and it was the only way to showcase their work globally. The study noticed two types of shows - films and games. Brands that presented fashion films are GCDS, Colina Strada, Boramy vague, Ottolinger, Miu Miu, Balmain, Burberry, Edem, Thom Browne, Alexandre Vauhier, Moschino, ACT N°1, Salvatore Ferragamo, Coperni, Coach, Lanvin, Dries Van Noten and Kenzo. Fashion shows presented an entertaining component: Marc Jacobs, Valentino, Gucci, Christian Louboutin, and Balenciaga. On the positive side, these digital collections could overcome physical barriers through virtualisation and non-direct communication, and the brands' power to entertain was reinforced. However, on the downside, there is a need for more attention from those observing the products and a deficiency of a sense of reality.

Specialised companies in the technology market increasingly focus on developing digital fashion products because fashion corporations want to create identical digital twins of their products to expand their offerings and are looking to this type of service. Digital products are made with hyper-realistic images, which can be used in online catalogues, social media, and website pages to attract customers. These technological agencies have an extended network of fashion brand clients who seek their services without having to hire 3D specialists in their departments.

Table 6 details relevant agencies in the technology sector that create digital fashion twins:

Table 6. Tech agencies that make product digital twins

Company	About	3D technology characteristics	Type of Software	Fashion Brand Collaboration
Altava Group	Platform avatar-centric for social media and games (Altava Group, 2023)	High-quality 3D designs for gaming, metaverse platforms, AR, and VR	N/A Probably 3D software for AR/VR and 3D design software	Burberry, Diesel, Balmain, Bulgari, and Tom Browne (Hickman, 2023)
Seamm	Marketplace platform to purchase digital twin + physical garment (Olkhovskaia, 2023)	Creates NFT of physical garments and send the two for the client that can access through Qr Code (Olkhovskaia, 2023)	N/A Probably 3D software for AR/VR and 3D design software	Alexandra Moura, Martina Spetlova, Artflash Armenia, Clear to Rain**,** Misha Libertee Libertee (Seamm Technologies Inc., 2023)
BRIA – (Brooke Roberts Innovation Agency)	British tech agency that creates materials-tech products connecting manufacturers with brands (Roberts-Islam, 2019)	Retail Target reduced: less 65% physical sampling and reduced market time to 3 months to 2 weeks (Roberts-Islam, 2019)	Optitex (Roberts-Islam, 2019b)	Luxury brands and medium brands, example: Target (Bria, 2023)
Style.me	3D assets platform with digital twins using virtual fitting plugs linked to online stores and AR e-commerce (Style.me, 2022)	Less 50% returns and reduce overproduction. Less 3300 water litres and emits 97% fewer Co2 emissions (Style.me, 2022)	N/A Probably 3D software for AR/VR and 3D design software	Diane von Furstenberg, Boda Skins, Reina Olga, CLA, Nesting Olive (Style.me, 2022)
BinaryCloth	Bangladesh company has 3D development service with AR/VR solution (Binarycloth, 2023)	Provide different services: 3D apparel design, fabric digitalization, custom Mock-up (Binarycloth, 2023)	Clo3D (Binarycloth, 2023) and probably 3D software for AR/VR	RALPH, Scrappy apparel, ATHIFY, Famme (Binarycloth, 2023)
Koffeecup	Digital production agency specialises immersive technologies (Koffee Cup Ltd, 2023)	Creates digital clothing for fashion brands to use in multiple	N/A Probably 3D software for AR/VR and 3D design software	Burberry and brands & marketing agencies (Koffee Cup Ltd, 2023) (Burberry Group plc, 2018)

		platforms (Koffee Cup Ltd, 2023)		
3Dear	Scandinavian company specialise in 3D product development, digital pattern sampling (3Dear, 2023)	Partner with Sandqvist, they reduce emissions by 5-6 tonnes of CO2 per year (Magnusson, 2022)	Clo3D (Magnusson, 2022)	Sandqvist, Björn Borg, APPLETREES (3Dear, 2023)
Obsess	Online shopping interface using 3D immersive tools for improve e-commerce (Obsess, 2023)	Increase: 61% session time and 26% higher order value (Obsess, 2023)	N/A Probably 3D software for AR/VR and 3D design software	Ralph Lauren, Tommy Hilfiger, Prada, LVMH, Kering (Obsess, 2023)
Hyphen	Digital transformation services industries: fashion, marketing, and retail (Hyphen-Group, 2023)	Creates digital clothing for luxury fashion brands (Hyphen-Group, 2023)	N/A Probably 3D software for AR/VR and 3D design software	Versace, Etro, Diesel, Baily, Tod's, Max Mara, Versace (Hyphen-Group, 2023)
PlatformE	Technology platform-based product development digitalization for brands, technology connecting e-commerce, and production (Portugal Têxtil, 2022b)	Less 80% sample number (Portugal Têxtil, 2023), 40% reduction in lead times and 50% inventory reduction (PlatformE, 2023)	N/A Probably 3D software for AR/VR and 3D design software	Farfetch, El Corte Inglés (Portugal Têxtil, 2022b) Gucci, Kering, Fendi, Dior, Nordstrom, Saint Laurent Paris, LVMH (PlatformE, 2023)

Note. Table made by own author

Technology is crucial in the retail industry to elevate design, branding, and marketing strategies. "Phygital" merges the physical and digital worlds, enabling retailers to leverage the latest AR, AI, NFTs, and blockchain technologies. Fashion brands can use digital platforms to showcase their fashion shows and offer personalised experiences to customers. By incorporating gamification, retailers can encourage customers to express themselves and personalise their shopping experiences (Boardman et al., 2024).

When discussing digital twins in fashion, it is important to mention Digital Twin NFTs. NFTs are a component of blockchain that is tokenised and recorded on the blockchain infrastructure. In the fashion industry, some brands are making NFTs associated with digital replicas of their physical garments, known as digital twin NFTs. The first digital twin NFTs in fashion have fashion designer Martine Jarlgaard's collaboration with the blockchain platform - Provenance, which registers use the app to see all the information about their garments: raw materials, manufacturers, and Finnish garments in stores (Prahl, 2017). After this, in 2021, Aura - a blockchain consortium, includes Prada, Louis Vuitton,

LVMH and Cartier to offer access to luxury product history and authenticity proof from sourcing to second-hand markets (Joy et al., 2022; Vrljanac et al., 2023). Another example is the French luxury brand Bulgari, which introduced the Octo Finissimo Ultra watch, which features a QR code embedded with NFT digital art (Macit, 2023).

The luxury brands - Bulgari, Gucci, Burberry, Dior, Tommy Hilfiger, Ralph Lauren, Estée Lauder, and Louis Vuitton - are investing in new technologies like AI and BCT to improve revenue and increase consumer experience between different platforms, such as gaming and digital collection (Burberry Group plc, 2018; Joy et al., 2022) Other fashion brands invest in making their digital twin NFTs, such as Nike, Gucci, Dolce & Gabbana, Dior, and Burberry for NFT (Bao et al., 2024; Vrljanac et al., 2023), and Adidas for NFTs (Park & Moon, 2023) show in Figure 2.11.

Figure II.11. Digital twin of B33 sneakers (Dior, 2023).

Luxury brands like Gucci, Givenchy, and Tiffany & Co. are using NFTs to enter the Metaverse. Gucci created a GOOD GAME ecosystem to interact with Roblox, launched a virtual "Gucci Arcade", and partnered with Tennis Clash and Snapchat. Givenchy collaborated with digital artist Chito to create 15 NFTs and partnered with Animal Crossing and Roblox to release makeup products and an online game called "Givenchy Beauty House" (D. Chen et al., 2022). Also, LVMH, Burberry, Ralph Lauren, and Louis Vuitton are investing in blockchain (NFTs) to verify the authenticity of digital images and AI technologies to improve customer interactions (Joy et al., 2022).

For instance, in 2021, Burberry opened a "social retail store" in China, offering exclusive content and personalised experiences with digital animal characters interacting with the physical store. French fashion house Hermès has also adopted Web3 technologies to sell virtual goods, cryptocurrencies, and NFTs. French fashion brand Balmain has partnered with Barbie to create three tokens (Macit, 2023). Other examples are Columbia Sportswear and Target, which use AR and VR technologies to improve their brands in many departments: design, sampling, product development, marketing, and improving customer experience in stores (Prahl, 2017).

CHAPTER - III

Digital clothing simulation for fashion Design

3.1. Framework

The digital clothing simulation framework represents a significant transition in how the fashion industry approaches design, production, and marketing, offering increased efficiency, sustainability, and opportunities, improving company and customer relationships, introducing sustainable production techniques, and influencing education and everyday life (Nobile et al., 2021). The integration of digitalisation in the fashion ecosystem is proposed to solve the problems of time and material consumption in fashion creation, meaning that using digitalisation in all stages of the product life cycle development involving all participants creating a cyber-physical system producing products in small quantities, order-to-make and customising them (Pereira et al., 2022).

In the fashion industry, the Covid-19 pandemic forced fashion brands to invest and rethink new digitalisation forms, implementing innovation throughout their supply chain to reach the consumer. 3D virtual simulation systems for fashion design began in the mid-1990s with computer-aided design tools like Lectra and Modaris. This technology led to developing 2D tools such as Photoshop, Illustrator, Aftereffects, and advanced 3D tools like Clo3D. These tools offer designers real-time interaction between 3D simulations and virtual clothing, which not only saves time but also reduces costs. When it comes to the design process, integrating 3D technology into it enables fashion designers' endless possibilities for creative expression and visualize clothing digitally, simulate fabric draping and texture maps, and virtually observe garment fitting, leading to more precise designs, minimizing the need for produce physical samples, saving time, costs, and resources, and reducing design iteration cycles (Choi, 2022).

3D design tools are meant to complement traditional methods, not to replace them. These existing tools improve the efficacy of key factors in the garments' design and development process. The goal is to shorten the design and prototype cycle, simplifying the process currently dependent on physical samples and fit sessions (Goldstein et al., 2009). Traditionally, fashion designers only had to learn to draw by hand and sew and know about fibres, fabrics, trims, accessories, and finishes. These types of high knowledge could take years to develop, normally ten to 12 years, including education (Meta, 2023).

Over the years, new fashion design models have emerged based on digitisation, virtual fitting, and big data analyses to improve efficiency and quality. Previously, fashion brands had to buy trend forecasting books (e.g. Wgsn, Carlin or Pecler) to predict future consumer choices. Nevertheless, fashion designers can use big data analysis to identify preferred elements of their audience, like colours, styles, materials, and other aesthetic characteristics. Also, consumers can be part of their choices using CAD systems to improve the performance of virtual try-ons, but guided by fashion design experts because customers, when they buy the clothes, do not pay attention to other characteristics like the performance of textile materials or functionality like temperature (heat/humidity), pressure (function), and comfortable (fitting, fabric properties) (Zhao et al., 2021).

Also, 3D technology can give advantages in other areas that complement the design, such as using virtual simulations for marketing purposes and creating engaging digital experiences for customers, including virtual fashion shows, interactive digital catalogues, and immersive advertising campaigns (Siersema, 2015). Attention should be directed towards training and skill development to ensure successful implementation. This process includes educational initiatives for students and designers to acquire 3D design skills and ongoing skill enhancement programs for industry professionals (Fu, 2020; Papachristou & Zolota-Tatsi, 2024).

3.2. 3D programs in industry

A report from The Industry Global News predicts the 3D fashion design software market will be valued globally in 2019 at 58 thousand dollars and in 2028 will reach 1,2 million dollars (Industry Global News 24, 2020). Fashion companies can benefit from investing in 3D technology as it is in high demand. Understanding the history and evolution of 3D programs is essential, with research focused on programs used in textile/apparel industries. The evolution of 3D software in fashion has its origins in other programs from other industries, specifically CAD/CAM software. This software system originated in the aerospace, automobile, and engineering industries (Papahristou, 2016; Riesenfeld et al., 2015).

Seeing the improvements using CAD systems, the textile industry was inspired and brought this software to adjust to its manufacturing, taking some time to have the software we know today. Initially, traditional garment CAD systems only allowed the visualisation of flat clothing pieces in 2D. Later, it was possible to add 3D visualisation with the evolution of technology. Nowadays, there is still a distinction between CAD software that pattern makers mostly operate in the textile industry's production and 3D fashion design software development handled by fashion designers or pattern makers, being a more intuitive software that allows the creation of virtual pieces without thinking about physical limitations, especially in fitting.

Virtual design improves aesthetics, reduces overproduction, and promotes sustainability and social equity. Digitally created products save time and resources, easing economic risk and helping small creators with niche

markets. Immaterial products enable new fashion design and business models in the digital economy. Virtual products interact with humans through augmented reality, virtual collections, and CGI models (computer-generated imagery). A 3D model enables fashion designers to modify virtual pieces in real time, called "virtual prototyping". This process results in accurate digital simulations, making communication easier and speeding up the correction of the garment's fit and graphics. Three-dimensional software monitors comfort and fit and allows designers to test the garment on various body types, resulting in more informed and sustainable design decisions (Santos et al., 2020).

3.2.1. 2D CAD software in fashion industry

From the late 1980s to the early 1990s, the fashion industry saw the beginnings of fashion design software, only in 2D. These early programs focused on pattern-making and basic design features. The first studies in CAD systems for fashion design began in late 1980 with the research of author Magnenat-Thalmann for MIRALab (Meng et al., 2012). By the early 1990s, CAD/CAM technology had increased in the textile industry. However, it started being used in other industries like material machining in aerospace for management inventory, ordering, and sales analysis, among other purposes. 2D CAD systems allow the manipulation of garment pieces faster and easier than the normal pattern-making process. Also, it allows to graduate pieces for any size and places automatically pattern pieces to minimise fabric waste (Collier & Collier, 1990). Other studies, such as Hinds and McCartney scanning a tailor dummy to create a virtual mannequin, using a design platform to create flat patterns to visualise 3D garments without inserting the measurements manually (Hinds & McCartney, 1990; Hinds et al., 1992).

Another paper shows testing in different materials and pieces of clothing using CAD software showing 3D visualisation but needing some improvements in mechanical analysis from friction clothes in contact with the virtual body, as well as distortion and stress of the cloth in the curved 3D surface for realist look (Hardaker & Fozzard, 1998; Ito et al., 1992; Okabe et al., 1992). At the end of 2000, McCartney showed evolution in CAD systems for garment design by incorporating both 2D and 3D, which facilitates the creation of 3D garments with drape simulation of two woven fabrics for visualisation in the 3D body (McCartney et al., 2000). Since then, more scientific articles have been published using CAD software to demonstrate the system's evolution, which is becoming more efficient with quality and precision (Abecassis-Moedas, 2006; Fang & Ding, 2008; Fontana et al., 2005; Kim & Kang, 2002; Kim & Park, 2007; Li & Lu, 2014; Liu et al., 2010; Magnenat-Thalmann & Volino, 2005; Meng et al., 2010; Sul & Kang, 2006; Wang et al., 2011).

Two types of CAD systems exist in the fashion industry market defended by most researchers: the "2D-to-3D approach makes flat patterns initially to put in 3D mannequins - *VstitcherTM (Browzwear), Accumark VstistcherTM (Gerber), Haute Couture 3D (PAD system), Modaris 3D FIT (Lectra), edit Simulator (Tukatech), 3D Runway (OptiTex), Vidya (Assyst-Bullmer)* - the "3D to 2D" approach - *3D Interactive software (TPC), 3D Runway (OptiTex)* - which creates

the first 3D models of the garments to transform them into 2D pattern pieces. At the time, Sayem suggested that to improve the work of fashion, designers and patternmakers must have better 3D interface of a garment into 2D to enhance designers' requirements in CAD systems (Sayem et al., 2010). Hwang added that the theory of these two approaches in the simulation was more accurate for film animation or virtual characters but not so good for clothing production because the simulation takes time and needs simpler models. Moreover, he noticed that separate companies develop 2D and 3D programs, making it difficult to transition between them. He recommended that pattern-making software companies create better interfaces to connect programs in the future (Young Hwang & Hahn, 2017).

By the late 1990s, basic 3D functionalities began to be introduced, primarily used for simple draping and visualisation. The early 2000s marked significant advancements in 3D capabilities with software like Lectra's - Modaris incorporating advanced 3D tools for better garment visualisation and fitting. In the mid-2000s, more comprehensive 3D fashion design software entered the market, with tools like Optitex and Gerber-AccuMark offering integrated 3D solutions covering everything from patternmaking to draping. The 2010s saw the rise of specialised 3D fashion software such as CLO3D and Browzwear, known for their advanced 3D garment simulation capabilities, allowing designers to create detailed and realistic virtual prototypes, and reducing the need for physical samples. The student researched CAD programs available in the market, such as Browzwear, Optitex, Tukatech, Modaris, and Gerber, which include 3D virtual try-ons as part of their 2D software systems.

a. Browzwear

Software company that offers four platforms for corporate users and VStitcher for young designers. The latter includes patternmaking tools and rendering capabilities, while the other platforms provide fabric analysis (Fabric Analyzer - FAB), block pattern technology, and collaboration space. In addition, Lotta software is compatible with Adobe Photoshop and Illustrator. Using Bronzeware's software can lead to significant savings, including up to 80% of fabric waste, a 50% reduction in salesperson samples, and a reduction in traditional sampling time from two to four weeks to mere minutes (Browzwear Group, 2022). On average, fashion brands can produce less than 35% of samples (Binnis, 2019). Browzwear has over 650 clients, including Puma, Nike, Superdry, PVH, Lidl, Dickies, Target, VF Corporation, Under Armour, Columbia Sportswear, Artistic Milliners and Odlo (Browzwear Group, 2023). An example of collaboration was in 2019 when Browzwear partnered with Jeanologia to create sustainable denim clothing. They used Adobe Substance to add texture to materials (A. Lee, 2020).

Figure 3.1 represents an example of the 3D image by Browzwear.

Figure III.1. Digital Workflow Browzwear (Browzwear, 2023).

b. Modaris

Lectra Modaris is a CAD software that enables designers to create and modify 2D patterns for different types of clothing, such as womenswear, menswear, and childrenswear (Zhang & Barbour, 2020). The software offers a virtual pattern manipulation, drafting, and grading method to assist designers throughout the pattern development process. In recent years, they have added a 3D prototyping and fit-try-on feature to incorporate into the virtual body (Lagė et al., 2020). The list of clients incorporated Dior, Hugo Boss, Hermes, Christian Lacroix, Givenchy, Kenzo, Thierry Mugler, Gucci, Burberry, H&M, Yves Saint Laurent, and Sonia Rykiel (López, 2018). Figure 3.2 shows an optimization of fabric using Modaris V8.

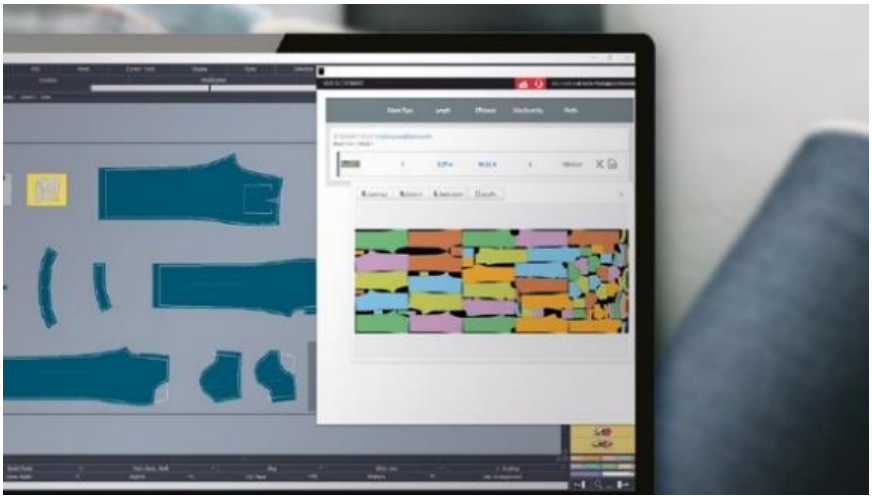

Figure III.2. Fabric consumption estimates through Modaris (Lectra, 2023).

c. Gerber

Gerber Technology's AccuMark is a software program specifically used to create two-dimensional patterns (Guo & Istook, 2023). Although generic vector graphics software programs, such as Adobe Illustrator, can be operated for patternmaking, AccuMark is more suitable for customisation in the industry, provided that the user has adequate patternmaking knowledge (Rafek et al., 2024). Clients included Adidas, Levi's, GAP, Nike, Ralph Lauren, Triumph, and Abercombie & Finch (López, 2018).

Figure 3.3 exhibits an example of Gerber AccuMark.

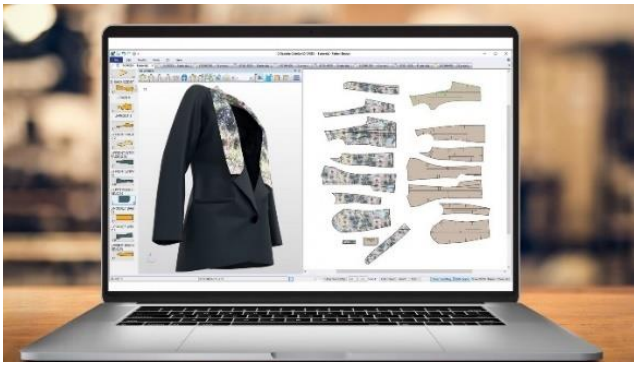

Figure III.3. Gerber AccuMark 3D (Lectra, 2023).

d. Optitex

CAD software creates patterns, fabric simulations, colourways, prints, tension maps, and avatars (DMCA, 2023). It offers 2D/3D design and visualisation for fashion supply chains, compatible with major CAD formats (Sarakatsanos et al., 2021). Figure 3.4 is taken from Optitex with Under Armour brand.

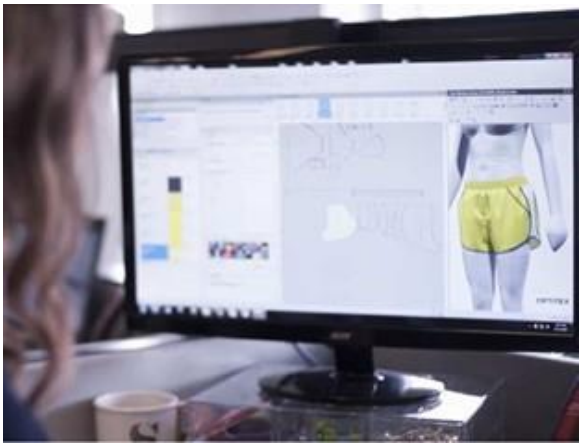

Figure III.4. 3D image from Optitex with Under Armour (Optitex, 2022).

e. Tukatech

Tuka Tech is a software that specializes in virtual prototyping and allows users to transform 2D patterns into 3D designs. They offer a textiles, prints, and graphics library compatible with Adobe Illustrator (Salia, 2023). Additionally, they provide many services, such as automatic fabric spreading machines, cutting machines, and unit production systems (Tukatech, 2023). Figure 3.5 presents an example of a 3D image from Tuka3D software.

Figure III.5. Representation of simulation in Tuka3D software (Tukatech, 2023).

3.2.2. 3.2.2. 3D CAD software in fashion industry

The evolution of 3D Modelling software across industries began in the 1960s with the first graphical user interface software invented by Ivan Sutherland in 1963 with Sketchpad. In 1982, with the launch of AutoCAD, engineering and architecture sectors adopted these for designing complex components. Next, 3D CAD programs for design and prototype for industries such as automotive and aerospace began in the mid-1980s - CATIA. The revolutionary 2D software in the 1990s expanded the emergence of advanced 3D modelling software for animation and gaming sectors - Autodesk Maya, 3DS Max and Blender. These technologies have been adopted since the beginning of the millennium, with the introduction of architectural software like SketchUp and Revit. 2015, 3D printing revolutionised manufacturing by facilitating rapid prototyping in different industries (Ekaran, 2021).

As the late 2010s and early 2020s approached, 3D fashion design software became more mainstream and integral to the workflow of many fashion brands. This era also saw increased collaborative features, supporting remote teamwork on designs. The 2010s marked a significant rise in the use of 3D technology in product design and rapid prototyping across various industries. Integrating VR and AR with 3D software was defined by enhancing various industries from design to virtual production in movies and video games - Unreal Engine and Unity Engines. In the 2020s, 3D technology has become more sophisticated and mainstream, extending to education and training for interactive learning experiences, showcasing its pervasive and transformative impact across multiple fields with cloud-based 3D modelling and collaborative platforms to support remote and joint work. Nowadays, the evolution of AI and machine learning is used to integrate 3D modelling and simulation to improve quality and save time (Bhattacherjee, 2023).

The 2020s brought technological advancements, with fabric simulation, AI, and machine learning greatly enhancing software capabilities. The Covid-19 pandemic sped up the adoption of these tools as the fashion industry adapted to remote working and digital presentations. Over these decades, 3D fashion design software has evolved from basic 3D visualisation to sophisticated tools capable of creating highly realistic garment designs, revolutionising fashion design and production processes. CAD/CAM software is used in fashion design and can be classified in 2D software like Illustrator and Photoshop or 3D software such as Optitex, Vidya, V-Stitcher, and Modaris (Kiliç & Ceylan, 2024).

Virtual simulation systems such as CLO3D, Marvelous Designer, Style 3D, and DC Suite can help create custom fashion designs with various styles, colours, and patterns (Choi, 2022). 3D software specific to the fashion industry has many advantages that are revolutionising several aspects in other departments like design, production, marketing, and sales (Fashion United, 2023) Various software is similar in creating digital products, workflow, avatars, patternmaking, and rendering. However, the quality is different and incompatible with other software (Baukh, 2022).

It permits digital sketching, patternmaking, fabric simulation, colours and print variations, virtual fitting/sizing, 3D rendering, virtual showroom, technical specifications, and integration with manufacturers and producers. It allows digital garments, campaigns, cost savings, improved education/ training, and collaboration that increases sustainability in these sectors (Fashion United, 2023). Moreover, 3D clothing design enables customization for non-standard sizes (Lee, 2014). Their systems and tools aim to supplement existing methods rather than completely replace them (Wagner & Kabalska, 2023).

The information was collected through scientific papers that reported using different 3D fashion design software development in the textile and fashion market. This type of software focuses on giving a realistic fit through drape, fabric, and texture that adapts to the user's body shape characteristics. Their results are presented here:

a. Clo3D

CLO Virtual Fashion Inc. owns two popular 3D fashion software programs in the textile industry – Clo3D and Marvelous Designer. These software programs create virtual clothing designs and simulations, develop patterns and grading, and include assets such as garments, avatars, and animation. The software is cross-platform compatible with Adobe Illustrator, Substance, Blender, and VMOD 3D Library (Clo3D, 2023). The client base includes luxury brands such as VF Corp, PVH, Farfetch, Gucci and Dior (McDowell, 2020), and freelance designers with 270 clients globally, including Hugo Boss, Inditex, and Adidas (BoF, 2020).

Academic studies have shown that this software is precise in pressure maps (Wang & Cho, 2021), can precisely duplicate fabric, pattern, colour, and patterns of real physical garments (Xu et al., 2021), and has a positive effect on virtual clothing and human body dressing (Huang & Huang, 2022). However, fabric analysis shows that draping behaviour needs to be precise enough (Ashmawi et al., 2021) in knitted fabrics for women's sportswear (El-Newashy

& El-Sayed, 2022). Despite this, academic papers show that this software improves creativity in student teaching, saving resources and time (Hu, 2022). The benefits of virtual patternmaking are compared to traditional patternmaking, with improved creativity, productivity, prototyping, design accuracy, product development process, and modelling (Habib et al., 2023).

Figure 3.6 displays Clo3D software.

Figure III.6. Representation of Clo3D software (Interline, 2022).

b. Marvelous Designer

Marvelous Designer is a versatile software for creating realistic 3D clothing assets. It is widely used in various industries such as virtual effects, film, video games, fashion (Makryniotis, 2015), VFX, Design, and Architecture (CLO Virtual Fashion, 2023). CLO Virtual Fashion Inc. developed it and can be integrated with other software like 3D Max, Maya, and ZBrush (Levy, 2022).

Figure 3.7 presents a 2D window and a 3D window from Marvelous Designer.

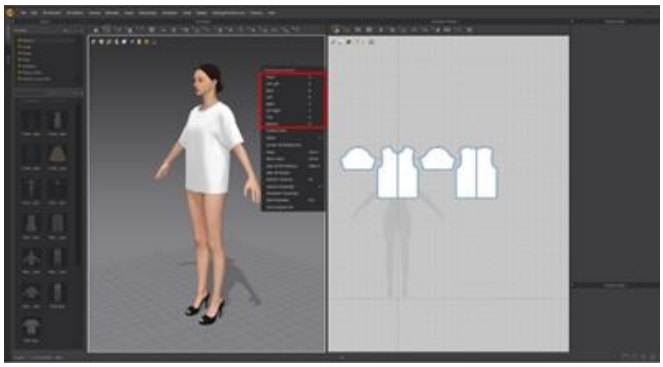

Figure III.7. 3D Garment View Controls of Marvelous Designer (Marvelousdesigner, 2023).

c. Style3D

Style 3D is a Chinese company owned by Linctex that offers a fully integrated system consisting of three key parts: 3D Design Studio, Fabric Design Studio, and Style 3D Cloud (Wong et al., 2022). In 2023, Style 3D acquired the Assyst software, which provides a digital fashion infrastructure, a library of assets, a marketplace, and a cloud. The platform can also scan materials and generate photorealistic digital swatches that can be used like digitally designed fabrics (Première Vision, 2023).

One example of a workflow of Style3D software is presented in Figure 3.8.

Figure III.8. Style3D workflow (Premierevision, 2023).

d. Unreal Engine

Unreal Engine's cloth simulation is GPU-based and offers multiplatform support for both AR and VR. However, it is only available for desktop applications and does not provide cross-platform support (Sarakatsanos et al., 2021). Figure 3.9 illustrates a model using Unreal Engine software.

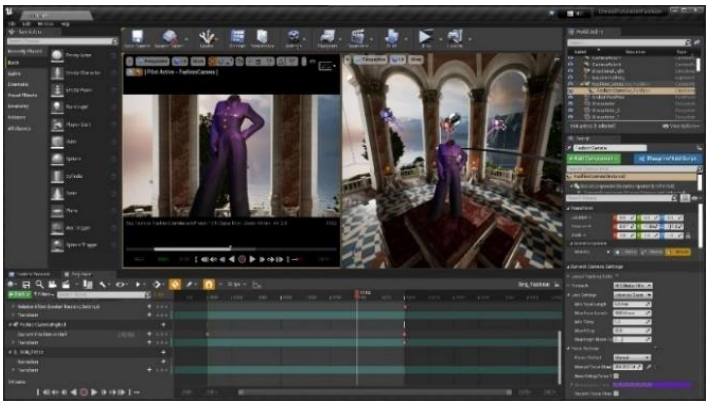

Figure III.9. Unreal Engine simulation of 3D catwalk (Unrealengine, 2023).

3.2.3. CGI Platform

Three-dimensional modelling uses avatars to provide realistic representations in various industries, such as fashion, gaming, film, VR or AR. People need to believe that characters are real, and engaging with them in virtual environments allows them to personalise and customise to increase consumer experience. 3D body-scanning systems can generate digital avatars to create various sizes within virtual environments (Papahristou & Bilalis, 2017).

3D clothing design enables customisation for non-standard sizes (Lee, 2014). Another significant example of support is using digital avatars, which improves training simulation for students, saves resources and enhances trainee practice. Through social media and e-commerce, avatars improve social interaction engagement and communication and create great marketing content and advertisements to captivate young audiences. The purpose of creating digital clothing for fashion companies is to make more revenue, like producing digital twins or NFTs for games. With the digital revolution in the supply chain, the fashion/textile industry must create a holistic ecosystem around sustainable strategies, building production and turning to digital garments in different stages of the product life cycle. The key to a successful digital product development strategy is to build assets that can be leveraged in the market, often building a digital pipeline. In this 3D journey, a piece essential in the supply chain puzzle is to develop virtual bodies that permit the development of properly fit standards for virtual garments with multi-faceted tools in 3D modelling, enhancing realism and personalisation in digital creations and improving functionality and user engagement in various applications across different sectors.

Below are some of the custom virtual avatars available to use in a wide range of 3D software, which can be exported to 3D fashion design software, such as Daz 3D, Mixamo, Alvanon and Union Avatars:

a. Alvanon

A company specialising in fashion technology provides advanced sizing and fit tools for creating accurate apparel products. The company has three distinct businesses: Physician Alvaform (Physical avatars), Virtual Alvaform (3D avatars), and Alvanon Body Platform (a database of virtual bodies) (Alvanon, 2023). Founded in 2001, offers precision to brands worldwide, with a database containing over 6,000 virtual bodies based on body scans of Alvanon's client fit models (Forrest, 2022) – Figure 3.10. The clients can reduce fit errors and speed up the process with ready 3D samples from the Alvanon Body Platform (Inside Textiles Ltd, 2020). At 3D software partners such as Browzwear, Clo3D, Lectra, Optitex, Gerber, Shima Seikei and DC Suite which are compatible with their systems (Gill, 2015b). Their clients list included Patagonia, Under Armour, Walmart, and Karl Lagerfeld (Alvanon, 2023) (Holmes, 2019).

Figure III.10. Custom virtual avatar using Alvanon platform (Alvanon, 2023).

b. Union Avatars

Linking Realities S.L. is a company that specialises in creating hyper-realistic avatars for fashion clients such as Mango and Teresa Helbig. Their software is compatible with Unity and Unreal Engine (Linking Realities S.L., 2023). Punto Fa, S.L., a fashion company, has invested in Linking Realities S.L. and uses its avatars in its fashion collections (Pavarini, 2023). Presentation of a collection is show in Figure 3.11 using Union Avatars platform.

Figure III.11. Union Avatars platform (Unionavatars, 2023).

c. Daz3D

Multiplatform integrated 3D software character/3D model creation system (Daz 3D, 2023) with 3D avatars with different types of bodies, like trans, plus-size, and many others (Heuritech SAS, 2023). It is compatible with other 3D modelling software's, such as Maya, Blender, Unity, Unreal and Cinema 4D (Heuritech SAS, 2023). This 3D modelling software, Daz Studio, can export animated OBJ files for use with 3D fashion design software such as Marvelous Designer (Makryniotis, 2015). The next update of Daz3D is Genesis 9 presented in Figure 3.12.

Figure III.12. Genesis 9 of Daz3D (Daz3D, 2023).

d. Mixamo

Mixamo is a web-based tool from Adobe product incorporated SaS service for 3D character animation (Adobe, 2023b) that lets users create 3D character animations without prior experience (Ardiyan, 2023). It automatically applies a human skeleton and offers a vast library of animations with different types of bodies. The generated models are compatible with various game engines and 3D software such as Blender, Unreal Engine, and Unity (Meier et al., 2021) Also, avatars can be exported to 3D fashion software choosing 3rd party avatar (Glascoe et al., 2022) such as Clo3D, Browzwear or Style3D. Freelance designers or 3D designers use this software (Adobe, 2023). Some academic studies used Mixamo to studie virtual try-on technology, one example is Figure 3.13.

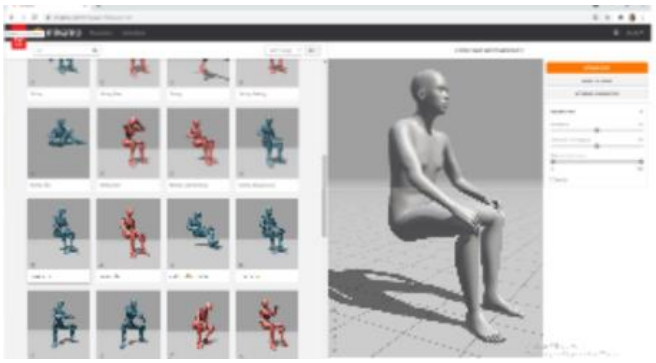

Figure III.13. Mixamo platform (Meier et al., 2021).

3.3. Advantages / Efficiency of using 3D programs in fashion

3D software specific to the fashion industry has many advantages that are revolutionising several aspects in different departments, such as design, production, marketing, and sales (Fashion United, 2023). The fashion industry counts on diverse software, such as Clo 3D, Marvelous Designer, Browzear, Tuka 3D, and Roman CAD. They are similar in creating digital products, workflow, avatars, patternmaking, and rendering. However, the quality is different from each other, and it is not compatible with other software (Baukh, 2022). It permits digital sketching, patternmaking, fabric simulation, colours and print variations, virtual fitting/sizing, 3D rendering, virtual showroom, technical specifications, and integration with manufacturers and producers. It allows digital garments, campaigns, cost savings, improving education/ training, providing collaboration, and increasing sustainability in these sectors (Fashion United, 2023). Learning any 3D fashion design software for beginners may take a few weeks to several months, depending on the learning motivation and practice of the tools. Learning the user interface, creating basic garment designs, simulating fabric behaviour, and working with patterns and textures are important. It does not require knowledge of patternmaking, but it is a plus because this software is intuitive for any user. For complex projects, this software relates to other platforms to create more realistic images; for example, Clo 3D can use Daz3D to export avatars that can dance and move in as many positions as possible. Table 7 shows the advantages and disadvantages of 3D software in fashion and textiles:

Table 7. Advantages and Disadvantages of 3D fashion software

Advantages	Disadvantages
Promote sustainability by reducing materials waste and environmental impact by minimising the carbon footprint on the planet (water, energy, among others)	Difficulties in representing the fabric's physical properties and missing the feeling of a physical fabric/accessories
Digital prototyping of clothing, including garments, accessories, and footwear	New infrastructure and processes required to support 3D workflows
Improve product quality by avoiding errors in production	Loss of touch and feel
Efficiency to speed up the design process and promote iteration between the teams	Investing time to learn how to use this software
Saving money, time, and resources in production, for example, reducing travels of physical samples	Costs for acquiring the 3D fashion design software
Precision in patternmaking and grading that includes adjusting patterns for different sizes and fits	Have computers that have hardware requirements that can run good graphics
Promote collaboration between fashion designers, patternmakers, manufacturers, and 3D designers	People with training in this software with training in fashion

Combining technology with the fashion industry	It takes time to train people
Creates a more competitive portfolio for fashion designers and can create virtual shows online	Colour depends on monitor adjustments of monitors
Pre-sale of the product without being produced	
Increase creativity by doing unless designs	
More realism in virtual garments, like fabric's thickness and stretch to the texture, as how the fabric folds and falls on a real human body draping	

Note. Table made by own author

3.4. Creation of fashion collections using 3D software

3.4.1. Digital fashion in the development of fashion collections

Digital product creation (DPC) involves the process of digitizing materials, 3D pattern simulation, and 3D assets for customer-facing experiences in eCommerce and other domains. DPC applications include digital textile and fashion design, pattern generation, fitting evaluation, style editing, and virtual try-on. Each application contributes to the increased assessment of design concepts and closer collaboration with the supply chain without needing physical samples. However, integrating 3D product creation with enterprise technology that includes supporting data for manufacturing and sales is still a work in progress. Digital twins, virtual fashion shows, and virtual retail spaces represent exciting new business models for virtual fashion products (Conlon & Gallery, 2023).

DPC is a process that designs and develops products in 3D by integrating 2D CAD patterns with digital materials into 3D simulation software (e.g. Clo3D). DPC combines 3D modelling (3D CAD) with a Digital material library (DML) to create a digital prototype for adjusting garments' fitting and draping (The Interline, 2022). DPC ecosystems have CAD systems, scanners for bodies/ materials/ trims/ packaging, digital material platforms, computer-generated images, rendering capabilities, virtual try-on engineering, and digital colour management. They improve product aesthetics and provide virtual try-ons for customers (The Interline, 2022). Representation of Digital product creation using 3D software is presented in Figure 3.14.

Figure III.14. Representation of 3D Digital product creation (Issuu, 2020).

During the design phase, it's crucial to have precise control and guarantee of virtual simulations (Cugini et al., 2007). The design of virtual garments is made of 3D avatars, virtual fabrics, and trims, among others. Testing various colours, textures, prints, and shapes is possible without producing a sample (Garza, 2023). 3D fashion design technology transforms the apparel, fashion, and luxury (AF&L) industry, facilitating the design process and reducing time, cost, and environmental impact. 3D and AR experiences increase the brand connection between fashion brands and consumers. Several renowned companies, such as Adidas, Hugo Boss, and Louis Vuitton, have integrated 3D solutions into their design processes (Adobe, 2023).

For at least 50 years, CAD software has been developing for the fashion industry to execute garment design while reconciling traditional methods more efficiently with modern technology in an automated way (Y. A. Lee, 2014b). The fashion industry requires advanced engineering skills to create realistic virtual garment simulations, including fabric modelling, virtual clothing simulation, and 3D visualisation. To achieve digital fashion, 3D clothing CAD systems are crucial by generating virtual garments in 3D space based on 2D design patterns while considering the deformable behaviour of textile materials (Geršak, 2022). The concept of 3D is crucial in the fashion design process as it plays a significant role in developing fashion products (Papahristou & Bilalis, 2017). Some of the most popular 3D CAD software used in fashion and game design are Browzwear V-Stitcher, Optitex PDS, and Lectra Modaris 3D. Additionally, there are 3D virtual simulation systems such as CLO3D, Marvelous Designer, and DC Suite. These tools can be used to customise fashion designs in styles, colours, and patterns (Choi, 2022) (Sarakatsanos et al., 2021).

Various 3D tools can be used in the fashion industry in digital product development. For instance, the book "3D Fashion Design" (Makryniotis, 2015) illustrates different 3D fashion design techniques such as making an avatar using Daz3D, manipulating image patterns and retouching final image using Adobe Photoshop, converting file format using

Clo3D, creating digital garments using Marvelous Designer, V-Stitcher or Optitex and rendering using Maya or Blender. Finally, Rhino creates jewellery, and accessories are generated using Octane. An interesting example of an interactive VR application for fashion designers is presented in a current study by (Sarakatsanos et al., 2021) using Browzwear to create garments, Unity Engine to assemble VR scenes and transform digital assets into VR, and Mixamo to provide avatar animation. All this is necessary to export the designs in various formats to be compatible. This application allows fashion designers to improve their 3D visualisation skills and create immersive VR experiences.

Traditional and digital elements complement each other. An online and offline launch express the design's full meaning (R. Dai, 2023). Fashion companies now offer capsule, short, medium, or long collections, and the development team must manage different cycles. Reducing the average number of sample iterations from five to two can result in significant savings by eliminating back-and-forth shipping charges and delays caused by other time zones and languages (Papahristou, 2016).

Designers and companies are adopting new strategies to reduce negative social and environmental impacts as the fashion industry moves towards sustainability. Fashion collections can be used as a design tool to reduce pollution in the fashion system (Ræbild & Bang, 2018). Despite the vast research on the fashion design process and creativity, little attention has been paid to the role of collections in fashion design practice and consumption, as well as their strategic potential (Ræbild & Bang, 2017). Figure 3.15 shows an illustration adapted to show case the development of digital fashion creation.

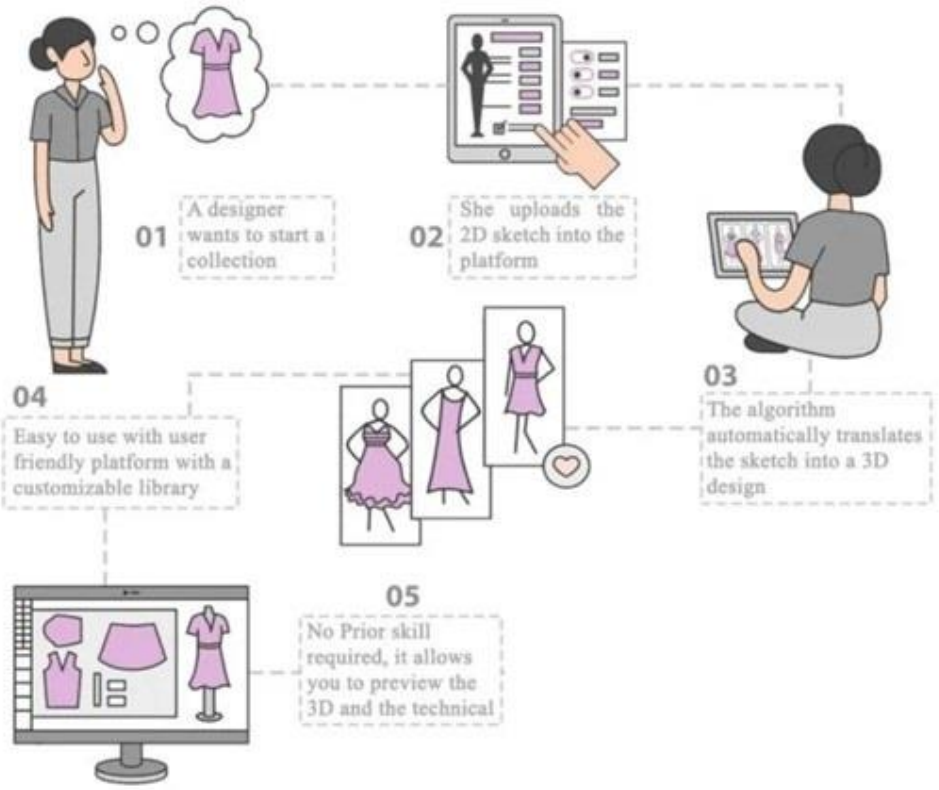

Figure III.15. Development of digital fashion creation (Medium, 2020).

The profession of fashion designing began with C.F. Worth 150 years ago (Särmäkari, 2023). Fashion designers create clothes that interpret zeitgeist, expressing the spirit of the times by interpreting trends through physical work, such as examining drawings and patterns, handling materials, and collaborating with their teams. Clothes are important for expressing identities and communicating in social environments (Särmäkari & Vänskä, 2022). Designers use data and implicit knowledge to create clothing for situations influenced by embodied experiences and emotions (Särmäkari & Vänskä, 2022).

The fashion industry embraces new technologies like 3D CAD software, digital co-creation platforms, code, and rapid manufacturing. This is driven by ethical awareness, e-commerce, and real-time communication among globally dispersed networks. Adopting these technologies has led to the modernisation of the profession and a shift away from designer-centered ideals, including exploring the possibilities of AI (Särmäkari & Vänskä, 2022). A new wave of designers has joined the path of 3D fashion without forgetting the legacy of fashion craftsmanship. To work with fashion professionals is necessary to know traditional methods but, more importantly, to learn new skills in technology to stand out in the job market, increasing chances of success, like expanding knowledge increases creativity, productivity and innovation, as well adaptability to the changing industry, grow efficiency in workflow, generating collaboration between

teams and surge more skills that can adapt to a competitive market globally, this takes to upgrading diverse career paths, continuous learning and creating a personal brand (Learn 3D-Fashion, 2023).

Technology provides better solutions for fashion companies that give more efficiency and captivate other audiences and consumers to buy their products. 3D design improves the value chain for the fashion industry because it boosts designers' creativity and optimises production, retailers, and distribution (Tessone, 2022).

Producing a virtual fashion show is a complex process involving several steps. The first step is creating an avatar. Afterwards, add the avatar movement through motion capture technologies that imitate the real world in the virtual stage that can be seen from several viewpoints (Cugini et al., 2007).

The fashion industry has gone digital due to the pandemic, with luxury brands leading. Burberry has incorporated smart clothes and hologram shows to represent the digital nature of fashion shows. The promotion of collections now happens entirely in digital environments, and some fashion shows are even presented in 3D with 360 VR glasses. One designer used clo3D to create digital clothing, reducing waste by eliminating the need for pollution reduction, fabric cutting, and sample production. However, only a few garments were produced (Kaya et al., 2022). Digital transformation has significantly impacted the design process due to the rapid evolution of technology. The fashion industry has also quickly implemented the latest tools and techniques to enhance design and development. It facilitates the traditional development process, saving time, money, and resources and promoting sustainability in the long run. Moreover, it facilitates collaboration among all stakeholders involved in the process. 3D digital design systems and tools aim to supplement existing methods rather than completely replace them (Wagner & Kabalska, 2023).

Previous studies on digital fashion collections since the 2000s analysed fashion shows created with digital images (S. R. Lee & Kim, 2011; Wu et al., 2013) identified three types of fashion shows between 2006 and 2013. The first type involves real fashion shows combined with a mix of digital technology, such as film and video, used by Alexander McQueen, Burberry, John Galliano, and Diesel. The second type is the digital fashion show, incorporating only digital images utilised by Victor & Rolf, Gareth Pugh, Ralph Lauren, Stefan Eckert, and Jehee Sheen. The third type is the 3D digital fashion show, articulated 3D technology used by Ecole de Paris, Fnc Kolon, Young-A Ko, and Harriette Kim. One example that can be point out: in 2012, Final Fantasy characters were used to showcase the Prada SS/12 collection in a fashion presentation using 3D simulations (Siersema, 2015).

In 2018, Carlings, a retail brand, presented the first digital collection to be sold online, the "Neo-Ex" collection; each piece was priced between €10 and €30 (Rodriguez Sanchez & Garcia-Badell, 2023) (Stanley, 2018), presented in Figure 3.16.

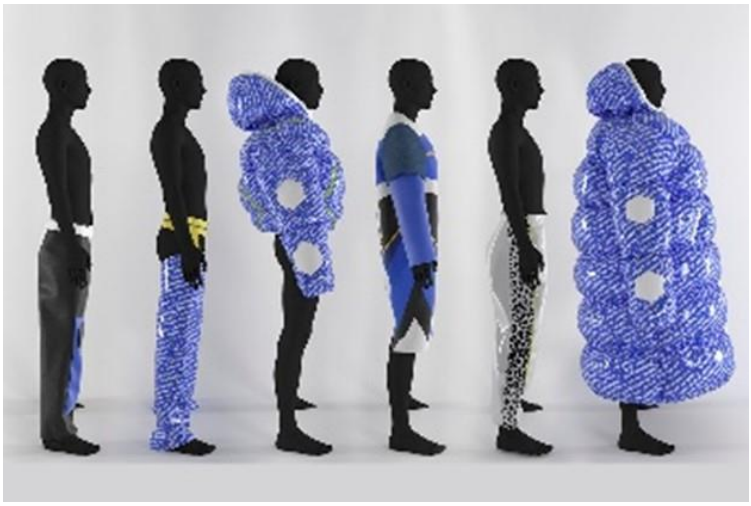

Figure III.16. Neo-Ex collection by Carlings (Hypebeast, 2018).

Nike has been at the forefront of bringing 3D technology into its e-commerce business. It all started in 2013 when they started experimenting with 3D Printing to manufacture shoes. Then, in 2019, they used AR technology to allow customers to try on shoes virtually through their app. Nike has partnered with Z-emotion, a 3D technology provider, to offer its customers an interactive 3D shopping experience (Digital Fashion Academy, 2023). Based on statistics from a previous event held by Z-emotion in 2019, customers are 44% more likely to add a product to their cart when they see a 3D asset than a flat product image. This number increases to a 65% conversion rate when a consumer can view and interact with a product in AR (The Interline, 2021).

Another example: In 2020, the brand Hanifa launched a collection called Pink Label Congo, which was showcased live-streamed as a virtual fashion show on Instagram Live (Segran, 2020) using realistic 3D animation and CAD software using 3D technology, moving against a black background without being worn by a model (Nasr, 2023) (H.-M. Chen & Che, 2023), see in Figure 3.17.

Figure III.17. Hanifa's collection Pink Label Congo (Segran, 2020).

3.4.2. Relevance of digital fashion in the fashion design landscape

Digital fashion was valued at $40 billion in 2022 (Forrest, 2022). It has transformed the fashion industry by changing how businesses communicate, design, produce, and retail their products. Fashion companies must adopt a complete end-to-end digital product development, and greater digital skills are required from stakeholders, including digitising materials and using 3D assets in eCommerce and other customer-facing experiences involved in DPC ecosystem. 3D virtual product prototype development allows for more design concept evaluations and closer collaboration with the supply chain. However, integrating 3D product creation in broader enterprise technology ecosystems is still in progress (Conlon & Gallery, 2023). Digital fashion design is a market for creating and developing virtual clothing used in digital environments that can also be used in games through skins and NFT trading. Furthermore, digital twins, virtual fashion shows, and virtual retail spaces like Metaverse. This recent market constantly expands, creating opportunities for new specialists: digital designers, token investors, system developers, programmers, and cybersecurity (Audaces, 2023). These increase revenue from accelerating online channels and improving the value chain, bringing transparency and inclusivity (Heuritech SAS, 2023).

"Digital fashion is not going to replace physical clothing, but it is definitely going to become an integral part of us. Digital fashion is an important opportunity to redefine business models and build a more sustainable."

Modnova, founder of DRESSX (as cited in R. Dai, 2023, pag. 83)

In the conventional fashion process, fashion brands would have designers and stitchers create prototypes in-house. However, in the high-fashion and luxury sector, using digital prints and expensive fabrics makes it challenging to produce physical prototypes. Some brands, such as Roberto Cavalli, still employ hand-made crafting techniques to design paper dolls for fabric positioning (Papahristou, 2016).

The fashion industry has integrated 3D processes for creating and combining designs. Technological advancements have made representing garments more realistic and merging them into the fashion industry easier. New methods of communication have emerged, enabling the fast and real-time dissemination of products digitally. Virtual products offer benefits to the industry, including enhanced creativity, sustainability, integration with AI, and rapid prototyping. Digital tools are transforming design practices, making it crucial to understand digital languages for future fashion preparation (L. R. Santos et al., 2020). Digital software is a powerful tool for creating visions of their inspirations and expressions (Ryder, 2023). So, for the development of the 3D fashion design process it is necessary to make patterns and 3D images through Clo3d, Marvelous Designer or Browzwear (Learn 3D-Fashion, 2023), for increased textures included in Adobe Substance Suite (Thomas, 2021) and 3D rendering for complex models incorporate in Blender, Make Human, Maya, Daz studio, Unreal Engine and ZBrush. As well as, made animations and digital motion for digital creations for skins or NFT (Dahle, 2022) Moreover, they are used to present collections. A representation of 3D jacket is presented in Figure 3.18.

Figure III.18. Floating 3D Mesh Jacket (Interline, 2022).

3D apparel design on a human model allows for simulating effects, avoiding repetitive fitting and manual changes. Designers and pattern makers can work together, visualise sizes, and switch between 2D and 3D formats, which gives a significant advantage (Papahristou, 2016). To dominate the art of digital garment creation is necessary to know how to manipulate the shape and appearance of each piece of a garment, including textures, fabrics, and colours, to create a 3D model that can look in 360 degrees angles and details. Digital fashion companies Atacac and

The Fabricant used 3D design tools such as Clo3D, Adobe Photoshop, Blender, Cinema 4D, Houdini and After Effects to create digital clothing (Särmäkari, 2023).

In 3D product development, different types of technologies exist inside this sector: 3D design software, 3D body scan, VR & AR (virtual and augmented reality), PLM software (product lifecycle management), digital textile printing and laser cutting. The 3D design software allows the creation of digital prototypes and visualisation of products to reduce physical prototypes and speed up the product development processes (Zvekic, 2023). Four departments - design, sales, buyer, and factory - are involved in multiple steps to create a garment using traditional methods. This results in a complex network that takes time and can cause communication difficulties between stakeholders, making it costly. In the case of design development, it can involve six or more iterations. Papahristou's diagram illustrates the processes of each department to reach the production phase, presented in Figure 3.19:

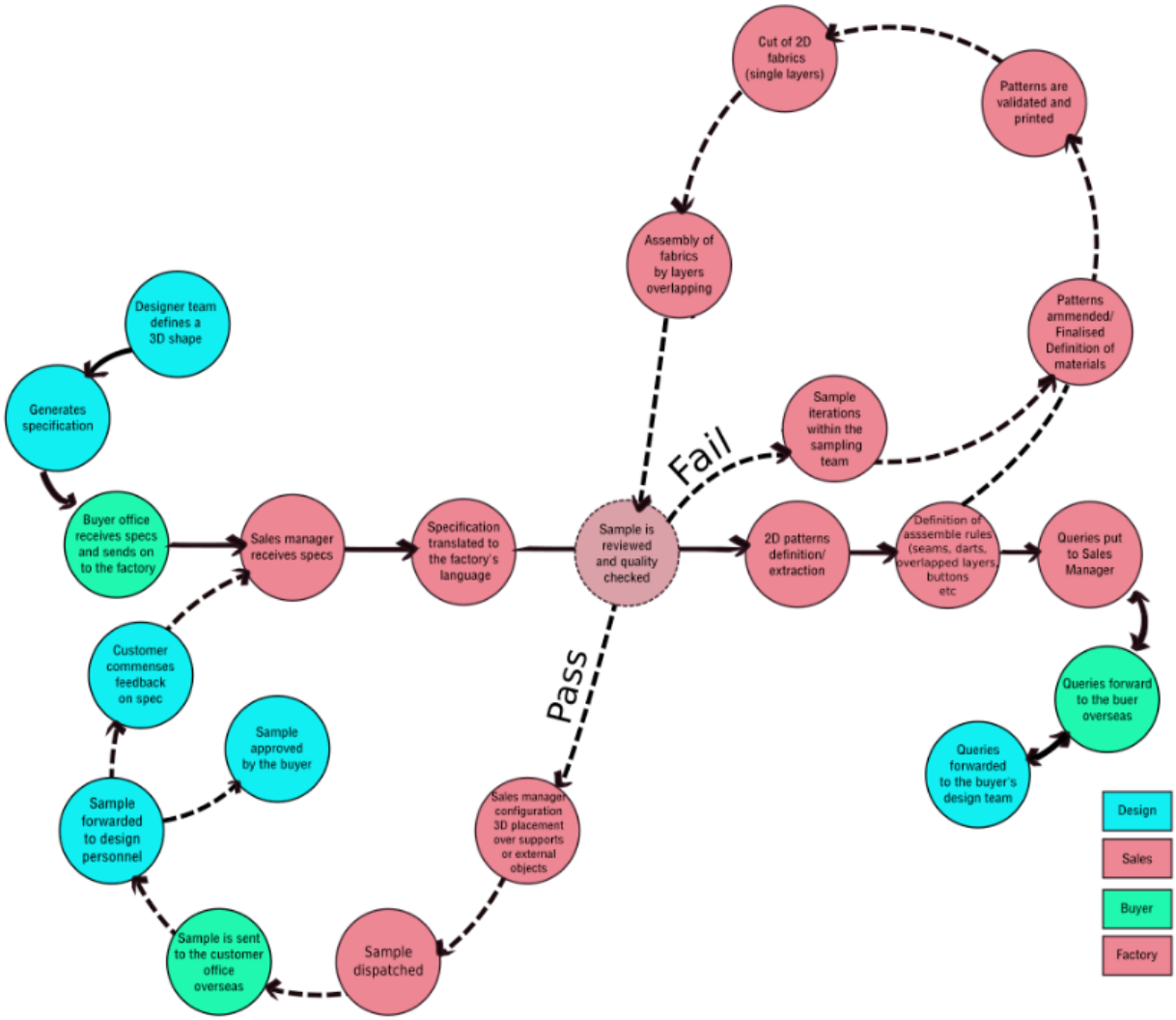

Figure III.19. Traditional roadmap pf garment sample development process (Papahristou, E., 2016).

In 2005, Violino supported improving the fashion design process to offer new ways to improve design techniques in the apparel industry by directly using 3D tools to develop virtual clothing (Volino et al., 2005). It requires two types of skills for 3D fashion designers to develop throughout their careers: Design and Technical skills. Specifically, in Design Skills, it is necessary to know the fundamentals (garment construction, fabric selection, colour theory, and trend analysis), know 3D modelling software (used for creating virtual clothing prototypes), as well texture creation (creating custom textures or sourcing existing ones from libraries to match the desired look) and familiarity in CAD software (that can be import patterns into to 3D modelling software). To emphasise, knowing to work with 3D tools is not a synonym for knowing 3D fashion design because the Design discipline is a skill that is developed apart, and this is why brands are looking for fashion designers to the 3D world because they have skills differentiated for 3D designers. Generally, 3D designers work with 3D software design to create solid objects, like AutoCAD. However, to create digital garments, it is necessary to work with other types of 3D software to create flexible objects to represent fabric draping. Finally, technical skills like 3D modelling software, pattern making, tech packs, and rendering/visualisation techniques are needed (Learn 3D-Fashion, 2023).

Nowadays, in the digital fashion market, fashion designers must learn to use 3D software (before it was only used by 3D designers) because these skills stand out from the job offers' needs and are the pillars of becoming the key technologies within the supply chain. Fashion designers can use 3D technology to create initial designs in a 3D space, experiment with fabrics and colours, and communicate ideas with the team in a true-to-life 3D environment within hours instead of weeks (Papahristou, 2016). To highlight, when we reduce the time of making physical samples, designers can dedicate and focus more time on betting better in creating a virtual piece that gives more efficiency, speeds the process, and saves money. In the future, the fashion design market will be a hybrid between the physical and digital worlds, transforming the design process (Garza, 2023). There are various career choices for a 3D fashion market: fashion brands, fashion tech startups, studios, textile/apparel manufacturers, fashion consultancies, gaming companies, VR/AR companies and e-commerce platforms (Learn 3D-Fashion, 2023).

3.4.3. Importance of Co-design and partnerships

Fashion brands must change their mindset, shift organizational processes/strategies, and invest in digital transformation to revolutionise the textile industry by optimising value chains. They are aligned with consumer behaviour, turning to digital platforms to express themselves and engage with each other. Allows brands to invest in this niche, creating custom products, giving personalised experiences, and creating a strong relationship with customers. It also allows technological advantages to be ahead of competitors, making them more efficient, sustainable, and customer centric (Larocheski, 2023). Establishing performance metrics and continuous improvement mechanisms are essencial to using 3D technology in fashion. Defining key performance indicators (KPIs) empowers

success measurement in various aspects, such as design efficiency, consumer engagement, and sustainability (Hong et al., 2019). After all, establishing feedback loop mechanisms ensures an iterative process of improvement based on insights from designers, consumers, and all stakeholders (X. L. Liu et al., 2020) to improve the use of 3D technology in fashion product development.

Companies can benefit from creating a Digital Transformation Team (DTT) that comprises professionals from various departments, such as pattern makers, designers, technical developers, sourcing and production experts, IT specialists, engineers, and project managers trained in specialized 3D technology. It can give the team a competitive edge if they collaborate with people from a mature digital industry, as these industries have vast knowledge that can be utilised to improve the fashion sector (The Interline, 2022). To achieve success in DPC, companies must invest in their workers' learning, foster team collaboration, and leverage vendor expertise, along with the right balance of people, processes, and technology (The Interline, 2022).

Digital and physical product creation should merge to enhance the field for fashion companies to succeed in the new digital era. The fashion industry will require hybrid techniques to produce physical goods using digital methods. Bringing together expertise and opening new possibilities can reconcile digital and physical tools (The Interline, 2022).

In the textile and clothing industry, digital prototypes facilitate product development. Papahristou (2016), show that using 3D virtual prototype technology with the right tools can reduce development time by 20% to 50%. This technology allows for collaboration between individuals with different skills and competencies involved in the process's various stages, ensuring (Papahristou & Bilalis, 2017).

Also, as previous before, brands can collaborate with digital fashion agencies, CGI experts and digital fashion offices such as Gucci, Louis Vuitton, and Sunnei, to digitize business operations and potentialise their business (Casciani et al., 2022).

Finally, with the investment on digital fashion education in universities, future students can be more prepare for the job market (Tepe & Koohnavard, 2023) . One example that can be highlighted: in 2022, five of eight top fashion universities included 3D fashion software in their program. Parson, IFM (The Institut Français de la Mode), and Ravensbourne University London are teaching Clo3D in their program. IFA teaches 3D tools like the DC Suite, and the London College of Fashion teaches 3D software for gaming, like Unity and Unreal (Bain, 2022). Central Saint Martins, Istituto Marangoni, Esmod, The Swedish School of Textiles, Royal College of Art, Polimoda, and VIA University College have available digital courses and 3D tools software (Dahle, 2022) (Ryder, 2023). Currently, 119 universities globally use Clo3D, such as Politecnico Milano and Arts University Bournemouth (Clo3D, 2023). Also, 138 universities/schools use Browzwear software (Browzwear Group, 2023).

CHAPTER - IV

Case Studies

4.1. Data screening / Process selection

The initial phase of the dissertation involved comprehensive bibliographical research focusing on identifying fashion companies and fashion brands that utilise 3D technologies in product development and integration into their collections. This exploration, however, needed more academic resources. Consequently, the research extended to major fashion brands, revealing a notable need for more information. The brands' reluctance to disclose commercially sensitive data that could compromise their competitive advantage is a reason for the lack of information.

Given these limitations, this research methodology pivoted towards leveraging online resources. A rigorous selection process was employed to identify the most credible and relevant online sources, predominantly websites and fashion-specific digital platforms. While providing brief information, these sources were combined to understand the subject comprehensively, leading to exhaustive research that transited for several months and culminated in a rich data repository for this dissertation.

From the gathered information, thirty fashion businesses were initially identified such as Alexandra Moura, Adidas, APG & CO, Becri Group, Burberry, Besteseller, Crystal, Decathlon, DvF, Impetus, Freemans PLC, H&M, Hugo Boss, Kookaï, Levi's, Marc Cain, Marks & Spender, Mango, Puma, Prada Group, Petratex, Renner, Roberto Cavalli, Sandqvist, Steven Passaro, VF Corporation, Tommy Hilfiger, Under Armour, Valerius, and Zara. These 30 options were assembled into groups: fashion companies, fast-fashion brands, fashion designer brands, and manufacturers that use 3D technology.

In order to select the final three fashion brands, namely Hugo Boss, Tommy Hilfiger and Renner, the information was analysed and organized into groups. This was done to improve information organization. The groups were classified as fashion brand companies, fast-fashion brands, fashion designer brands and manufacturers that use 3D technologies to develop digital products and present them in online collections. Table AB shows the final three fashion companies. The companies not selected, namely Decathlon, Adidas, VF Corporation, Under Armour, Puma, Kookai, APG & CO, Levi Strauss & CO, Freemans PLC, Bestseller, Marks & Spencer and Sandqvist are listed in Table AC. H&M, Mango, and Zara are the fast fashion brands on Table AD. The fashion designer brands are Steven Passaro, Alexandra Moura,

DvF, Prada Group, Roberto Cavalli, Burberry, and Marc Cain, listed in Table AE. Lastly, Table AF shows the suppliers that use this technology: Valerius, Impetus, Petratex, Crystal and Impetus Group.

Table AA is in Appendix, which summarizes the final selection criteria used for the thirty brands in the research. These criteria include being a 3D technology pioneer, having more than 50% of a digital collection, investing in 3D technology, and having 3D virtual clothing software or collaboration with agencies.

The criteria for selecting brands were based on the available information regarding their digital fashion collections. The first criterion was that the company should have produced more than 50% of their collections digitally. The second criterion was focused on businesses that were pioneers in investing significantly in digital technologies and were transparent in sharing relevant information with the public. Companies that provided vague or unverifiable data on their use of these technologies were excluded. The final criterion evaluated the reasons and investments made by these brands in continually adopting and improving 3D technology, especially in enhancing digitalisation across their value chains. The emphasis was on improving design, marketing, and customer experience, with the goal of reducing their environmental footprint. Table AA includes additional data showing which brands use digital agencies to develop their digital products instead of investing in a 3D department.

The three selected companies have in common the use of 3D technology to enhance design and improve production, leading to cost and time efficiency, rapid prototyping, customisation, and investment in sustainability. These brands also focus on sustainability, using 3D technology to minimise waste. The keyways to make virtual prototyping (reduce sampling rounds) are to have their digital showrooms or virtual runways to showcase their product collections, implement personalisation and customisation into their products according to their customers' choices and implement sustainable production practices using digitalization.

4.2. Final Cases: Hugo Boss, Tommy Hilfiger, and Renner

A study was conducted on three fashion companies – Hugo Boss, Tommy Hilfiger, and Renner - to examine their brand histories and evolution. The research also investigated the 3D technologies these companies use and the tools they utilise to develop 3D products and integrate them into their collections. Although these three brands operate in different segments of the fashion industry, they all employ technology to increase their sales through online channels, attract younger audiences, and optimise their resources. They use 3D visualisation software to create digital assets without unnecessary physical prototypes, saving development time and reducing costs.

The case: Hugo Boss

a. History

Hugo Boss is a German fashion company with two brands - HUGO and Boss (Hugo Boss AG, 2023). The company was founded by Hugo Ferdinand Boss in 1924 in Metzingen. Initially, the factory produced uniforms for the German army and SS during the Second World War, which proved to be very profitable. However, in the 1960s, the company was on the verge of bankruptcy. In 1969, the brothers Jochen and Uwe Holy took over the company and transformed it into an international brand (Köster, 2011). In the 1970s, the brand experienced a surge in sales as men were attracted to its suit aesthetic. In 1977, the brand was rebranded as HUGO BOSS.

In the 1980s, the company diversified its portfolio, adding fragrance licensing, eyewear, footwear, watch licensing, golf wear, and leather goods. To expand its reach, HUGO BOSS began sponsoring motorsports and golf players. Between 1993 and 2006, the company launched two new brands - HUGO, with a progressive and innovative style, and BALDESSARINI, with a luxurious and sophisticated appeal. After this, the company added womenswear, BOSS Orange, BOSS GREEN, BOSS Selection, BOSS Selection Tailored Line, childrenswear, and home wear. Since 2008, the company has been selling its products online. In 2012, it launched its first runway show. Since 2013, HUGO BOSS has collaborated with German football to dress athletes in business and casual attire outside the pitch. After 2017, the company returned to its origin and consolidated all its brands into two - BOSS and HUGO.

Since 2021, HUGO BOSS has presented its strategy to become a leading premium tech-driven fashion platform worldwide.

2022, the company plans to attract new young clients globally; it opened a digital campus in Oporto and Meiningen (Hugo Boss AG, 2023). Hugo Boss is committed to developing new technologies for sustainable fashion in its brand. They strive to become a leading premium tech-driven fashion platform worldwide and implement personalisation and omnichannel customer experience to achieve this goal. To enhance efficiency in its value chain, the company utilises digital designs for prototyping, reviews, and changes for suppliers and retail partners. This approach eliminates the need to ship physical samples back and forth, thus saving time and money.

b. Digital Transformation

2012, the company began investing in 3D technology to develop products such as knitwear, skirts, and jerseys. Two years later, in 2015, they expanded their offerings to outerwear and sportswear (which accounts for 5% of their products). 2017, they added classic lines, including blazers. By 2018, 40% of Hugo Boss' product development used 3D technology. According to Russell (2022), creating a physical prototype took two to four weeks, while a digital alternative took a week to a few days.

Hugo Boss launched their first digital collection in 2020, shown in Figure 4.1, consisting of 105 pieces for the Pre-Fall 21 season, including clothing, footwear, and accessories for the BOSS Men's Casual Wear Collection. It was made available for purchase in stores in April. The high-quality renders enable the creation of a lookbook with avatars and digital garments and a digital showroom to view and combine products in a 65-inch touchscreen, enhancing brand image and sales communication.

Figure IV.1. First collection from Hugo Boss (Hugo Boss, 2020).

McDowell (2021) states that over 50% of collections will be produced digitally in collaboration with global fabric and trimming suppliers by 2021. By 2022, the author predicts that 80% of all collections will be digital, from initial sketches to finished products, including fabric and colour selection, prototyping and product development. The shift towards digitalisation will improve the Product Development Department by reducing sample costs and providing more options for combining fabrics and cuts. It will also increase the value chain's flexibility by shortening the go-to-market time and responding to new trends more efficiently. The new process will also be more sustainable and provide more opportunities to implement creative concepts (Hugo Boss Group, 2020). The company uses Clo3D to develop the collection, as shown in Figure 4.2.

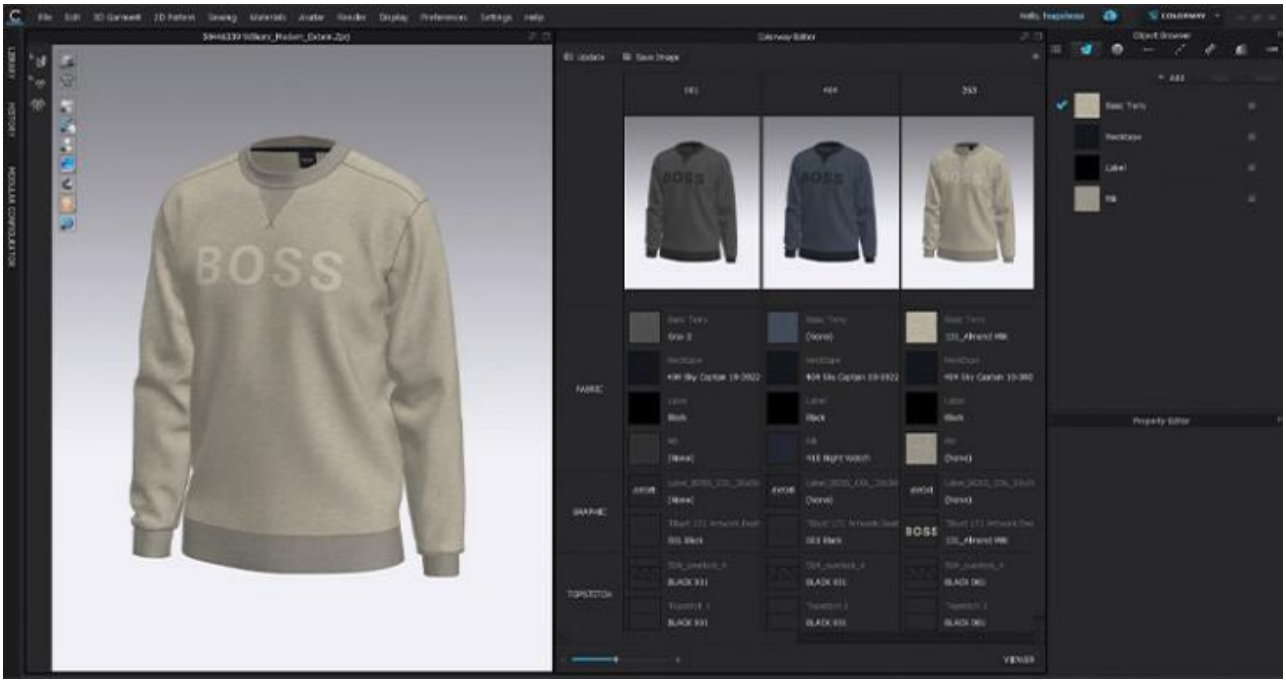

Figure IV.2. 3D model from Clo3D made by Hugo Boss (Hugo Boss, 2023c).

Since 2022, Hugo Boss has partnered with Adobe Substance to enhance their 3D designs and replicate complex fabric textures, embroidery, or knits. They use Adobe Substance 3D Sampler to create more realistic 3D images. They use Adobe Substance 3D Sampler and Adobe Substance 3D Stager to refine colours or lighting (Braun, 2022) show in Figure 4.3. The company has around 400 to 500 employees working across various departments, including design, patternmaking, material library management, and art. They use the Adobe Substance collection to promote innovation in all sectors and work in 3D throughout all value chain stages.

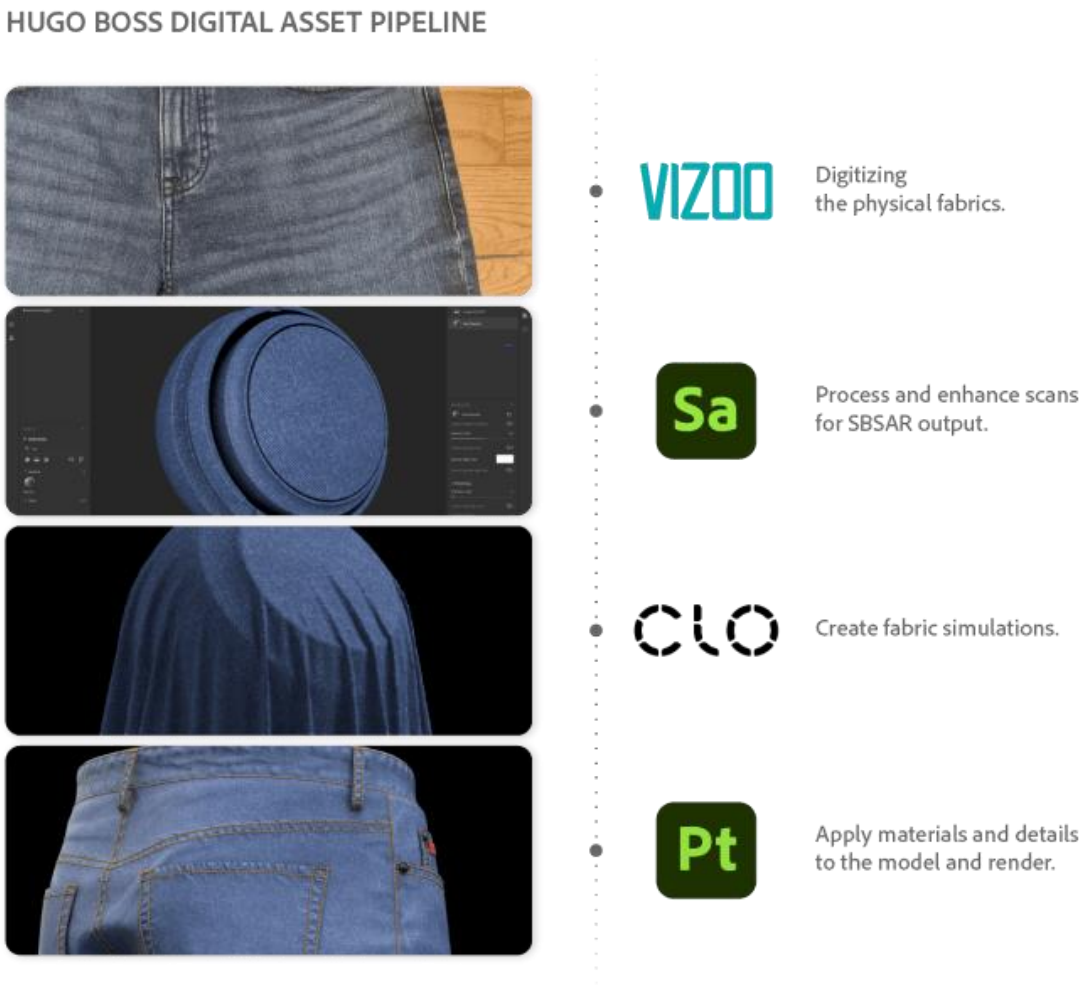

Figure IV.3. The Digital Transformation Journey (Adobe, 2023).

They have reported that using 3D models has reduced the timeline from six months to eight weeks, approximately 85% faster than the creation-to-shelf timeline. Additionally, it has reduced the physical samples per collection by over 30%. They have digitised about 64% of design workflows and aim to reach 90% the following year (Adobe, 2023). Figure 4.4 presents an example of digitalised design.

Figure IV.4. Photorealistic quality of 3D designs (Adobe, 2023).

Currently, the company has 250 employees working in e-commerce, Advanced Business Analytics, Technology, and Data Platforms. They are building a digital campus in Oporto, Portugal, Figure 4.5 - to drive digital sales, improve customer experience, and streamline work processes (Hugo Boss AG, 2023).

Figure IV.5. HUGO BOSS Digital Campus in Porto, Portugal (Hugo Boss, 2023).

Designers use various software programs to digitise physical samples and create 3D assets. One such program is Vizoo, which creates files in the SBSAR format. These files are then passed on to Substance 3D Sampler, which is used to create patterns with the help of Clo3D, Figure 4.6. Finally, Adobe Substance Paint is used to apply texture to the patterns. Designers can also create new materials with Substance Designer, which is useful when creating new materials that are unavailable in the existing library (Adobe, 2023).

Figure IV.6. Representation of 3D design workflow made by Hugo Boss team (Adobe, 2023).

Only a few academic studies are available on how Hugo Boss is using 3D technology, but three articles discuss why they are using it. For instance, (Lin & Ingaramo, 2023) mentioned that the company launched the "Mission 3D" project in 2017 to create 80% of its collections using only digital methods. Additionally, Nam & Kim (2021) discussed the availability of 3D virtual fitting rooms for a limited collection of men's suits on the Hugo Boss men's suits website. Another example is the study conducted by (Fähnle et al., 2013), which suggests that using 3D images in campaigns can increase brand awareness, as it portrays the brand as innovative and fashion-oriented. Therefore, incorporating the three-dimensional campaign logo can enhance the spread of the message. The company is investing in new ways to reach new consumers, such as break into the Metaverse, Figure 4.7. In 2023, they did that with their Spring/ Summer 2023 fashion show.

Figure IV.7. Hugo Boss S/S 2023 Fashion Show in Metaverse (Hugo Boss, 2023).

The case: Tommy Hilfiger

a. History

The brand is part of Phillips-Van Heusen Corporation Corp, which owns Calvin Klein, Warners, True & Co, and Olga. Tommy Hilfiger is a premium company founded in 1985 by American designer Thomas Jacob Hilfiger. The brand is globally recognised as a lifestyle brand of "Classic American Cool" that blends traditional and modern elements with a classic and preppy style. Its characteristics are vibrant colours (red, white, and blue, representing the American flag), clean lines, and a casual and sporty aesthetic. Hilfiger was a pioneer in collaborating his brand with celebrities like The Rolling Stones, David Bowie, Britney Spears, and Lenny Kravitz, among others. The inspiration behind his career is "F.A.M.E." (fashion, art, music, and entertainment). Tommy Hilfiger is a famous lifestyle brand with a wide range of products for women, men, and children, offering clothing, accessories, jewellery, footwear, fragrances, and home furnishings. The company has over 1,800 retail stores and online shops across 100 countries on five continents. They focus on sustainability by using eco-friendly materials and production methods, including 3D software – Figure 4.8, to reduce their environmental impact.

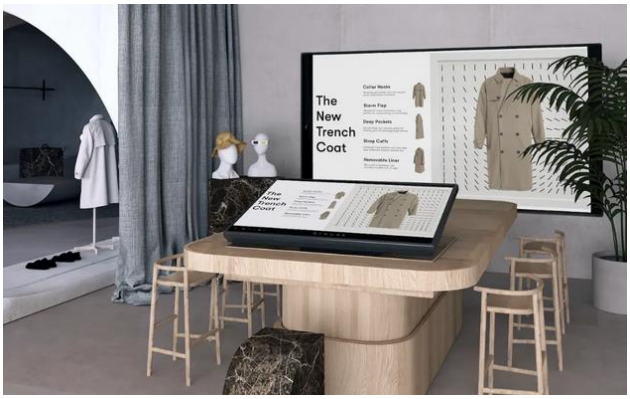

Figure IV.8. Stitch showroom (Stitch, 2023).

b. Digital Transformation

In 2014, Tommy Hilfiger faced a growing demand for its products worldwide. To address this demand, the brand created the first digital showroom in the fashion industry, Stitch, Figure 4.9. This showroom has six essential elements: software, hardware, furniture, lighting, samples, and fixtures. The brand implemented Stitch in its offices worldwide, including Amsterdam, London, Milano, New York, and Dusseldorf.

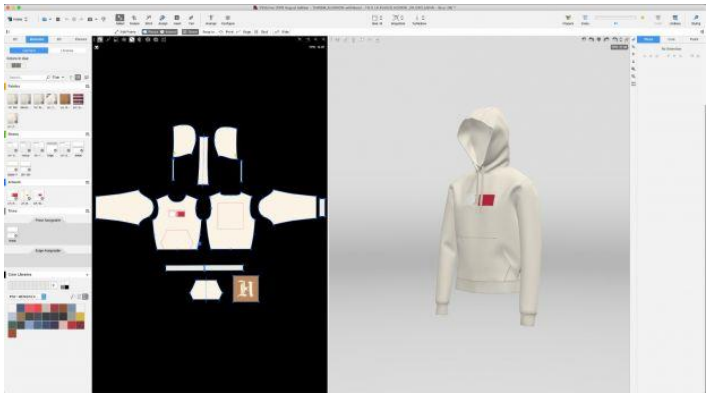

Figure IV.9. Tommy Hilfiger's 3D design (Tafreschi, 2019).

In 2015, P.V.H. Corp started investing in 3D design technology, and in 2017, they trained their designers in 3D design. In 2019, they launched a digital capsule collection and announced their plan to digitise their entire value chain using 3D design technology. They founded a "Stitch" tech incubator dedicated to digitising all collections and developed a digital fabric, pattern, and colour asset library. By 2021, 80% of the product groups will be designed in 3D. Figure 4.10 presents an example.

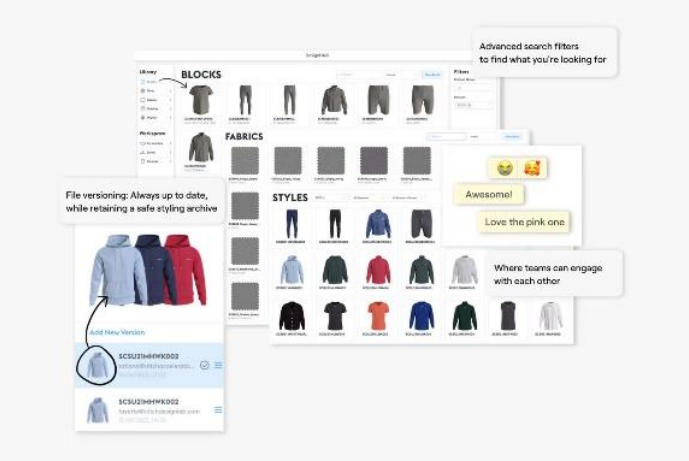

Figure IV.10. Stitch's 3D design software (Mcdowell, 2019).

From Spring 2022, all Tommy Hilfiger collections started being 100% digital, as presented in Figure 4.11. The company will no longer need to produce physical samples; all garments will be created in a digital hub. With 3D design/ sampling, the brand has reduced the development process by two weeks. This reduction allowed them to focus on producing products only when needed, shortening preparation time by 50% and increasing brand orders by 60%.

Figure IV.11. 3D Design using Stitch platform (Mcdowell, 2019).

In September 2022, Tommy Hilfiger's fashion show combined physical and virtual experiences by featuring live models and digital avatars streamed on Roblox, presented in Figure 4.12 (PVH Corp., 2023). According to the P.V.H. Report 2022, the company has been investing in 3D design technology since the COVID-19 pandemic to reduce time and samples in the early stages of the design process.

Figure IV.12. The phygital collection Parallel by Tommy Hilfiger (Seamm, 2023).

Academic studies have discussed Tommy Hilfiger's use of 3D technology over time. For instance, (Vrljanac et al., 2023) reported that TH offered VR headsets to customers to experience their 2015 Autumn/ Winter fashion show. Another example was the launch of a 3D technology-based collection with products modelled on virtual avatars in the fall of 2020, as described by (Choi, 2022). (Särmäkari, 2023) the company plans to virtualise their design processes and showrooms by 2022. (Papachristou & Bilalis, 2020) also discussed using Stitch and AI to create profitable new pieces by combining popular attributes and trends from past designs. Finally, (Joy et al., 2022) mentioned that Tommy Hilfiger's website uses virtual consultants for human interaction instead of chatbots.

Nowadays, Tommy Hilfiger is partnering with technology companies like DressX to diversify their offer of digital platforms in multiple platforms, like social media or Metaverse, Figure 4.13.

Figure IV.13. Tommy Hilfiger in Metaverse Fashion Week 2023 (Cryptoinvestornewsnetwork, 2023).

The case: Renner

a. History

Renner Group started as a textile factory in Porto Alegre, Brazil, in 1912. In 1940, it became a department store: in 1965, it was incorporated as Lojas Renner S.A. Today, it is the largest omni-retailer for fashion and lifestyle in Brazil. Renner S.A. operates 600 physical stores and employs 21,000 people in Brazil, Argentina, and Uruguay. The company has five brands: Camicado (home and decoration), Uello (logistics management), Repassa (clothing, footwear, and accessories reselling), Ashua (plus-size fashion), Youcom (young urban fashion) and Realize (financial institution). The company was a pioneer in measuring customer satisfaction and organised its collections according to different lifestyle segments. Additionally, it was the first brand to have two circular stores that use and reuse materials, and its digital collections feature more sustainable products (Lojas Renner S.A., 2023).

b. Digital Transformation

In 2022, the Brazilian group Renner created a 100% capsule digital collection for Autumn/Winter 2022, Figure 4.14; the virtual pieces are available in e-commerce AR (Farias, 2022). The collection had nine looks with 15 sporty women's products (a mix of tailoring, digital prints, and natural textures), presented by Rennata, a digital persona at Renner (Bragado, 2021). The company uses modelling and simulation software for fabrics, textures, and prints (Revista Têxtil, 2023). They have a virtual reality shop, "3D Renner store", where consumers can see the garments and details. To create this collection, they analysed human proportions and scanned high-compression fabrics to create clothes that adapt to daily routine, being comfortable and wearable (Baldioti, 2022).

Figure IV.14. 3D collection from Renner (Gbljeans, 2023).

The group is investing in product development using three-dimensional (3D) technology. By 2023, approximately 40% of the items in the brand's women's sportswear line will be digitised from end to end, bringing efficiency and sustainability to the creation process. The new collection sees a 25% reduction in the marketing team and a 50% reduction in the generation of physical samples. At the end of April, a women's collection from Get Over, the brand's sports line, arrived in physical stores and e-commerce, with almost 90 pieces developed from end to end with 3D, using advanced tools in all stages of designing the items, including the design, modelling, and approval of clothes. Approximately 40% of Get Over's feminine products are created virtually, with 3D, presented in Figure 4.15.

Figure IV.15. Piece 100% digital by Renner (Heloisatolipan, 2022).

The brand is a pioneer in incorporating phygital fashion into retail, with design teams collaborating with the Digital Hub and the Innovation Lab, multidisciplinary centres created by Renner to drive innovation in the business. Technology has given the company even greater agility and sustainability in product development. In this Get Over collection, for example, the digitisation of processes made it possible to reduce the technical development time of the product by 25%, which is the time it takes from the conception of an item to its availability for sale. The generation of physical samples for collection approval was 50% lower than conventional. The process involves a series of steps: designing clothes in a virtual environment quickly and intuitively; the existence of a library of digital textile materials and digital mannequins, which make it possible to experiment with textures and colours in pieces that adapt to different body types; real-time visualisation, so designers can see how creations will look in the online world before physically producing them; and approval of parts at all stages, reducing the need for physical samples. Example of first immersive collection made by Renner is presented in Figure 4.16.

Figure IV.16. Renner's first collection 100% digital (Bragado, 2021).

Renner uses Korean software CLO3D — the world's leading digital fashion simulator. The communication of Get Over's new products also carries an innovative and phygital footprint in Metaverse – Figure 4.17. The photos on e-commerce and social networks will mix images of the 3D pieces with accurate models wearing the physical clothes. The campaign will also have the participation of influencers who are partners of the brand and Rennata, Renner's digital persona (TI Inside Comunicações, 2023).

Figure IV.17. Metaverse S/S 23 collection by Renner (Lojasrenner, 2023).

By 2023, Renner has the strategy to incorporate 3D technology in all stages of the development of its collections. Renner began a training and qualification phase for its suppliers to help incorporate 3D into the production process of new collections. Around 100 partners are being prepared to create clothes using this technology, which simulates

digital fashion. The training covers more than 180 professionals. With the training, suppliers selected by Renner will be able to create digital prototypes of new pieces using 3D mannequins and digitised fabrics, which include precise details of finishing, texture, and colours. These files are analysed by retailers online in real-time and undergo design adjustments and wearability adaptations before reaching the final approval phase. This initiative is part of the retailer's strategy to incorporate 3D technology in all stages of developing its collections in the production chain, speeds up the creation process, known as the time to market (the period from product conception to availability in stores), and reduces the need to produce multiple physical samples throughout the process.

Renner plans to gradually extend this type of training to other partners at different production stages. Renner has a digital fashion hub and pioneered by launching a capsule collection made entirely with 3D technology as part of its Autumn/Winter, campaign last year – Figure 4.18. Since then, the retailer has promoted immersive fashion shows and other innovative initiatives integrating the physical and digital worlds. Renner already produces a significant part of its collections digitally, using 3D technology. Approximately 40% of the products in the Get Over line, which encompasses women's sportswear, are created exclusively virtually. This approach resulted in a 25% reduction in production time for these items and a 50% decrease in physical sample creation, thanks to the successful implementation of 3D. Three-dimensional technology is also gradually introduced into some pieces in the men's collection, a casual line from Renner (Mercado & Consumo, 2023).

Figure IV.18. 100% 3D collection used @iamsatiko by Renner (Lorena, 2023).

CHAPTER - V

5.1. Discussion results

The study was carried out by studying the case studies of Hugo Boss, Tommy Hilfiger, and Renner. The analysis focuses on the initial trajectory of these companies investing in 3D technology. Initially, these companies had a small team working on 3D and later invested in software, materials, and personnel to grow the department. These companies were among the first fashion brands in their countries to invest in 3D technology to develop their collections and presentations, such as Renner in Brazil.

Even though they did not know the profit percentage or return from consumers, they had an advantage over their competitors. Consumers increasingly focused on experiencing new online alternatives, such as Tommy Hilfiger, when investing in the Stitch platform to showcase their collections and improve communication between global stakeholders.

This investment paid off as many companies now invest in this technology and hire qualified people from digital areas to improve their digital products and collection presentations. The purpose is to increase the percentage of online collections, reduce costs, time, travel, and materials, and produce samples only when necessary.

In the future, the focus will not only be on brands or fashion companies but also on their suppliers and everyone involved in transforming the fashion market into a more digital one with better communication, improvements in product delivery time, reduced unnecessary interactions, and making the fashion industry more efficient and sustainable.

CHAPTER - VI

Conclusions & Discussion Future

6.1. Conclusion

This dissertation explores the use of 3D technology in the fashion industry, specifically how fashion designers can use it to enhance their products and collections. The study focuses on three fashion brands, Hugo Boss, Tommy Hilfiger, and Renner, that have invested in 3D technology for design and product development and are presented in the study case methodology. The 3D software used for virtual modelling originates from the CAD system. Digitalization technologies have improved it, making it easier to create virtual clothes designs without requiring advanced modelling knowledge.

Using digital development, designers can reduce the use of materials, save time, and boost creativity by removing physical restrictions. It is important to note that digital fashion is not meant to replace traditional fashion but rather enhance it. This combination is intended to improve product sustainability, efficiency, and quality. 3D software, such as Clo3D or Style3D, in combination with CGI platforms, helps create realistic avatars. Joined with material software to improve texture of digital fabrics, it can also increase the range of product offerings, such as digital twins or NFTs, which are present in other industries and represent a new branch of fashion. 3D technology allows designers to work online efficiently and realistically without starting from scratch. The realistic representation of 3D designs offers stakeholders the same perception of the design, leaving no room for inaccurate interpretations. Moreover, obtaining feedback from all stakeholders involved in different process phases is easier with 3D technology, increasing productivity and efficiency in the design process while reducing prototypes.

Although 3D technology has many advantages in the fashion industry, it also has some drawbacks. One of the main disadvantages is the need for more realism provided by it. The digital fabrics cannot correspond 100% to the physical prototype, and the virtual world has no sense of touch. Another disadvantage is the complexity of 3D software, which requires extensive knowledge, skills, and technical education to master. Obtaining skills in 3D software is necessary to develop models, which can be a challenging task for fashion designers who have yet to receive training in this area. Finally, accepting these digital changes takes considerable outcomes for the organization's employees.

Nevertheless, these three case studies demonstrate that investing in 3D technology is profitable, and these obstacles can be overcome. By keeping up with these technological changes, fashion brands can attract new customers, increase brand engagement with consumers, and improve the presentation of their collections.

This study encountered several limitations, primarily due to the need for more academic papers in this specialized field. However, this gap in literature presents a unique opportunity for future research to explore topics pertinent to the fashion industry. Another significant challenge was accessing information from fashion companies. These brands often hide their critical data to prevent competitors from gaining a strategic advantage, making comprehensive analysis difficult. Consequently, much of the information had to be gathered from various news articles and documents scattered across the internet. This process was not only time-consuming but also necessitated rigorous verification of the reliability of these sources.

In conclusion, 3D digital design technology uses software like Clo3D or Style3D that can be combined with 3D modelling software to create texture-increasing realistic images. Custom avatars and three-dimensional environments can also be added to the digital assets library. Manufacturing and production use 3D CAD systems like Browzwear or Modaris and 3D printing for virtual prototyping. Lastly, AR or VR technologies are utilised for marketing to reduce physical events, cut emissions, and waste, and promote inclusivity and eco-friendly tech.

6.2. Future research

Scientific articles suggest technological enhancements to simplify software compatibility and improve computer systems, quality, and online marketing. The textile and fashion industry needs improvement to increase sustainability, reduce costs, and enhance communication and efficiency. Companies must invest in new technologies as technology advances to keep up with upcoming changes and reach new consumers. Future studies can investigate how DT reduces environmental impact, and companies must keep improving technology to collaborate with designers and retailers worldwide.

For example, Wagner & Kabalska, (2023) argue that future studies can investigate how DT reduces environmental impact, measure the saved materials/water/dye treatments, and compare DT's carbon footprint to other digital technologies (Wagner & Kabalska, 2023). Also, 3D software and NFTs must be compatible with multiple platforms in the future (Joy et al., 2022). Additionally, designers and retailers worldwide have unique processes. Software companies need to keep improving technology to collaborate effectively with them all (Papahristou, 2016).

In the future, physical and digital experiences will merge to create "phygital" experiences in fashion brands, resulting in cross-platform purchases. Fashion brands can improve their retail experience using AR technology, which can change how customers interact with the brand and personalize products for their tastes, increasing profits (Armstrong & Rutter, 2017).

Finally, the fashion industry is set to benefit significantly from the latest digital technologies, mainly 3D design. This technology will enable professionals to visualize products better and collaborate more effectively with multiple stakeholders and experts in other industries. As a result, there is potential for even greater innovation and transformation in the fashion market shortly.

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Appendix

Table AA. Analysis table of fashion brands and companies that use 3D software in their collections and selection criteria

Selection criteria	Final selection	Fashion companies												Fast Fashion							Fashion Designer						Manufacturers					
	Hugo Boss	Renner Group	PVH Group	Decathlon	Adidas AG	VF Corporation	Under Armour	Puma	Kookai	APG & CO	Levi S. & CO	Freemans PLC	Besteseller	Marks & S.	Sandqvist	Zara	H&M Group	Mango	Alexandra M.	DvF	Seven Passaro	Roberto Cavalli	Prada Group	Marc Cain	Burberry	Becri Group	Impetus Group	Petratex	Valérius	Crystal Group
3D technology pioneer	✓		✓		✓		✓	✓																								
+50% Digital collection	✓	✓	✓																													
3D technology investment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3D virtual clothing software	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓									✓	✓		✓		✓	✓	✓	✓	✓	✓	✓
Collaboration with Agencies					✓			✓					✓	✓	✓	✓	✓	✓	✓	✓			✓		✓							

Table AB. Analysis table of the three fashion companies and final selection

Fashion company – Final selection				
Fashion company	**3D technology pioneer**	**% Digital collection**	**3D technology investment / reasons**	**3D virtual clothing software used**
Hugo Boss Group	Since 2012, invested in 3D technology; Investment in various sectors – R&D, Marketing campaigns to development and share 3D images; Transparency in sharing information about new investments made by the company;	80% (2022) 90% (2025)	Two digital campuses in Oporto and Metzingen, total of 400-500 workers (Hugo Boss AG, 2023). Growing digital collections: from 5% in 2015 to 80% in 2022 (Hugo Boss Group, 2020; McDowell, 2021; Russell, 2022). First digital collection with 105 pieces in 2020 (McDowell, 2021)	Clo3D, Adobe Substance, Vizoo (Braun, 2022) (Adobe, 2023c)
PVH Group – Tommy Hilfiger	Since 2015, invested in 3D technology; Investment in various sectors – R&D, Marketing campaigns to development and share 3D images; Transparency in sharing information about new investments made by the company;	80% (2021) 100% (2022)	First digital showroom of fashion industry with six elements: Software, Hardware, Furniture, Light, samples and fixtures (MDS, 2019; Warren, 2020). Incorporation of Stitch in 2017 and digitize all value chains in 2019 (FashionUnited, 2022).	Stitch
Renner Group	Since 2018/2019, invested in 3D technology; Investment in various sectors – R&D, Marketing campaigns to development and share 3D images. Transparency in sharing information about the company;	100% (2022)	In 2022 presented a 100% digital collection with 15 AR looks (Farias, 2022) (Bragado, 2021). Incorporated 3D technology in all supply chain by 2023. Digital fashion hub producing 40% of its collections, resulting in a 25% reduction in production time and 50% physical sample (Mercado&Consumo, 2023).	CLO3D (TI Inside Comunicações, 2023)

Companies analysed for categories

Fashion companies using 3D sampling – See Table AC

a. Decathlon

Decathlon is a sports goods French retailer with over 1,700 stores in 59 countries and over 50 sub-brands. About 850 engineers and 300 designers work on product design (Decathlon, 2022). The company previously used Assyst and Shima Seiki's APEXFiz software to improve operations. Assyst provided 3D software to create garments in different colours and "virtual product shots" (Prahl, 2017). APEXFiz created 3D renderings and virtual samples for socks, reducing sampling errors and providing accurate data for manufacturing (Inside Textiles Ltd, 2023). Since 2019, Decathlon has implemented a 3D design process and uses a Vizoo-type scanner, Adobe Substance, Clo3D, and Blender for creating digital materials, garments, and 3D environments, show in Figure AA. This process has reduced the development time by less than 33% on apparel and bags, reduced the number of prototypes by less than 33% on footwear, and increased the number of Colour, Materials, Finish (CMF) iterations between ten and 60 times (Bosset, 2023).

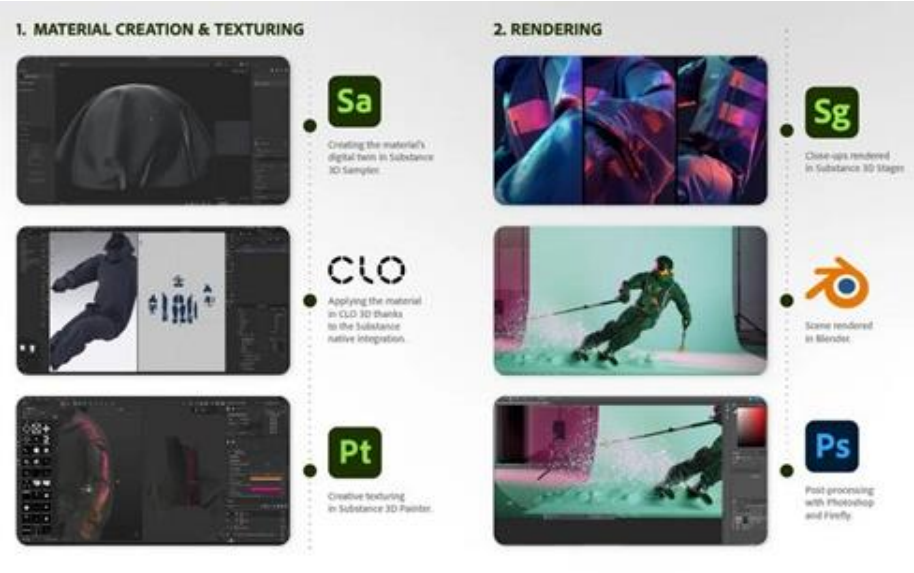

Figure AA. Decathlon digital transformation pipeline (Adobe, 2023).

b. Adidas AG

Adidas invested in 3D software and saved nearly 1 million samples between 2010 and 2013 to create and share designs (Barrie, 2013). The company plans to invest over $1 billion in digital transformation from 3D creation to sales by 2025 (Adidas AG, 2021). Adidas' Speed factory in Ansbach created virtual replicas of its footwear and

apparel to simulate their performance and improve product quality, such as show in Figure AB (Olkhovskaia, 2023). Also, they have more than 1000 tech/digital employees (Berthiaume, 2021). Adidas is scaling its use of 3D design to develop products faster and eliminate the need for physical samples shipped from Asia (Mixson, 2022). More than €5 billion of Adidas' sales already come from products created with 3D design (Bain, 2021).

Figure AB. Smart Mirror By Adidas (Adidas, 2019).

c. VF Corporation

VF Corp has invested in 3D design for several years to create digital products for marketing, e-commerce, point of sale, and manufacturing. The company has built digital libraries of materials and trims and conducted AR experiments. Brands like Wrangler® and Lee® have used Browzwear software for digital sample development. VF Corp has combined all its brands to reduce product development cycles by rendering clothing using 3D avatars (Browzwear Group, 2017). This has reduced the time previously taken to move from product design to a prototype being manufactured from six weeks to four days (Souza, 2021). VF Corp invests in digital technology to create 3D product renders to reduce prototypes, eliminate waste, speed up the supply process and improve the customer experience (VF Corporation, 2022). In 2021, North Face (VF brand) partnered with DDIGITT (3D digital product creation agency) to create 3D assets of iconic TNF duffel bags - Figure AC - giving more realism and storytelling of their digital products (Souza, 2021). The 2023 Report of CDP Climate Change of VF Corp (VF Corporation, 2023) states that potential opportunities include cost savings from 3D sampling and circular business model initiatives to extend the lifecycle of products and materials.

Figure AC. Digital twin of Duffel Bag designed in 3D (Platforme, 2023).

d. Under Armour

Since 2016, the brand has been using Optitex, a 3D software, to reduce product development time by 50%. This replaced the manual design process, which took three weeks to receive a physical sample. With Optitex, the team can attend sales meetings with virtual prototypes in under eight weeks (Optitex, 2016). In 2019, they partnered with Alvanon to improve their avatars for market parameters (Holmes, 2019). Under Armour now uses Browzwear's tools and Browzwear University for real-time collaboration during fittings and efficient marketing and sales purposes with hyper-realistic 3D models in digital product creation (Browzwear Group, 2023c), show in Figure AD.

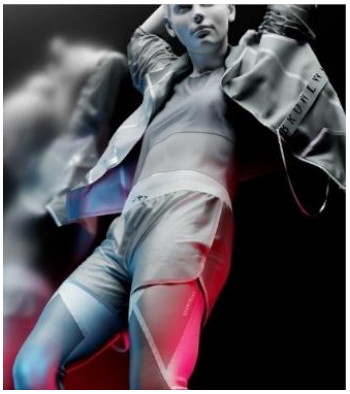

Figure AD. 3D outfit from the Browzwear collaboration with Under Armour (Browzwear Group, 2023).

e. Puma

Puma is a large sportswear manufacturer that was founded in 1948. They specialise in producing footwear, apparel, and accessories. To reduce the time between product development, Puma partnered with Browzwear in 2017. This allowed them to create an efficient workflow in product development with VStitcher. The collaboration between global teams over digital prototypes accelerated the approval processes. Browzwear is part of the platform Metail,

which allows users to simulate photorealistic digital garments on a real person. PUMA adopted 3D technology, avoiding the need for physical samples, and saving time and money on design and logistics (Oliveira, 2022). This provides design teams with solutions like EcoShot® and helps to promote trust in digital garments (Browzwear Group, 2020), and example is provided in Figure AE.

Figure AE. Representation of Puma 3D design (Oliveira, 2022).

f. KOOKAÏ

Australian brand (Browzwear Group, 2023d). Used 3D visual effects – VFX, (Bestseller, 2021) reporting using Browzwear soflware leads to less 50% reduction in physical sampling (Browzwear Group, 2023d), presented in Figure AF. Now uses AI platform - Pttrns.ai – to rendering (NLdigital, 2023). Browzwear (Browzwear Group, 2023).

Figure AF. KOOKAÏ partner with Browzwear (Browzwear Group, 2023).

g. APG & Co

Owner JAG brand, Australian fashion brand. Created in January 2022, uses 3D design technology. Reportedly, it has cut its sampling costs by 50%. In addition to design, JAG has incorporated 3D technology into marketing for the AW23 collection (Apparel Resources, 2023).

h. Levi Strauss & Co.

Levi's brand, F.L.X. project own by Eureka Innovation Lab develop 3D digital design and laser finishing technology that enables a more responsive supply chain while vastly reducing the number of chemicals needed for the finishing process. Moreover, they implemented a digital sampling platform, helping to reduce waste, save resources, improve delivery time and build-to-last products for personalised customers (Levi Strauss & Co., 2021), implementing a sustainable program "sustainable fashion" category encompasses various possible meanings and practices (Vrljanac et al., 2023). They used Browzwear (Sourcing Journal, 2022). Levi's implemented inventory monitoring in 2013 to avoid deadstock. In 2017, an innovation research institute was created to research denim.

i. Freemans PLC

Owner Bonprix Germany brand will launch a new collection for their five brands with 3D software (Bonprix, 2019) investing in digitalising the entire product development process until 2025 using Assyst (acquired by Style3D (Otto Group, 2023). 3D Vidya by Assyst (acquired by Style3D).

j. Bestseller

Own VILA brand is Danish company. It improves design, collaboration, contributing to a more sustainable supply chain (Delogue, 2021). Its collaboration with agency N'Fellows and Vonoa for creating a 3D virtual sampling collection using Clo3D (Delogue, 2021) as display in Figure AG.

Figure AG. VILA fashion collection.

k. Marks & Spencer

A UK fashion company invested in Optitex, 3D software (Abdulla, 2022), reducing cost and lead time by about 50% of the product development process. It reduced retailers' lead time from 24 weeks to three weeks (Russell, 2020)**.**

l. Sandqvist

Scandinavian accessories brand Sandqvist, created in 2004, developed 3D rendering during Covid-19 to market content for their website and social media in partnership in 3Dear agency, Figure AH (3Dear, 2023)**.** They saw it as an opportunity to make some difference and increase flexibility in creating and updating some designs. They collaborated with 3Dear, which reduced CO2 emissions by five to tonnes per year (Magnusson, 2022)**.**

Figure AH. 3D renderings Sandqvist's (Magnusson, 2022).

Table AC. Fashion company analysis table with selection criteria

Fashion companies				
Fashion company	**3D technology pioneer**	**% Digital collection**	**3D technology investment / reasons**	**3D virtual clothing software used**
Decathlon	No	N/A	Reduce 33% lead time. Product design: +850 engineers, +300 designers	Clo3D, Adobe Substance, Blender, APEXFiz
Adidas AG	Yes	N/A	€5 billion sales with 3D design; Invest +$1 billion until 2025 to digital transformation for 3D creation process: +1000 tech/digital workers	N/A
VF Corporation	Yes	N/A	Reduce product development cycles from six weeks to four days	Browzwear (jeans division)
Under Armour	No	N/A	Reducing around 50% of product development time	Optitex and Browzwear
Puma	Yes	N/A	Efficient workflow in product development Reducing costs. Accelerate approval processes	Browzwear
KOOKAÏ	No	N/A	Less 50% sampling	Browzwear
APG & Co	No	N/A	Sampling costs -50%	Clo3D

Next page continuous

Fashion companies				
Fashion company	**3D technology pioneer**	**% Digital collection**	**3D technology investment / reasons**	**3D virtual clothing software used**
Freemans PLC	No	N/A	Reducing physical samples, resources, cost	Assyst (owner Style3d)
Bestseller	No	N/A	Improve collaboration, Short samples Shorten lead times	N/A Collaboration with Vonoa and creative agency N'Fellows
Marks & Spencer	No	N/A	Reducing physical samples, resources, cost	Optitex
Sandqvist	No	N/A	Reducing physical samples, resources, cost	N/A 3Dear agency

Fast Fashion brands using 3D sampling – See Table AD

a. Zara

Spanish fast fashion brands have implemented technological advancements such as RFID, 3D printing, and automated sewing machines to facilitate fast production and delivery of new designs (Untaylored, 2023). Zara reduced sampling by 80% in product development by using 3D digital fashion with stakeholders for quick design creation and better communication (Gibbons, 2023). Zara's tech strategy includes optimal inventory distribution with RFID tags and Smart Dressing Rooms for an efficient shopping experience (S. Kim et al., 2019). In social media, the brand is sharing digital twin of their clothes, Figure AI.

Figure AI. Representation 3D image Zara's (Estudio Gaumé, 2023)

b. H&M

In 2019, H&M utilised Shima Seiki software to produce digital knitting samples (Mowbray, 2019). By 2020, they aimed to create a Zero Waste Dress using 3D design tools and zero waste pattern-cutting techniques. H&M's innovation lab explored 3D technology, creating digital samples, personal avatars, and fitting rooms. They developed an AR app to scan customers' bodies, creating a digital twin with their measurements and reducing returns. "Movebox," an AI tool, distributes products where there is more demand. H&M is developing a Circulator Academy and an online learning hub for a circular fashion and climate-positive operation by 2030 (H&M Group, 2023a). They collaborated with Magic Leap and Mar Warpin Media to create "Redesign Lab," Figure AJ, personalised digital twin clothing and

produced in stores (Carter, 2022). H&M uses 3D visualisation and invests in 3D software tools to reduce physical samples (H&M Group, 2023b).

Figure AJ. H&M virtual showroom (H&M Group, 2022).

c. Mango

Spanish brand owned by Punto Fa S.L. They have their Barcelona headquarters more than 500 people working in 3D technology. Currently, using Clo3D. Later they implement an AI generative platform to create patterns, garments, fabrics, and prints (Moreno, 2023) 3D technology to minimize sample production during the product development stage (Halliday, 2023) (BoF & Mckinsey & Company, 2022)**.**

Table AD. Fashion designers' analysis table with selection criteria

Fashion brands				
Fashion company	**3D technology pioneer**	**% Digital collection**	**3D technology investment / reasons**	**3D virtual clothing software used**
Zara	No	N/A	3D sampling, RFID tags and Smart Dressing Rooms	N/A
H&M	No	N/A	Save resources, Reduced number of samples, Optimize pattern efficiency though less waste of materials	Clo3D Shima Seiki software (knitting)
Mango	No	N/A	More 500 people work with technology innovations	N/A

Fashion Designers houses using 3D sampling – See Table AE

a. Alexandra Moura

Portuguese fashion brand that customized its phygital collection with digital twin and used Decentraland with AR try-on, Figure AK (Simões, 2021). It reduced its timelines to two months (Seamm Technologies Inc., 2023) partnered with Seamm (Simões, 2021).

Figure AK. Digital Twin of Alexandra Moura x Seamm (Seamm, 2022).

b. DvF

American fashion designer Diane von Furstenberg (Style.me, 2022), personalized customer experience with 3D models in e-commerce with the implementation of made-to-order (Heuritech SAS, 2023). It partnered with Style.me to implement 3D models in their website, Figure AL, increasing the online shopping experience through styling and virtual fitting (Style.me, 2022).

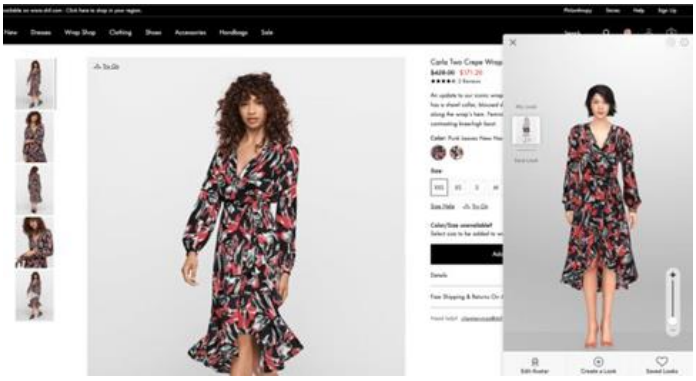

Figure AL. DVF partner with Style.me (Style.me, 2023).

c. Steven Passaro

Paris-based designer uses pattern cutting and traditional couture techniques (Passaro, 2023a). It reported that efficiency boost improved pattern creation for jackets by 50%, design toiling by 66%, and sample production by 66% (Passaro, 2023b). Used Clo3D, Style3D, and Browzwear (Passaro, 2023b), represented in Figure AM. Used Clo3D, Style3D and Browzwear (Passaro, 2023b). The private label works with France and Portugal manufactures (Passaro, 2023b).

Figure AM. Example of 3D images of Steven Passaro (Passaro, 2023).

d. Roberto Cavalli

Italian brand uses 3D garment simulation or virtual prototyping Optitex (Young Hwang & Hahn, 2017). Previously, Roberto Cavalli used handmade techniques to create designs, Figure AN. They made paper dolls and used pins to determine a print position on models (Papahristou & Bilalis, 2017).

Figure AN. Roberto Cavalli paper samples (Papahristou, 2016).

e. Prada Group

Italian luxury company owned Prada, Miu Miu, Luna Rossa, Church's, Car Shoe and Pasticceria Marchesi. Prada teamed up with Accenture to create a digital twin of their America's Cup sneakers, enabling them to develop a 3D configurator that allows customers to customise their sneakers online. The configurator generates real-time, high-resolution images of over 50 million possible shoe configurations. Prada also created an enhanced version to use in stores (Accenture, 2023). Also, the company build real-time personalised customer experiences across in-store and digital worlds through recommendation products that are personalised in the in-store experience and online. Plus improve the garment/ accessory development prototypes with hyper-realistic looks, Figure AO (Adobe, 2023). In 2023, Prada Group partner with Adobe using Adobe Experience Cloud with Adobe Real-Time Customer Data Platform (collect data), Adobe Journey Optimizer (customer profiles and personalised experiences), as well Adobe Substance 3D. Furthermore, the group collaborated with other industries such as NASA and other sportwear brands (Adobe, 2023).

Figure AO. 3D image from Prada x Accenture (Accenture, 2023).

f. Marc Cain

A German brand, that uses Clo3D. The collections were quickly visualised and can be used in purchasing, design, cutting, production, marketing, or sales, creating end-to-end integration, giving value to the entire supply chain (Sourcing Journal, 2020). Figure AP shows an example of 3D image.

Figure AP. 3D images by Marc Cain (Sourcing Journal, 2020).

g. Burberry

Burberry used AI to improve sales and customer satisfaction through personalised customer management programs, which led to a 50% increase in repeat customers. The app suggests clothes based on other customers' preferences (Vrljanac et al., 2023). They partner with Koffeecup agency to created authentic digital twins, Figure AQ.

Figure AQ. Example of digital twin develop by Koffeecup for Burberry (Osservatorio, 2020).

Table AE. Fashion brands' analysis table with selection criteria

Fashion brands				
Fashion company	**3D technology pioneer**	**% Digital collection**	**3D technology investment / reasons**	**3D virtual clothing software used**
Alexandra Moura	No	N/A	Customizable phygital collection only in 2 months	N/A Partner with agency: Seamm
DvF	No	N/A	Style.me creates 3D models from 3D scanning technology to use e-commerce	N/A Partner with agency Style.me
Steven Passaro	No	N/A	Pattern creation from 1 day to half day (-50%) Design Toiling from 3 days to 1 day (-66%) Sample production needed 3 samples for 1 sample (-66%) Two collections with 94 pieces saved: 96,360 € and 4,921 kg CO2	Clo3D Style3D Browzwear
Roberto Cavalli	No	N/A	Reducing physical samples, resources, cost	Optitex

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Fashion brands				
Fashion company	**3D technology pioneer**	**% Digital collection**	**3D technology investment / reasons**	**3D virtual clothing software used**
Prada Group	No	N/A	Improve 3D design to reimagine garment prototyping and customer experience	Adobe Substance and partner with
Marc Cain	No	N/A	Created digital garments and virtual space for showroom	Clo3D
Burberry	No	N/A	Save resources, Reduced number of samples, Optimize pattern efficiency though less waste of materials	N/A Partner with Koffeecup agency

Manufacturers using 3D sampling – See table AF

a. Becri Group

Portuguese manufacturer specialized in apparel production, produces from XS to XXL (Becri Group, 2023). They used Clo3D, Figure 66, to reduce lead times and produce virtual samples in less than a day, Figure AR. Two design teams with six designers dedicated to 3D (Portugal Têxtil, 2022). They have clients mid-range level brand, Inditex Group (Portugal Têxtil, 2019).

Figure AR. 3D image made in Clo3D by Becri Group (Becri Group, 2023).

b. Impetus Group

Portuguese underwear brand (Impetus) and manufacturer for other brands (Impetus Group, 2021). Since 2021, the company invested in 3D modelling using Clo3D to accelerate digital garments personalisation (Impetus Group, 2021). Clients: Private labels, El Corte Inglés (Impetus Group, 2021). Figure AS shows an example of 3D sampling image.

Figure AS. 3D render made by Impetus (JornalT, 2022).

c. Petratex – Confecções SA

Since 2015, the Portuguese manufacturer uses 3D, Figure AT. One of its departments used Clo3D personalised garments and avatars and visualise 360º degrees. Reduces costs, waste, planning, and simplifying decisions. They have a wide range of client's Private labels, technical clothing linked to high-competition sports and Haute couture production (Petratex, 2023).

Figure AT. Example of 3D render made by Petratex (Petratex, 2023).

d. Valérius - Têxteis, SA

Portuguese company Valérius Hub (Rodrigues, 2020) and the Dielmar brand invested in a 3D design center (Lusa, 2023) In 2022, they invested in Metaverse collection called MEET IN META, Figure AU (Jornal T, 2022). They used Clo3D to reduce sampling, showing prints and colour variations (Rodrigues, 2020) models and fit testing in sizes ranging from XS to XXL (Valérius Hub, 2023). Clients: Private label for USA, Canada, Germany clients (Jornal T, 2023).

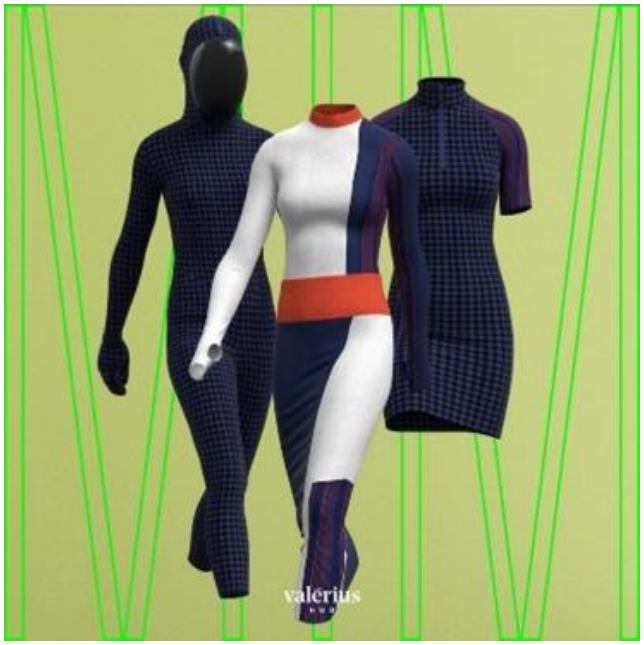

Figure AU. 3D image by Valérius (Valérius Hub, 2019).

d. Crystal International Group Limited

Hong Kong manufacturing mill company with five segments: Lifestyle, Denim, Intimates, Sweaters and Sportswear/Outdoor Apparel (Varshney, 2023) (Blomquist, 2022). Crystal has used 3D virtual sampling, presented in Figure AX for product development since 2017, saving over 50% time and shortening the cycle to three days. Digital sampling increased by 400% in 2020. In 2019, converted 80% digital workflows and reduced sample production by 75%. By 2021, about 90% sampling development (Varshney, 2023). Used VStitcher – Browzwear (Varshney, 2023). Clients range: Levi's, GAP, H&M, UNIQLO (Crystal International Group Limited, 2023) Old Navy, Puma, Under Armour, A&F, Target (Lam, 2023).

Figure AX. Crystal 3D virtual sampling (Fibre2fashion, 2019).

Table AF. Fashion manufactures' analysis table with selection criteria

Fashion Manufacturers				
Fashion company	**3D technology pioneer**	**% Digital collection**	**3D technology investment / reasons**	**3D virtual clothing software used**
Becri Group	No	N/A	Reduce lead times and produce virtual samples in less than a day	Clo3D
Impetus Group	No	N/A	Accurately visualize the fabric Reduce time	Clo3D
Petratex – Confecções SA	No	N/A	Customize and simulate fabrics, colours, prints, as well, visualize 360° degrees each piece. Reduce physical samples and upgrade patterns	Clo3D
Valérius - Têxteis, SA	No	N/A	Improve collaboration and communication Efficiency in the product development process	Clo3D
Crystal International Group Limited	No	N/A	Save resources, Reduced number of samples, Optimize pattern efficiency though less waste of materials	Browzear