How can the fashion industry be sustainable? The use of immersive technology in Fashion Design for innovation, digital transformation, and sustainability.

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Abstract

The fashion industry is currently facing an increased pressure to adopt sustainable practices, and immersive technology can achieve this goal. This thesis explores how digitised processes can contribute to sustainability by streamlining the design and development phase of the fashion supply chain. Furthermore, importance is placed on defining and highlighting the necessity of sustainable efforts in combating fashion over-production and over-consumption by examining Anthropocene, the effects of COVID-19, and environmental pollution. The thesis argues that the digitisation of the fashion industry as an effective response to these challenges, demonstrating how immersive media— 2D and 3D computer-aided design technologies—help reduce waste and improve efficiency in design and development which is stage one of the fashion supply chain.

This thesis examines three core discourses, sustainability, technology, and digital twinning through both theoretical and practical lenses. The analysis is enriched by investigating contemporary practitioners whose methodologies engage with these discourses, including independent designers, collaborative initiatives, brands, and alternative business models. In addition, insights from my own practice-led project, which draws on the work of Kim Fraser (2009), Holly McQuillan (2020), and others, evaluate the effectiveness of developing two virtual fashion collections.

Furthermore, the intersection of fashion and gaming is explored through the application of game design methodologies in a non-game context. This is investigated by accurately designing, developing, and marketing fashion collections within a digital framework. The study also examines how this approach influences the marketing of the collections to the consumer with the use of the final project outcomes

of a digital film and still images. These insights collectively help gauge the effectiveness of technologically driven sustainable fashion practices.

Introduction

This thesis explores to what extent can the fashion industry be sustainable using immersive technology. The contextual analysis of the thesis discusses sustainability, technology and the digitisation of the fashion industry, highlighting prevailing issues and solutions. Under sustainability, awareness is raised on industry concerns that should be promptly addressed, such as environmental effects, supply chain responsibility and transparency, Greenwashing, over-consumption, and over-production in the fashion industry. The thesis also reviews essential 3D design-based immersive technology employed by current practitioners, and business models that fosters technologically driven sustainability. This discussion helps highlight potential methodologies that can be adopted by designers and companies in the fashion industry to de-materialise the design and development process effectively. Furthermore, the thesis examines the digitisation of the fashion industry and digital twin technology. Lastly, the contextual analysis is expanded by my own practical project findings - implementing a digitised design and development methodology. This section critically reviews how effective streamlining the design and development cycle using immersive technologies can be, which is the first stage of the fashion supply chain and explores to what extent it can be sustainable.

Sustainability

The concept of *sustainability* has many definitions in the fashion industry due to the position of multiple actors within its eco-system. Within the supply chain, it is linked to achieving sustainability in design and manufacture through sustainable raw material usage. In the business and marketing sphere of fashion, it is defined as sustainable cooperate values and social responsibilities such as, fair worker conditions,

reducing greenhouse gas emissions and controlling production water pollution (Mesjar et al., 2023). Therefore, the fashion industry is under immense pressure to achieve 'sustainability'. Mesjar et al, (2023) argues that sustainability in the context of the fashion industry has also become "sustainable clothing", an umbrella term meaning the manner clothes are created, produced, and consumed in a sustainable manner while being aware of the environment. Moreover, Gwilt and Rissanen (2011) claim that "Sustainability" in general is interchangeable with recycling and environmental conservation, while the original rationale stemmed from the 1950's as a solution to ease global poverty. According to Du Pisani (2006), the term was first used within "German Forestry circles by Hans Carl von Carlowitz in *Sylvicultura Oeconomica* in 1713" with a focus on balancing forestry practices (Du Pisani, 2006, n.d. pg. 85). Moreover, the development of the industrialised world that followed World War 2 caused rapid exhaustion of raw materials and brought further focus to achieve sustainability. The transition to the state of Anthropocene also marked new adaptations of the original "sustainability movement" to "sustainable development" (Will Steffen, 2017). The term "Sustainable development" is supposedly coined by Barbara Ward, the founder of International Institute for Environment and Development (Du Pisani, 2006).

The environmental effects of the fashion industry

Professor Will Steffan (2017), discusses the transition from the Holocene - a period when Earth was in its pristine state with abundant resources approximately 11,700 years ago to the Anthropocene. He explains that this transition has occurred as the outcome of the collective of human industries, primarily operated by the world's wealthiest countries, have caused severe damage to the Earth —depleting resources at an alarming rate and polluting Earth's atmosphere with toxic emissions and waste. As a result of the industrial revolution (1750s-1850s) and the mid-20th century human activities, Earth has now entered the sixth mass extinction event. Steffan emphasises that solutions must be implemented to

mitigate further damage, either through control or adaptation. He further elaborates that humans underestimate their capacity for adaptation and suggests that embracing new methodologies to address the factors accelerating the Anthropocene would be the more cost-effective approach than crisis response measures. Thus, in 2015 a blueprint for sustainable development and preservation across multiple sectors of human industries was introduced by the United Nations (*THE 17 GOALS | Sustainable Development*, n.d.). Moreover, following COVID 19 in 2020, further efforts to achieve and implement sustainability was encouraged and led to the adoption of immersive technology as a solution among others to digitise human industries (Mesjar et al., 2023).

The fashion industry is notably one of the most polluting industries in the world. Liscio and Sospiro (2023) report that the fashion industry is responsible for 9% of global carbon emissions and 20% of water pollution. Fashion production also accounts for 9% of annual microplastic waste and contributes harmful dyes and toxic chemicals to water bodies, an issue projected to increase by 50% by 2030. The fashion industry also generates 92,000 tonnes of textile waste per annum because of the over-production of garments, also partially due to its consumer-driven nature (Liscio & Sospiro, 2023). Moreover, the fashion industry suffers approximately $100 billion (USD) in losses annually due to inadequate recycling practices and the underutilisation of materials and resources in the development, production, and manufacture of garments (Adamkiewicz et al., 2022). Thus, governments such as the UK (Environmental Audit Committee, 2019), the European Union (*Eco-design for Sustainable Products Regulation - European Commission*, n.d.), and the county of San Francisco in the state of California, USA (*How to Build a Circular Economy | Ellen MacArthur Foundation*, n.d.) demanded rapid changes to the supply chain of the Fashion industry and implemented a strict regime of sanctions, rules, and regulations (*Putting the Brakes on Fast Fashion*, 2018). This is coupled with the growing pressure from conscious

consumers for sustainable fashion products and practices with supply chain responsibility and transparency.

Supply chain responsibility and transparency

Farrer (2019) discusses the urgency of better product transparency and communication in the fashion industry. Farrer argues that this is crucial to better understand the state of the supply and disposal chain of fashion garments. Farrer reports that developments in industrial mechanisation such as, offshore sourcing and manufacturing, automation, predictive analysis fostering impulsive buying over informed consumption, have diminished the ability to gather, learn, and synthesise knowledge. This is due to consumers becoming increasingly dependent on such automated processes rather than engaging in decision-making through independent research, analysis, and information synthesis. Farrer observes this has affected fashion design, production, and consumption leading to blind fashion consumerism. Furthermore, Farrer states this has caused a disabling phenomenon, accelerating loss of essential skills and knowledge, where consumers are struggling to make informed choices on what to wear, how to design, consume, produce, and even re-use garments. Therefore, to counter this problem Farrer proposes setting innovative strategies that are technologically enhanced that will help raise awareness on responsible fashion choices (Farrer, 2019) and (Gwilt & Rissanen, 2010). However, this raises a contradiction, the technologically driven and automated processes that have contributed to this disabling phenomenon are also proposed as part of the solution through innovative, technology-enhanced strategies. Therefore, questions remain regarding the efficacy of technological solutions within the very system being critiqued.

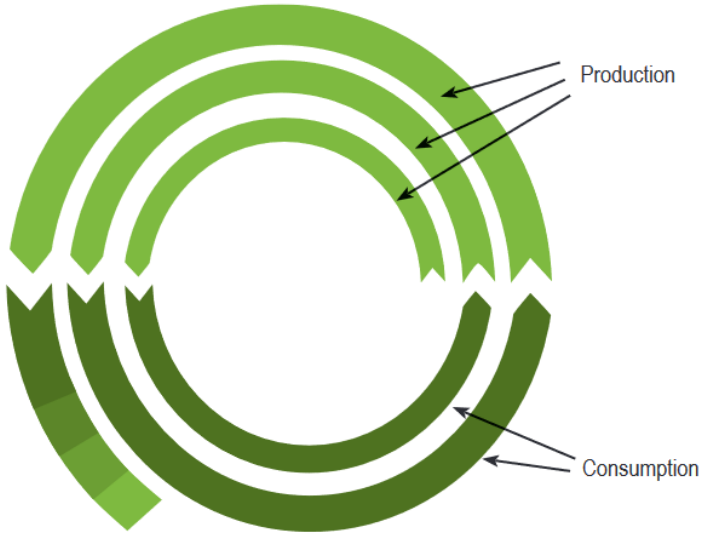
Greenwashing

It is apparent that the sustainability movement has become an elaborate economic development strategy for brands and businesses to *greenwash* their fashion products for better commercialisation (Gwilt & Rissanen, 2011). According to a study by Bank (2024), Greenwashing is defined as "the act or practice of making a product, policy, activity, etc. appear to be more environmentally friendly or less environmentally damaging than it really is." - further elaborating that it is an over-used scheme by brands and organisations to deceive consumers to buy sustainably labelled goods (Bank, 2024). According to Gwilt and Rissanen (2011), the original idea of sustainability has stretched out so far, that it is revolving around "sustainable products", "sustainable approaches", and "sustainable housing", of which the political idea of sustainable development has contributed to a collective notion that there is a common sustainability agenda or census. To further elaborate, the political discourse surrounding sustainability has contributed to the broadening of "sustainability" from an economic perspective; by effectively monetising it and this has shaped a widespread illusion among industrywide sectors of a universally agreed "sustainable" economy. Thus, brands and businesses exploit this "illusion" by Greenwashing products - an effective tactic to commercialise products.

In North America, Europe and the UK, large-scale fashion retailers greenwash their fashion products to appear sustainable due to stakeholder and investor pressure to increase sales, on top of catering to consumer demands and adhering to brand perceptions of ethical and environmental corporate values as corporations' decision making is based on profit. (Gwilt & Rissanen, 2011). Joan Farrer (2009) also reports that currently there are over 70 definitions for sustainability across multiple industries and illustrates the complexity of sustainability in the fashion industry as a three-legged stool. The three legs represent the people, profit and the planet as core foundations and the platform as sustainability. For the platform to last long, the three legs, i.e.: people, planet and profit must be equally solid. This suggests that profit is closely tied to sustainability, framing it primarily in economic terms.

Over-consumption and Over-production of fashion

Fashion consumers often chase novelty, identity, and immediate gratification through impulse buying, indulging in hedonism and satisfying materialism (Garcia-Ortega et al., 2023). A study by Garcia-Ortega et al. 2023 and Gupta et al. 2019 details how the pursuit of economic goals by fashion co-operations sustains the rapid turnover of fashion goods and resources, linking hedonistic values with consistent overconsumption of fashion. An example of the current fashion cycle is of a business that claims it is producing organic cotton shirts (planet) sourcing from an offshore factory that allegedly employs labourers who are underpaid (people) and delivers their "sustainably produced" shirts (profit) that are underpriced all around the globe; consumers are enticed to buy in bulk due to affordable rates disregarding quality, which leads to the over-consumption of "cheap" fashion. Hence, fashion businesses use a high-speed design, develop, production and manufacture system that effectively fuels a continuous over-production cycle accelerating the over-consumption rates. This is the business model of many current ultra-fast fashion brands, as well as fast fashion chains such as Shein and Temu (*The Ethical and Sustainability Concerns of Temu and Shein*, 2024). Thus, creating a never-ending cycle of ultra-fast fashion consumption and production.



The relentless cycles of production and consumption that is ever growing (Daly, 1992) and (Gwilt & Rissanen, 2011).

This model of fashion economy also contributes to high-volume fashion practices, where massive quantities of clothes leave production then retail warehouses, discarded to 3rd world-countries disguised as "*green-waste*" or "*recyclable textiles*". This model of "sustainability" generates profit for the few agencies at the top of the chain that manages the system of "green waste", while countries that agree to textile waste disposal, battle with handling clothing waste landfills. Though countries such as, Uganda and Tanzania have implemented incineration systems and second-hand clothing markets to manage textile waste (United Nations Conference on Trade and Development, 2024). However, despite these efforts, the rate of landfill generation has proven to be uncontrollable. Additionally, the incineration of garments results in the emission of harmful gasses in copious quantities, worsening air pollution. Consequently, this highlights the need for better solutions to manage textile waste as well, which is a causation of over-production. Therefore, how can we make the equation well-balanced between all three pillars of people, profit, and planet to make the foundation of sustainability truly durable?

Drivers of change in the fashion industry rely on both major shifts in production and concurrent changes in consumer demand and behaviour. These factors are not mutually exclusive, meaning responsibility lies with both, though not necessarily equally. (The Business of Fashion, The Business Case for Sustainable Fashion, 2025), (Garcia-Ortega et al., 2023), (Liscio & Sospiro, n.d.), (Silvestri, 2020), and (Ramos et al., 2023). Moreover, fashion economy's growth is tied to physical expansion, with production increasing exponentially through the cumulative use of raw materials which are limited, leading to environmental depletion (Gwilt & Rissanen, 2011). Therefore, regulating overproduction by decelerating this cycle would be the more ideal approach to address the over-production problem, thus controlling over-consumption.

This dilemma, to a certain extent is addressed with the digitisation of the fashion industry by adopting immersive media such as *3D CAD, AR,* and *VR etc*. Alternative strategies such as, collaborative consumption and circular models have also been proposed over the years, with strenuous effort to implement in curriculum and professional practice, yet so far these strategies account only for marginal shifts (Iannilli & Spagnoli, 2024). Moreover, the extent of sustainability that can be achieved with the effective adoption of immersive media is debatable due to high energy costs, scalability issues, skill shortage, technical proficiency, and consumer reluctance (Mesjar et al., 2023).

2. Technology

There is an increased demand in the Fashion Industry for the implementation of sustainable technology to streamline the supply chain process (Mesjar et al., 2023). Mesjar and colleagues state that interest has grown due to increased conscious consumer attention coupled with government demands to reduce and manage the fast fashion cycle, harmful industrial emissions, resource usage and waste generation in

the fashion industry. The study also reports that COVID 19 accelerated the adoption of immersive technology due to lockdowns disrupting the typical logistics and production systems that were predominantly physical, forcing to embrace digital systems. As professor Will Steffan elaborates in his studies, "if you drive a technological change/adoption up to 25% to 30%, it becomes self-sustainable". Therefore, it is evident that when a "traditional" system can no longer operate to its full potential under the pressure of rapidly evolving technology, it will force that scheme to adapt and make strategic changes to align with evolving environments (*Will Steffen*, 2017).

The digitisation of the fashion supply chain process is seen as a viable solution to address the rapid exhaustion of natural resources and its harmful effects on the environment. Experts also believe that this would help the "de-materialisation" of the Fashion industry (Särmäkari, 2023) to address the over-consumption and the over-production of fashion as a result of the Fast fashion business model.
The typical supply chain of the Fashion Industry originates from the Design and Development phase which is a strenuous iterative process. It then goes through production and manufacture and lastly consumption. Mesjar et al., 2023 states that originally immersive technologies such as, 3D visualisation, AR and VR were used to raise awareness towards the integration of sustainable technologies, while also helping reduce physical waste that is generated along the supply chain. Moreover, 3D renders of physical products can be evaluated across a variety of design variations without requiring physical production, helping product de-materialisation. Särmäkari (2023) reports that this process reduces lead times on labour and raw material logistics, while optimising time management and product delivery. One study conducted by Casciani et al. (2022) has determined that the digitisation of "fashion" has saved 3,300 Litres of water per garment and has positively impacted the reduction of the carbon footprint of fashion production and manufacture.

There is a general consensus that the reluctance for the integration of new technologies to the traditional supply chain cycle of the fashion industry is due to the requirement of high level of technical proficiency, which in turn demands high costs (Mesjar, Cross, Jiang, & Steed, 2023), even though there is an apparent skill gap in the present state of fashion designing in the industry. Mesjar et al. (2023) reviews multiple studies on the effectiveness of 3D design techniques to the traditional fashion design model to achieve sustainability. The study had concluded that due to the highly technical nature of the processes in adapting the technology, it was time-consuming to use AR/VR technologies, specifically in 3D modelling, at the time of the study. Moreover, Mesjar et al. (2023) finds that technology at the time was also premature for best potential application in design, yet technologies such as CAD and similar contribute effectively to reduce sampling resources, costs, and timescales. In addition, some of the most notable projects Mesjar et al. (2023) review is zero-waste fashion design with the integration of 3D design processes (McQuillan, 2020) and source-local and sell local/made-to-order business model starting with digitally prototyped/sampled digital twins (Black, 2019).

The brand Fabricant was the first to embrace a 3D digital design workflow, and Carlings was the first brand to launch a fully virtual clothing line for consumers (designboom, 2019). This methodology was later adopted by fashion studios such as Atacac, Neuro studio and DressX, who have become pioneers of this field. It is worth noting that the gaming industry is, in a sense, the true pioneer of 3D-based fashion design practices, which later trickled into the fashion design industry. This marked the "gamification" of Fashion. Micheletti (2017) refers to the Gamification of the fashion as the use of elements from games, such as game avatars, and design techniques in a non-game related context to transform "boring or repetitive fashion-related activities into more fun and engaging experiences" (Micheletti, 2017, p. 4). The author refers to this as a way to create a "fashion game" scenario to increase consumer engagement and to research inter-connecting opportunities from the gaming industry for fashion

product discovery, design, development, and marketing. The high-street luxury brand Louis Vuitton used the digital avatar of the game character "Lightning" from the Final Fantasy game series to create a digital spring/summer collection called "series 4" in 2016, which was immensely popular among its customer base and helped inter-connect two separate target markets of fashion and game (*"Lightning becomes a fashion icon in Louis Vuitton's 'Series 4' Campaign" - Square Enix North America Press Hub*, n.d.).

Immersive media in the fashion industry

The earliest technology that was adopted by the fashion industry was 2D-based CAD (computer aided designing) such as Adobe photoshop, and Illustrator that trickled down from the graphic design industry. Then, 3D technology-based design software with digital pattern making capabilities such as *Lectra, Gerber and CLO3D* was embraced. These were designed specifically for the Fashion Industry influenced by the Gaming development and design industry *(Marvelous Designer)* to better digitise and streamline the design and development process. These softwares contributed to digitise other parts of the fashion chain as well, such as streamlining fashion production and manufacture using digital Technical Specification Packs, digital prototypes, and samples.

Current practitioners: Independent Designers and methodology

There are many independent designers who have created their own methodology based on immersive technologies. They have become leading figureheads inter-connecting digital fashion technologies contributing to innovation and sustainability. Indie design practitioners such as Anifa Mvemba with her brand "Hanifa" and Trần Quỳnh Nhi have revolutionised the way creativity is presented, where they use NFTs and game design tactics such as, digital avatars to present collections, with the use of immersive technologies, creating ground-breaking projects where 3D visualised fashion collections were presented on a digital runway (Oni, 2025). Moreover, New Zealand designer Helena Steinmann with her brand

Weft digital, follows a methodology where she provides digital fashion design solutions to brands to integrate 3D into their value chain. Through Steinmann's brand, her professional practice has provided a solution to digital skill gaps and according to her promote the reduction of waste generation and fashion emissions with 3D product development (*Weft Digital Aotearoa*, n.d.). Thus, digitally driven processes have aided designers to better conceptualise their design and development processes, on top of streamlining production and manufacture to an "on-demand" business model avoiding mass production of collections. It has allowed them to be innovators among their peers as they now exist at the cross-roads of multiple industries, bridging a new skill gap of digital fashion product design, visualisation, and innovation.

Stephy Fung

Stephy Fung is a Chinese digital designer / artist based in London, England, UK. She comes from a Graphic design background, and currently follows a strict 3D CAD-based design methodology. She uses a specific design workflow between softwares CLO3D, Substance painter and Cinema 4D. Since her methodology and design aesthetic is innovative, her work exists at the intersection of graphic design and gaming industries, where she combines innovative immersive technologies with traditional design techniques to bring her ideas to life. She has done independent projects, as well as collaborative 3D-based digital fashion projects. Some of the most notable work includes projects for Dell, Paco Rabanne, Vogue Singapore, Lenovo, and Selfridges (Stephanie Fung, n.d.).

Stephy Fung in her online journal emphases that immersive technology is "rather about cleaning up the current industry through better waste management" and improving efficiency than displacing jobs (Fung, 2024). Through her work, Fung has demonstrated how immersive technology-based 3D design

methodologies can be utilised to foster a more sustainable fashion industry by streamlining fashion conceptualisation to production and manufacture.

"Digital fashion is the glow-up the industry needs. Less waste, greater efficiency, and more creativity. From gravity-defying looks to fiery fits, digital design lets you express yourself in ways you have dreamed of."

(*Stephanie Fung - The New Order - Selfridges x Digi-Gxl*, n.d.)

Anna Liedtke

Anna Liedtke, born in Germany also known as 'aschno' is a digital fashion designer based in Amsterdam, Netherlands. She comes from a fashion design background with management and creative direction expertise. "Liedtke now works as a freelance designer and previously served as content director for the renowned digital fashion brand The Fabricant, where she led a team of creatives on 3D fashion projects. Priorly she was the Senior project manager at Hugo Boss based in Amsteradam. Liedtke had started her

digital fashion design journey with the aim to reduce fashion waste generation in design and sampling with a focus on fostering fashion sustainability. This aim was a direct result of her experience at Hugo Boss, where she reports that the company had "one plane per month, which is going all over the world to just ship swatches from A to B" and also adding that the company had produced "thousands of prototypes per year, which would end up in trash because everything you produce for sample collection is not going to sell afterwards" (Roob, 2025).

Thus, Liedtke now follows a strictly 3D CAD-based methodology between softwares of CLO3D, Marvelous Designer, Substance Painter, and Unreal Engine 5. Liedtke also dictates that using a methodology that is based on digital technologies has helped her explore creative freedom to experiment with designs and has expanded her conceptualisation of fashion "far beyond what our reality could ever achieve" (*Anna Liedtke - COEVAL Magazine*, 2022).

> "I believe digital fashion provides the freedom for limitless creativity and envisions a future where everyone has the opportunity to create their own unique digital wardrobe."

(*WHOLELAND — Aschno*, n.d.)

Current Practitioners: Businesses and brands; their methodology and business model.

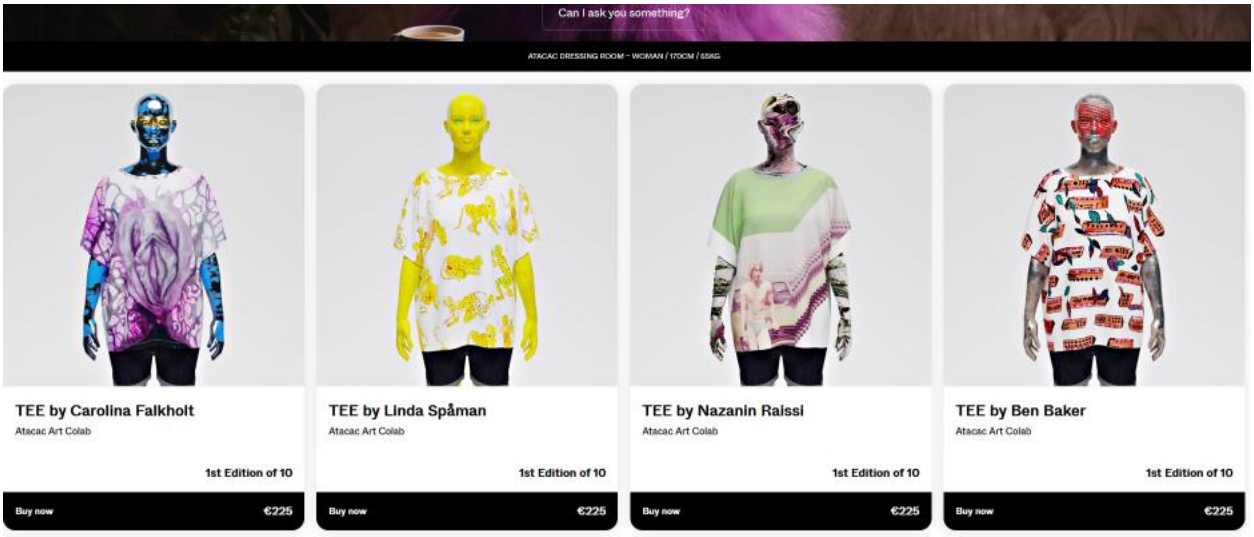
Atacac

Atacac is a digital fashion house that is pioneering the innovations in 3D fashion visualisation and sustainable technology using immersive technology. Two designers founded the house: a fashion designer specialising in R&D, Richard Lindqvist and a digital creative practitioner Jimmy Herdberg. Särmäkari (2023) dictates that when she had researched the studio, the company had nine employees, where each of them focused on a digital technology-based specialisation. Some of these specialisations are, 3D design-based fashion marketing and communication techniques, shareware-based digital pattern downloadables, digitisation of physical fabric swatches and 3D visualisation of garments.

The founder, Richard Lindqvist had researched on an alternative digital pattern cutting/ draping methodology in his studies and professional work at Atacac. This was called "Kinetic garment construction theory," a methodology based on the "static matrix of a non-moving body" with the combination of the "fundamental relationship between dress, garment construction, and the body, working from the body outward" (Lindqvist 2015, 348). This technology was experimented with the use of CLO3D and developed into a reverse production process to design and manufacture clothes. This started with the creation of a virtual sample then produced on-demand at their in-house micro factory (Särmäkari, 2023). Atacac also follows a unique pricing model where the earlier one would purchase their designs, the cheaper it would be. Thus, Särmäkari (2023) describes this creates a minimal "luxuriously priced" inventory for their customer base. Särmäkari (2023) reports that this business model used by Atacac facilitates "micro trend forecasting" that forces designers to keep evolving their

products throughout its “virtual” shelf-life. This theory is further supported by the findings of Kim Fraser in her studio-based research (Fraser, 2009), which was focused on fashion process rather than fashion artefact.

Fraser’s reflections on deconstruction/reconstruction methodologies to develop prototypes by a rigorous iterative process are most useful and can be applied to innovative exploration to mitigate design and development waste that is related to sustainability efforts in that context. These studies informed that the repeatability of fashion products, by focusing on developing prototypes, helped identify appropriate manufacturing knowledge/ techniques and processes required to successfully as well as efficiently “repeat” a product to ensure longevity, which is one of the fundamental aspects of sustainability the fashion industry is trying to achieve. Murray (2022) explains that upcycling textiles should not be merely conserving the resources that goes into production, but also should focus on the value embodied in them by the application of knowledge during their “re-circulation” (Murray, 2002). Which according to my point of view, is the fundamental design and development theory Atacac employs in their methodology. Atacac has further expanded their capabilities of digital transformative technologies with the integration of virtual assistants, virtual try-ons and AI- based design generation, which are all show-cased through their interactive 2D and 3D- based website Atacac.com.



(*Atacac Online Shop – with Virtual Fitting in Our Interactive Dressing Room*, n.d.)

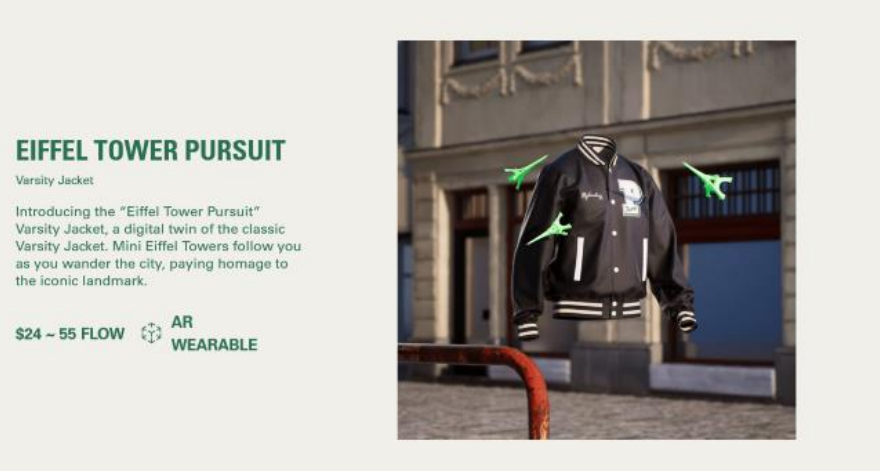
The Fabricant

The Fabricant is known as the first digital fashion house to pioneer digital fashion visualisation. The fully digital fashion house was founded in 2018 by Kerry Murphy who is a filmmaker and a VFX specialist along with Amber Jae Slooten who is a creative director. The design methodology used by Fabricant focuses on beginning with a concept or a client brief with a fully drafted technical specification pack. Then the garment design and development take place creating a "digital twin" in 3D format on CLO3D or Marvelous designer with the integration of Unreal Engine, Adobe substance painter, where the garment is digitally draped and designed on a 3D model/avatar. The garments are designed in 3D format as this is the house's design philosophy unless the garment is required specifically in physical form by the client. The house also believes that this design process creates a space for limitless creativity without any stereotypical design constraints of the fashion industry, some of which are closely related to culture, social roles, gender-bias (*FASHION STUDIES*, n.d.), and expectations (Crane, 1999). Crane dictates that cultural decorum, social roles and societal expectations coupled with industrial structures from mass-markets and luxury segments duly affect designers' roles hindering their innovative potential. Through

digital fashion processes, as elaborated by the Fabricant's brand ethos, these constraints can be overcome using 3D design tools that expand limitless creative expression, allowing a greater degree of creative fashion design innovation and exploration as the products exist in digital form and only through true query it is decided whether the product should be materialised.

Moreover, the fashion house Tommy Hilfiger approached the Fabricant in 2019 to digitally transform the company by 2022. They now use a business model where they start with creating and selling digital sample/ prototypes to made-to-order physical garments, exponentially reducing textile waste that is created during its cutting process and manufacturing. They have also significantly reduced the carbon footprint by incentivising digital consumerism (*The Fabricant*, n.d.) without creating a physical product unless by order.

Kerry Murphy, the founder of The Fabricant asserts that for brands and companies to ensure longevity, where fashion and technology is intertwining at a rapid pace, a notable change in attitude towards "transformation" and "adoption" in design technology is essential. He reflects that "our solution", reflecting on his digitised design methodology, "requires a shift in mindset, which can be very difficult for a brand or a company that has been doing things the same way for over 100 years" (Särmäkari, 2023). Stressing that business adaptation to digital transformation is inevitable.



(*Collections / The Fabricant*, n.d.)

3. Digitisation of the Fashion industry

The Fashion Industry has been increasing efforts in opportunities for sustainable transformation with the integration of immersive technologies to address accelerating environmental concerns of production and manufacturing. Studies have revealed that AI applications incorporated in different phases of the Fashion processes, such as fashion inspiration research, design, production, manufacture, marketing, sales, customisation, and overall streamlining of supply chain management have a greater chance of contributing to sustainable transformation and adaption of the fashion industry (Ramos et al., 2023) and (Bieńkowska, n.d.). Moreover, AI technologies in Fashion can help boost the industry's increasing efforts to move away from the Fast-fashion production cycles to sustainable ones, where the technology can provide predictive analysis to make production more efficient and enhance product longevity, while reducing the high-turnover rate of fast fashion.

The study conducted by Ramos, 2023, discusses that technologies such as, *Artificial Intelligence* and *Digital Twin/Digital Identity* technologies enables data-centric design, as well as information required to forecast "experience-oriented services" such as virtual fitting rooms and customisable virtual stylists

that has optimal efficiency. Ramos also reviews that AI technologies helps boost sustainability efforts by providing resource management analysis, waste control analysis, and predictive analysis for production (Ramos et al., 2023) helping cut product wastage (Rathore, n.d.). Bieńkowska, 2024 in her study "The effects of artificial intelligence on the fashion industry, opportunities and challenges for sustainable transformation" observes that despite the availability of opportunities in embracing automation technologies, limitations and challenges must be addressed for the successful implementation of digital technologies.

While the fashion industry currently uses these technologies in specific areas such as, Fabric textile production, Business to Business distribution and customer service operations (chatbots, AI stylists and virtual assistants) further quantitative research and monitoring can be conducted for better adoption and future opportunities in fashion curriculum. Though, limitations include maintaining facilities of large datasets that are live and static involving high implementation costs, which is a grave concern for companies that value profit goals over environmental preservation. Bieńkowska, 2024 also suggests that there can be a middle ground where commercial and environmental goals are equally satisfied to develop better strategies to implement and adopt automative technologies (Bieńkowska, n.d.). Additionally, the international research journal of Modernisation in Engineering Technology and Science in the study discusses that AI technology based on immersive experiences, especially virtual try-ons, AI-generative designing, digital fashion design, and digital twins can help explore individuality, self-identity and sustainability in the fashion industry (Guruprasad et al., n.d.).

Digital Twin technology

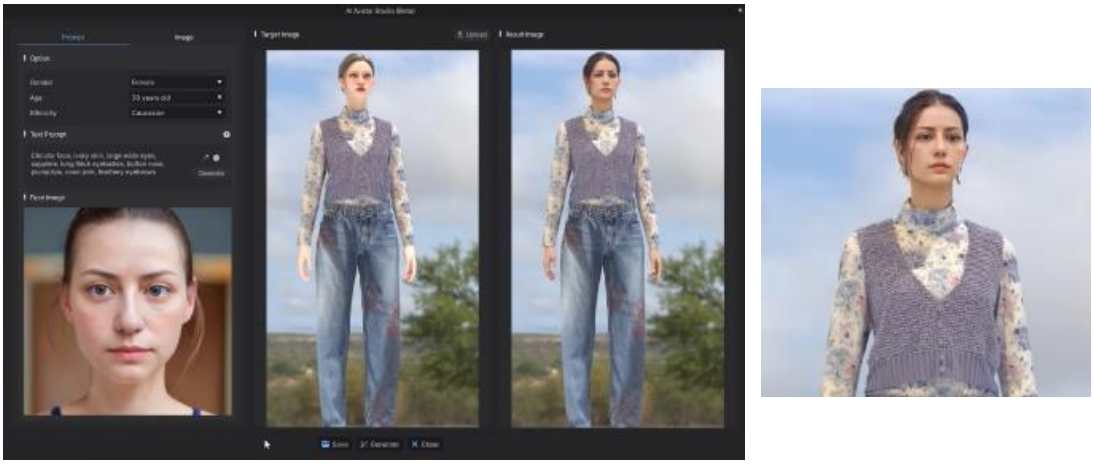
Digital Twinning is transforming the state of the fashion industry rapidly. A review by Wilking et al. (2021) converge on the definition that a Digital Twin is a "digital representation of a product instance"

that has many properties and behaviours of its physical counterpart with a Digital Shadow built by a "Digital Master" (Wilking et al. 2021, p. 1294). With the evolution of AI-based technologies such as DT revolutionising the fashion design, development, and production cycles by helping manage current physical and virtual sustainability metrics that are in place (Wagner & Kabalska, 2022). Some of which are, reducing carbon footprint, cost management, waste management, production water usage, and social Impact (Casciani et al., 2022). Wilking et al. (2021) states that there are many potential applications of digital twins that can be applied on various product life cycles, such as design, development, and implementation. These could either be system models, simulation models, and/or mathematical models, etc formed during the "virtual prototyping/ sampling" stage. An example would be the digital twins of models wearing 3D designed garments that help process fashion garment information based on its properties and behaviour data.

Digital twins can be visualised with technologies such as 3D modelling, AR/VR, digital prototyping/ sampling and these enable the de-materialisation of the current fashion industry supply chains, business models, retailing processes by streamlining design, prototyping and manufacture (Casciani et al., 2022). A study by Li and Liu 2024, reports that DTs that are applied during fashion product cycles such as design, identity verification, lifecycle tracking, intelligent manufacturing and immersive displays helps create new value by interconnecting NFT based ecosystems as well as games, extending fashion influence of brands and designers to virtual markets, where now the society is mostly virtually centralised (Li & Liu, 2024).

Digital twin of a pink blouse designed in CLO3D.

News—CLO. (n.d.). SwatchOn. Retrieved September 27, 2024, from https://swatchon.com/news/SwatchOn-partners-with-CLO-To-Forge-the-Future-of-Fashion-Digitization-7



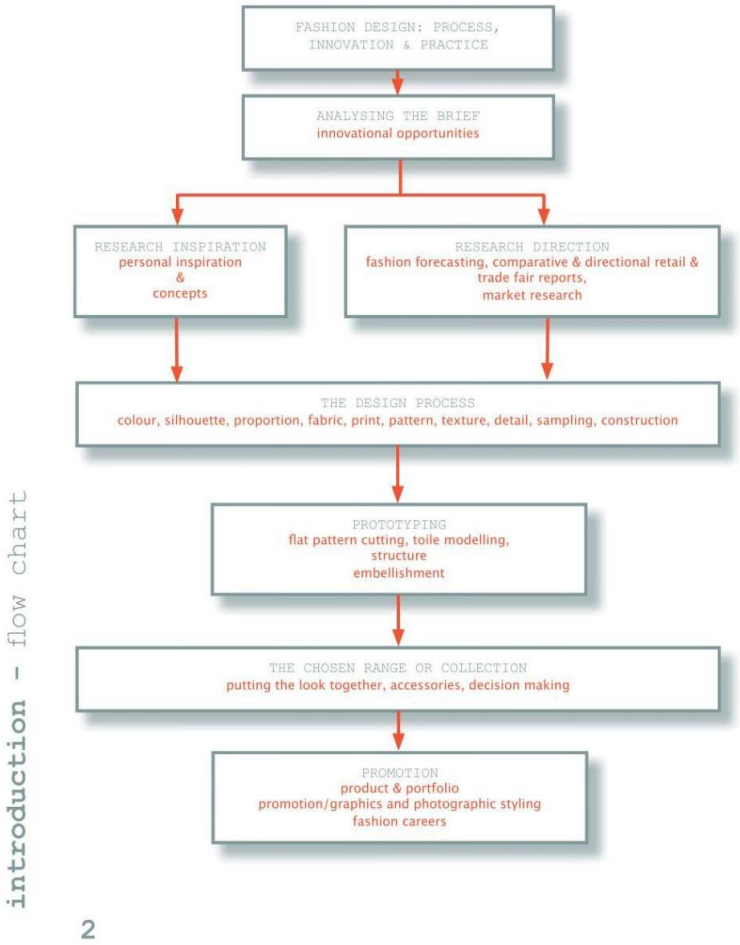
Digital twin of a human model generated using AI wearing a 3D outfit.

CLO (Director). (2024, July 3). *CLO 2024.1 New Feature Highlights (English)* [Video recording]. https://www.youtube.com/watch?v=2YrGzrVNZyc

It is evident that Digital twins help create product design and development transparency that can positively impact consumers as well fashion production life cycle be more sustainable. Sustainability benefits related to design such as, waste reduction from pattern making cycles to production and manufacture, demand management by fashion product forecasting, trend prediction and controlling over-production are success indicators (Akram et al., 2022). Though, implementation limitations with risks such as high initial investment, high-quality hardware and software, lack of qualified talent with technical skill requirements, reluctance for adoption due to fear of costs and loss should be addressed (Akram et al., 2022). A review by Akram, 2022 dictates that to answer these limitations, a rigorous process of sustainability impact evaluation must be put in place that produces measurable quantified data-driven insights rather than relying on qualitative assessments. In addition, Akram 2022 suggests that some technologies may be easier to adopt and show immediate results as compared to others (Akram et al., 2022) and (Casciani et al., 2022). For example, 2D and 3D design CAD software such as CLO3D, Style3D and Marvelous designer has a linear learning curve and is affordable - may prove beneficial for both smaller scale brands and individual creators as well as large scale organisations, as the fear of costs is the biggest limitation observed across the industry.

4. Discussion: practical project case study

My practical project component was critical to deduce the effectiveness of adopting immersive technologies in fashion design and development processes. This helped gauge how innovation and digital transformation solutions can help contribute to foster sustainability in the fashion industry. The project commenced with following the typical/ traditional design development methodology or the framework to conceptualise, design, develop and visualise the fashion collection.



The traditional fashion design methodology.

Mckelvey, K., & Munslow, J. (2012). *Fashion Design Process, Innovation & Practice* (2nd edition). A John Wiley and Sons, Ltd, Publication.

Following the above framework, specific components of the above methodology was digitised and experimented on as following: The digitisation of the design phase, prototyping, range plan and collection styling and promotion in reference to studies of Holly McQuillan (2020). The digitisation process was conducted with the use of digital design softwares, both 2D and 3D, such as Adobe photoshop, Adobe Illustrator, Apple Procreate, CLO3D, Marvelous Designer and Unreal Engine 5. This helped me function as a conduit between two distinct industries, fashion and gaming/VFX. Design and Development of the collection was unavoidably a hybrid process, where both manual design sketching,

illustration, development, and digital design development proved indispensable to ensure a successful and meaningful design experimentation creative practice.

Project Scope, Aim and Purpose

The main aim of the practical project was to create two fully virtual fashion collections with four looks each, where each look is a combination of a top and a bottom or a dress component. The target markets are primarily millennials, gen-z and gen-alpha who are easily influenced with digital technologies and virtual marketing tactics, as they now engage mostly in a virtual world setting and are trend-driven. In the context of industrial target markets, the gaming industry and VFX industries engaged in virtual modelling are targeted with the project outputs.

The primary collection explores the full potential of design and development capabilities of immersive technologies. This is creating digital twins of real-life couture designs that would be reflective of its physical existence in craftsmanship and design. The secondary collection is a ready to wear collection, which is a deconstructed/simplified version of the primary fashion collection. This collection reflects the design aesthetic and brand resonance of commercial brands such as NOMD, Zambesi and Zimmerman to explore more industry-based and manufacture-ready capabilities of digital twin product visualisation.

The secondary aim of this project is to showcase the 3D visualised garments through AI-generated models and digital twin models to explore capabilities of digital twin modelling technologies by creating digital prototypes to mitigate design and development waste and costs. The purpose of this methodology is to incentivise responsible fashion production and consumption through means of digital fashion design and consumerism, as well as effectively reducing fashion waste generated during the supply chain process of the apparel industry.

4.2: Project critical analysis

The digitisation of some of the most important components in developing a fashion collection was successful to a considerable extent as compared to the challenges and limitations that was overcome.

1. Efficiency in design, materials, and waste – In average, according to my own experience as a fashion designer and a creative director - a successful fashion collection requires at least a minimum of 6 months to rigorously design, develop and experiment with multiple, if not hundreds of samples and prototypes from swatch to sample. The digitised process was developed in reference to studies by Kim Fraser (2019) and Holy McQuillan (2020) on the repeatability of fashion garments, by focusing on developing multiple versions of a garment - identifying appropriate manufacturing knowledge/ techniques to efficiently "repeat" its design (Gwilt & Rissanen, 2011) by developing variations with the use of a digitised design process (McQuillan, 2020). In this sense, with the findings of Casciani et al. (2022) I have saved 3,300 litres of water per digitised prototype/sample. Moreover, a comparative assessment was conducted as part of the practical methodology, estimating the carbon emissions of traditional versus digitised fashion design processes. The estimation was based on secondary sources and assumption-based calculations derived from my design practice. For a two-hour design cycle, the traditional methodology resulted in an estimated emission of 1.53 kg CO_2e, whereas the digitised approach emitted approximately 0.116 kg CO_2e. This suggests a carbon footprint reduction of approximately 1.414 kg over five iterations (comprising four digital prototypes and one final physical garment) for a long-sleeve tailored women's button-down shirt. This process was seamless where I created two entire collections, with a set of designs, developments (fashion gesture-line ups), and prototypes

via digital media in just three months due to digital asset availability (fabrics, textiles, trims, digital models) - a 98% of dematerialisation, where the remaining 2% accounts for creative process journaling, paper and physical sketchbooks for a hybrid process of design.

2. Cost efficiency - All the costs were directed to software subscriptions and digital asset access, such as digital fabric libraries created by fabric production companies.
3. Design development speed - The nature of the digital design process of 2D and 3D allowed a faster revision and development cycle. Traditionally, an extra prototype of a garment would need an extra set of altered patterns, fabric yardage, textiles and sewing supplies and hours of manual labour.
4. Design accuracy for production and manufacture – Since I used ASTM sizing standards (American Society for Testing and Materials), which focuses on body measurement sizing charts for apparel sizing and fit to develop my designs on digital twins of body sizes 6 and 12 with graded patterns, this ensures my digital patterns are ready for production. I also used pattern nesting feature in CLO3D, which nested all the patterns on to my designated fabric roll.
5. Market Responsiveness – The readiness of the collection was months ahead of schedule, where original launch timeline of eight months was reduced to five months. This created an opportunity to engage participatory culture through social media queries for product feedback for further design refinements.

Limitations and implications

Some procedures, such as the iterative design process between CLO3D and Unreal Engine 5 deemed that, to a certain extent technology is part of the problem, where I struggled with downloading and

transporting design assets between softwares. Without adequate hardware and a reliable internet connection with high speed, there must be solutions put in place well before execution of the project.

Due to my design process relying on cloud-based and real-time rendering software such as CLO3D and Unreal Engine 5, alongside a digital library of assets, I also used virtual collaboration tools including Microsoft SharePoint, OneDrive, and Google Drive to manage design files. However, an unstable internet connection caused delays in uploading and downloading both large-scale and small-scale design assets. Due to Digital assets requiring to be downloaded for use unlike in a real-life design situation, for example, where you would just buy or hire a model, presented an inconvenient problem of material consistency. Though this process proved entirely cost effective, where I cut all the patternmaking, textile, and fabrication costs.

The maintenance of the sewing machinery to create and experiment with physical samples was also replaced with a singular computer machine, otherwise typically requiring consistent upkeep of fixing/replacing needles, removing stuck threads, oil refills, etc to work on just the physical samples and prototypes. I also observed that if one factor dependant on technology fails, I.e. the computer hardware or software, the project component could not be progressed to its full capacity.

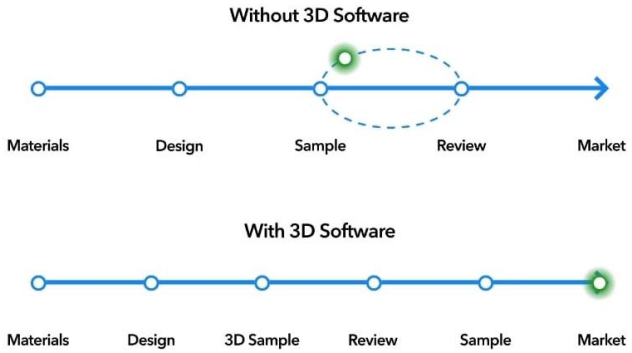
Moreover, the carbon footprint data between the traditional and the digitised suggest a substantial reduction, but the results are limited by the assumption-based methodology. As this methodology relied on sample scenario with several assumptive data, such as energy consumption, emission factor of New Zealand and typical fabric composition parameters. Therefore, the findings should be interpreted as a scenario-based estimation over an empirically verified data outcome.

There was also the need for high technical proficiency to manoeuvre the evolving nature of 3D design softwares and technology to harness the digital design capabilities to their full potential. It was imperative that I am well informed of the technical advancements/ state of the softwares, pipelines, and features throughout the project, consistently having the need to upskill my technical proficiency. I also discovered that the current state of technology (CLO3D and Unreal Engine 5) is evolving at a rapid rate with the development of AI as compared to when I presented this methodology proposal in 2023, which highlights the challenge of balancing conceptualisation, design, and production while keeping up with technological progress.

Though, I would agree that the opportunities that I observed through the project far outweigh the limitations discussed above. The best outcome was the time-efficiency of the project development framework, where I was months ahead in project deliverable timeline and the de-materialisation of the fashion design cycle. This allowed me to invest more time in project refinement throughout distinctive design methodology components. This also accelerated my product development processes, as I experimented and created multiple digital design prototypes and samples, as explored by the studies of Kim Fraser (2009). Therefore, cutting design and development waste altogether. It was apparent that this methodology was immensely cost effective and highly adaptive, where if physically created I would've required funds for fabrics, multiple iterations of prototypes, samples, mannequins, pattern-making supplies, travel for sourcing, extra time allocation for communication between cross-collaborators for design experimenting of textiles, a variety of sewing supplies, machinery and maintenance crew, etc.

The accuracy of garment visualisation was also high, as reflected by the digital patterns created in CLO3D on accurate ASTM standard digital twin body model measurements and showcased on US size 04

petite digital twins created using Metahuman Engine by Unreal Engine 5, adding to the realism factor. With the availability of the CLOSET CONNECT digital library of fabric assets that are provided by companies and the fabric creator in CLO3D, fabric accuracy was also accounted for, as I can mimic fabric property details down to its composition details.



Comparison of the design pipelines.

CLO | 3D Fashion Design Software. (n.d.). CLO Official Site. Retrieved September 29, 2024, from https://www.clo3d.com

Ultimately, I stress that this design methodology is complex, requiring a high level of technical proficiency to handle the effective utilising of softwares. Expertise in fashion design and patternmaking is also required to apply accurate fashion design and development techniques. Adapting to this methodology presents a steep learning curve in fashion and technology for a learner that may come from any design or computer science-based background. For this methodology to be successful, it is imperative that this procedure is implemented at an advanced level, where technology is readily available (hardware and software) and handled by senior levels of professional practitioners with a high technical proficiency, a keen sense of adaption and fashion design knowledge.

Conclusion

This thesis builds a review on how the fashion industry can be sustainable using immersive technology and assesses to what extent it can be achieved with its adaptation. Core discourses such as sustainability, technology, and digital identity are explored to inform the reader about current issues in the fashion industry, which have a drastic impact on the planet, both to its environment and the people. Additionally, the thesis presents a practice-based case study to address some of the most pressing issues by implementing a digitised fashion design and development methodology to the traditional framework - to explore how innovative digital transformative technologies can mitigate design waste, carbon emissions and reduce raw material usage.

The study draws inspiration from the gaming and 3D modelling industries, reviewing how their methodologies can be adopted to streamline the initial stage of the fashion supply chain with a creative and innovative edge. A contextual analysis is provided on current practitioners and business models using digitised design methodologies, enhancing the research angle on technological applications. Furthermore, a literature review encompassing scholarly and grey literature under the three main discourses supports the research. However, a key limitation for the progress of the project is that the specific methodology relies on emerging technology, presenting a lack of academic research applied in practice. Additionally, the rapid advancement of these technologies during the project's development timeframe compared to when it was proposed in 2023, created technical challenges, requiring continuous upskilling and troubleshooting of unforeseen software issues. This raises concerns about fully embracing a digitised methodology over a hybrid approach even though the outcome of the practical project helped mitigate production waste and carbon emissions of design and development logistics. Moreover, the requirement for advanced technological facilities, both software and hardware, was a significant investment, yielding innovation but also presenting financial challenges.

Ultimately, the study reveals that this methodology is better harnessed by practitioners with high technical proficiency and will be most effective when implemented at an advanced level in both design and technology. The study also finds that while virtual design may boost demand and help de-materialise segments of the fashion supply chain, it might not effectively address sustainability due to fashion's traditional economic model being relative to its physical growth. This highlights the importance of balancing technological innovation with practical accessibility in sustainable fashion design and development.

References

Adamkiewicz, J., Kochańska, E., Adamkiewicz, I., & Łukasik, R. M. (2022). Greenwashing and sustainable fashion industry. *Current Opinion in Green and Sustainable Chemistry, 38*, 100710. https://doi.org/10.1016/j.cogsc.2022.100710

Akram, S. V., Malik, P. K., Singh, R., Gehlot, A., Juyal, A., Ghafoor, K. Z., & Shrestha, S. (2022). Implementation of digitalized technologies for fashion industry 4.0: Opportunities and challenges. *Scientific Programming, 2022*(1), 7523246. https://doi.org/10.1155/2022/7523246

Alizadeh, L., Liscio, M. C., & Sospiro, P. (2024). The phenomenon of greenwashing in the fashion industry: A conceptual framework. *Sustainable Chemistry and Pharmacy, 37*, 101416. https://doi.org/10.1016/j.scp.2023.101416

Anna Liedtke—COEVAL Magazine. (2022, February 24). *COEVAL*. https://www.coeval-magazine.com/coeval/anna-liedtke

Aschno. (n.d.). *Home*. https://aschno.com

Atacac. (n.d.). *Drops | Products and NFTs*. Retrieved March 17, 2025, from https://atacac.com/drops/

Atacac. (n.d.). *Online shop – with virtual fitting in our interactive dressing room*. https://atacac.com/shop/

Atacac. (n.d.). *Online shop | Merging the virtual with the real*. https://atacac.com/

Atacac. (n.d.). *The company*. http://atacac.com/company/

Bank, E. (2024). Fashion's greenwashing problem and how to better protect consumers. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4849023

Bieńkowska, J. (n.d.). The effects of artificial intelligence on the fashion industry—Opportunities and challenges for sustainable transformation. *Sustainable Development, n/a(n/a)*. https://doi.org/10.1002/sd.3312

Casciani, D., Chkanikova, O., & Pal, R. (2022). Exploring the nature of digital transformation in the fashion industry: Opportunities for supply chains, business models, and sustainability-oriented innovations. *Sustainability: Science, Practice and Policy, 18*(1), 773–795. https://doi.org/10.1080/15487733.2022.2125640

CLO (Director). (2024, July 3). *CLO 2024.1 new feature highlights (English)* [Video recording]. https://www.youtube.com/watch?v=2YrGzrVNZyc

CLO Official Site. (n.d.). *CLO | 3D fashion design software*. Retrieved September 29, 2024, from https://www.clo3d.com

Collections / The Fabricant. (n.d.). *The Fabricant*. Retrieved April 27, 2025, from https://www.thefabricant.com/collections

Colombi, C., & D'Itria, E. (2023). Fashion digital transformation: Innovating business models toward circular economy and sustainability. *Sustainability, 15*(6), 4942. https://doi.org/10.3390/su15064942

Crane, D. (1999). Fashion design and social change: Women designers and stylistic innovation. *Journal of American Culture, 22*(1), 61–68. https://doi.org/10.1111/j.1542-734X.1999.00061.x

Designboom, kieron marchese I. (2019, November 18). Designers are now selling "digital clothes" that don't actually exist. *Designboom | Architecture & Design Magazine*. https://www.designboom.com/technology/digital-clothes-virtual-fashion-carlings-the-fabricant-11-18-2019/ Dokumen.Pub. (n.d.). *Fashion studies: Research methods, sites and practices*. Retrieved April 29, 2025, from https://dokumen.pub/fashion-studies-research-methods-sites-and-practices-9781472583178-9781472583161-9781474220163-9781472583185.html

Du Pisani, J. A. (2006). Sustainable development – Historical roots of the concept. *Environmental Sciences, 3*(2), 83–96. https://doi.org/10.1080/15693430600688831

Ecodesign for Sustainable Products Regulation—European Commission. (n.d.). Retrieved April 29, 2025, from https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-

labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en

Environmental Audit Committee. (2019). *Fixing fashion: Clothing consumption and sustainability* (Sixteenth Report of Session 2017–19). https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/1952.pdf

Farrer, J. (2019). *Fashion, dress and sustainability: Understanding luxury fashion in a circular economy*. Palgrave Macmillan.

FASHION STUDIES: Research Methods, Sites and Practices 9781472583178, 9781472583161, 9781474220163, 9781472583185. (n.d.). *Dokumen.Pub*. Retrieved April 29, 2025, from https://dokumen.pub/fashion-studies-research-methods-sites-and-practices-9781472583178-9781472583161-9781474220163-9781472583185.html

Fraser, K. (2009). *ReDress—ReFashion as a solution for clothing (un) sustainability* [Master's thesis, Auckland University of Technology]. https://hdl.handle.net/10292/817

Full article: Digital 3D fashion designers: Cases of Atacac and The Fabricant. (n.d.). Retrieved April 27, 2025, from https://www.tandfonline.com/doi/full/10.1080/1362704X.2021.1981657#d1e566

Fung, S. (2024, June 18). Digital fashion industry update [Substack newsletter]. *Digital Fashion Journal*. https://stephyfung.substack.com/p/what-is-the-digital-fashion-industry

Garcia-Ortega, B., Galan-Cubillo, J., Llorens-Montes, F. J., & de-Miguel-Molina, B. (2023). Sufficient consumption as a missing link toward sustainability: The case of fast fashion. *Journal of Cleaner Production, 399*, 136678. https://doi.org/10.1016/j.jclepro.2023.136678

Guruprasad, Prof. M., Verma, A. K., Chandran, A., Saluunke, A., Tushar, R., & Tarnekar, S. (n.d.). Intervention of AI in fashion industry. *International Research Journal of Modernization in Engineering Technology and Science*. https://doi.org/10.56726/irjmets

Gwilt, A., & Rissanen, T. (2011). *Shaping sustainable fashion: Changing the way we make and use clothes*. Earthscan.

Highsnobiety: Not in Paris | The Fabricant. (n.d.). *The Fabricant*. Retrieved March 17, 2025, from https://www.thefabricant.com/collection/highsnobiety-not-in-paris

How to build a circular economy | Ellen MacArthur Foundation. (n.d.). Retrieved April 29, 2025, from https://www.ellenmacarthurfoundation.org/

Iannilli, V. M., & Spagnoli, A. (2024). Conscious fashion culture: Rethinking consumption in contemporary fashion. *Fashion Highlight, 3*, 8–15. https://doi.org/10.36253/fh-2875

"LIGHTNING becomes a fashion icon in Louis Vuitton's 'Series 4' campaign"—Square Enix North America Press Hub. (n.d.). Retrieved April 29, 2025, from https://press.na.square-enix.com/LIGHTNING-BECOMES-A-FASHION-ICON-IN-LOUIS-VUITTONS-SERIES-4-CAMPAIGN

Liscio, M. C., & Sospiro, P. (n.d.). Life cycle assessment on fashion industry: Four case studies. *CEST2023, Athens, Greece*. https://doi.org/10.30955/gnc2023.00283

McDowell, M. (2020, April 28). Fashion brands embrace 3D design. *Vogue Business*. https://www.voguebusiness.com/technology/fashion-brands-embrace-3d-design

McFall-Johnsen, M. (n.d.). The fashion industry emits more carbon than international flights and maritime shipping combined. Here are the biggest ways it impacts the planet. *Business Insider*. Retrieved April 10, 2025, from https://www.businessinsider.com/fast-fashion-environmental-impact-pollution-emissions-waste-water-2019-10

McKelvey, K., & Munslow, J. (2012). *Fashion design process, innovation & practice* (2nd ed.). A John Wiley and Sons, Ltd. http://archive.org/details/fashion-design-process-innovation-practice-pdfdrive

McQuillan, H. (2020). Digital 3D design as a tool for augmenting zero-waste fashion design practice. *International Journal of Fashion Design, Technology and Education, 13*(1), 89–100. https://doi.org/10.1080/17543266.2020.1737248

Mesjar, L., Cross, K., Jiang, Y., & Steed, J. (2023). The intersection of fashion, immersive technology, and sustainability: A literature review. *Sustainability, 15*(4), Article 4. https://doi.org/10.3390/su15043761

Micheletti, A. (2017). Motivating and involving users through gamification: A proposal. In M. Agosti, M. Bertini, S. Ferilli, S. Marinai, & N. Orio (Eds.), *Digital libraries and multimedia archives* (Vol. 701, pp. 20–30). Springer International Publishing. https://doi.org/10.1007/978-3-319-56300-8_3

News—CLO. (n.d.). *SwatchOn*. Retrieved September 27, 2024, from https://swatchon.com/news/SwatchOn-partners-with-CLO-To-Forge-the-Future-of-Fashion-Digitization-7

Oni, M. (2025, January 22). How top indie fashion designers like Hanifa are embracing digital fashion. *The F\ Word**. https://thefword.ai/how-top-indie-fashion-designers-like-hanifa-are-embracing-digital-fashion/

PhygitalTwin | LinkedIn. (n.d.). Retrieved June 16, 2025, from https://uk.linkedin.com/company/phygitaltwin

Putting the brakes on fast fashion. (2018, November 12). *United Nations Environment Programme*. https://www.unep.org/news-and-stories/story/putting-brakes-fast-fashion

Ramos, L., Rivas-Echeverría, F., Pérez, A. G., & Casas, E. (2023). Artificial intelligence and sustainability in the fashion industry: A review from 2010 to 2022. *SN Applied Sciences, 5*(12). https://doi.org/10.1007/s42452-023-05587-2

Rathore, B. (n.d.). From trendy to green: Exploring AI's role in sustainable fashion marketing. *International Journal of New Media Studies, 6*(2). https://doi.org/10.58972/eiprmj.v6i2y19.120

Roob, C. (2025, June 16). Digital vs slow: The future of sustainable fashion | Atmos (2025). *Flybynightgraphics*. https://flybynightgraphics.com/article/digital-vs-slow-the-future-of-sustainable-fashion-atmos/1337

Särmäkari, N. (2023). Digital 3D fashion designers: Cases of Atacac and The Fabricant. *Fashion Theory, 27*(1), 85–114. https://doi.org/10.1080/1362704X.2021.1981657

Sayem, A. S. M. (2022). Digital fashion innovations for the real world and metaverse. *International Journal of Fashion Design, Technology and Education, 15*(2), 139–141. https://doi.org/10.1080/17543266.2022.2071139

United Nations Conference on Trade and Development. (2024). *Secondhand clothing markets: An overview in Uganda and the United Republic of Tanzania*. https://unctad.org/system/files/non-official-document/-smep-shc_19-11-2024-2-2.pdf

Silvestri, B. (2020). The future of fashion: How the quest for digitization and the use of artificial intelligence and extended reality will reshape the fashion industry after COVID-19. *ZoneModa Journal, 10*(2), Article 2. https://doi.org/10.6092/issn.2611-0563/11803

Stephanie Fung. (n.d.). Retrieved July 30, 2024, from https://stephyfung.com/home

Stephanie Fung—The New Order—Selfridges x Digi-Gxl. (n.d.). Retrieved April 25, 2025, from https://stephyfung.com/the-new-order-selfridges-x-digi-gxl

THE 17 GOALS | Sustainable Development. (n.d.). *United Nations*. Retrieved April 10, 2025, from https://sdgs.un.org/goals

The Business of Fashion (Director). (2025, April 11). *The business case for sustainable fashion | BoF CROSSROADS 2025* [Video recording]. https://www.youtube.com/watch?v=GtKTbRl8-CI

The Dark Side of Our Love Affair with Temu and Ultra-Fast Fashion. (n.d.). *Tearfund New Zealand*. Retrieved April 16, 2025, from https://www.tearfund.org.nz/Get-Involved/The-Dark-Side-of-Our-Love-Affair-with-Temu-and-Ultra-Fast-Fashion

The Ethical and Sustainability Concerns of Temu and Shein. (2024, May 29). *Me.Motherearth*. https://memotherearthbrand.com/blogs/plastic-free-living/the-ethical-and-sustainability-concerns-of-temu-and-shein

The Fabricant. (n.d.-a). *I Amsterdam*. Retrieved April 27, 2025, from https://www.iamsterdam.com/en/business/key-sectors-for-business/creative/stories/the-fabricant

The Fabricant. (n.d.-b). *The Fabricant: A premium digital fashion platform for brands*. Retrieved March 17, 2025, from https://www.thefabricant.com/for-brands

Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). What is a digital twin? – Definitions and insights from an industrial case study in technical product development. *Proceedings of the Design Society: DESIGN Conference, 1*, 757–766. https://doi.org/10.1017/dsd.2020.15

Weft Digital Aotearoa. (n.d.). *Weft Digital Aotearoa*. Retrieved June 18, 2025, from https://weftdigital.co.nz/

WHOLELAND — aschno. (n.d.). Retrieved April 25, 2025, from https://aschno.com/wholeland

Wilking, F., Schleich, B., & Wartzack, S. (2021). Digital twins – Definitions, classes and business scenarios for different industry sectors. *Proceedings of the Design Society, 1*, 1293–1302. https://doi.org/10.1017/pds.2021.129

Will Steffen—The beginner's guide to the Anthropocene. (2017, August 26). *RNZ*. https://www.rnz.co.nz/national/programmes/saturday/audio/201856208/will-steffen-the-beginner-s-guide-to-the-anthropocene