9th International scientific conference
„Contemporary trends and innovations in the textile industry“
17-18th September, 2026, Belgrade, Serbia

DIGITAL 3D GARMENT DEVELOPMENT PROCESS: FROM CONCEPT TO VIRTUAL PROTOTYPE

Professional paper
DOI: 10.5937/CT_ITI26028B

Nadiia P. Bukhonka

University of Novi Sad, Technical faculty "Mihajlo Pupin" Zrenjanin, Serbia
E-mail: nbukhonka@gmail.com, ORCID ID: 0000-0002-2753-2440

ABSTRACT: *The digital transformation of the apparel industry is increasingly driven by the integration of 2D pattern development and 3D virtual simulation technologies. This study focuses on the digital 3D garment development process using VStitcher (Browzwear), presenting a structured workflow from the initial design concept to the final virtual prototype. The proposed approach emphasizes the transition from traditional physical sampling to digital prototyping, enabling improved efficiency, faster design interactions, and reduced material consumption. The workflow includes 2D pattern construction, material definition and mapping, virtual garment assembly, 3D simulation, and fit evaluation on a digital avatar. The results demonstrate that integrating 2D and 3D environments creates a continuous feedback loop that supports iterative refinement of design parameters and early detection of construction and fit issues. The study further confirms that virtual prototyping, supported by styling tools, enhances garment evaluation by enabling advanced manipulation and simulation of manual fitting adjustments. This contributes to reduced physical sampling, improved development accuracy, and increased workflow efficiency. However, simulation accuracy remains dependent on precise pattern construction, material parameter definition, garment complexity, and user expertise, while certain tactile fabric properties cannot yet be fully replicated digitally. Overall, the study demonstrates that 3D garment development systems such as VStitcher provide a robust methodological framework for more efficient, accurate, and sustainable apparel product development in both industrial and educational contexts.*

Keywords: *digital garment development, 3D apparel design, virtual prototyping, VStitcher (Browzwear), garment simulation.*

DIGITALNI 3D PROCES RAZVOJA ODEĆE: OD KONCEPTA DO VIRTUELNOG PROTOTIPA

APSTRAKT: *Digitalnu transformaciju industrije odeće sve više pokreće integracija 2D razvoja krojeva i 3D tehnologija virtuelne simulacije. Ova studija se fokusira na proces digitalnog 3D razvoja odeće korišćenjem VStitcher-a (Browzwear), predstavljajući* *strukturirani tok rada od početnog koncepta dizajna do finalnog virtuelnog prototipa. Predloženi pristup naglašava prelazak sa tradicionalnog fizičkog uzorkovanja na digitalno prototipiranje, omogućavajući poboljšanu efikasnost, brže interakcije sa dizajnom i smanjenu potrošnju materijala. Tok rada uključuje 2D konstrukciju krojeva, definisanje i mapiranje materijala, virtuelno sklapanje odeće, 3D simulaciju i procenu pristajanja na digitalnom avataru. Rezultati pokazuju da integracija 2D i 3D okruženja stvara kontinuiranu povratnu spregu koja podržava iterativno usavršavanje parametara dizajna i rano otkrivanje problema sa konstrukcijom i pristajanjem. Studija dalje potvrđuje da virtuelno prototipiranje, uz podršku alata za stilizovanje, poboljšava procenu odeće omogućavajući naprednu manipulaciju i simulaciju ručnog podešavanja pristajanja. Ovo doprinosi smanjenju fizičkog uzorkovanja, poboljšanoj tačnosti razvoja i povećanoj efikasnosti toka rada. Međutim, tačnost simulacije i dalje zavisi od precizne konstrukcije kroja, definicije parametara materijala, složenosti odeće i stručnosti korisnika, dok se određena taktilna svojstva tkanine još uvek ne mogu u potpunosti digitalno replicirati. Generalno, studija pokazuje da 3D sistemi za razvoj odeće, kao što je VStitcher, pružaju robustan metodološki okvir za efikasniji, precizniji i održiviji razvoj proizvoda odeće, kako u industrijskom tako i u obrazovnom kontekstu..*

Ključne reči: *digitalni razvoj odeće; 3D dizajn odeće; virtuelno prototipiranje; VStitcher (Browzwear); simulacija odeće.*

1. INTRODUCTION

The fashion industry is undergoing a profound digital transformation driven by advances in computer-aided design (CAD), computer-aided manufacturing (CAM), simulation tools, immersive visualization technologies, and, more recently, artificial intelligence (AI). These developments have fundamentally reshaped the garment development process, shifting traditional workflows based on manual sketching, physical patternmaking, and iterative sampling toward digitally integrated approaches. Within this context, 3D garment development has emerged as a key innovation, enabling garments to be designed, simulated, and evaluated in virtual environments before physical production [1]-[3]. The integration of AI further enhances these capabilities through automated design generation, predictive fit analysis, and optimization of material and construction parameters, improving efficiency and decision-making throughout the development cycle [4], [5].

A major advantage of the 3D garment development process is its ability to support a structured workflow from concept creation to virtual prototyping. Using specialized software, designers can develop digital patterns, define material properties, assemble garments, and evaluate fit and appearance on digital avatars. This approach facilitates rapid design iterations, reduces development time and costs, and minimizes dependence on physical samples [6]. The process typically consists of interconnected stages, including concept development, digital pattern construction, 2D/3D garment assembly, fabric simulation, and virtual fit evaluation. Through continuous feedback between these stages,

design, fit, and construction parameters can be iteratively refined, leading to shorter development cycles (by 50-75%) and improved product accuracy [7]-[11].
Beyond efficiency gains, 3D fashion design contributes to sustainability by reducing material consumption, textile waste, and the environmental impacts associated with physical sampling (Figure 1). Virtual sampling decreases the use of water, dyes, and chemicals and can reduce emissions by up to 97% [7], [13]. In addition, digital technologies enhance customization, visualization, and collaboration, while supporting faster time-to-market and more flexible product development processes [13], [13].

Figure 1: Key impacts and benefits of 3D fashion design in apparel development

Despite these benefits, several challenges remain. The accuracy of virtual simulations depends on the precise representation of material properties, garment construction details, and user expertise. Complex material behavior and certain tactile characteristics cannot yet be fully replicated in digital environments, limiting the complete replacement of physical prototyping. Furthermore, successful implementation requires not only technological infrastructure but also effective workflow integration and a strong foundation in patternmaking and garment construction principles [15], [16].
Although the benefits of 3D garment development are widely recognized, there remains a need for a clearer methodological understanding of how the complete digital workflow is

structured and implemented in practice. Therefore, the aim of this study is to analyze the digital 3D garment development process – from concept to virtual prototype – within a structured and iterative framework using VStitcher (Browzwear). Specifically, the study examines the key stages of the workflow, evaluates the role of enabling technologies in design optimization and workflow integration, assesses the effectiveness of virtual prototyping in reducing physical sampling, and identifies the principal limitations and factors influencing successful implementation. The findings contribute to a better understanding of digital garment development methodologies and support their application in both industry and education.

2. RESEARCH METHODOLOGY

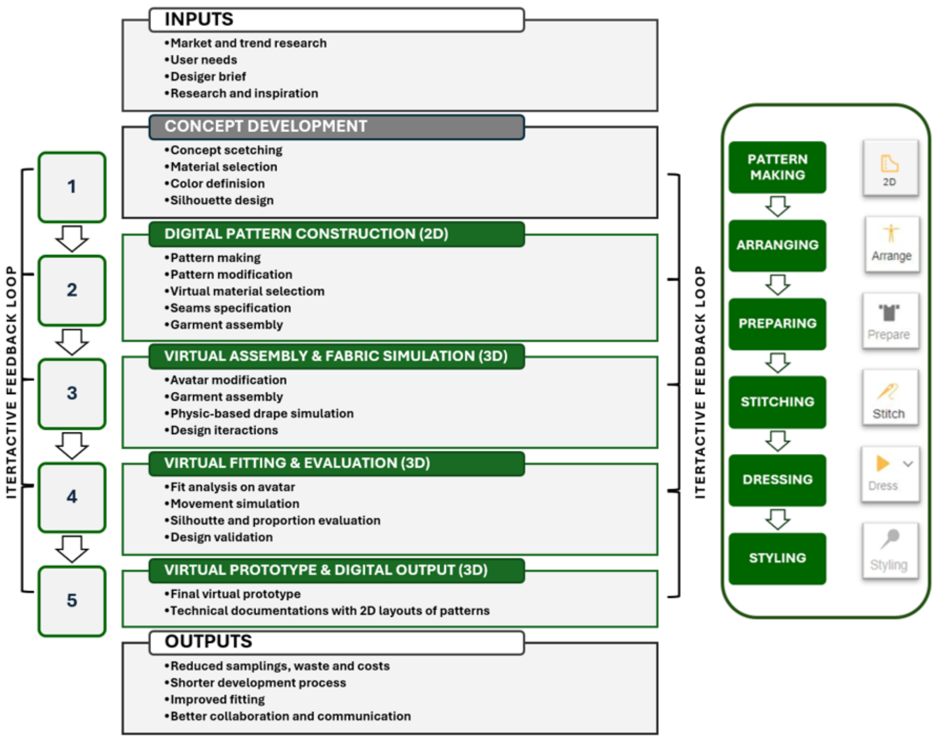
2.1. Method

Various software solutions support digital garment development, ranging from traditional 2D CAD systems, such as Gerber AccuMark and Lectra Modaris, to fully integrated 3D systems, including CLO3D, V-Stitcher (Browzwear), Optitex, and Style3D Studio. While traditional CAD systems primarily focus on pattern construction and grading, advanced 3D systems integrate digital patternmaking, fabric digitalization, virtual fitting, and garment simulation into a unified environment. These capabilities enable realistic evaluation of garment fit, drape, and construction prior to physical production, thereby reducing the need for physical samples and improving development efficiency. Among these solutions, V-Stitcher provides advanced fabric simulation through its Fabric Analyzer (FAB), which incorporates measured material properties to enhance simulation accuracy and support reliable virtual prototyping.

Based on these capabilities, V-Stitcher (Browzwear) was selected as the system for this study. The digital 3D garment development process – from concept development to virtual prototyping – was examined using the conceptual framework developed in this study. As illustrated in Figure 2a, the framework defines the key stages of the workflow and their iterative interactions, while Figure 2b presents its practical implementation within the VStitcher environment.

Figure 2(a) presents the overall workflow as a structured, iterative process that progresses from initial inputs to final outputs. The process begins with design inputs, including market and trend analysis, user requirements, and creative inspiration, which inform the concept development. This is followed by digital pattern construction in 2D, where garment patterns are created and prepared for simulation through the selection of virtual materials and seam specifications during garment assembly. The workflow then advances to 3D virtual assembly and fabric simulation, enabling a realistic representation of garment construction and material behavior. In the next stage, virtual fitting and evaluation are performed to assess fit, movement, and proportions on digital avatars. The process concludes with the generation of a virtual prototype and digital outputs, including technical documentation and production-ready data. As indicated by the feedback loops, all stages are interconnected, enabling continuous refinement and iterative optimization throughout

development. The main outcomes of this workflow include sampling, shorter development time, improved fit accuracy, and enhanced communication.
Figure 2(b) illustrates the operational implementation of this framework in the VStitcher (Browzwear) environment. The workflow is organized into sequential modules – pattern making, arranging, preparing, stitching, dressing, and styling – which correspond to the stages defined in the conceptual model. This alignment demonstrates how theoretical principles of digital garment development are translated into practice using specialized 3D software tools, enabling a streamlined and integrated workflow from concept to virtual prototype.



a) b)

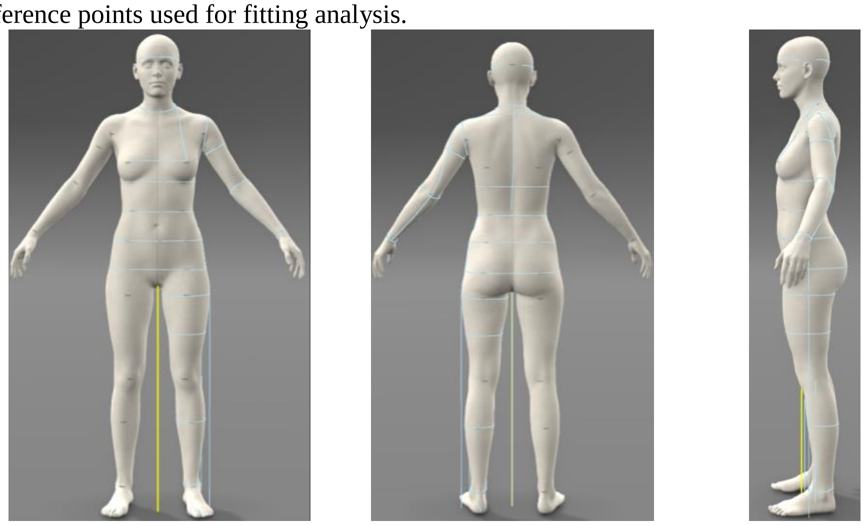
Figure 2: Conceptual framework of the digital 3D garment development process (a), and enables possibilities in VStitcher (Browzwear) (b)

Overall, the figure highlights the relationship between the conceptual framework and its practical implementation, emphasizing the role of digital technologies in enabling an efficient, iterative, and simulation-driven approach to garment development.

2.2. Materials

Digital avatar

The digital avatar Olivia, used for T-shirt simulation, is presented in Figure 3. The avatar was configured with symmetric positioning and the original body resolution, and human friction was enabled to ensure realistic interaction between the garment and the body during virtual fitting. Figure 3 illustrates the avatar Olivia with a fit marker texture from multiple views: front, back, and left, providing a clear visualization of body geometry and the reference points used for fitting analysis.



a) b) c)

Figure 3: Avatar Olivia in fit markers texture: a) front view, b) back view, c) left view

General body measurements of the digital avatar Olivia are presented in Table 1. The Table 1 provides a detailed overview of the avatar’s configuration for size EU38, including general settings such as:

- body resolution – original,
- texture – fit markers,
- avatar friction – human.

The anthropometric data are organized into three categories: general body measurements, upper body measurements, and lower body measurements. This structured dataset includes standardized body dimensions such as height, shoulder width, bust, waist, hip, and limb circumferences, ensuring an anatomically accurate digital representation of the human body. These parameters enable consistent and reliable assessment of garment fit, proportion, and silhouette behavior within the virtual environment.

Table 1: General body measurements of the digital avatar Olivia

Category	Parameter	Unit	Value
General body measurements	Height	cm	168.0
	Head circumference	cm	54.4
	Neck circumference	cm	35.0
	Shoulder width	cm	36.2
	Nape-to-waist length	cm	40.8
Upper body measurements	Bust circumference	cm	88.0
	Underbust circumference	cm	74.6
	High point shoulder (HPS) to apex	cm	25.3
	Apex-to-apex distance	cm	18.8
	Waist circumference	cm	68.0
	Armhole circumference	cm	36.5
	Arm length	cm	53.6
	Elbow circumference	cm	23.1
	Wrist circumference	cm	15.0
	Bicep circumference	cm	27.1
Lower body measurements	High hip circumference	cm	83.8
	Hip circumference	cm	93.0
	Thigh circumference	cm	50.9
	Knee circumference	cm	31.0
	Knee height	cm	45.5
	Calf circumference	cm	32.6
	Ankle circumference	cm	23.2
	Inseam length	cm	80.0
	Outseam length	cm	107.5
	Foot length	cm	23.8

Garment product

A women's T-shirt (EU38) with a simple construction – featuring a crew neckline, set-in short sleeves, a slim silhouette, and a rounded hemline – was selected as the garment model for this study (Figure 4). The T-shirt was chosen due to its widespread use in fashion collections and its relevance as a basic apparel item for evaluating digital garment development processes. Two color/material variations were developed: a solid white version and a green-striped version.

Figure 4 presents the developed T-shirt in both variants: solid white and green-striped, shown from multiple views (front, back, and side), enabling a comprehensive visualization of silhouette and construction details.

The white T-shirt was constructed using single-jersey knitted fabric for the main garment parts (front, back, and sleeves) in white color (Pantone 11-1001 TCX), while a 1×1 rib knitted fabric was used for the neckband. The green-striped version was developed using single jersey jacquard knitted fabric with a green striped pattern (YKK 018 with dark green stripes) for the main parts, combined with a 1×1 rib knitted fabric for neckband in green color (YKK 018). These material combinations were selected to evaluate the influence of fabric structure and pattern on garment appearance and simulation behavior.

a) b) c) d)

Figure 4: Women's T-shirt in solid white color (a-c) and green stripes color (d): a) and d) front view, b) back view, c) left side view

The construction pattern pieces of the T-shirt are shown in Figure 5.

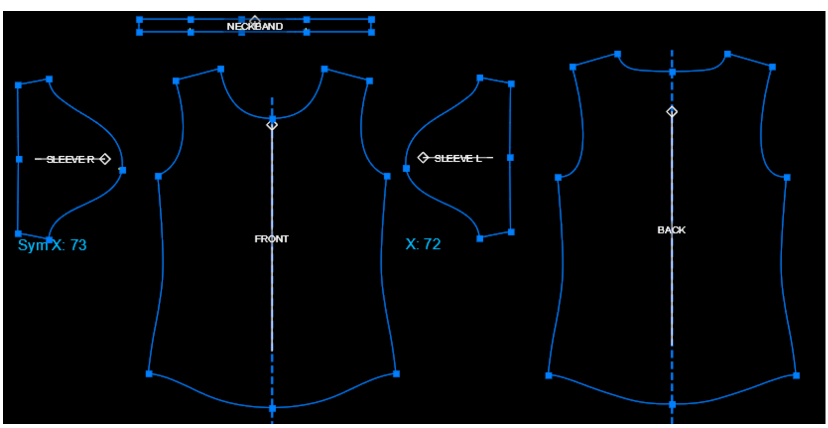
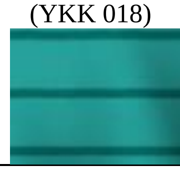


Figure 5: T-shirt construction pattern pieces – front, back, right sleeve, and left sleeve

Table 2 presents the main characteristics of the virtual materials used in the T-shirt simulation, organized by T-shirt part (front, back, sleeves, and neckband). Three knitted fabric types were defined: single jersey (plain), single jersey jacquard, and 1×1 rib. The single jersey (plain) fabric was applied to the main parts of the white T-shirt (front, back, and sleeves) in white (Pantone 11-1001 TCX), while the single jersey jacquard fabric was used for the striped version in green (YKK 018) with dark green stripe detailing. The 1×1 rib fabric was assigned to the neckband in both variants, using white for the plain T-shirt and green (YKK 018) for the striped version.

Table 2: Main characteristics of the virtual materials used for the T-shirt simulation

Chacteristic	Unit	White (front, back, sleeves)	Green stripes (front, back, sleeves)	White/green (neckband)
Knit fabric	-	single jersey (plain)	single jersey jacquard	1x1 rib
Main color	-	white (Pantone 11-1001 TCX)	green (YKK 018) 	white (Pantone 11-1001 TCX)/green (YKK 018)
Fabric composition	%	cotton 100%	cotton 60%, polyester 40%	cotton 100%
Weight	g/m^2	180	180	270
Friction	-	0.2	0.2	0.2
Thickness	mm	0.76	0.80	1.00
Bend in width and length (WxL)	dyn*cm	114.47 x 124.64	25.98 x 11.74	31.46 x 334.96
Stretch in width and length (WxL)	N/m	259.73 x 446.42	107.34 x 39.24	24.86 x 608.90
Stretch linearity in width and length (WxL)	%	48.93 x 0	25.65 x 5	0 x 0
Shear	N/m	79.33	58.39	18.2
Shear linearity	%	27.16	34.67	68.5

The results show clear differences among virtual knitted fabrics. The single jersey jacquard fabric exhibits greater flexibility in the width direction and lower bending stiffness, which is consistent with typical material behavior [17]. The neckband material (1×1 rib), characterized by the greatest thickness, demonstrates higher bending resistance, particularly in the length direction, supporting its structural function in maintaining neckline stability. In tensile behavior, the single jersey (plain) fabric shows higher stretchability, especially in the length direction, indicating greater extensibility and recovery potential. Shear properties also vary among materials; the rib fabric exhibits the

lowest shear stiffness, making it highly deformable and particularly suitable for shaping and stabilizing the neck opening. Overall, this combination of these materials provides a balanced performance in terms of stability, elasticity, and comfort, which is essential for realistic virtual garment simulations and digital prototyping.
Silhouette variants of the women's T-shirt are presented in Table 3. These variants (Table 3) can be developed using the SmartDesign function in VStitcher (Browzwear), which enables the creation of different design options by modifying body fit, neckline shape, sleeve type, and hemline form.

Table 3: Main design differences among silhouette variants

Design element	Silhouette variants				
Body	 Slim	 Regular	 Loose		
Neckline shape	 Crew neck	 Scoop neck	 Boat neck	 V neck	 Deep V neck
Sleeve type	 Short	 Long			
Hemline from	 Straight	 Rounded			

Table 3 outlines the key garment design elements and their variations in silhouette and style considered in this study. It classifies four main design or structural components: body silhouette, neckline shape, sleeve type, and hemline form. The body silhouette is defined through slim, regular, and loose fits, representing progressively increasing ease and garment volume. Neckline shape options include crew, scoop, boat, V-neck, and deep V-neck styles, reflecting variations in coverage and aesthetic expression. Sleeve options are categorized as short or long, corresponding to functional and seasonal requirements. Hemline forms are defined as straight or rounded, indicating differences in garment shape and visual flow. This typology enables systematic comparison and consistent parameterization in the analysis of garment design variations.

3. RESULTS AND DISCUSSIONS

The 3D garment development workflow in VStitcher (Browzwear) represents a structured and iterative process that integrates 2D pattern construction with 3D simulation and virtual fitting, enabling a continuous feedback loop between design and validation (Figure 2b). In line with the study objectives, the results are discussed through the main stages of the digital garment development process, the role of enabling technologies, the effectiveness of virtual prototyping, and the identified limitations.

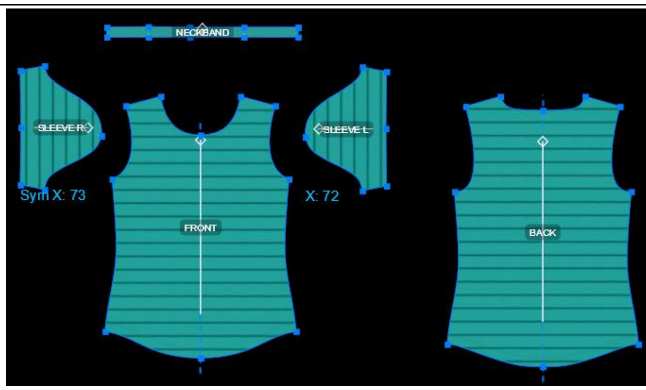
The process begins with translating the design concept into digital pattern pieces within the 2D workspace (Figure 6a). Pattern creation is performed either through direct digital drafting or by importing CAD files (.DXF, .AAMA, .ASTM). In practise, adapting existing base patterns with similar construction proved to be the most efficient approach, enabling faster development and more precise control of garment form and fit. This stage is essential for ensuring structural accuracy, including correct seam allowances, grainline orientation, and compliance with technical specifications, which form the foundation for reliable 3D simulation.

The critical aspect at this stage is material mapping on pattern pieces, particularly for fabrics with directional characteristics such as stripes or motifs. Accurate alignment is essential for maintaining aesthetic consistency and seam continuity, especially at key junctions between front, back, and sleeve parts. This was confirmed during virtual assembly and visualization (Figure 7e–h), where potential misalignment issues were identified early in the digital process.

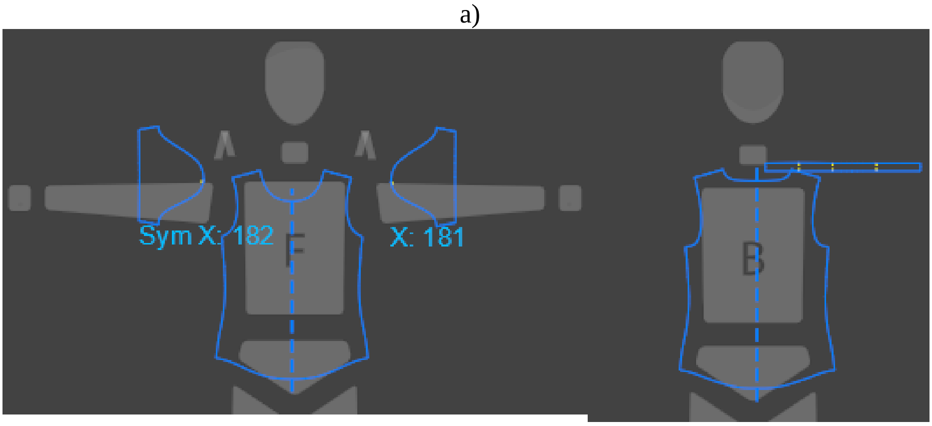
Following pattern development, the pattern pieces are organized in the 2D workspace according to grain line direction and arranged on the avatar in the 2D and 3D workspace for virtual fitting on the avatar (Figures 6b–6c). This bidirectional interaction between 2D and 3D environments demonstrates a strong workflow integration and supports continuos iterative refinement of design decisions.

The 3D avatar provides a multi-angle visualization (front, back, side, top, and bottom views), enabling early evaluation of symmetry, proportion, and spatial fit. Based on these assessments, pattern adjustments are iteratively performed in the 2D environment, including modifications of shape, ease distribution, and seam positioning. This feedback loop significantly reduces reliance on physical sampling and improves design efficiency.

The stitching phase is defined digitally in the 2D environment, where seam connections and construction logic are established prior to simulation. Once assembled in a 3D environment (Figure 6d), the garment exhibits simulated realistic fabric behavior, including tension distribution, deformation, and drape interactions with the avatar body.



a)



b)

c)

d)

Figure 6: 3D T-shirt development process in VStitcher: a) creating a pattern in 2D and positions of the materials on the pattern pieces, b) arranging in 2D, c) arranging in 3D, d) stitching in 3D (*Positions of avatar (b): F – front, B – back)*

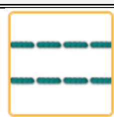
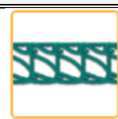
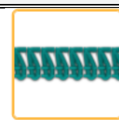
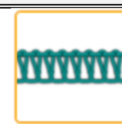
The results indicate that virtual prototyping is effective for predicting garment fit and silhouette behavior prior to physical production. The final simulation (Figure 7) enables a comprehensive evaluation of garment aesthetics, movement, and structural balance. Additionally, fit refinement can be performed using styling tools that simulate the manual adjustments typically carried out on a physical mannequin. These tools allow advanced manipulation of the draped garment, including repositioning across different avatar poses, correcting drape issues in layered outfits, adjusting and locking pattern pieces, refining seam and stitch placement, and controlling internal garment parts such as pockets. Garments can also be repositioned if displaced during simulation, improving overall balance, appearance, and realism. Consequently, styling functions contribute significantly to achieving an accurate and optimized virtual fit before physical prototyping. Iterative adjustments based on simulation feedback further enhance design precision and reduce the need for multiple physical samples.

a) b) c) d)
e) f) g) h)

Figure 7: 3D T-shirt development process in VStitcher for white (a-c) and green-striped (e-h) variations during dressing and styling:
a) and e) right view, b) and f) front view, c) and g) back view, d) and h) left view

Seam characteristics and their structural implications are summarized in Table 4, where seam types defined according to ISO standards (ISO 301, ISO 401, ISO 514) are compared. The analysis highlights the influence of seam construction on garment stability, flexibility, and visual appearance, emphasizing the importance of accurate digital construction logic in the virtual environment.

Table 4: Type and main characteristics of the seams

Characteristics of the seam	Type of the seam			
	ISO 406		ISO 514	
	face	back	face	back
Texture of seam				
Line count	1		1	
Length, SPC	3.94		7.87	
Width, cm	0.51		0.32	
Space, cm	0.02		0.01	
Used stitches	Sleeve cuffs, bottom hem, and neckline topstitching		Side, shoulder, armhole, neckline seams	
Materials	polyester threads 25 tex in white and green colors			
**SPC – stitches per centimeter*				

Despite these advantages, several limitations were identified during the implementation of the digital workflow. The accuracy of virtual simulation strongly depends on precise pattern construction and accurate material parameter definition. In addition, the effectiveness of virtual prototyping is influenced by garment complexity and user expertise in both patternmaking and software operation. Complex garment structures may require additional manual adjustments, which can reduce workflow efficiency. Furthermore, although VStitcher provides advanced visualization capabilities, certain tactile and real-world fabric behaviors cannot yet be fully replicated in the digital environment.

4. CONCLUSION

This study analysed the digital 3D garment development process in VStitcher (Browzwear) for women's T-shirts within a structured, iterative framework from concept development to virtual prototyping. The results demonstrated that integrating 2D pattern construction, 3D simulation, and virtual fitting enables a continuous feedback loop that supports efficient design validation and systematic optimization throughout the garment development process.

The findings confirmed that accurate digital pattern construction and material mapping are critical factors influencing the quality of virtual simulation and the realism of garment appearance. The interaction between 2D and 3D work environments supports interactive refinement of garment geometry, fit, seam positioning, and aesthetic properties, enabling early detection and correction of design inconsistencies prior to physical prototyping.

The study also demonstrated the effectiveness of virtual prototyping for evaluating garment fit, silhouette, drape behavior, and structural balance. The use of styling tools further enhanced the refinement process by enabling advanced manipulation of the garment and simulating manual fitting adjustments typically performed on physical prototypes. As a result, the digital workflow helps reduce the number of physical samples required, improves development accuracy, and increases process efficiency.

However, simulation accuracy remains dependent on precise pattern construction, correct definition of material parameters, garment complexity, and user expertise in both patternmaking and software operation. In addition, certain tactile and real fabric behaviors cannot yet be fully replicated in the virtual environment.

Overall, the study confirms that 3D garment development systems, such as VStitcher, have significant potential to improve product development process in both industrial and educational contexts. The presented workflow contributes to a clearer methodological understanding of digital garment development and supports further implementation of virtual prototyping technologies in sustainable and efficient apparel design practices.

REFERENCE

[1] Nayak, R., Truong, H., Pal, R. (Eds.). (2025). *Use of digital and advanced technologies in the fashion supply chain*. Springer. https://doi.org/10.1007/978-981-97-7528-6

[2] Glogar, M., Petrak, S., Mahnič Naglič, M. (2025). Digital technologies in the sustainable design and development of textiles and clothing – A literature review. *Sustainability*, 17, 1371. https://doi.org/10.3390/su17041371

[3] Papahristou, E. (2016). *The effective integration of 3D virtual prototype in the product development process of the textile/clothing industry* (Doctoral dissertation, Technical University of Crete.

[4] Wu, X., Li, L. (2025). Qualitative-empirical insights into generative AI for textile design in the fashion design process. *International Journal of Design Creativity and Innovation*, 13(4), 322–357. https://doi.org/10.1080/21650349.2025.2529167

[5] Lee, S. young, Law, M., Hoffman, G. (2025). When and How to Use AI in the Design Process? Implications for Human-AI Design Collaboration. *International Journal of Human–Computer Interaction*, 41(2), 1569–1584. https://doi.org/10.1080/10447318.2024.2353451

[6] Browzwear Marketing Team. (2024, September 10). *Ultimate guide to 3D fashion design*. Browzwear. https://browzwear.com/blog/ultimate-guide-to-3d-fashion-design

[7] Textile World. (2024, March). *Game-changing benefits of 3D digital sampling*. Textile World. https://www.textileworld.com/textile-world/features/2024/03/game-changing-benefits-of-3d-digital-sampling/

[8] The Impact of AI and 3D Digital Tools on Fashion Product Development. (2025). In Future Priorities for Design, Branding, Marketing and Retail: The Era of Technology

and Sustainability. Emerald Publishing. https://doi.org/10.1108/978-1-83608-806-620251003

[9] Conlon, J., Gallery, C. (2024). Developing digital skills: a fashion business masterclass in virtual 3D prototyping with Style3D. *International Journal of Fashion Design, Technology and Education*, 17(1), 76–85. https://doi.org/10.1080/17543266.2023.2247425

[10] Papahristou, E., Bilalis, N. (2017). Should the fashion industry confront the sustainability challenge with 3D prototyping technology. *International Journal of Sustainable Engineering*, 10(4–5), 207–214. https://doi.org/10.1080/19397038.2017.1348563

[11] Shimaseiki Spotlight. (n.d.). *What is virtual sampling?* Retrieved from https://spotlight.shimaseiki.com/en/wearware/what_is_virtual_sampling

[12] Bahar Erdem, S., Buyukkamaci, N., Birol, S. (2026). Environmental benefits of virtual sampling for garment production. *Journal of Cleaner Production*, 538, 147401. https://doi.org/10.1016/j.jclepro.2025.147401

[13] Bukhonka, N., Pešić, M., Nemeša, I., et al. (2026). An analysis of the current state of pre-consumer textile waste in textile manufacturing: A case study. *Res. J. Text. Appar,* 1–20. https://doi.org/10.1108/RJTA-07-2025-0157

[14] Browzwear Marketing Team. (2024, August 6). *What is 3D fashion design and how does it impact the future of fashion?* Browzwear. https://browzwear.com/blog/what-is-3d-fashion-design-and-how-does-it-impact-the-future-of-fashion

[15] Gangoda, A., Krasley, S., Cobb, K. (2023). AI digitalisation and automation of the apparel industry and human workforce skills. *International Journal of Fashion Design, Technology and Education*, 16(3), 319–329. https://doi.org/10.1080/17543266.2023.2209589

[16] Noor, A., Saeed, M. A., Ullah, T., Uddin, Z., Ullah Khan, R. M. W. (2022). A review of artificial intelligence applications in apparel industry. *The Journal of The Textile Institute*, 113(3), 505–514. https://doi.org/10.1080/00405000.2021.1880088

[17] Spencer, D.J. (ed.). (2001). *Knitting Technology: A Comprehensive Handbook and Practical Guide*. 3rd ed. Cambridge: Woodhead Publishing Limited.