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Advanced Methods for Fabric Hand Digitalization: Enhancing Traceability in Wool Manufacturing

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Abstract

Fabric hand properties significantly influence consumer satisfaction and product quality in the textile industry. This study investigates the application of the Fabric Touch Tester (FTT) and Fabric Big Data (FBD) platform for digitising and tracing fabric hand properties during wool textile manufacturing. The research builds on prior studies, confirming that FTT effectively quantifies hand properties during manufacturing, while the FBD platform enables real-time visualisation and networked access to production data. Results reveal that this approach allows fabric properties during manufacturing to be well monitored and enable manufacturers to consider whether redundant steps could be eliminated to enhance resource efficiency. Additionally, this study demonstrates how integrating digital tools into production workflows aligns with ESG and ESPR goals by reducing waste and optimising resource use. These findings offer practical guidance for advancing sustainable textile manufacturing, laying the foundation for more intelligent and transparent production systems.

Keywords: Fabric Touch Tester (FTT); Fabric Hand; Textile Manufacturing; Digitalization; Traceability.

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1 Introduction

The textile and apparel industry accounts for approximately 10% of total carbon dioxide emissions, making it the second largest source of industrial pollution after aviation [1, 2]. Under the current global market and regulatory environment, Environmental, Social and Governance (ESG) are becoming critical considerations in the textile and apparel industry [2]. According to the EU strategy for sustainable and circular textiles, 'making products more durable, reliable, reusable, upgradable, reparable, easier to maintain, refurbish and recycle, and energy and resource-efficient' is important for industries when product design. This includes the implementation of digital product passports for product manufacturing process transparency [3-5].

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With the combination of intelligent digital technology and the current demands of ESG regulations, the Fashion Big Data (FBD) platform designed by Digital Clothing Ltd. provides the fashion industry with a comprehensive data digitalisation and product traceability platform [6-10].

The Fashion Big Data Business Model (FBD_BModel) can serve as both a SaaS (Software as a Service) platform and a cloud computing platform. It is specifically designed for the fashion retail and textile industry, integrating an Interactive Design System (IDS) and a Supply Chain and Production Management System (SCPMS) [9]. The FBD_BModel has developed the functional Cloud Computational Interactive Design System (CC_IDS) to transform traditional supply chains into digital, knowledge-based networks, enhancing connectivity and efficiency [6]. It also enables a more responsive, flexible, and efficient supply chain within the fashion industry [7, 8].

In addition to the FBD_BModel, the FBD-Big Data Technology Platform for Textile Supply Chain enables detailed tracking of quality, business, and environmental indicators from the fibre to the finished garment. The Fabric and Garment module also considers biometric fit, hand feel, skin feel, and thermal comfort, which are generally unavailable in most systems. The platform also supports digital data that follows regulatory and standardisation for certifying the functional qualities of fibres, yarns, fabrics, and garments, ensuring comprehensive quality assurance throughout the production process [8, 10].

Fabric hand often be defined as the impressions obtained when fabrics are touched, squeezed, rubbed, or handled [11-16], which is crucial in the wool textile industry and directly influences consumer preference and product value [15, 17-20]. Numerous manufacturing processes are designed to optimise fabric hand quality, especially in the finishing stages [21-23]. However, these processes often involve high energy consumption and resource wastage, making pursuing more sustainable manufacturing practices an urgent need in the industry [24, 25]. In this context, achieving the digitalisation and traceability of hand-made fabric during the finishing stages to improve product quality and energy efficiency is important in wool textile production.

Researchers have developed several measurement methods to evaluate fabric hand properties. Approaches such as Fabric Assurance by Simple Testing (FAST) developed by CSIRO and the Kawabata Evaluation System for Fabric (KES-F) created by Kawabata's research team are prominent in this area [26-28]. Both systems effectively introduced predictive models that assess fabric tactile sensations based on physical properties. However, their limitation lies in the high cost and time required for measurements, as each module must be assessed individually and sometimes even twice for both directions [28]. Other approaches include the comprehensive handle evaluation system for fabrics and yarns (CHES-FY), Wool HandleMeter, PhabrOmeter, Instron, and Fabricometer, which scholars have also developed and utilised for tactile properties testing [15, 28-32]. Nevertheless, these approaches still face limitations. For example, PhabrOmeter will not provide physical interpretations of the test results, HandleMeter can only be used to measure certain characteristics of hand feel [28]. The Fabric Touch Tester (FTT) was developed to address the limitations of previous systems. Four modules (compression, thermal, bending and surface) are integrated into the instrument, which allows simultaneous evaluation of various perspectives of fabric physical properties in a single test within just five minutes [17, 28, 32]. In addition to saving testing time and being highly efficient, FTT also has advantages, including being suitable for all types of fabrics with thicknesses lower than 5 mm, a high degree of intelligence, and comprehensive data collection [32]. According to the FZ/T 01166-2022 'Textile Fabric Touch Determination and Evaluation Method: Multi-Index Integration Method' published by the Ministry of Industry and Information Technology of China, FTT complies with the requirements of this new standard and is capable of providing standardised measurements of fabric hand [33].

This study builds on our previous research, published in the TBIS 2024 proceedings, in which we initially demonstrated the potential of FTT in the manufacturing process of wool textiles [34]. The research not only confirms the ability of FTT to efficiently quantify fabric hand information during the manufacturing process but also indicates that digitising and tracing fabric hand data throughout the production process has the potential to enhance quality monitoring, improve energy efficiency in manufacturing, and optimise supply chain management within the textile industry. However, our previous research did not address how to translate fabric feel data into visualisation and networking formats. This paper aims to demonstrate methods for digitising and tracking fabric hand data during the manufacturing process through the FBD platform and to conduct a more comprehensive analysis of the data obtained from the fabric during the finishing stages.

2 Materials and Methods

2.1 Fabric Collection

Ten 100% wool semi-worsted fabrics from different stages during finishing procedures are collected, and Fig. 1 illustrates the specific stage for fabric choosing. All the selected fabrics have undertaken the same manufacturing processes before 1st shearing. After 1st shearing, the fabrics of short pile styles (fabric 4, 6, 7, 8 and 9) and long pile styles (fabric 5 and 10) were manufactured and collected. Both short and long-pile-style fabrics go through three times calendering and shearing processes; the difference between them is about the distance of the machine blade from the fabric during the shearing process. Each experimental fabric is cut into 8 pieces (4 frontside and 4 backsides) of L-shaped samples with a length of 310 mm and a width of 110 mm (200 mm arms) based on the test requirements of FTT.

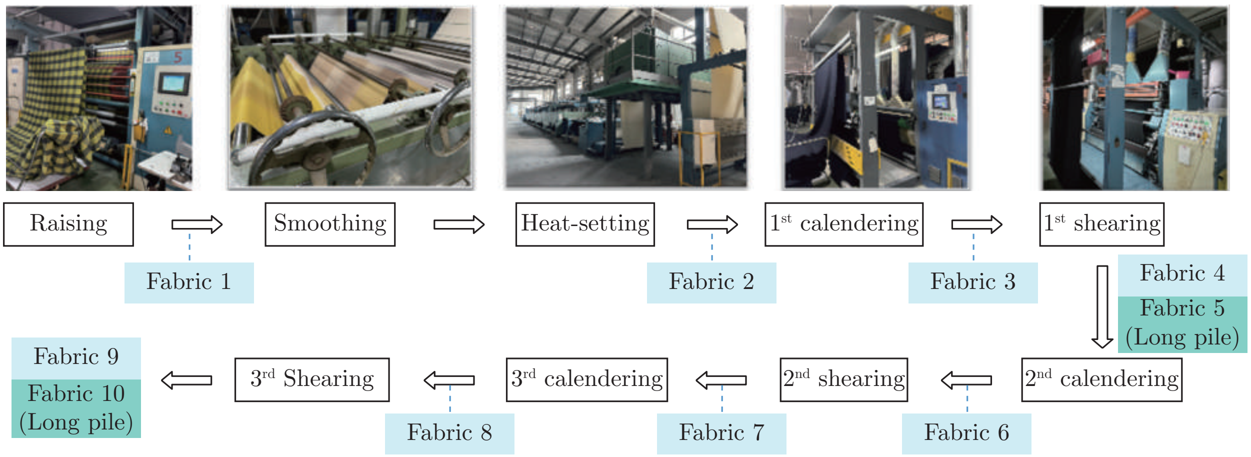


Fig. 1: Flowchart for choosing fabric from finishing procedures

2.2 Objective Assessment

In this research, the Fabric Touch Tester (FTT) developed by SDL Atlas was used to test and evaluate fabric smoothness, softness, warmth, and total hand properties [35]. Table 1 illustrates the modules of FTT and the mechanical properties indices that will be obtained after testing. All collected fabrics were stored at conditions of 20±2 °C and 65±5% RH for 24 hours. Visible creases have been removed before testing, and ASTM standard D1776 was followed for sample preparation and testing [36]. The test is carried out immediately after the fabric has been collected and left for 24 hours, which helps to maintain its tactile properties during the manufacturing process. Fabrics were tested sequentially on the front and back during the test as per FTT's instructions.

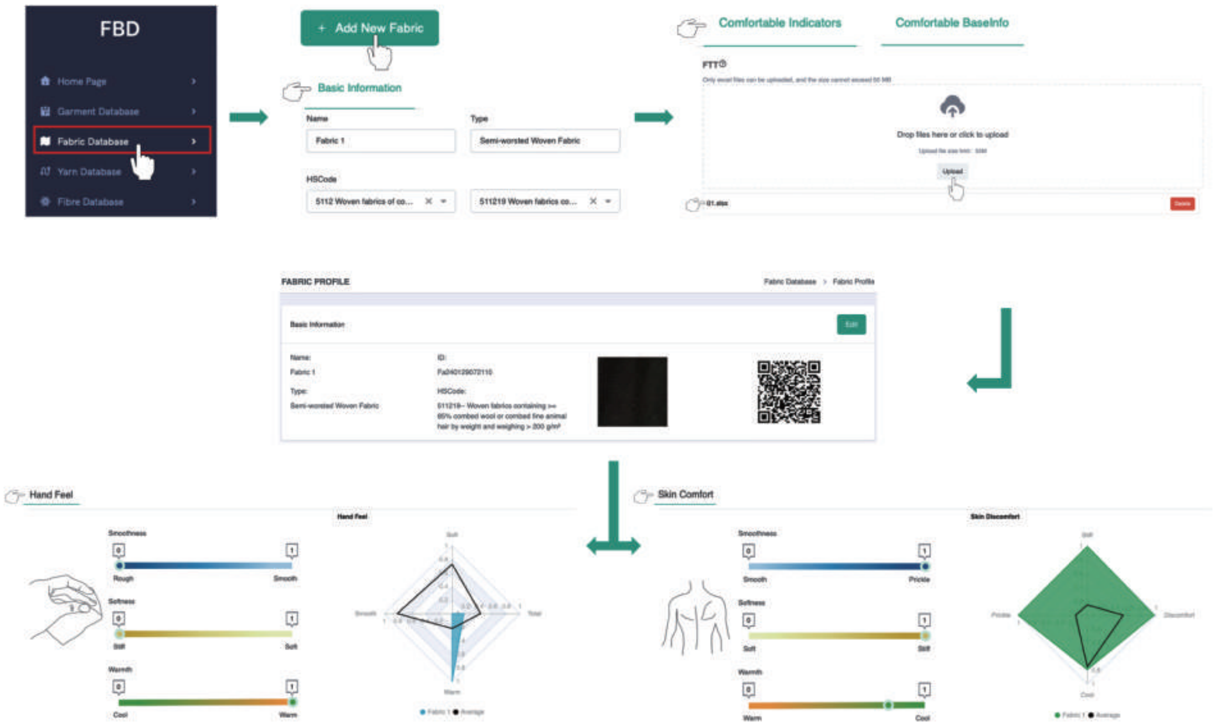
Table 1: List of modules and parameters of FTT

Module	**Indices**	**Description**	**Unit**
Bending	BAR	Bending average rigidity	$\mathrm{gf{\cdot}mm{\cdot}rad^{-2}}$
	BW	Bending work	$\mathrm{gf{\cdot}mm{\cdot}rad}$
Compression	T	Thickness	mm
	CW	Compression work	$\mathrm{gf{\cdot}mm}$
	CRR	Compression recovery rate	$\mathrm{nul(gf{\cdot}mm{\cdot}gf^{-1}{\cdot}mm^{-1})}$
	CAR	Compression average rigidity	$\mathrm{gf{\cdot}cm^{-2}{\cdot}mm^{-1}}$
	RAR	Recovery average rigidity	$\mathrm{gf{\cdot}cm^{-2}{\cdot}mm^{-1}}$
Heat Flux	TCC	Thermal conductivity when compression	$\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$
	TCR	Thermal conductivity when recovery	$\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$
	$\mathrm{Q_{max}}$	Thermal maximum flux	$\mathrm{W{\cdot}m^{-2}}$
Friction	SFC	Surface friction coefficient	$\mathrm{nul(gf{\cdot}gf^{-1})}$
Roughness	SRA	Surface roughness amplitude	µm
	SRW	Surface roughness wavelength	mm

2.3 Fabric Hand Digitalization

The FBD platform will enable the digitisation and visualisation of fabric hand data obtained from the FTT in this research. Fig. 2 demonstrates the process of digitalising the fabric hand data with the application of the FBD platform, and the hand and skin sensory data will be presented (fabric 1 as an example). The focus of this research is on fabrics, and therefore, the 'Fabric Database' will be used. After clicking 'Add new fabric,' the basic information about the fabric, including Name, Type, and HS Code, should first be entered. The HS Code helps ensure that fabrics within the same category are compared, preventing comparisons between fabrics with significant differences due to classification. Subsequently, the fabric hand data obtained from the FTT will be uploaded to the 'Comfortable Baseinfo' section.

After uploading the files and clicking 'done', the fabric will have its own 'Fabric Profile', which contains basic information about the fabric. The QR code on the page enables people to scan and get information on both hand feel and skin comfort. For the hand feel section, the index for softness, smoothness, warmness, and total hand feel properties will be shown on the radar chart. Regarding skin comfort, the radar chart illustrates the 'skin discomfort' index, which includes the stiff, prickle, cool and discomfort index. In addition, the average value of fabrics under the same HS code category is shown on radar charts to allow people to understand the fabric's hand and skin comfort properties.



Name: Fabric 1
Type: Semi-worsted Woven Fabric
HSCode: 5112 Woven fabrics of co... 511219 Woven fabrics co...

Basic Information

Name: Fabric 1
ID: Fa240129072110
Type: Semi-worsted Woven Fabric
HSCode: 511219– Woven fabrics containing >= 85% combed wool or combed fine animal hair by weight and weighing > 200 g/m²

Fig. 2: Operation flowchart for fabric hand digitalization on FBD fabric database system

2.4 Statistical Analysis

In this research, the data collected from assessments was systematically analysed using the one-way ANOVA technique within the Minitab Statistical Software, and a 95% confidence interval was employed to determine the significance level.

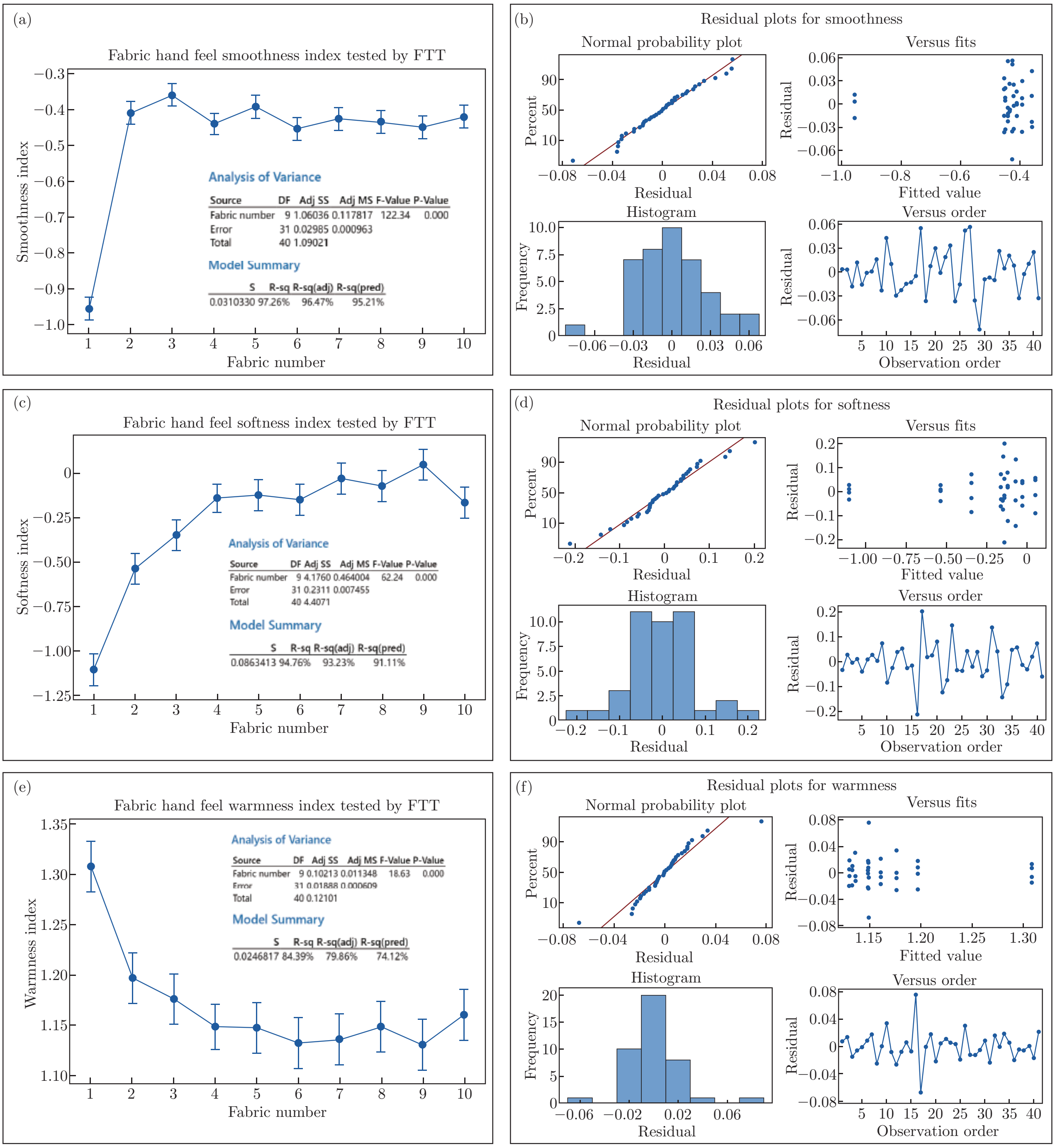
3 Results

3.1 Objective Assessments Results

3.1.1 Primary Sensory Indices

The tactile data obtained from the objective assessments by the FTT illustrate how fabric hand quality evolves throughout the various stages of the partial finishing manufacturing processes. In terms of the overall standard deviation From the FTT data, 95% of the FTT evaluations have within 10%, and 70% of that have within 5%, indicating the consistency of the FTT evaluations. According to the F-value obtained from the FTT evaluation, the parameters related to fabric hand feel and skin comfort exhibited results where smoothness (122.34; 184.80) was greater than softness (64.24; 104.70), which in turn greater than warmness (18.63; 12.34). Based on this, it can be concluded that the variations in warmth indices are less obvious in the finishing processes involved than those in smoothness and softness.

Regarding the fabric and hand feel data obtained (Fig. 3), the data obtained by fabric 1 are relatively independent of other fabrics according to the results. The smoothness and softness index for hand feel have improved by over 50% after the smoothing and heating processes, while the warmness index decreased by 8.4%. During the subsequent finishing processes, the change in hand properties gradually decreased, and the softness index of the fabric showed an upward trend, while the warmth index showed a downward trend.



(a)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fabric number	9	1.06036	0.117817	122.34	0.000
Error	31	0.02985	0.000963		
Total	40	1.09021			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0310330	97.26%	96.47%	95.21%

(c)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fabric number	9	4.1760	0.464004	62.24	0.000
Error	31	0.2311	0.007455		
Total	40	4.4071			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0863413	94.76%	93.23%	91.11%

(e)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fabric number	9	0.10213	0.011348	18.63	0.000
Error	31	0.01888	0.000609		
Total	40	0.12101			

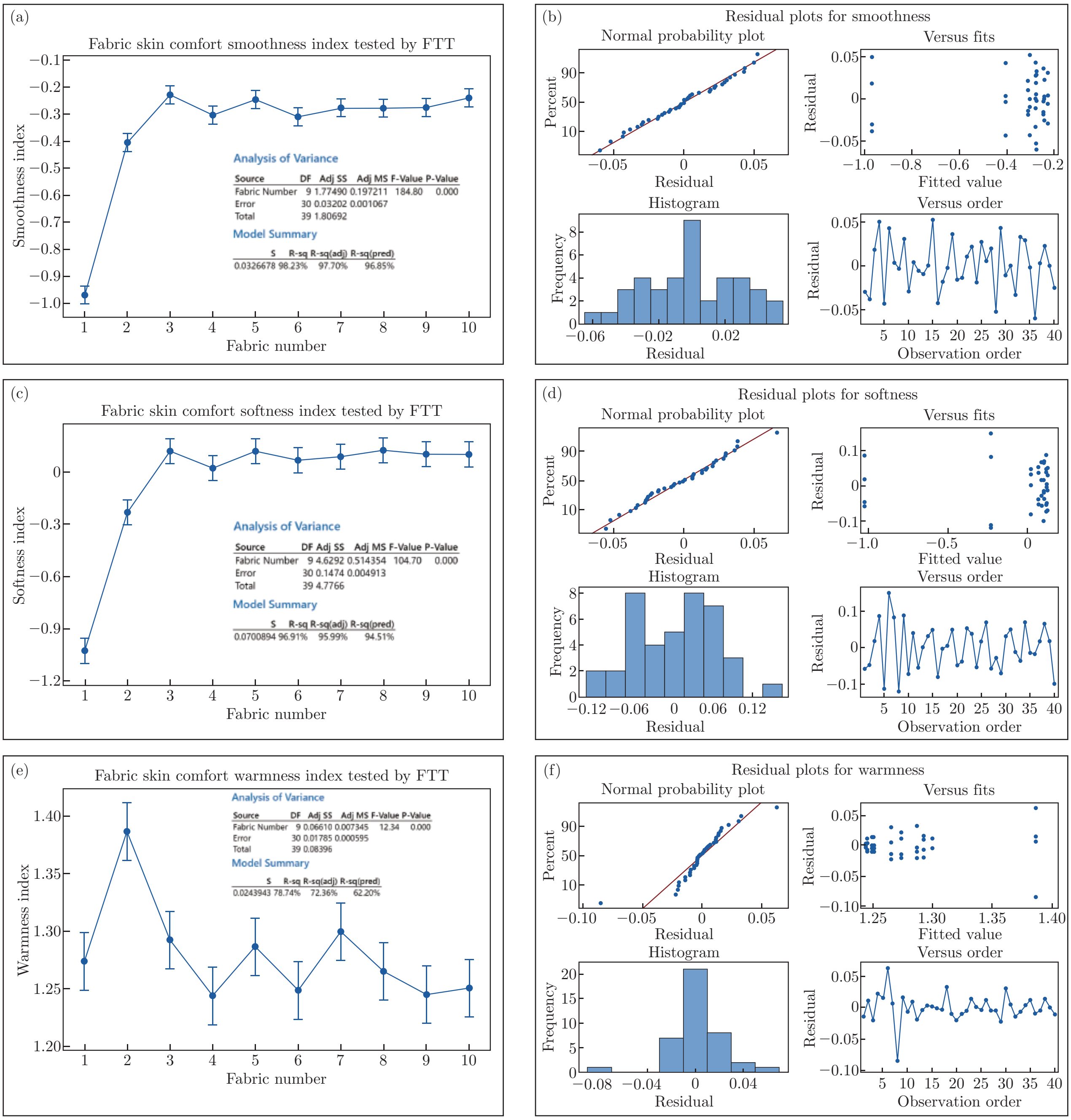
Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0246817	84.39%	79.86%	74.12%

Fig. 3: Fabric hand feel data evaluated by FTT: (a) Interval plot of smoothness data, (b) Residual plots for smoothness data, (c) Interval plot of softness data, (d) Residual plots for softness data, (e) Interval plot of warmness data, (f) Residual plots for warmness data

From the perspective of skin comfort properties obtained by the FTT (Fig. 4), similar to the hand feel results, the smoothness and softness index improved by over 50% from fabric 1 to fabric

2, and the changes during the following finishing processes became less apparent. The warmness index exhibited a small range of variation and reached its highest value in fabric 2.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fabric Number	9	1.77490	0.197211	184.80	0.000
Error	30	0.03202	0.001067		
Total	39	1.80692			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0326678	98.23%	97.70%	96.85%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fabric Number	9	4.6292	0.514354	104.70	0.000
Error	30	0.1474	0.004913		
Total	39	4.7766			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0700894	96.91%	95.99%	94.51%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Fabric Number	9	0.06610	0.007345	12.34	0.000
Error	30	0.01785	0.000595		
Total	39	0.08396			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0243943	78.74%	72.36%	62.20%

Fig. 4: Fabric skin comfort data evaluated by FTT: (a) Interval plot of smoothness data, (b) Residual plots for smoothness data, (c) Interval plot of softness data, (d) Residual plots for softness data, (e) Interval plot of warmness data, (f) Residual plots for warmness data

3.1.2 Bending

Regarding the bending properties of the selected 10 fabrics, Bending Average Rigidity (BAR) and Bending Work (BW) were tested using the FTT, and the corresponding results are illustrated in

Fig. 5. The BAR and BW exhibit similar trends in the same direction. The indices for BARa (Fig. 5(a)) and Bwa (Fig. 5(c)) show a gradual decrease from fabric 1 to fabric 4, while BARe (Fig. 5(b)) and BWe (Fig. 5(d)) display a significant drop between fabric 1 and fabric 2. For BARa and BWa, the indices fluctuate slightly from fabric 4 to fabric 10. In contrast, the indices for BARe and BWe remain relatively stable after fabric 3. Regarding the final products, the long-pile style fabric demonstrates higher BAR and BW values than other fabric types.

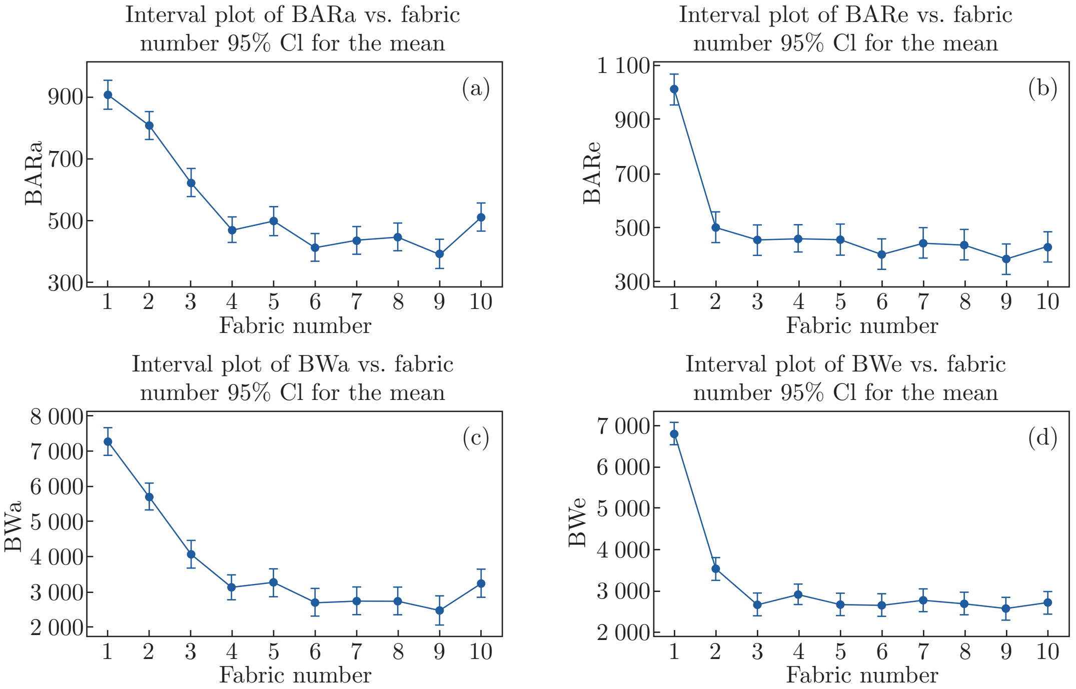


Fig. 5: Fabric bending properties evaluated by FTT: (a) Interval plot of BARa, (b) Interval plot of BARe, (c) Interval plot of BWa, (d) Interval plot of BWe

3.1.3 Compression

Five compression-related indices were obtained from FTT, as shown in Table 1. This section focuses on the analysis of the indices Thickness (T) and Compression Work (CW) (Fig. 6). From fabric 1 to fabric 2, after smoothing and heat-setting, the fabric thickness experienced a significant reduction, dropping from 3.47 mm to 2.74 mm. In the subsequent processes, the thickness fluctuated around 2.5 mm (Fig. 6(a)). In terms of CW, the value increased significantly from fabric 1 (4459) to fabric 2 (5121) but showed a sharp decline to 3959 for fabric 3. CW values exhibited minor variations from fabric 3 to fabric 10, stabilising around 3750, except for fabric 6, where a notable decrease to 3299 was observed (Fig. 6(b)).

3.1.4 Heat Flux

Figure 7 illustrates the Q_{max} values, representing the thermal maximum flux, for both the fabrics' hand side (Fig. 7(a)) and skin side (Fig. 7(b)). For the hand side Q_{max} (Fig. 7(a)), the values demonstrate a fluctuating pattern across the 10 fabrics. Fabrics 3, 5 and 10 have notably higher Q_{max} values and these fabrics belong to long-pile fabrics. Conversely, fabric 1 has the lowest. Q_{max}

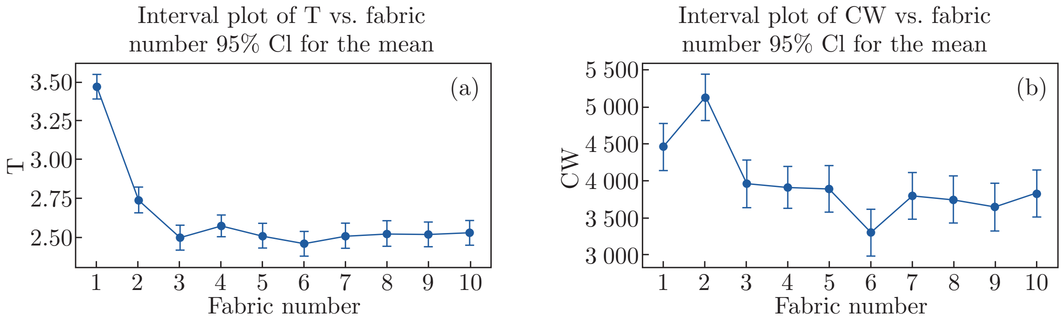


Fig. 6: Fabric compression properties evaluated by FTT: (a) Interval plot of T, (b) Interval plot of CW

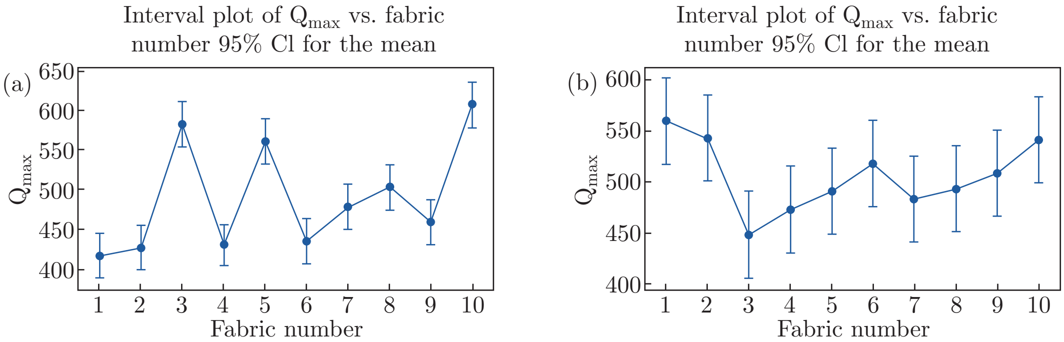


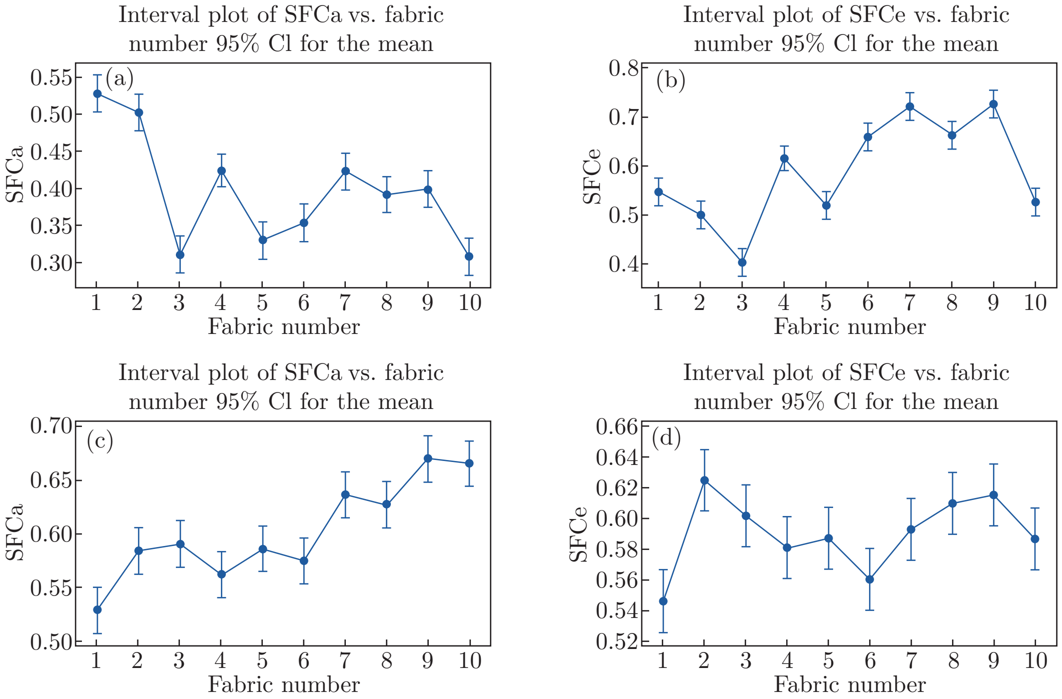
Fig. 7: Fabric flux properties evaluated by FTT: (a) Interval plot of hand side Q_{max}, (b) Interval plot of skin side Q_{max}

values, suggesting low heat flux capabilities. In contrast, the skin side Q_{max} (Fig. 7(b)) shows a general upward trend from fabric 3 to fabric 10. This indicates that the finishing processes of calendering and shearing likely improve the thermal conductivity on the skin-contact surface as production progresses. In general, long-pile style fabrics will show higher. Q_{max} value than short-pile style fabric for both sides.

3.1.5 Friction

The friction properties of the ten fabrics were evaluated using the Surface Friction Coefficient (SFC) index, with data obtained through the FTT. The results are presented in Fig. 8. For the hand side SFC (Fig. 8(a), (b)), the warp and weft direction values exhibit a decreasing trend from fabric 1 to fabric 3. This indicates that after smoothing, heat-setting, and calendering processes, the surface friction on the hand side is reduced. Regarding the hand side SFCa, the values decrease following calendering (fabrics 6 and 8) and increase after shearing (fabrics 7 and 9). Additionally, long-pile style fabrics show lower-hand side SFCa values compared to short-pile style fabrics (fabrics 5 and 10). For the hand side SFCe, the overall trend across the production process shows an increase. Similar to the warp direction of the hand side SFCa, the SFCe value for finished long-pile style fabrics is lower than that of finished short-pile style fabrics.

From the perspective of the skin side SFC (Fig. 8(c), (d)), the SFCa values exhibit an overall upward trend throughout the production process. The SFCe values, however, show a decline from fabric 2 to fabric 6, followed by an increasing trend from fabric 6 to fabric 9. Notably, for both the warp and weft directions and the hand and skin sides, the SFC values for finished long-pile


Interval plot of SFCa vs. fabric number 95% Cl for the mean

Interval plot of SFCe vs. fabric number 95% Cl for the mean

Interval plot of SFCa vs. fabric number 95% Cl for the mean

Interval plot of SFCe vs. fabric number 95% Cl for the mean

Fig. 8: Fabric friction properties evaluated by FTT: (a) Interval plot of hand side SFCa, (b) Interval plot of hand side SFCe, (c) Interval plot of skin side SFCa, (d) Interval plot of skin side SFCe

style fabrics are consistently lower than those for finished short-pile style fabrics.

3.2 Fabric Hand Digitalization on FBD Platform

Using the FBD platform, fabric hand and skin comfort data is visualised through radar charts, providing an intuitive display of the results.

3.2.1 Hand Feel

According to the radar charts (Fig. 9), the overall hand properties of the fabrics improved significantly after the smoothing and heat-setting processes (from fabric 1 to fabric 2). They showed gradual enhancement in subsequent production stages. Among the ten fabrics, fabric 1 exhibited the highest warmness value but the lowest smoothness and softness values. In contrast, fabric 9 demonstrated the lowest warmness value while achieving the highest softness value, and fabric 3 recorded the highest smoothness value. Additionally, the radar charts revealed that after the second and third shearing processes, there is no substantial difference in the overall hand feel and fabric performance. These findings highlight the impact of specific finishing processes on tactile properties while implying diminishing returns in fabric improvement with repeated shearing.

3.2.2 Skin Discomfort

Regarding skin discomfort (Fig. 10), the radar charts indicate that fabric 1 exhibits the highest level of skin discomfort among the ten fabrics. It also shows the highest prickle and stiffness

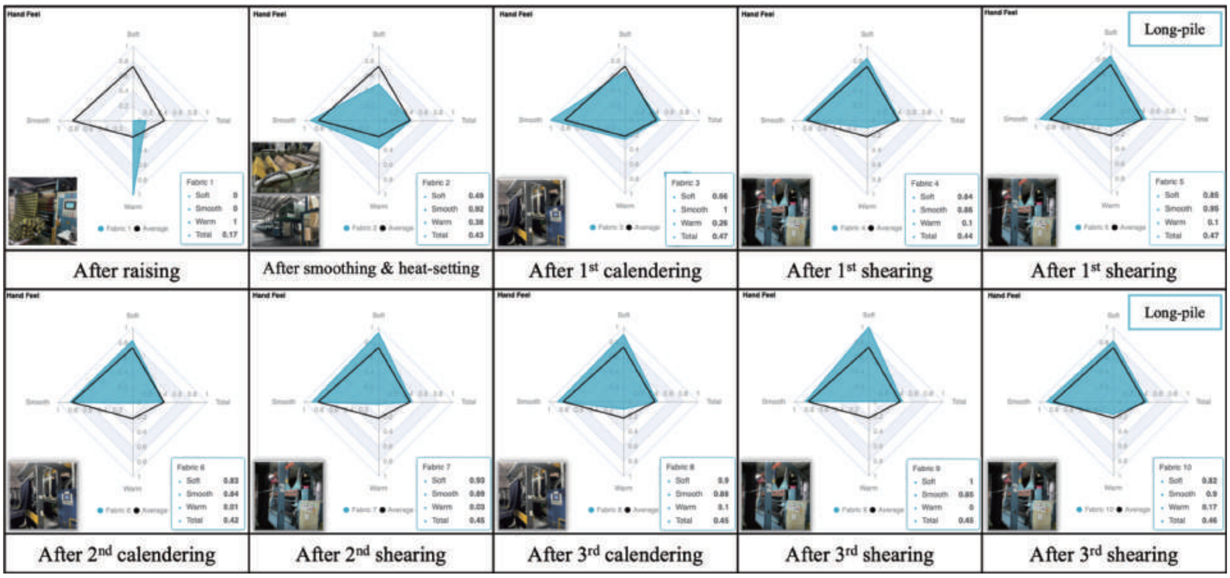


Fig. 9: Radar charts for fabric hand feel index on FBD platform

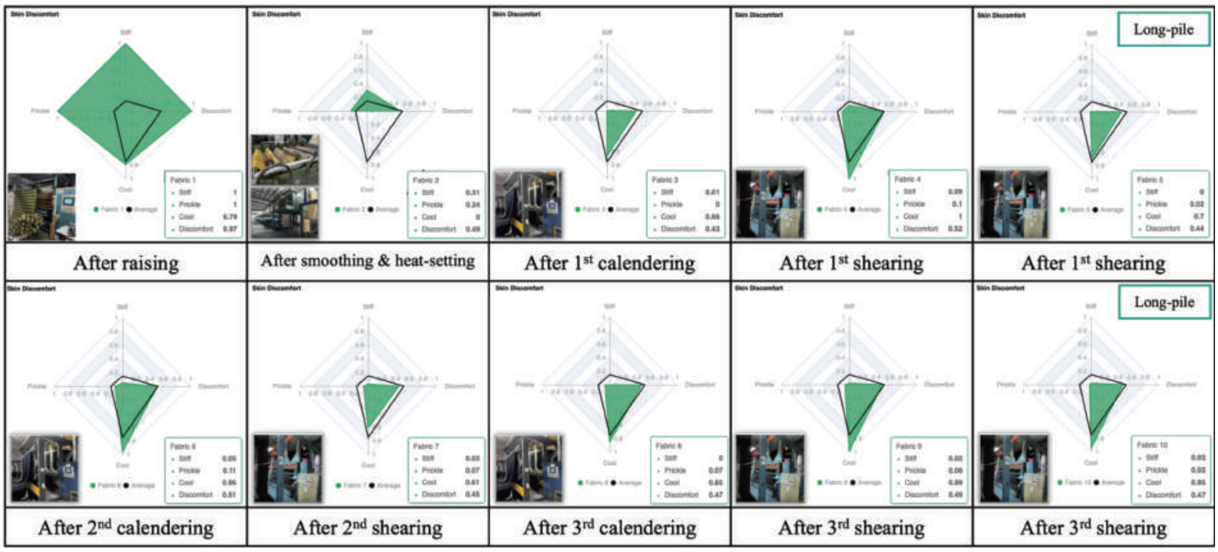


Fig. 10: Radar charts for fabric skin discomfort index on FBD platform

values. Conversely, fabric 2 is the warmest fabric when in contact with the skin, while fabric 4 is the coolest. Fabrics 5 and 8 display the lowest stiffness values, whereas fabric 10 exhibits the lowest prickle value. For skin comfort, the differences between fabrics after the second and third shearing processes are primarily observed in their warmness properties. The fabric after the third shearing process (fabric 9) demonstrates a greater coolness compared to the fabric after the second shearing process (fabric 7).

4 Discussion

The FTT test results for the ten selected fabrics are consistent with previous studies, indicating that the finishing procedure can significantly improve the fabric's hand feel and skin comfort

[21-23, 37-39]. Previous literature have addressed FTT's outstanding ability to quantify the hand performance of various fabrics [28, 32-34]. However, previous research did not address how to digitise and trace fabric into a visualised form during manufacturing processes. This study demonstrated that the fabric hand properties could be digitised and traced well through the application of the FBD platform after testing by FTT.

Our previous research engaged textile industry stakeholders to discuss the potential of using FTT to digitize and trace fabric hand properties during manufacturing. The outcomes highlighted several benefits, including improved control over the production process and fabric hand quality, reduced fabric waste due to undesired hand standards, simplified and refined manufacturing processes, and integration of hand data with production systems for automated intelligent production [34]. This study further visualises and digitises fabric hand data using FTT, enabling stakeholders to access production process information more transparently through a simple QR code scan, irrespective of geographic location. Focusing on the radar charts for fabric hand properties, comparing fabric after the second calendering and shearing process (fabric 7) and after the third (fabric 9) reveals no significant difference in overall hand feel. According to previous studies, this insight suggests that if quality requirements are met, the third calendering and shearing process could be simplified to two steps in practical production.

Incorporating digital technology into production activities allows manufacturers to optimise resource allocation efficiency while reducing waste and emissions during the production process [40]. If manufacturers are aware of the target fabric hand properties, they can optimise process parameters and workflow configurations by tracking the hand properties throughout the production process with digital technology. This approach aligns with the objectives of the Ecodesign for Sustainable Products Regulation (ESPR) and ESG regulation, specifically the goal of "making products more energy- and resource-efficient." [3, 41].

The findings provide valuable insights for the wool manufacturing industry, particularly in optimising finishing processes to achieve fabrics with superior thermal and tactile properties. These advancements can help manufacturers achieve greater sustainability in production while ensuring that fabric performance meets consumer demands, enhancing customer satisfaction.

One limitation of this study is the focus on a limited range of wool fabric types. Further research incorporating diverse fabric compositions and production methods is needed to validate the generalizability of the findings.

5 Conclusion

This study demonstrated the feasibility of integrating FTT with the FBD platform to digitise and trace fabric hand properties during wool textile production. The findings confirm that finishing processes significantly enhance fabric hand properties. Additionally, visualised data, such as radar charts, revealed opportunities to optimise manufacturing by reducing redundant steps without compromising quality. These advancements provide actionable insights for improving production efficiency, reducing waste, and aligning with sustainability goals, such as ESPR and ESG standards. However, the study is limited to specific wool fabric types, and future research should expand to a broader range of textiles and explore the integration of real-time monitoring systems in automated production. Overall, this research highlights the transformative potential of digital technologies in driving innovation and sustainability in the textile industry.

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