

A general linear model to evaluate the shrinkage of manufactured denim pants

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The study reported the development of a statistical model to evaluate and prevent fabric shrinkage in denim pants during industrial seaming operations, particularly after finishing treatments. Denim pants are assembled using various seam types, including flat-felled seams, safety stitch seams, and lockstitch seams, with consistent sewing parameters such as fabric composition, stitch type, stitch density (percentage per centimetre), and sewing thread count.

A factorial design methodology was employed to evaluate shrinkage across various seam types under actual industrial conditions. Based on data collected from different finishing treatments, statistical models were developed to predict the extent of shrinkage in denim pants. These models were further validated and refined using data from five industrial production orders, which improved their predictive accuracy and practical applicability.

Results indicate that the models can be effectively integrated into production planning, enabling manufacturers to optimize sewing and finishing processes. The models also support the implementation of digital processing techniques, reducing waste and execution time in line with Industry 4.0 principles, thereby enhancing efficiency and sustainability in denim manufacturing

Keywords: Finishing treatments, Garment, General linear model, Seam, Shrinkage

1 Introduction

Customers choose garments based on aesthetic appeal, fashion trends, comfort, price, and durability. Generally, studies that deal with the effect of different seam types on shrinkage during finishing treatments are limited to those of home laundering¹⁻⁵.

Designers must consider the best method for stitching the garment together when deciding on their style mode (fabric and pattern).

This will partly depend on the type of fabric, use of the garment, and the desired type of finish. Many seams have been developed over the years to carry out different applications. The seam type used to sew a garment often produces various changes in the dimensional stability of the cloth during finishing treatments and laundering. The assembled techniques and finishing treatments commonly lead to uncontrolled cloth shrinkage, which restricts finishers from achieving the specific shades and effects demanded by customers⁶. Additionally, the ability to consistently reproduce these finishing effects remains difficult with the methods currently used by manufacturers⁷⁻¹⁰.

Much research has increasingly focused on the washing process and its impact on the shrinkage of textile products, particularly denim. Studies have shown that laundering types, finishing treatments, their sequence, and ironing can significantly influence the dimensional stability of garments¹¹⁻¹⁵. For example, Khedher and Jaouachi developed a principal component analysis-based model linking denim mechanical properties, such as tear and breaking strength, to garment shrinkage after industrial washes¹⁶. Similarly, Zareen et al. demonstrated that enzyme-stone washing produces limited dimensional instability, with shrinkage generally below 3%¹⁷, while Özkan et al. highlighted that washing method, yarn type, and twill weave direction strongly affect both shrinkage and mechanical performance¹⁸. These findings underscore the complexity of shrinkage dynamics and the need for predictive, process-aware modelling. Additionally, Nahid *et al.* compare sustainable denim finishing techniques—ozone washing and laser fading—with conventional denim washing methods. It highlights how these eco-friendly processes reduce water, chemical, and energy consumption while maintaining desirable aesthetic effects. The study emphasises their potential to replace traditional, resource-intensive denim treatments¹⁹.

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On the other hand, Weispfenning *et al.* run experiments with different denim fabrics and washing processes to understand shrinkage variability using a log-linear variance model²⁰. Furthermore, Shahid *et al.* compare dye-blended rigid versus stretch yarns in denim, showing how material composition (cotton, elastane, polyester) affects shrinkage behaviour when washed: cotton shrinks more than polyester, and elastane-containing yarns exhibit different shrinkage and recovery dynamics²¹. Similarly, Yun *et al.* developed a digital method (utilising grid dots on fabric) to accurately measure shrinkage (warp, weft, and area) and damage after washing, validating the method under realistic washing cycles²².

Many researchers have studied shrinkage in denim fabrics; however, investigations focusing specifically on shrinkage at the seam types in jeans remain limited. Indeed, Maarouf demonstrates that for denim manufacturing, optimizing stitch density is crucial — too high a density can lead to puckering (a bad appearance), but too low a density reduces seam strength and efficiency²³. In addition, Malek *et al.* studied the sewn-quality index. In fact, they showed that this quality index is highly useful for the denim industry: before production, manufacturers can simulate seam quality based on fabric and sewing parameters, optimize them, and thereby reduce defect rates (seam slippage, puckering, low efficiency)²⁴.

For this reason, the present research addresses this gap by examining shrinkage behavior in denim pants during industrial seaming, focusing on different seam types — flat-felled seams, safety stitch seams,

and lockstitch — under consistent sewing parameters (fabric composition, stitch type, stitch density, and thread count).

2 Materials and Methods

Four types of fabrics are selected for this study (Table 1).

They were used to manufacture jeans pants (Fig. 1) in this research.

They are sewn with different stitches (Fig. 2) using various sewing machines following a well-defined experimental design²⁵ (Table 2).

The different types of seams used are:

- **Flat-felled seam** (2 x401): A fully enclosed, two-needle seam in which the raw fabric edges are turned under and stitched between two rows of parallel topstitching. This seam type provides high tensile strength, excellent fray resistance, and a clean, durable interior and exterior finish.
- **Safety stitch seam** (ISO 516): A combined construction seam consisting of an overedge stitch that encloses the raw edge and a parallel chainstitch that reinforces the seam line. This configuration offers high elasticity, edge-finish stability, and resistance to seam slippage, making it suitable for load-bearing or stretch-prone areas.
- **Lockstitch seam for hem finishing** (ISO 301): A single-needle lockstitch used to secure the lower hem. This stitch type forms an interlocking thread structure with balanced tension, producing a stable, low-bulk finish with strong dimensional stability after laundering.

Table 1 — Fabric Specifications

Fabric code	Composition		Basis Weight, g/m ²	Yarn count (tex)		Twists, trs/m		Yarn density	
	Warp yarns	Weft yarns		Warp yarns	Weft yarns	Warp Yarn	Weft yarns	Warp Density, picks/cm	Weft Density, ends/cm
	T_1	100% cotton	96% cotton / 4% elastane	367	59	50	600	635	30
T_2	100% cotton	96% cotton / 4% elastane	465	82	50	500	635	30	22
T_3	100% cotton	100% cotton	368	82	60	500	635	30	22
T_4	100% cotton	100% cotton	450	60	50	500	589	28	19

- **Lockstitch seam for waistband (belt) attachment** (ISO 301): A single-needle lockstitch used to join and topstitch the waistband. Its tight, secure interlocking structure ensures consistent seam alignment, minimal distortion under tension, and a clean, structurally stable waistband finish.

Experimental designs are essential in this study because they provide the strongest method for

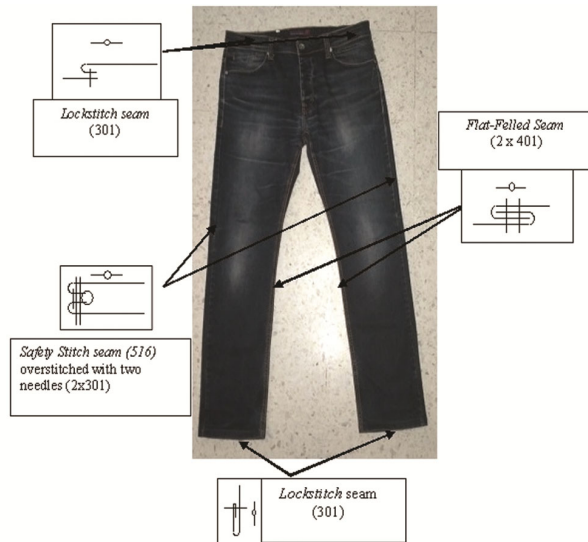


Fig. 1 — Industrial seam types used in the manufacture of pants

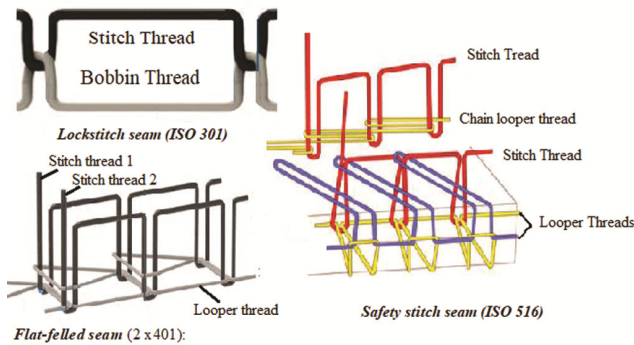


Fig. 2 — seam types

establishing causal relationships. By deliberately manipulating an independent variable while controlling other possible influences, we can determine whether changes in one factor directly produce changes in another. This high level of control, achieved through techniques such as random assignment and standardized procedures, reduces the impact of confounding variables and strengthens the internal validity of the findings. Experimental designs are also highly replicable, as their structured protocols allow repeating studies and verifying results. Additionally, they provide precision in measurement, enabling the accurate testing of specific hypotheses and contributing to the refinement of theoretical models^{26,27}.

The experimental design in this study consisted of 7 discontinuous factors: Washing Types (*D*), Type of Fabric (*T*), Spray (*S_p*), Brushing (*B_r*), Resin Treatment (*R_e*), Bleach Treatment (*B*), and Pressing "TOOPER" (*P*).

Washing Types (*D*): 5 levels, Type of Fabric (*T*): 4 levels, Spray (*S_p*): 3 levels, Brushing (*B_r*): 2 levels, Resin Treatment (*R_e*): 2 levels, Bleach Treatment (*B*): 2 levels, Pressing "TOOPER" (*P*): 2 levels.

After the sewing steps, each pair of pants underwent different washing processes, followed by various special treatments prior to finishing with cationic softening. Lastly, to finish the pants, single and tandem topplers were used to press them.

Various washing techniques were used to finish the manufactured pants. An industrial rotating drum machine loaded with 80 kg of clothing (about 140 pairs of pants) was used for all wet processing. Table 3 provides specifics about the recipes and treatment conditions.

At the end of the wet processing stage, the jean pants are extracted and dried in a tumbler at 95 °C for 45 min. Shrinkage measurements were then taken on

Table 2 — Experimental design

Factors/ Levels	Washing Types, <i>D</i>	Type of Fabric, <i>T</i>	Spray, <i>S_p</i>	Brushing, <i>B_r</i>	Resin Treatment, <i>R_e</i>	Bleach Treatment, <i>B</i>	Pressing "TOOPER", <i>P</i>
1	Rinse, <i>R</i>	<i>T</i> ₁	Permanganate- Spray, <i>Pe</i>	Brushing, <i>B_r</i>	Resin Treatment, <i>R_e</i>	Bleach, <i>B</i>	Pressing, <i>P</i>
2	Stone, <i>S</i>	<i>T</i> ₂	Pigment-spray, <i>Pi</i>	No Brushing, <i>NB_r</i>	No Resin Treatment, <i>NR_e</i>	No Bleach, <i>NB</i>	No Pressing, <i>NP</i>
3	Double Stone, <i>DS</i>	<i>T</i> ₃	No spray <i>N</i> , <i>Sp</i>	-	-	-	-
4	Mixte Stone, <i>M</i>	<i>T</i> ₄	-	-	-	-	-
5	Enzyme, <i>E</i>	-	-	-	-	-	-

Table 3 — Finishing processing conditions

Treatments	Conditions
Resin- treatment	<ul style="list-style-type: none"> - Application in a spraying booth equipped with rubber balloons, Sprayed solution: 25% of DMDHEU / 75% water, Sprayed volume on all the pants: - 200mL/ pant, Pick up after spraying: 33%±3% - Drying after resin spraying: 10 min at 90 °C - Resin polymerization: 15min at 140°C
Brushing	<ul style="list-style-type: none"> Application of an automatic robot with plastic brushers Rotational speed: 120 rpm (tr/min) Linear Speed of the brushes: 20m/min Passes number: 3 times
Rinse	<ul style="list-style-type: none"> -Desizing at 50°C for 30min with 2% amylase, 1% anti-back-staining agent and LR = 1/5 -Rinsing with cold water for 2 min and LR =1/10 -Desizing at 50°C during 30min with 2% amylase and 1% anti-back-staining agent, LR = 1/5 - Rinsing with cold water for 2 min and LR =1/10
Enzymatic wash	<ul style="list-style-type: none"> - Enzymatic washing at 50°C for 45min with 1.5% of cellulase enzyme and 1% anti-back-staining agent, LR = 1/5 - Rinsing with cold water for 2 min and LR =1/10 (80kg for a load of 140 pants) -Desizing at 50°C during 30min with 2% amylase, 1% anti-back-staining agent and LR = 1/5 - Rinsing with cold water for 2 min and LR =1/10
Stone wash	<ul style="list-style-type: none"> -stone washing at 50°C during 45min with 50% of pumice stones, LR = 1/5 - Rinsing with cold water for 2 min and LR =1/10 - Remove the stones - Rinsing with cold water for 2 min and LR =1/10 - Temperature = 50°C - Time of washing = 45 min - Stone: new stones and worn-out stones (80kg for a load of 140 pants) -Desizing at 50°C during 30min with 2% amylase and 1% anti-back-staining agent, LR = 1/5 - Rinsing with cold water for 2 min and LR =1/10
Mixed wash	<ul style="list-style-type: none"> - Mixed washing at 50°C for 45 min with 25% of pumice stones, 1.5% of cellulase enzyme, and 1% anti-back-staining agent, LR = 1/5 - Rinsing with cold water for 2 min and LR =1/10 - Remove the stones - Rinsing with cold water for 2 min and LR =1/10 (80kg for a load of 140 pants) - Rinsing with cold water for 2 min and LR =1/10 - Bleaching at 50°C during 10 min with 20g/L of sodium hypochlorite (12° chlorinate), LR = 1/10 - Rinsing with cold water for 2 min and LR =1/10
Bleaching (discolouration)	<ul style="list-style-type: none"> - Neutralisation in a cold bath for 5 min with 2g/L sodium metabisulfite Two rinses with cold water for 2 min, LR =1/10 (80kg for a load of 140 pants) - Application in a spraying booth equipped with rubber balloons: Sprayed solution: 20g/L of potassium permanganate, sprayed volume = 60 ±5 mL for a surface of 0.2m², Distance of pulverisation = 45±5 cm, Pressure = 2.5 bar, passes number = 3 times
Permanganate spray	<ul style="list-style-type: none"> - Drying at 80°C during 40min then cooling at ambient air during 2min - Neutralization at 40°C during 15min with 2g/L sodium metabisulfite - Rinsing with cold water for 2 min, LR =1/10
Pigment-spray	<ul style="list-style-type: none"> - Application in a spraying booth equipped with rubber balloons, Sprayed solution: pigment color cc, Sprayed volume on all the pants: 200mL/ pant, Pick up after spraying: 33%±3% - Polymerization: 20min at 150°C - Steaming time: 4s
Pressing on the pants topper	<ul style="list-style-type: none"> - Pressure: 200mbar - Pressing Time: 4s - Cooling time: 4s
Softening	<ul style="list-style-type: none"> - Treatment with 2% of cationic softener at 40°C for 10 min, LR =1/10 (80kg for a load of 140 pants)

four different seam areas of each pair of jeans: the flat-felled seam on the outer leg, the overlock stitch (safety stitch) sewn along the edge of one or two fabric layers, the lockstitch on the belt, and the hemming²⁵⁻²⁸.

ISO Standards 3759 (ISO, 2011) and 5077 (ISO, 2008)^{29,30}, which provide standardized methods for the preparation, marking, and assessment of dimensional changes in textile fabrics and clothing, were followed in all measurements. These techniques are intended especially to evaluate deformation and shrinkage brought on by typical treatments like steaming, washing, and water immersion³¹. In order to ensure consistency and comparability of results across various samples and treatment conditions, the shrinkage values were computed using the formula given in Equation (1).

$$Sh (\%) = \frac{(L_0 - L)}{L_0} \times 100 \quad \dots(1)$$

where *Sh* is the shrinkage value of the tested fabric after treatment, expressed as a percentage; and L_0 is the initial length of the tested fabric, expressed in meters, L is the length of the tested fabric after treatment, expressed in meters.

A factorial design analysis was performed based on the experimental plan shown in Table 2. The selected treatments and their levels resulted in a complete factorial design ($4 \times 2 \times 2 \times 5 \times 2 \times 3 \times 2$), covering five washing processes and generating 960 experimental combinations^{32,33}. This design was repeated three times, totalling 2,880 experiments conducted under industrial conditions^{34,35}.

Predictive models for calculating the shrinkage rate of clothing after industrial finishing processes were created by statistically analysing the resulting shrinkage data using the General Linear Model (GLM).

The GLM is an ANOVA procedure in which the calculations are performed using a least squares regression approach to describe the statistical relationship between one or more predictors. This modeling technique made it possible to pinpoint important variables affecting shrinkage and produced accurate forecasts for a range of seam types and treatment scenarios.

3 Results and Discussion

To determine the fabric shrinkage of completed pants in various seam types, four models have been developed: flat-felled seam, overlock stitch (safety

stitch ISO 516), and lockstitch (ISO 301) on the hemming and belt. To optimise the model, the primary effect, interaction plot, and analysis of variance (ANOVA) were used to identify significant differences among the treatments.

Analysis of Variance (ANOVA) is a statistical method used to evaluate whether the means of two or more populations differ significantly. It examines the effect of one or more factors by comparing the mean responses across the various levels of these factors. The null hypothesis posits that all population means (i.e., the means for each factor level) are equal, whereas the alternative hypothesis asserts that at least one of these means differs from the others³⁶.

The result of an ANOVA is considered statistically significant when the p-value associated with the F-statistic is less than the chosen significance level (α), typically 0.05.

- If $p < \alpha \rightarrow$ Reject the null hypothesis. This means there is sufficient evidence to conclude that at least one group mean differs from the others.
- If $p \geq \alpha \rightarrow$ Fail to reject the null hypothesis. This means there is no significant evidence that the population means differ.

The ANOVA results showed that the treatment of Brushing is not significant ($p - value > 0.05$) while fabric type, laundering, special treatments, spraying, bleaching, and topping have a significant effect ($p - value = 0$) on shrinkage (Table 4).

An interaction plot is a valuable tool in factorial ANOVA because it visually illustrates how the effect of one factor changes across the levels of another factor. By displaying the mean response for each combination of factor levels, the plot helps researchers easily identify whether an interaction is present. When the lines in the plot are parallel, it suggests that no interaction exists and that the factors operate independently. However, when the lines diverge, converge, or cross, this indicates an interaction, meaning the influence of one factor depends on the level of the other. Overall, interaction plots play an essential role in clarifying and communicating interaction effects in multifactor experimental designs³⁷.

The interaction between the treatment of Brushing and all of the studied treatments is not significant. Similarly, the interaction is significant between the other treatments. Consequently, the statistical analysis's findings were incorporated into the established equations of the interrelationship between

Table 4 — Analysis of Variance.

	Flat-felled seam zone shrinkage	Safety stitch zone shrinkage	Lockstitch belt zone shrinkage	Lockstitch hem zone shrinkage
<i>T</i>	0.000	0.000	0.000	0.000
<i>R_e</i>	0.000	0.000	0.000	0.000
<i>B_r</i>	0.994	0.958	0.992	1.000
<i>D</i>	0.000	0.000	0.000	0.000
<i>B</i>	0.000	0.000	0.000	0.000
<i>S_p</i>	0.000	0.000	0.000	0.000
<i>P</i>	0.000	0.000	0.000	0.000
<i>T</i> × <i>R_e</i>	0.404	0.000	0.000	0.000
<i>T</i> × <i>B_r</i>	1.000	1.000	1.000	1.000
<i>T</i> × <i>D</i>	0.000	0.000	0.000	0.000
<i>T</i> × <i>B</i>	0.000	0.000	0.000	0.294
<i>T</i> × <i>S_p</i>	0.072	0.000	0.000	0.588
<i>T</i> × <i>P</i>	0.852	0.973	0.000	0.818
<i>R_e</i> × <i>B_r</i>	0.998	0.958	0.992	0.994
<i>R_e</i> × <i>D</i>	0.000	0.000	0.000	0.000
<i>R_e</i> × <i>B</i>	0.000	0.000	0.000	0.000
<i>R_e</i> × <i>S_p</i>	0.000	0.000	0.000	0.000
<i>R_e</i> × <i>P</i>	0.007	0.138	0.000	0.241
<i>B_r</i> × <i>D</i>	1.000	1.000	1.000	1.000
<i>B_r</i> × <i>B</i>	0.998	0.955	0.966	0.994
<i>B_r</i> × <i>S_p</i>	1.000	0.997	1.000	1.000
<i>B_r</i> × <i>P</i>	0.998	0.958	0.966	0.994
<i>D</i> × <i>B</i>	0.000	0.000	0.000	0.000
<i>D</i> × <i>S_p</i>	0.000	0.000	0.000	0.000
<i>D</i> × <i>P</i>	0.000	0.000	0.000	0.000
<i>B</i> × <i>S_p</i>	0.000	0.000	0.000	0.000
<i>B</i> × <i>P</i>	0.000	0.192	0.000	0.172
<i>S_p</i> × <i>P</i>	0.000	0.000	0.059	0.285

the various treatments and their interactions. These equations represent significant effects of every studied parameter (*p* – value < 0.05).

Finally, there is a significant difference in the shrinkage value between the flat-felled seam, overlock stitch, and lockstitch, which can be explained by the different places where the shrinkage is measured²⁶. The shrinkage measured on the sides of the denim pants (flat-felled seam or overlock stitch) is on the warp direction of the fabric, but the shrinkage measured on the waist or hem (lockstitch) is on the weft direction of the fabric. Because the adjusted regression coefficient test yields a regression coefficient that is extremely close to 1, it demonstrates that the modeling of shrinkage for the lockstitch (belt and hem) is validated (Table 5). The expressions of these three models are given below in 3.1 subsection.

Table 5 — Results of the testing of the adjusted regression coefficient for shrinkage

Responses	<i>R</i> ² _{adj}
Modelling of Flat-Felled Seam Zone Shrinkage	0.9793
Modelling of Safety Stitch zone shrinkage	0.9564
Modelling of Lockstitch belt zone shrinkage	0.9761
Modelling of Lockstitch hem zone shrinkage	0.9721

3. 1 Expression of the Four Models

3.1.1 Modelling of Flat-Felled Seam Zone Shrinkage

$$\begin{aligned}
 \hat{y} &= 5.42745 + [-0.112309. 0.165316. -0.161503. 0.108496][T] \\
 &+ [-0.249128. 0.249128][R_e] \\
 &+ [-1.18146. -0.00158. 0.348767. 0.553698. 0.298045][D] \\
 &+ [0.327434. -0.327434][B] + [0.319927. -0.14726. -0.172667][S_p] \\
 &+ [0.06476. -0.06476][P] \\
 &+ \begin{bmatrix} 0.028681 & -0.000087 & -0.007517 & -0.013976 & -0.007101 \\ -0.030125 & 0.003955 & 0.008747 & 0.011316 & 0.006107 \\ 0.032597 & -0.004226 & -0.006656 & -0.011865 & -0.00985 \\ -0.031153 & 0.000358 & 0.005426 & 0.014525 & 0.010844 \end{bmatrix} [T] \\
 &\times D + \begin{bmatrix} -0.009351 & 0.009351 \\ 0.011497 & -0.011497 \\ -0.013101 & 0.013101 \\ 0.010955 & -0.010955 \end{bmatrix} [T \times B]
 \end{aligned}$$

$$\begin{aligned}
 &+ \begin{bmatrix} -0.306097 & -0.066455 & -0.068955 & -0.106385 & -0.064302 \\ 0.306097 & -0.066455 & -0.068955 & -0.106385 & -0.064302 \end{bmatrix} [R_e \\
 &\quad \times D] + \begin{bmatrix} -0.018170 & 0.01817 \\ 0.01817 & -0.01817 \end{bmatrix} [R_e \times B] \\
 &+ \begin{bmatrix} -0.013622 & -0.008358 & -0.005264 \\ 0.013622 & -0.008358 & -0.005264 \end{bmatrix} [R_e \times S_p] \\
 &+ \begin{bmatrix} 0.003587 & -0.003587 \\ -0.003587 & 0.003587 \end{bmatrix} [R_e \times P] \\
 &+ \begin{bmatrix} -0.279014 & 0.279014 \\ 0.279014 & -0.279014 \end{bmatrix} [D \times B] \\
 &+ \begin{bmatrix} 0.07767 & -0.07767 \\ 0.099962 & -0.099962 \\ -0.026288 & 0.026288 \\ 0.12767 & -0.12767 \end{bmatrix} [D \times S_p] \\
 &+ \begin{bmatrix} -0.247792 & 0.125063 \\ 0.23997 & -0.011837 & 0.01216 \\ 0.126045 & -0.063434 & -0.062611 \\ 0.023823 & -0.015448 & -0.008375 \\ 0.073927 & -0.03201 & -0.066237 \end{bmatrix} [D \times S_p] \\
 &\quad + \begin{bmatrix} -0.026931 & 0.026931 \\ -0.010698 & 0.010698 \\ 0.003122 & -0.003122 \\ 0.002149 & -0.002149 \end{bmatrix} [D \times P] \\
 &\quad + \begin{bmatrix} 0.032358 & -0.032358 \\ -0.071976 & 0.034753 & 0.0037223 \\ 0.071976 & -0.034753 & -0.0037223 \end{bmatrix} [B \times S_p] \\
 &\quad + \begin{bmatrix} -0.01992 & 0.01992 \\ 0.01992 & -0.01992 \end{bmatrix} [B \times P] \\
 &\quad + \begin{bmatrix} 0.024948 & -0.024948 \\ -0.011948 & 0.011948 \\ -0.013 & 0.013 \end{bmatrix} [S_p \times P]
 \end{aligned}$$

3.1.2 Modelling of Safety Stitch Zone Shrinkage

$$\begin{aligned}
 \hat{y} &= 3.68557 + [-0.127625 \ 0.177833 \ -0.172 \ 0.121792][T] \\
 &+ [-0.367278 \ 0.367278][R_e] \\
 &+ [-1.02878 \ 0.150194 \ 0.284257 \ 0.355941 \ 0.238388][D] \\
 &+ [0.316132 \ -0.316132][B] \\
 &+ [0.418243 \ -0.192517 \ -0.225726][S_p] \\
 &+ [0.061597 \ -0.061597][P] + \begin{bmatrix} 0.012222 & -0.012222 \\ -0.021458 & 0.021458 \\ 0.022319 & -0.022319 \\ -0.013083 & 0.013083 \end{bmatrix} [T \times R_e] \\
 &+ \begin{bmatrix} 0.033476 & 0.003806 & -0.013174 & -0.027635 & 0.003527 \\ -0.051358 & 0.001125 & 0.015257 & 0.02774 & 0.007236 \\ 0.052295 & -0.008347 & -0.011715 & -0.019441 & -0.012792 \\ -0.034413 & 0.003416 & 0.009632 & 0.019336 & 0.002029 \\ -0.014688 & 0.014688 \end{bmatrix} [T \\
 &\times D] + \begin{bmatrix} 0.02066 & -0.02066 \\ -0.018701 & 0.018701 \\ 0.012729 & -0.012729 \end{bmatrix} [T \times B] \\
 &+ \begin{bmatrix} -0.011187 & 0.006073 & 0.005114 \\ 0.020271 & -0.005969 & -0.014302 \\ -0.022313 & 0.00774 & 0.014573 \\ 0.013229 & -0.007844 & -0.005385 \end{bmatrix} [T \times S_p] \\
 &+ \begin{bmatrix} 0.020559 & -0.088556 & 0.06516 & 0.058406 & -0.055569 \\ -0.020559 & 0.088556 & -0.06516 & -0.058406 & 0.055569 \end{bmatrix} [R_e \times D] \\
 &+ \begin{bmatrix} -0.044007 & 0.044007 \\ 0.044007 & -0.044007 \end{bmatrix} [R_e \times B] \\
 &+ \begin{bmatrix} -0.057201 & 0.024184 & -0.033017 \\ 0.057201 & -0.024184 & 0.033017 \end{bmatrix} [R_e \times P] \\
 &+ \begin{bmatrix} -0.146913 & 0.146913 \\ 0.121507 & -0.121507 \\ 0.001889 & -0.001889 \\ -0.08799 & 0.08799 \\ 0.111507 & -0.111507 \end{bmatrix} [D \times B] \\
 &+ \begin{bmatrix} -0.180135 & 0.083125 & 0.09701 \\ 0.00891 & 0.003837 & -0.012747 \\ 0.092556 & -0.041372 & -0.051184 \\ 0.033788 & -0.028316 & -0.005472 \\ 0.044881 & -0.017274 & -0.027607 \end{bmatrix} [D \times S_p] \\
 &\quad + \begin{bmatrix} -0.022135 & 0.022135 \\ 0.014514 & -0.014514 \\ -0.02309 & 0.02309 \\ -0.007552 & -0.007552 \\ 0.038263 & -0.038263 \end{bmatrix} [D \times P]
 \end{aligned}$$

$$\begin{aligned}
 &+ \begin{bmatrix} 0.118847 & -0.055101 & -0.063746 \\ -0.118847 & 0.055101 & 0.063746 \end{bmatrix} [B \times S_p] \\
 &\quad + \begin{bmatrix} 0.013465 & -0.013465 \\ -0.011233 & 0.011233 \\ -0.002232 & 0.002232 \end{bmatrix} [S_p \times P]
 \end{aligned}$$

3.1.3 Modelling of Lockstitch Belt Zone Shrinkage

$$\begin{aligned}
 \hat{y} &= 0.877066 + [-0.30251 \ 0.317309 \ -0.312844 \ 0.298045][T] \\
 &+ [-0.206413 \ 0.206413][R_e] \\
 &+ [-0.391997 & -0.088576 & 0.146198 & 0.27026 & 0.064115][D] \\
 &+ [0.149378 & -0.149378][B] + [0.151257 & -0.064337 & -0.08692][S_p] \\
 &+ [0.03826 & -0.03826][P] + \begin{bmatrix} 0.066524 & -0.066524 \\ -0.069295 & 0.069295 \\ 0.069024 & -0.069024 \\ -0.066253 & 0.066253 \end{bmatrix} [T \times R_e] \\
 &+ \begin{bmatrix} 0.131191 & 0.02166 & -0.052142 & -0.076344 & -0.024365 \\ -0.138073 & -0.026979 & 0.051649 & 0.093003 & 0.0204 \\ 0.135969 & 0.025326 & -0.056115 & -0.087122 & -0.018058 \\ -0.129087 & -0.020007 & 0.056608 & 0.070463 & 0.022023 \end{bmatrix} [T \times D] \\
 &+ \begin{bmatrix} -0.050212 & 0.050212 \\ 0.052247 & -0.052247 \\ -0.051045 & 0.051045 \end{bmatrix} [T \times B] \\
 &+ \begin{bmatrix} 0.04901 & -0.04901 \\ -0.038563 & 0.020198 & 0.018365 \\ 0.041743 & -0.026622 & -0.015121 \\ -0.040563 & 0.021115 & 0.019448 \end{bmatrix} [T \times S_p] \\
 &+ \begin{bmatrix} 0.037383 & -0.014691 & -0.022692 \\ 0.104330 & 0.043965 & 0.048497 & -0.171955 & -0.024837 \\ -0.10433 & -0.043965 & -0.048497 & 0.171955 & 0.024837 \end{bmatrix} [R_e \times D] \\
 &+ \begin{bmatrix} -0.019087 & 0.019087 \\ 0.019087 & -0.019087 \end{bmatrix} [R_e \times B] \\
 &+ \begin{bmatrix} -0.012826 & 0.006267 & 0.006559 \\ 0.012826 & -0.006267 & -0.006559 \end{bmatrix} [R_e \times S_p] \\
 &+ \begin{bmatrix} -0.004024 & 0.004024 \\ 0.004024 & -0.004024 \end{bmatrix} [R_e \times P] + \begin{bmatrix} -0.027503 & 0.027503 \\ 0.00609 & -0.00609 \\ -0.039726 & 0.039726 \\ 0.034545 & -0.034545 \\ 0.026594 & -0.026594 \end{bmatrix} [D \times B] \\
 &+ \begin{bmatrix} -0.044347 & 0.021872 & 0.022475 \\ -0.011986 & 0.006785 & 0.005201 \\ 0.007562 & 0.002115 & -0.009677 \\ 0.071625 & -0.044135 & -0.02749 \\ -0.022854 & 0.013363 & 0.009491 \\ -0.00701 & 0.00701 \end{bmatrix} [D \times S_p] \\
 &+ \begin{bmatrix} -0.008382 & 0.008382 \\ -0.002983 & 0.002983 \\ 0.011219 & -0.011219 \\ 0.007156 & -0.007156 \end{bmatrix} [D \times P] \\
 &+ \begin{bmatrix} 0.052715 & -0.025233 & -0.027482 \\ -0.052715 & 0.025233 & 0.027482 \end{bmatrix} [B \times S_p] \\
 &+ \begin{bmatrix} 0.006128 & -0.006128 \\ -0.006128 & 0.006128 \end{bmatrix} [B \times P]
 \end{aligned}$$

3.1.4 Modelling of Lockstitch Hem Zone Shrinkage

$$\begin{aligned}
 \hat{y} &= 2.03548 + [-0.047326 \ 0.064424 \ -0.065646 \ 0.048548][T] \\
 &+ [-0.159444 \ 0.159444][R_e] \\
 &+ [-0.492059 & -0.035062 & 0.160528 & 0.300806 & 0.065787][D] \\
 &+ [0.089611 & -0.089611][B] + [0.132521 & -0.056531 & -0.07599][S_p] \\
 &+ [0.033431 & -0.033431][P] + \begin{bmatrix} 0.005097 & -0.005097 \\ -0.004069 & 0.004069 \\ 0.005167 & -0.005167 \\ -0.006195 & 0.006195 \end{bmatrix} [T \times R_e] \\
 &+ \begin{bmatrix} 0.011823 & 0.00441 & -0.003819 & -0.007431 & -0.004983 \\ -0.013469 & -0.004424 & 0.003875 & 0.008736 & 0.005282 \\ 0.015281 & 0.003007 & -0.004667 & -0.010083 & -0.003538 \\ -0.13635 & -0.002993 & 0.050461 & 0.008778 & 0.003239 \\ -0.159601 & 0.057292 & 0.00566 & 0.006562 & 0.090087 \end{bmatrix} [T \times D] \\
 &+ \begin{bmatrix} 0.159601 & -0.057292 & -0.00566 & -0.006562 & -0.090087 \\ -0.007868 & 0.007868 \end{bmatrix} [R_e \\
 &\times D] + \begin{bmatrix} 0.007868 & -0.007868 \\ -0.012639 & 0.004976 & 0.007663 \end{bmatrix} [R_e \times B] \\
 &+ \begin{bmatrix} -0.012639 & 0.004976 & 0.007663 \end{bmatrix} [R_e \times S_p]
 \end{aligned}$$

$$\begin{aligned}
 & + \begin{bmatrix} -0.001816 & 0.001816 \\ 0.018722 & -0.00609 \\ -0.016174 & 0.016174 \\ 0.002924 & -0.002924 \\ -0.003656 & 0.003656 \end{bmatrix} [D \times B] \\
 & + \begin{bmatrix} -0.0159410 & 0.009569 & 0.006372 \\ -0.011688 & 0.005906 & 0.005782 \\ 0.025014 & -0.017288 & -0.007726 \\ 0.041403 & -0.022462 & -0.018941 \\ -0.0387880 & 0.024275 & 0.014513 \end{bmatrix} [D \times S_p] \\
 & + \begin{bmatrix} 0.021274 & -0.021274 \\ -0.0035 & 0.0035 \\ -0.006451 & 0.006451 \\ -0.003188 & 0.003188 \\ -0.0081350 & 0.008135 \end{bmatrix} [D \times P] \\
 & + \begin{bmatrix} 0.037556 & -0.021142 & -0.016414 \\ -0.037556 & 0.021142 & 0.016414 \end{bmatrix} [B \times S_p]
 \end{aligned}$$

3.2 Examining the Validity of the Model

To validate the models for each response, a standard analysis of variance (ANOVA) was applied to assess the agreement between model predictions and observed measurements. This approach allowed us to optimise the three models and evaluate their predictive capability for shrinkage across different zones defined in the experimental design. The validity of the shrinkage prediction models was further confirmed by comparing the predicted shrinkage values with the actual measurements from additional finished samples produced under industrial conditions.

3.2.1 Statistical Validation

Analysis of variance (ANOVA) with the Fisher test (F-test) is the foundation of this validation method³⁸. Equation (2) is used to calculate the F-value, which is then compared to the critical F-value derived from conventional F-distribution tables.

$$F_{calculated} = \frac{\text{Mean Sum squares between groups}}{\text{Mean Sum squares within groups}} \dots(2)$$

The critical F-value is determined for a significance level of $\alpha = 0.05$, corresponding to a 95% confidence level. If the calculated F-value exceeds the critical F-value from the table, the null hypothesis is rejected. This indicates, with 95% confidence, that the variance between groups is not due to random chance but is instead influenced by the tested factor¹⁹. As shown in Table 6, the four models evaluated are statistically significant and reliable, as indicated by the Fisher test at a 5 % significance level.

3.2.2 Practical Validation

The model validation was conducted under real industrial conditions, where various laundering types were applied using washing machines processing 100 kg batches of denim pants. Specifically, jeans with five different pocket designs were tested across

Model	F-test calculated, F	F-test table, F5%
Model: Flat-Felled Seam zone shrinkage	7299.88493	1.61
Model: safety stitch zone shrinkage	4818.40636	1.61
Model: Lockstitch belt zone shrinkage	3690.93033	1.58
Model: Lockstitch hem zone shrinkage	3920.16279	1.68



Fig. 3 — The five samples tested in production for model validation

five distinct production outputs (P.O.1, P.O.2, P.O.3, P.O.4, and P.O.5). The main differences between these production outputs were the fabric types and the finishing treatments applied. For confidentiality reasons, details regarding the specific industrial orders and customers are not disclosed in this study, as per company policy (Fig. 3).

Every sample (P.O.) underwent various washing procedures and additional special treatments. Table 7 lists each sample's various parameters along with their respective levels. To determine the high level of the factor that could be utilised in each model to accurately estimate the final shrinkage after finishing treatments, the fabric's highest measured shrinkage value is fixed.

The theoretical (\tilde{y}) and experimental values (y) are compared in order to examine the efficacy of the used method. The accuracy of the developed regression model²⁸ can be enhanced by the difference ($Error(\%)$) between these results (see Equation 3).

$$Error(\%) = \frac{(y - \tilde{y})}{y} \times 100 \dots(3)$$

Table 8 displays the measured shrinkage following production as well as the model-estimated results (the theoretical or predicted shrinkage value) for each reference. These findings demonstrate that the discrepancy between the model-estimated and

Table 7 — Parameters' identification

Industrial codification	Parameters	Level
P.O.1	Fabric type: 3	3
	Resin- treatment	1
	Washing types: Rinse	1
	Spray: Permanganate-spray	1
	Pressing	1
P.O.2	Fabric type: 2	2
	Washing types: Mixed (Stone and Enzyme)	4
	Bleach-treatment	1
	Pressing	1
P.O.3	Fabric type: 1	1
	Washing types: Double Stone	3
	Spray: Permanganate-spray	1
	Pressing	1
P.O.4	Fabric type: 2	2
	Washing types: Enzymatic	5
	Spray: Permanganate-spray	1
	Pressing	1
P.O.5	Fabric type: 4	4
	Washing types: Double Stone	3
	Bleach-treatment	1
	Pressing	1

P.O.1: First Production Output; P.O.2: Second Production Output; P.O.3: Third Production Output; P.O.4: Fourth Production Output; P.O.5: Fifth Production Output.

measured values is less than 2.6% of the observed shrinkage. This level of agreement aligns with the results reported by Akcagun²⁸ and provides industrial practitioners with real-world validation of the predictive accuracy of their existing shrinkage models. From a production standpoint, such validation strengthens confidence in using model-based predictions for production planning, quality control, and waste-reduction strategies, since more reliable estimates of shrinkage allow manufacturers to adjust tooling, compensate for dimensional changes, and minimize rework.

Therefore, in theory, the ultimate shrinkage of a manufactured item could be expressed as follows:

Otherwise, the results of the theoretical models (predicted shrinkage) for each production output and the measured shrinkage after production are summarized in Table 8. They also display the error range values for each of the pants' fabrics under study. The difference between the experimental and theoretical values aids in shrinkage prediction and can be used to automatically produce a positive outcome, according to the results obtained. Additionally, the error range, which ranges from -2.534304 % to 2.244622 %, illustrates how successful the established model is.

Table 8 — Results of measurements

Fabric code	Response	Predicted shrinkage \hat{y}	Measured shrinkage y	Error(%)
P.O.1	<i>Flat-Felled Seam zone shrinkage</i>	3.61	3.62	0.20
	<i>Safety Stitch zone shrinkage</i>	2.25	2.25	-0.08
	<i>Lockstitch belt zone shrinkage</i>	0.23	0.23	0.43
	<i>Lockstitch hem zone shrinkage</i>	1.25	1.25	-0.16
P.O.2	<i>Flat-Felled Seam zone shrinkage</i>	6.45	6.44	-0.15
	<i>Safety Stitch zone shrinkage</i>	4.40	4.50	2.24
	<i>Lockstitch belt zone shrinkage</i>	2.25	2.24	-0.45
	<i>Lockstitch hem zone shrinkage</i>	2.59	2.58	-0.39
P.O.3	<i>Flat-Felled Seam Zone Shrinkage</i>	6.13	6.15	0.29
	<i>Safety Stitch zone shrinkage</i>	4.26	4.25	-0.24
	<i>Lockstitch belt zone shrinkage</i>	0.81	0.79	-2.53
	<i>Lockstitch hem zone shrinkage</i>	2.35	2.34	-0.46
P.O.4	<i>Flat-Felled Seam Zone Shrinkage</i>	6.26	6.25	-0.23
	<i>Safety Stitch zone shrinkage</i>	4.49	4.50	0.22
	<i>Lockstitch belt zone shrinkage</i>	1.60	1.62	1.08
	<i>Lockstitch hem zone shrinkage</i>	2.23	2.2	-1.37
P.O.5	<i>Flat-Felled Seam Zone Shrinkage</i>	6.40	6.38	-0.31
	<i>Safety Stitch zone shrinkage</i>	4.39	4.38	-0.23
	<i>Lockstitch belt zone shrinkage</i>	1.65	1.64	-0.94
	<i>Lockstitch hem zone shrinkage</i>	2.45	2.44	-0.44

P.O.1: First Production Output; P.O.2: Second Production Output; P.O.3: Third Production Output; P.O.4: Fourth Production Output; P.O.5: Fifth Production Output.

Indeed, it can be very useful for industrialists, giving them practical help to make suitable decisions.

The practice of the models produced gave very good measurement accuracy, and the errors did not exceed $\pm 2.54\%$ of the shrinkage rate. In practice, this error is very negligible since it does not exceed 3 mm for a shrinkage of 10 cm. Theoretically, the final shrinkage value of a manufactured denim pants can be determined using equation 4:

$$y = \tilde{y} \pm 2.54 \% \quad \dots(4)$$

where \tilde{y} is the measured shrinkage value, and y is the predicted one.

Finally, the proposed model also contributes significantly to ongoing digital transformation efforts within manufacturing environments. By providing accurate, data-driven predictions of ultimate shrinkage, the model can be integrated into digital workflows such as simulation systems, digital twins, and model-based process control. This enhances real-time decision-making, increases process transparency, and reduces dependence on empirical trial-and-error approaches. From a lean manufacturing perspective, the model supports waste elimination by reducing dimensional variability, minimizing scrap and rework, and improving first-time-right production. Consequently, the enhanced predictive capability not only strengthens digital manufacturing ecosystems but also aligns directly with lean principles aimed at maximizing value while reducing non-value-added activities.

4 Conclusion

The primary objective of this study was to develop reliable predictive models for estimating fabric shrinkage in denim pants during the seaming process, particularly after the application of various industrial finishing treatments. To achieve this, an extensive experimental methodology was employed, involving 960 factorial design combinations carried out under real industrial conditions and replicated three times. Shrinkage behavior was evaluated across different seam types, including flat-felled seams, safety stitches, and lockstitches, after subjecting the denim to diverse laundering processes, resin finishes, and special treatment sequences.

The analysis demonstrated that the type of industrial seaming, the presence of resin treatment, and the specific succession of finishing processes all exert significant influence on the final shrinkage of denim

garments. Based on these findings, four predictive models were established to forecast shrinkage in critical areas of the pants across different treatment combinations. Validation using five independent production outputs confirmed a strong correlation between predicted and experimentally measured shrinkage values, highlighting the robustness and practical reliability of the developed models.

The significance of this work lies in its potential to enhance production planning, reduce material waste, and minimize rework, key elements in advancing toward Industry 4.0-aligned manufacturing. By integrating these models into routine production processes, manufacturers can better control garment dimensions, optimize treatment sequences, and improve overall efficiency, thereby reinforcing both digital transformation initiatives and lean manufacturing practices within modern production systems. Future work may focus on expanding the model to incorporate additional fabric types, automated data acquisition systems, integration with CAD/CAM workflows for automated shrinkage compensation, real-time monitoring for adaptive control, and advanced machine learning approaches to enhance prediction accuracy and real-time decision-making capabilities.

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