Loop Length of Plain Single Weft Knitted Structure with Elastane

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ABSTRACT

For decades, scientists have been trying to define relationships among yarn parameters, knitted fabric parameters, and knitting parameters with loop models. Recently, the geometrical loop models have returned to focus as they assist finding the effective parameters which cause dimensional changes during relaxation. Furthermore, they help designing knitted structures for technical applications and obtaining computer simulations of knitted structures. In the past, geometrical loop models considered more or less porous structures and the yarns used were mostly conventional, without elastane. The behavior and characteristics of compact knitted fabrics made from elasticized yarns have been investigated only recently. In general, mostly the structures with plated elastane threads have been analyzed. The aim of the research was to study the geometrical parameters (yarn thickness, loop width, loop height, fabric thickness, loop length) of plain single weft knitted structures made from various elasticized yarns, in comparison to equivalent structures made from conventional yarns. In the study, the most frequently applied loop models for the loop length calculations were evaluated with the emphasis on their adequacy for elasticized knitted structures. A new loop model for an elasticized weft knitted structure based on the multiple linear regressions was defined.

INTRODUCTION

As early as in the first half of the 20th century, scientists tried to define relationships among yarn parameters, knitted fabric parameters and knitting process parameters with loop models. The first loop models dealing with the single knitted structure were geometrical and relatively simple [1–3], and they only approximately corresponded to the yarns and knitted structures applied at that time. The subsequent models were more complex [4–11], and played an important role in the control of knitted fabric dimensions and mass per unit area. Later on, loop models [12–16] were designed for graphic simulations and knitted structure planning. Supported by the latest expertise, testing and measuring techniques, e.g. electron microscopy [13,14] and computer aided image analysis [15], loop models enabled a more precise specification of the loop shape and size, depending on the geometrical parameters of the loop. Contemporary computer graphics have been lately used to additionally illustrate the knitted loop geometry [16,17]. In addition to mechanical and energy loop models, which interpret the behavior of knitted structures under loading, the geometrical loop models have recently returned to focus. Geometrical loop models assist finding the effective parameters which cause dimensional changes during relaxation, enable planning the production of a piece of fabric before knitting, assist designing knitted structures for technical applications, obtain computer simulations of knitted structures for design or fault-assessing purposes, help creating a physical loop model, help evaluating curling etc [17].

Due to the three-dimensional curved shape of the loop, knitted structures are generally more porous and extensible than other textile structures. On the other hand, contemporary knitted fabrics with incorporated elastane usually exhibit a very compact structure due to extensive shrinking relaxation after knitting, wet finishing and care processes. In the past, various geometrical loop models considered more or less porous structures, e.g. open, normal and to a certain degree also closed (compact) structures [2–10,12]; however, the yarns used were mostly conventional, i.e. without elastane. The behavior and characteristics of compact knitted fabrics made from elasticized yarns have not been investigated until recently [18–21]. In general, mostly the structures with plated elastane threads have been analyzed [22–24].

The aim of the presented investigation was to study the geometrical parameters (yarn thickness, loop width, loop height, fabric thickness, and loop length) of plain single weft knitted structures made from various elasticized yarns, in comparison to equivalent structures made from conventional yarns. One of the objectives was to evaluate the most frequently applied loop models for the loop length calculations with the emphasis on their adequacy for elasticized knitted structures, and another was to define a new weft knitted loop model based on the multiple linear regressions.

GEOMETRICAL LOOP MODELS

The most distinctive characteristic of a knitted structure is its complex geometry. As loop length (ℓ) is considered to be the primary knitted structure parameter [3], its relation to other geometrical loop parameters has been a preferred research topic for over fifty years now. In order to predict the dimensional characteristics of knitted fabrics, basic knitted loop geometrical parameters and their interdependence have been most often analyzed, i.e. loop width (A), loop height (B), loop length (ℓ), yarn thickness (d) and fabric thickness (t).

Yarn diameter or yarn thickness (d) is a basic yarn parameter. It depends on yarn linear density, yarn type, yarn structure and its material composition. With unchanged loop width and loop height, yarn thickness influences loop length and knitted fabric porosity/compactness [25–27]. Loop width (A) is inversely proportioned to horizontal density (Dh), also referred to as wale density of a knitted fabric (W). Similarly, loop height (B) is inversely proportioned to vertical density (Dv), also denoted as the course density of a knitted fabric (C). The knitted fabric horizontal density is defined by the knitting machine gauge and the yarn input tension; it changes only slightly with the change of the yarn input tension for conventional yarns and substantially for elasticized yarns. The vertical density of a knitted fabric changes with the couliering depth change, i.e. machine cam setting. With the couliering depth increase, loop length increases and simultaneously, vertical density is reduced [25,27]. The horizontal and vertical density, i.e. wale and course density do not directly influence the knitted structure compactness/openness. With an identical horizontal and/or vertical density value, the knitted structure made from thicker yarn is more compact. With an identical yarn diameter value, a knitted structure with higher horizontal and/or vertical density becomes more compact [25,27]. Fabric thickness (t) is one of the important knitted fabric parameters, influencing insulation properties, air permeability, UV radiation protection, handle, material consumption etc [20]. Loop length (ℓ) is influenced by yarn input tension, knitted fabric take-down tension, knitting velocity, friction in the knitting zone, machine gauge, couliering depth defined by machine cam setting, yarn structure, yarn linear density etc [25].

Various geometrical loop models define loop length in relation to various parameters of the loop. In this research, only the knitted loop models defining loop length (ℓ) in relation to basic loop dimensions, i.e. loop width (A), loop height (B) and yarn thickness (d), were analyzed, as these parameters can be simply measured in real knitted fabrics. The simplified loop length equations defining special cases of loop configurations, e.g. normal and closed (compact) knitted structure, were also taken into consideration. A more detailed review of the most noted geometrical knitted loop models, including Leaf and Glaskin's, Munden's and Korlinski's model, is presented elsewhere [28]. In these models, the loop length is defined as the function of parameters others than loop width and height, and yarn thickness.

Peirce's Loop Model

In his study, Peirce [2] presumed that a knitted structure is normal when adjacent yarns within a knitted fabric are joined in contact points only. The projection of the loop onto the fabric plane is composed of the circular needle and sinker arcs connected with straight lines i.e. loop legs. The loop is three-dimensional, which means that the loop arcs and legs lie on the cylinder surface with curvature radius (R) and the axis parallel to the course direction. For a normal structure, loop length (ℓ) depends only on yarn thickness (d) [2]:

$$\ell = 16.66\, d \tag{1}$$

Taking into account that an ideal real knitted fabric does not necessarily exist as a normal structure, Peirce adjusted his loop model also for open (more porous) knitted fabrics in which adjacent yarns are not in contact. In this case, he anticipated loop elongation by inserting yarn segments to the loop arcs, and between the arcs and loop legs. The loop length of the open knitted structure (ℓ) defined by Peirce is [2]:

$$\ell = 2A + B + 5.94\, d \tag{2}$$

where A is loop width, B is loop height and d is yarn thickness. Peirce [2] did not test the adequacy of his model with laboratory measurements and analyses of real knitted fabrics. The adequacy of his model was verified through experimental work by Fletcher and Roberts [29–31]. Peirce's loop model was quoted, commented upon and tested directly or indirectly by other authors as well, *inter alia* by Shinn [32], Munden [3], Knapton et al [33] etc.

Dalidovich's Loop Model

Dalidovich's general loop model [8] is three-dimensional. It presumes that the knitted structure is open, and that there is a distance between the sinker and the needle arcs of the loop. According to Dalidovich [8], loop length (ℓ) is a function of loop width (A), loop height (B) and yarn thickness (d). Assuming the simplifications that the loop is planar, that the loop legs are parallel to the ordinate and that their length equals the loop height (B), loop length (ℓ) is [8]:

$$\ell = 1.57A + 2B + \pi d \quad (3)$$

According to Dalidovich, the loop length (ℓ) of a normal structure only depends on yarn thickness (d) and can be calculated with a simple equation:

$$\ell = 16.64d \quad (4)$$

Dalidovich's general loop model has often been used for the estimation of yarn consumption in the production planning and theoretical research of a single knitted structure [34–37].

Vekassy's Loop Model

Vekassy [5] derived his loop model from Dalidovich's model of the non-stressed loop [8] and the results of Doyle's research [38]. He presumed that the yarn is entirely even, its cross section circular and its diameter a constant. The elementary Vekassy's loop general model is a space-curve, namely a cycloid arising from crossing the cylinder jacket with three parallel cylinder jackets. The loop consists of four equally long parts. The loop length equation is very complex, defining the loop length in dependence of the radius of the cylinder holding up the loop, the radii of the cylinders around which the needle and sinker arcs are bent, and the loop element projections onto the fabric plane [5,39].

Additionally, Vekassy also defined a simplified equation for the loop length of a normal knitted structure in which the needle and sinker arcs are in contact. The loop length (ℓ) of the normal structure is only dependent on yarn thickness (d):

$$\ell = 17.33d \quad (5)$$

Moreover, Vekassy anticipated the structure being more closed than the normal structure. He presumed that the needle and sinker arcs are elliptical, and that they are in contact in both horizontal and vertical directions. The loop height of the closed structure is smaller than the height of the normal loop structure. The loop length (ℓ) of the closed knitted structure is:

$$\ell = 13.396\,d \approx 13.40\,d \quad (6)$$

where d is yarn thickness.

Morooka & Matsumoto & Morooka's Loop Model

Although Morooka & Matsumoto & Morooka's loop model [12] represents the loop as the element of a knitted fabric lying on the cylinder which is a part of a three-dimensional structure, in reality, it is a planar loop model. The authors based this statement with the negligible fabric thickness in relation to the needle and sinker arc within a hosiery fabric. Morooka & Matsumoto & Morooka [12] presumed an open structure for the general loop shape in which the needle and sinker arcs are in contact neither in the vertical nor in the horizontal direction. With the derivation from the original Morooka & Matsumoto & Morooka's loop model and introduction of loop width (A), loop height (B) and yarn thickness (d), the general equation for the loop length (ℓ) calculation is [39]:

$$\ell = A + 2B + 4.28\,d \quad (7)$$

Discussion on Presented Geometrical Loop Models

Eq. (7) of the Morooka & Matsumoto & Morooka's loop model shows the loop length dependence on loop width (A), loop height (B) and yarn thickness (d), similar to Peirce's loop model of the open structure and Dalidovich's general loop model. The coefficients of the above mentioned three models differ, since Dalidovich assumes the semicircular shape of the needle and sinker arc, Peirce assumes the straight yarn portions in the semicircular loop crown and straight loop legs, and Morooka & Matsumoto & Morooka assume straight yarn portions only within the needle and sinker arc of the loop.

Apart from the Munden's loop model, defining the relationship between fabric density and loop length with the so-called Munden constants [3], Peirce's and Dalidovich's loop models have been the most usable for weft knitted structure planning and analysis due to their simplicity. They define a normal, open and under limited conditions also a closed structure. However, they have been used mostly for the study of the knitted fabrics made from conventional yarns without elastane addition. Vekassy's general model [5] presents the real, three-dimensional knitted structure most adequately; nevertheless, it is generally too complex for fabric planning [25,39]. Morooka & Matsumoto & Morooka's loop model was developed to explain the knitted structure of the extended hosiery fabric and has not been used for the production and simulation planning.

None of the researchers developed a simple loop model defining the loop length (ℓ) of a closed, i.e. compact, knitted structure produced by knitting elasticized yarns, depending on loop width (A), loop height (B) and yarn diameter (d). Therefore, on the basis of experimental results, a new geometrical model was developed based on the multiple linear regressions in order to enable the production calculations for elasticized single knitted structures.

EXPERIMENTAL

Sample Preparation

The experiments were carefully planned and the samples specially made for the research purpose. The yarn samples were made from two types of staple fibers, i.e. viscose (CV) and polyacrylonitrile (PAN). From each raw material, elastomeric yarns with the same linear density (100 tex) were made to order with three different spinning/twisting processes, i.e. mouliné twisted yarn (composed of elastomeric core-spun yarn and yarn without elastane, both ring-spun), core-twisted yarn (elastane filament yarn, core-twisted with two ring-spun yarns) and core-spun yarn (yarn with an elastane core and staple fiber sheath covering). For a comparison, ring-spun yarns without elastane from 100% viscose and 100% polyacrylonitrile fibers with equal linear density as elastomeric yarns were produced as well *(cf. Table I)*.

TABLE I. Yarn structure.

yarn type	yarn structure
mouliné	ring-spun elastomeric core-spun yarn + ring-spun conventional yarn
core-twist	elastane filament yarn + 2 ring-spun conventional yarns
core-spun	elastane filament yarn + fibre sheath
conventional	ring-spun yarn without elastane

TABLE II. Yarn characteristics and labeling.

yarn sample	material composition	yarn type	yarn labeling
1	97.8% CV 2.2% EL	mouliné	MOU
2	97.8% PAN 2.2% EL		
3	97.8% CV 2.2% EL	core-twist	C-TW
4	97.8% PAN 2.2% EL		
5	97.8% CV 2.2% EL	core-spun	C-SP
6	97.8% PAN 2.2% EL		
7	100% CV	conventional	CONV
8	100% PAN		

The yarns were produced at the spinning factory Predilnica Litija. Elasticized yarns were made on core ring spinning machines Krusik – Zinser TB-317, while conventional non-elasticised yarns were made on conventional ring spinning machines Krusik – Zinser TB-317. Mouliné twisted yarns were further processed on automatic Savio winding machines, doubled on Rite doubling machines and twisted on SaurerAllma twisting machines. Core-twisted yarns were doubled and twisted on Hamel machines. Mouliné twisted yarns and core-twisted yarns were produced with the nominal twist of 500S, while single yarns (elastane core-spun yarns and comparative ring-spun yarns without elastane) were produced with the nominal twist of 221Z and 281Z, respectively (cf. *Table II*).

The knitted samples were produced on an electronic flat weft knitting machine UNIVERSAL MC 720, gauge E8. All samples were knitted with equal yarn input tension, on an identical set of needles, equal knitted fabric take-off and at identical environment conditions. From each yarn, the samples were knitted in two densities obtained with two cam (couliering depth) settings. Density 1 was set to achieve an optimal structure of the knitted fabrics made from conventional yarns without elastane after relaxation. Density 2 was set to achieve an optimal structure of the knitted fabrics made from elasticized yarns after relaxation. The samples were knitted directly from original yarn packages with no intermediate winding; no lubricant was used.

TABLE III. Knitted sample labeling according to material composition, yarn type, relaxation and density.

yarn	relaxation	density 1 – D1 (more compact)	density 2 – D2 (less compact)
1	dry DR	CV MOU DR D1	CV MOU DR D2
	wet WR	CV MOU WR D1	CV MOU WR D2
2	dry DR	PAN MOU DR D1	PAN MOU DR D2
	wet WR	PAN MOU WR D1	PAN MOU WR D2
3	dry DR	CV C-TW DR D1	CV C-TW DR D2
	wet WR	CV C-TW WR D1	CV C-TW WR D2
4	dry DR	PAN C-TW DR D1	PAN C-TW DR D2
	wet WR	PAN C-TW WR D1	PAN C-TW WR D2
5	dry DR	CV C-SP DR D1	CV C-SP DR D2
	wet WR	CV C-SP WR D1	CV C-SP WR D2
6	dry DR	PAN C-SP DR D1	PAN C-SP DR D2
	wet WR	PAN C-SP WR D1	PAN C-SP WR D2
7	dry DR	CV CONV DR D1	CV CONV DR D2
	wet WR	CV CONV WR D1	CV CONV WR D2
8	dry DR	PAN CONV DR D1	PAN CONV DR D2
	wet WR	PAN CONV WR D1	PAN CONV WR D2

The relaxation process was based on the Starfish procedure [40,41], and the findings of Fletcher and Roberts [42,43] and Hurley [44]. First, all samples were statically dry relaxed. After the dry relaxation, a half portion of each sample was additionally dynamically wet relaxed (consolidated). The wet relaxation process comprised laundering at 30°C (delicate laundry program), short spinning, 40-minute drying (delicate laundry program), four cycles of alternating short rinsing and 40-minute tumble drying (delicate laundry program), and placing wet relaxed samples flat to the standard environment for at least 24 hours after the last drying cycle was finished. Within the wet relaxation process, no chemicals were used.

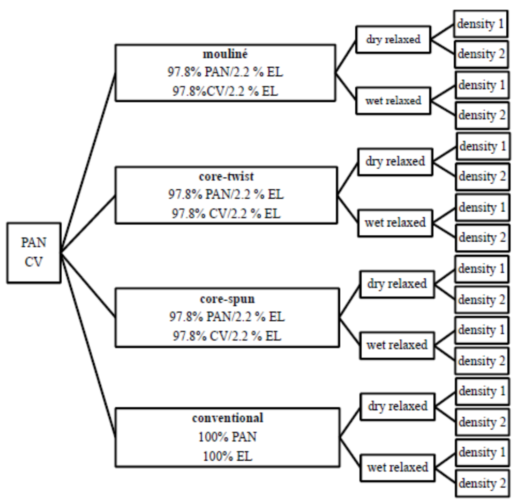

FIGURE 1. Knitted sample preparation diagram.

Combining two fiber types, four yarn structures, two density levels and two relaxation procedures, altogether 32 different knitted samples were prepared (cf. *Table III* and *Figure 1*).

Research Methods

Yarn and knitted fabric parameters were determined with laboratory tests. Loop width (A) and loop height (B) were measured with image analysis. Loop length (ℓ) was determined by uncurling the thread unraveled from the fabric on the Instron 6022 dynamometer and measuring its length [25]. Yarn thickness (d) was determined with the modified Sadikov method [45], a contactless projection-calculating procedure, developed at the Moscow Textile Institute. Fabric thickness (t) was measured with a Mitutoyo fabric thickness tester.

To evaluate the adequacy of theoretical geometrical loop models and their accordance with the measured values of the loop length, the Pearson correlation coefficient was calculated for all yarns and also separately, for conventional yarns without elastane and elastane core yarns, respectively.

The impact of independent variables on loop length (ℓ) was studied with the multiple linear regressions [46]. On the basis of a linear model with three predictors (as described in Eq. (2), Eq. (3) and Eq. (7), it is possible to calculate loop length (ℓ) in dependence of loop width (A), loop height (B) and real yarn thickness (d), as stated hereafter. Since in the compact knitted structures made form elasticized yarns, the wet relaxed loop configuration reflects in the fabric thickness increase [20], also the linear model with 4 predictors (loop width (A), loop height (B), yarn thickness (d) and fabric thickness (t) was studied.

RESULTS AND DISCUSSION

Loop Parameters

Loop parameters of the investigated knitted structures were examined in order to evaluate the adequacy of analyzed loop models for the knitted fabrics made from elastane core-spun yarns.

TABLE IV. Knitted fabric parameters: loop width (A), loop height (B), loop length (ℓ).

sample			knitted fabric parameters					
			loop width A (mm)		loop height B (mm)		loop length ℓ (mm)	
			D1	D2	D1	D2	D1	D2
1	MOU CV-EL	DR	1.99	2.07	1.24	1.27	8.68	11.99
		WR	1.55	1.92	0.85	1.13	8.67	11.39
2	MOU PAN-EL	DR	2.09	2.26	1.30	1.74	8.87	11.75
		WR	1.73	1.91	0.97	1.08	8.64	11.49
3	C-TW CV-EL	DR	2.02	2.32	1.22	1.51	8.93	11.57
		WR	1.64	1.87	0.88	1.03	8.71	11.46
4	C-TW PAN-EL	DR	2.11	2.17	1.34	1.73	8.97	11.85
		WR	1.70	1.87	0.96	1.12	8.72	11.70
5	C-SP CV-EL	DR	1.93	2.15	1.03	1.20	8.67	11.64
		WR	1.50	1.74	0.73	0.90	8.25	11.33
6	S-SP PAN-EL	DR	2.13	2.44	1.23	1.52	8.86	11.76
		WR	1.71	2.00	0.88	1.07	8.75	11.40
7	CONV CV	DR	2.23	2.96	1.69	2.47	8.72	11.50
		WR	2.66	3.30	1.47	2.16	8.47	11.29
8	CONV PAN	DR	2.18	2.64	1.63	2.84	8.69	11.48
		WR	2.15	2.60	1.56	2.25	8.63	11.32

Table IV shows that loop length decreases during the process of consolidation; however, this decrease is not substantial (0.1–4.8%). According to the findings of other researchers [47], the loop configuration and geometry change during the relaxation and consolidation. The loop geometry changes affect loop width and height, and fabric thickness significantly, but not loop length. Moreover, *Table IV* shows that the addition of elastane does not significantly influence the loop length of fabrics knitted at the same cam settings (couliering depth) and relaxed with the same process. However, their loop configuration changes; therefore, loop width and height, and fabric thickness change as well (cf. *Table IV* and *Table V*). This is associated with the variation of other parameters describing the compactness of knitted structures, as it was established in previous investigations [19].

TABLE V. Knitted fabric parameters: fabric thickness (*t*) and yarn thickness (*d*).

sample			knitted fabric parameters		
			fabric thickness *t* (mm)		yarn thickness *d* (mm)
			D1	**D2**	
1	**MOU CV-EL**	**DR**	1.62	1.95	0.88
		WR	1.87	2.03	1.15
2	**MOU PAN-EL**	**DR**	1.53	1.78	0.90
		WR	2.18	2.54	1.25
3	**C-TW CV-EL**	**DR**	1.50	1.75	0.72
		WR	1.97	2.34	0.94
4	**C-TW PAN-EL**	**DR**	1.55	1.88	0.76
		WR	1.96	2.17	1.13
5	**C-SP CV-EL**	**DR**	1.76	2.27	0.79
		WR	2.06	2.34	1.27
6	**S-SP PAN-EL**	**DR**	1.72	2.06	0.76
		WR	2.39	2.71	1.23
7	**CONV CV**	**DR**	1.03	0.90	0.65
		WR	1.26	1.08	0.71
8	**CONV PAN**	**DR**	1.17	1.16	0.60
		WR	1.37	1.32	0.63

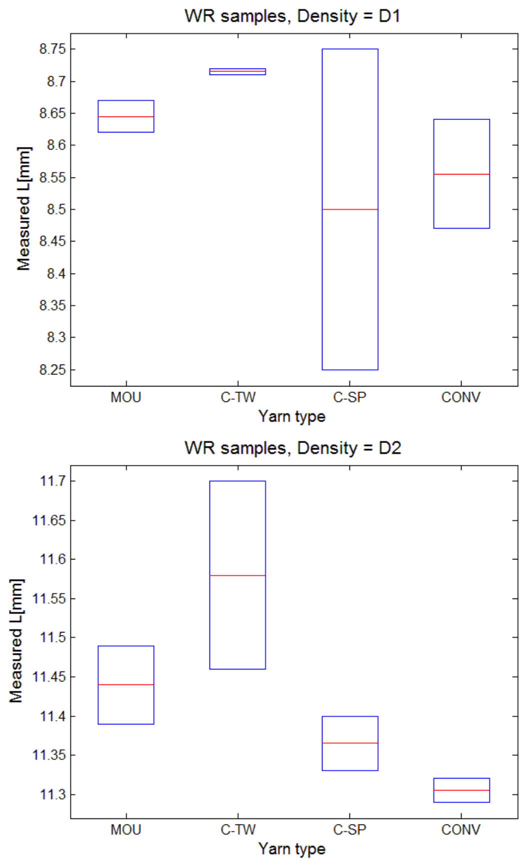

FIGURE 2. Box plots for measured loop length of D1 (top) and D2 (bottom) wet relaxed samples.

TABLE VI. Loop length (ℓ), measured and calculated with Peirce's, Dalidovich's and Vekassy's loop models for normal and closed structures.

sample			**ℓ measured (mm)**		**ℓ calculated by loop models (mm)**			
			D1	**D2**	**Pier norm Eq. 1**	**Dalid norm Eq. 4**	**Vekas norm Eq.5**	**Vekas closed Eq. 6**
1	**MOU CV-EL**	**DR**	8.68	11.99	14.66	14.64	15.25	11.79
		WR	8.67	11.39	19.16	19.14	19.93	15.41
2	**MOU PAN-EL**	**DR**	8.86	11.75	14.99	14.98	15.60	12.06
		WR	8.62	11.49	20.83	20.80	21.66	16.75
3	**C-TW CV-EL**	**DR**	8.93	11.57	12.00	11.98	12.48	9.65
		WR	8.71	11.46	15.66	15.64	16.29	12.60
4	**C-TW PAN-EL**	**DR**	8.97	11.85	12.66	12.65	13.17	10.18
		WR	8.72	11.70	18.83	18.80	19.58	15.14
5	**C-SP CV-EL**	**DR**	8.67	11.64	13.16	13.15	13.69	10.59
		WR	8.25	11.33	21.16	21.13	22.01	17.02
6	**S-SP PAN-EL**	**DR**	8.86	11.76	12.66	12.65	13.17	10.18
		WR	8.75	11.40	20.49	20.47	21.32	16.48
7	**CONV CV**	**DR**	8.72	11.50	10.83	10.82	11.26	8.71
		WR	8.47	11.29	11.83	11.81	12.30	9.51
8	**CONV PAN**	**DR**	8.69	11.48	10.00	9.98	10.40	8.04
		WR	8.64	11.32	10.66	10.65	11.09	8.58

TABLE VII. Loop length (ℓ), measured and calculated with Peirce's, Dalidovich's and Morooka & Matsumoto & Morooka's loop models for open structures.

sample			ℓ measured (mm)		ℓ calculated with loop models (mm)					
					Peirce open cf. Eq. 2		Dalidovich open cf. Eq. 3		M&M&M open* cf. Eq. 7	
			D1	D2	D1	D2	D1	D2	D1	D2
1	MOU CV-EL	DR	8.86	11.99	10.44	10.64	8.35	8.55	8.22	8.38
		WR	8.67	11.39	10.77	11.79	7.72	8.87	8.15	9.08
2	MOU PAN-EL	DR	8.86	11.75	10.82	11.60	8.69	9.83	8.52	9.57
		WR	8.62	11.49	11.86	12.33	8.58	9.08	9.02	9.42
3	C-TW CV-EL	DR	8.93	11.57	9.53	10.41	7.85	8.91	7.52	8.41
		WR	8.71	11.46	9.74	10.34	7.29	7.93	7.42	7.93
4	C-TW PAN-EL	DR	8.97	11.85	10.07	10.58	8.38	9.25	8.04	8.88
		WR	8.72	11.70	11.07	11.55	8.14	8.71	8.46	8.94
5	C-SP CV-EL	DR	6.67	11.64	9.56	10.19	7.56	8.26	7.36	7.93
		WR	8.25	11.33	11.27	11.92	7.80	8.52	8.40	8.98
6	S-SP PAN-EL	DR	8.86	11.76	9.99	10.90	8.17	9.24	7.82	8.71
		WR	8.75	11.40	11.61	12.37	8.31	9.12	8.73	9.38
7	CONV CV	DR	8.72	11.50	10.01	12.23	8.92	11.61	8.39	10.67
		WR	8.47	11.29	11.00	12.96	9.33	11.71	8.62	10.65
8	CONV PAN	DR	8.69	11.48	9.52	11.66	8.53	11.69	7.98	10.88
		WR	8.64	11.32	9.64	11.25	8.49	10.59	8.00	9.84

*Morooka & Matsumoto & Morooka's loop model

From the measured knitted fabric parameters presented in *Table IV* and *Table V,* loop lengths were calculated for each sample, using Eq. (1)–(7). The calculated loop lengths for normal and closed structures are given in *Table VI*. The calculated loop lengths for open structures are given in *Table VII*. Both tables also include the measured loop lengths for comparison.

The measured loop lengths of elasticized (MOU, C-TW, C-SP) and conventional (CONV) wet relaxed (WR) samples, separately for D1 and D2 density, are presented in two simplified Box plots (cf. *Figure 2*). The top and bottom edge of each box denotes the loop length value that corresponds to the PAN and CV fiber type used. The middle horizontal line indicates the corresponding mean value. It can be noticed that – unlike for the samples with higher density (D1) – for the less compact fabrics (D2), conventional, non-elasticized samples exhibit lower loop length than any of the samples containing elastane.

TABLE VIII. Statistical significance of difference between loop parameters of mouliné elasticized (MOU) and conventional (CONV) samples.

p-value		MOU/CONV							
		CV				PAN			
		DR D1	DR D2	WR D1	WR D2	DR D1	DR D2	WR D1	WR D2
ℓ	t-test	0.628	0.034	0.098	0.426	0.078	**0.009**	0.948	0.116
	F-test	0.788	0.004	0.452	0.396	0.225	0.636	0.752	0.338
A	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.810	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.503	0.004	0.000	0.000	0.026	0.000	0.000	0.000
t	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.000	0.000	0.569	0.025	0.026	0.000	0.000	0.000

TABLE IX.. Statistical significance of difference between loop parameters of core-twist elasticized (C-TW) and conventional (CONV) samples.

p-value		C-TW/CONV							
		CV				PAN			
		DR D1	DR D2	WR D1	WR D2	DR D1	DR D2	WR D1	WR D2
ℓ	t-test	0.041	0.512	0.028	0.111	0.027	**0.001**	0.432	**0.000**
	F-test	0.431	0.676	0.781	0.310	0.049	0.514	0.895	0.348
A	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
t	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.103	0.158	0.241	0.320	0.000	0.000	0.000	0.000

TABLE X. Statistical significance of difference between loop parameters of core-spun elasticized (C-SP) and conventional (CONV) samples.

p-value		C-SP/CONV							
		CV				PAN			
		DR D1	DR D2	WR D1	WR D2	DR D1	DR D2	WR D1	WR D2
ℓ	t-test	0.588	0.152	0.107	0.728	0.285	0.069	0.468	0.630
	F-test	0.757	0.933	0.149	0.580	0.006	0.033	0.157	0.007
A	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	t-test	0.000	0.000	0.022	0.000	0.000	0.000	0.000	0.000
	F-test	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.000
t	t-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-test	0.002	0.002	0.004	0.634	0.000	0.000	0.011	0.000

Statistical t- and F-tests were performed on the measured yarn and knitted fabric parameters to determine whether the corresponding elasticized (EL) and conventional, non-elasticized (CONV) fabrics samples differ significantly at the 99.0% confidence level in their means and standard deviations, respectively. For the loop length calculations, 10 samples were used while for the loop width, loop height and fabric thickness the statistics was based on 20 samples. The results – P values – are presented in *Tables VIII to X*.

Inspection of the loop length ℓ data reveals that both means as well as standard deviations are similar to one another for the majority of the examined EL-CONV fabrics pairs, since P values generally exceed 0.01. Only three PAN pairs – MOU DR D2, CTW DR D2 and CTW WR D2 – exhibit more pronounced differences in the means (t-test: $P < 0.01$). This can be explained by the fact that the less compact elasticized structures relax more after knitting and relaxation which leads to bigger differences in their loop lengths compared to conventional structures.

The situation is totally different, however, for the other three parameters. With the loop width A, loop height B and fabric thickness t, the pairs' means are substantially different in virtually all of the cases – the only exception being loop height mean for the CV CSP WR D1 pair – investigated in our study. This can be explained by different configuration of the knitted loops made from elasticized yarns compared to the loops made from conventional yarns. The dimensions of the rectangular solid outlining the loop curve differ significantly for the relaxed elasticized and non-elasticized samples, respectively. Elasticized yarns extend considerably in the knitting zone. After being removed from the machine, substantial shrinkage of the elasticized knitted structure occurs due to the yarn relaxation and yarn compression within the loop which influences the loop curve shape.

Adequacy of Loop Models for Knitted Fabrics Made From Elastane Core-Spun Yarns

To evaluate the adequacy of various loop models for the calculation of loop length, the Pearson's correlation coefficient was calculated for all yarns and also separately, for conventional yarns without elastane and elastane core-spun yarns, respectively (cf. *Table XI*).

TABLE XI. Loop models' adequacy.

correlation coefficient			
loop model	yarn structure		
	CONV+EL	CONV	EL
Peirce – normal structure	–0.03	–0.05	–0.09
Peirce – open structure	0.48	0.83	0.33
Dalidovich – open structure	0.53	0.95	0.68
Dalidovich – normal structure	–0.03	–0.05	–0.09
Vekassy – normal structure	–0.03	–0.05	–0.09
Vekassy – closed structure	–0.03	–0.05	–0.09
M&M&M – open structure*	0.56	0.96	0.51

*Morooka & Matsumoto & Morooka's loop model

From *Table XI*, it can be seen that as anticipated, the structures made from conventional yarns without elastane, correspond well to the studied geometrical loop models for open structures, defining loop length (ℓ) as the function of loop width (A), loop height (B) and yarn thickness (d). The measured loop length values correlate well to the loop model by Morooka & Matsumoto & Morooka, and Dalidovich's model for open structures (correlation coefficients 0.96 and 0.95, respectively); they correlate moderately to Peirce's loop model for open structures (correlation coefficient 0.83). The structures made from elastane core-spun yarns correlate moderately to the evaluated loop models (correlation coefficients 0.33 and 0.68). The correlation coefficients related to each of the nine open structure models – Peirce's, Dalidovich's and Morooka & Matsumoto & Morooka's for CONV+EL, CONV and EL fabrics – were found to be statistically significant at the 95% confidence level.

The adequacy analysis of loop models shows that the investigated loop models cannot be generally applied for all knitted structures, both conventional and elasticized. It also shows that the simple loop models, describing normal and closed knitted structures and defining loop length (ℓ) as the function of yarn thickness (d) only, have no applicative value for either conventional or elasticized knitted structures. The results presented in *Table XI* clearly show that a new simple loop model for the structures made from elasticized yarns should be defined.

Multiple Linear Regression

In order to define the mathematical models valid for both, conventional and elasticized single knitted structures, the impact of independent variables to loop length was studied with the multiple linear regression [46].

Preliminarily, a general linear model with four predictors, i.e. loop width (*A*), loop height (*B*), yarn thickness (*d*) and knitted fabric thickness (*t*), was obtained for all knitted fabrics, elasticized and conventional – Eq. (8).

$$\ell = 0.80\,A + 2.45\,B - 1.17\,d + 3.43\,t \tag{8}$$

The model is very good, as it explains more than 99% ($R^2_{adj.}$ = 99.4%) of the variability in loop length (ℓ). For the use of this model, knitted fabric thickness measurements are required.

In order to eliminate the fabric thickness measurements and simplify the calculation, a linear model with three predictors, i.e. loop width (*A*), loop height (*B*), yarn thickness (*d*), was developed according to Eq. (2), Eq. (3) and Eq. (7). On the basis of this model, it is possible to calculate loop length (ℓ) for all knitted fabrics, elasticized and conventional, as stated hereafter – Eq. (9).

$$\ell = 1.92\,A + 1.41\,B + 4.59\,d \tag{9}$$

The model is good, as it explains more than 98% ($R^2_{adj.}$ = 98.5%) of the variability in loop length (ℓ).

Following the research aim, the samples were then divided into two groups, separating conventional knitted fabrics from elasticized knitted fabrics. The group of elasticized yarns comprised mouliné, core-twisted and core-spun yarns. Again, linear models with three predictors, i.e. loop width (*A*), loop height (*B*), yarn thickness (*d*), were generated.

According to the model, the loop length of conventional samples can be calculated as presented in Eq. (10).

$$\ell = 0.80\,A + 2.58\,B + 4.26\,d \tag{10}$$

The model explains more than 99% (R^2 = 99.8%) of the variability in loop length (ℓ).

The loop length of elasticized samples made from various types of elastomeric yarns can be calculated as presented in Eq. (11).

$$\ell = 2.46\,A + 2.11\,B + 2.98\,d \tag{11}$$

The new loop model for the elasticized single weft structure is good as it explains more than 98% ($R^2_{adj.}$ = 98.8%) of the variability in loop length (ℓ).

CONCLUSIONS

The study of the scientific literature showed that the knitted loop geometry represents the foundation of the novel knitted structure production planning and graphic simulation. In the past, mostly the geometry of knitted structures made from conventional yarns without elastane was examined and defined with loop models. The relationships among yarn parameters and knitted fabric parameters of contemporary elasticized knitted fabrics exhibiting a very compact structure after full relaxation have not been systematically studied and analyzed. The loop models for elasticized knitted structures have not been defined. The adequacy of most frequently applied loop models for the loop length calculation of elasticized knitted structures has not been evaluated.

The research results showed that the elastane addition does not significantly influence the loop length of fabrics knitted at the same cam settings and relaxed by the same process. However, their loop configuration changes; therefore, the loop width and height, and fabric thickness change as well.

As anticipated, the structures made from conventional yarns without elastane show the best agreement with the studied geometrical loop models for open structures. Elasticized structures cannot be modeled well with the existing geometrical loop models. Therefore, the investigated loop models cannot be generally applied when designing both conventional and elasticized single weft knitted fabrics. For both conventional and elasticized knitted fabric planning, the following new general loop model can be applied:

$$\ell = 1.92\ A + 1.41\ B + 4.59\ d$$

For elasticized single weft knitted structures, a new mathematical model is proposed:

$$\ell = 2.46\ A + 2.11\ B + 2.98\ d$$

REFERENCES

[1] Tompkins, E.; *Science of knitting*; Wiley: New York, 1914.

[2] Peirce, F.T.; Geometrical principles applicable to the design of functional fabrics; *Textile Research Journal* 1947, *17*, 123–147.

[3] Munden, D.L.; The geometry and dimensional properties of plain-knitted loop; *Journal of the Textile Institute* 1959, *50*, T448–T471.

[4] Leaf, G.A.V.; Glaskin, A.; The geometry of a plain knitted loop; *Journal of the Textile Institute* 1961, *46*, T587–T605.

[5] Vékássy, A.; Examination of the cover-factor and specific weight of weft-knitted or looped basis texture based on the exact value of the loop length; *Acta Technica* 1960, *31*, 69–102.

[6] Suh, M.W.; A study of the shrinkage of plain knitted cotton fabric, based on the structural changes of the loop geometry due to yarn swelling and deswelling; *Textile Research Journal* 1967, *37*, 417–431.

[7] Dalidovich, A.S.; *Teorii perepletenii i analiz trikotaza*; Gizlegprom: Moscow, 1934.

[8] Dalidovich, A.S.; *Osnovi teorii viazaniia*. Moscow: Legakaja industrija, 1970.

[9] Nawrocki, R.; Parametry struktury dzianin lewo-prawych, wykonanych z przedz teksturowanych; *Przeglad Wlokienniczy* 1971, *25*, 331–333.

[10] Korlinski, W.; Teoretisch-empirisches Verallgemeinerungsmodell des Rechts/Links-Gestrickes; *Melliand Textilberichte* 1985, *9*, 729–733.

[11] Pijanowski, R.; Srubowy model oczka dla rzadkowego splotu lewoprawego; *Przeglad Wlokienniczy* 1987, *41*, 360–363.

[12] Morooka, Hi.; Matsumoto, Y.; Morooka, Ha.; A geometric analysis of the stitch form of a circular plain knit fabric inserted over a cylinder; *Textile Research Journal* 1998, *68*, 930–936.

[13] Demiroz, A.; Dias, T.; A study of the graphical representation of plain-knitted structures. Part 1: Stitch model for the graphical representation of plain-knitted structures; *Journal of the Textile Institute* 2000, *91*, 463–480.

[14] Demiroz, A.; Dias, T.; A study of the graphical representation of plain-knitted structures, Part 2, Experimental studies and computer generation of plain knitted stitches; *Journal of the Textile Institute* 2000, *91*, 481–492.

[15] Little, T.J.; Hepworth, A.; The determination of fabric loop length; *Textile Research Journal* 1977, *57*, 795–801.

[16] Kurbak, A.; Plain Knitted Fabric Dimensions (Part II); *Textile Asia* 1998, *78*, April, 36–44.

[17] Kurbak, A.; Ekmen, O.; Basic Studies for Modeling Complex Weft Knitted fabric Structures, Part I: A Geometrical Model for Widthwise Curlings of Plain Knitted Fabrics; *Textile Research Journal* 2008, *78*, 198–208.

[18] Pavko-Cuden, A.; Lumpert, G; Analysis of knitted structure from core-spun elastomeric yarn; *Tekstilec* 2003, *46*, 354–360.

[19] Pavko-Cuden, A.; Parameters of compact single weft knitted structure (Part 2): Loop modules and Munden constants – compact and supercompact structure; *Tekstilec* 2010, *53*, 259–272.

[20] Pavko-Cuden, A.; Parameters of compact single weft knitted structure, Part 3: Fabric thickness and Knapton constant; *Tekstilec* 2011, *54*, 5–15.

[21] Chathura, N.H.; Bok, C.K.; Dimensional Stability of Core Spun Cotton/Spandex Single Jersey Fabrics under relaxation; *Textile Research Journal* 2008, *78*, 209–216.

[22] Stjepanovic, Z. et al; Research on the effect of some knitting parameters on properties of cotton/Lycra knitted fabrics during relaxation process. *Tekstilna industrija* 2010, *58*, 22–31.

[23] Bayazit Marmarali, A.; Dimensional and Physical Properties of Cotton/Spandex Single Jersey Fabrics; *Textile Research Journal* 2003, *73*, 11–14.

[24] Abdessalem, S.B. et al; Influence of Elastane Consumption on Plated Plain Knitted Fabric Characteristics; *Journal of Engineered Fibers and Fabrics*; 2009, *4*, No. 4, pp. 30–35.

[25] Pavko-Cuden, A.; *Study of the weft knitted loop*; Doctoral thesis, University of Ljubljana: Ljubljana, 2005.

[26] Vrljicak, Z. et al; Analysis of Loop Parameters for Plain Jersey Knitted Fabrics; *Tekstil* 2002, *52*, 225–231.

[27] Pavko-Cuden, A.; Parameters and performance properties of plain knitted fabric with elastomeric yarns; *Tekstilec* 1999, *42*, 104–114.

[28] Pavko-Cuden, A.; Parameters of compact single weft knitted structure, Part 1: Loop modules and Munden constants – state of research; *Tekstilec* 2010, *53*, 205–214.

[29] Fletcher, H.M.; Roberts, S.H.; The geometry of plain and rib knit cotton fabrics and its relation to shrinkage in laundering; *Textile Research Journal* 1952, *22*, 84–88.

[30] Fletcher, H.M.; Roberts, S.H.; The geometry of knit fabrics made of staple rayon and nylon and its relationship to shrinkage in laundering; *Textile Research Journal* 1952, *22*, 466–471.

[31] Fletcher, H.M.; Roberts, S.H.; Relationship of the geometry of plain knit cotton fabric to its dimensional change and elastic properties; *Textile Research Journal*, 1954, *24*, 729–737.

[32] Shinn, W.E.; An engineering approach to jersey fabric construction; *Textile Research Journal* 1955, *25*, 270–277.
[33] Knapton, J.J.F. et al; The dimensional properties of knitted wool fabrics, Part 1: The plain knitted structure; *Textile Research Journal* 1968, *38,* 999–1012.
[34] Stupica, I.; Cesnik, L.; Relaxation of Knit Goods after Knitting and Ironing; *Tekstil* 1987, *36*, 586–695.
[35] Vrljicak, Z.; Determining Yarn Consumption in a Loop; *Tekstil* 2000, *49*, 609–617.
[36] Vrljicak, Z. et al; Analysis of Loop Parameters for Plain Jersey Knitted Fabrics; *Tekstil* 2003, *52*, 225–231.
[37] Vrljicak, Z.; Stahov, N.; Design and Manufacture of Single Jersey Weft Knitted Fabrics of Different Density; *Tekstil* 2005, *54*, 440–447.
[38] Doyle, P.J.; Fundamental aspects of the design of knitted fabrics; *Journal of the Textile Institute* 1953, *44*, P561–578.
[39] Pavko-Cuden, A.; Geometrical models of weft knitted loop: open, normal and compact structure; *Tekstilec* 2010, *53*, 113–138.
[40] Heap, S.A. et al; Prediction of finished weight and shrinkage of cotton knits-the Starfish project, Part 1: Introduction and general overview; *Textile Research Journal* 1983, *53*, 109–119.
[41] Heap, S.A. et al; Prediction of finished relaxed dimensions of cotton knits – the Starfish project, Part 2: Shrinkage and the reference state; *Textile Research Journal* 1985, *55*, 211–222.
[42] Fletcher, H.M.; Roberts, S.H.; The geometry of plain and rib knit cotton fabrics and its relation to shrinkage in laundering; *Textile Research Journal* 1952, *22*, 84–88.
[43] Fletcher, H.M.; Roberts, S.H.; The geometry of knit fabrics made of staple rayon and nylon and its relationship to shrinkage in laundering; *Textile Research Journal* 1952, *22*, 466–471.
[44] Hurley, R.B.; The dimensional stability of acrylic knit fabrics; *Textile Research Journal* 1996; *36*, 989–993.
[45] Kudriavin, L. (ed). *Laboratory practice in knitting technology*; Mir Publishers: Moskva, 1985.
[46] Bona, M; *Statistical methods for the textile Industry*; Biella: Biella, 1993.
[47] Anand, S.C. et al; Effect of laundering on the dimensional stability and distortion of knitted fabrics; *Autex Research Journal* 2002, *2*, 85–100.

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