# PREDICTING FABRIC WEIGHT PER UNIT AREA OF SINGLE- AND DOUBLE-KNITTED STRUCTURES USING APPROPRIATE SOFTWARE

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## *Abstract*

*This project deals with the prediction of knitted fabric weight per unit area using appropriate software called proKNIT. This software has been designed according to the existing literature, and can determine the weight of knitted fabrics in different relaxing conditions by entering process and material variables, such as the type of fabric and fibre, knitting machine gauge, yarn count, fabric loop length and tightness factor. The prediction of the fabric weight is dependent upon the dimensional parameters of $K_c$, $K_w$, $K_s$ and R, which have been entered into the system. Therefore, proKNIT can calculate the fabric weight of single- and double-knitted structures, i.e. plain-knit, purl, 1×1 rib, 2×2 rib and interlock, for natural fibres such as cotton/cotton blends and wool/wool blends.*

## *Key words:*

*single-knitted structure, double-knitted structure, fabric weight, prediction, proKNITsoftware*

## Introduction

Research concerning knitted fabric geometry extends over 90 years, with the first publication in this field having been made by Tompkins [6], who made some simple assumptions on a geometrical model. Many structures have been studied on the basis of a number of different approaches, which have given results of greater or lesser importance. For example, simple geometrical models were presented by Chamberlain [11] and Pierce [20], although insufficient practical experience made it impossible for them to justify their general acceptance, while Leaf & Glaskin [13] also presented a model which exhibited a continuous torsion force, but which was also limited in application. The most important studies, which have yielded the most useful information for a practical approach and provided the basis and the necessary tools for further studies, have come on the one hand from Doyle [1], who found that the stitch density depends only on the loop length and is independent of the yarn and knitting variables, and Munden [2] on the other, who based his own approach on Doyle's research and then took it one step further.

## Geometry of plain-knitted fabrics

On single jersey fabrics, Munden suggested that the knitted loop length would take a natural shape when released from mechanical strains, and is independent of the yarn properties. A further study by Munden [3] has shown that the dimensions of plain-knitted wool fabrics, in a state of minimum energy, are dependent only upon the length of the yarn knitted into each loop. His experimental studies have indicated that courses and wales per unit length and loop length are related to each other by constants as follows:

$$K_c = c.p.i \times \ell \quad (1)$$
$$K_w = w.p.c. \times \ell \quad (2)$$
$$K_s = S \times \ell^2 \quad (3)$$
$$K_r = R = \frac{c.p.i}{w.p.i} = \frac{K_c}{K_w} \quad (4)$$

In the original publication, there is $K_2=K_c$, $K_3=K_w$, $K_1=K_s$ and $K_4=K_r=R$. In the above equations, c.p.i. and w.p.i. define the courses per inch and the wales per inch respectively. S is the loop density, and is calculated by multiplying courses and wales per inch. Finally $\ell$ is the loop length, which can be measured in inches, and $K_r$ or R is the loop shape. The above equations (1-4) are significant because the length of yarn in the knitting loop is the major factor determining the fabric dimensions. Additionally, fibre content and state of relaxation can also be identified as variables, which produce different constant values. Munden initially defined two distinct, differently relaxed states; the dry-relaxed state, where the fabric has been left to relax for a specific time off the machine in a dry condition, and the wet-relaxed state where the fabric is left static to soak in water. Experimental studies by Munden [2] on wool plain-knitted fabrics produced the values presented in Table 1 below for the two relaxed states.

**Table 1.** Values of constants (K) for fabric geometry on plain knit [2]

| Fabric state | Parameter | | | |
|---|---|---|---|---|
| | $K_c$ | $K_w$ | Ks | R |
| Dry-relaxed | 5.0 | 3.8 | 19.0 | 1.31 |
| Wet-relaxed | 5.3 | 4.1 | 21.6 | 1.29 |

Knapton et al. [4] found that neither the dry nor the wet-relaxed state for plain knit loop shape were predictable. They suggested some form of fabric agitation to allow the loops to find their least-strained shape within the fabric, using a tumble-drying technique to allow drying without felting. This state was defined as 'fully-relaxed' and is achieved when the fabrics have been thoroughly wetted out for 24 hours in water at $40^0$C, briefly hydro-extracted to remove excess water, and tumble-dried for a period of one hour at $70^0$C. The constant values (K) that were achieved in this state with 95% confidence limits are:

$K_c$ = 5.5 ± 0.2
$K_w$ = 4.2 ± 0.1
$K_s$ = 23.1 ± 1.0
R = 1.30 ± 0.05

Postle [5] presented a set of constant values for wool fibres for all three of the above-mentioned states, which appeared to be slightly different from those presented by the others. Also, both Postle and Munden were in agreement concerning the values of K and R, in particular, which are influenced by the cover factor. The dimensions of a fully-relaxed fabric are stable if the yarns have been adequately treated against felting. The values obtained by Postle are presented on Table 2.

**Table 2.** Values (K) of constants for fabric geometry on plain knit [5]

| Fabric state | Parameter | | | |
|---|---|---|---|---|
| | $K_c$ | $K_w$ | Ks | R |
| Dry-relaxed | 4.7±0.3 | 4.0±0.7 | 18.0±1.0 | 1.16±0.12 |
| Wet-relaxed | 5.4±0.2 | 4.2±0.1 | 22.8±0.9 | 1.28±0.04 |
| Fully-relaxed | 5.8±0.2 | 4.3±0.1 | 25.2±0.6 | 1.32±0.04 |

Regarding plain knits, another aspect needs some clarification. This has to do with the cover factor, which is equivalent to the tightness factor. Munden [8] initially suggested the following practical expression for the cover factor:

$$CF = \frac{1}{\ell\sqrt{N}} \quad (5)$$

where N is the worsted yarn count, and ℓ is the loop length in inches. In this expression, a number of omissions and assumptions are made, which means that the expression cannot be regarded as representative of the factorial area occupied by the knitted loop. However, this expression was extremely practical and easily calculated, and had a potential use in the factory.

Postle [7] proposed the term 'tightness factor' to describe such a formula, and he defined it as:

$$TF = \frac{\sqrt{tex}}{\ell} \quad \text{.......................................................(6)}$$

where tex is the yarn linear density and ℓ is the loop length. It was recommended that the loop length be presented in millimetres with an average value of 1.46. Baird & Foulds [9] used the above equation in a factorial analysis of two shrink-resist treatments, and measured the loop length in centimetres with cover factors of 13.2 to 17.5.

## Geometry of double jersey knit fabrics

A theoretical approach on double-knitted structures was presented by Nutting & Leaf [10], who introduced a constant value and a term concerning the yarn diameter on the basis of the equations 1 and 2 above, which can be written in the form:

$$\frac{1}{C} = A\ell + DT^{\frac{1}{2}} \quad \text{.......................................................(7)}$$

where A and D are constants whose numerical values will depend on the fabric construction, T is the yarn tex value and C (or W) refers to courses and wales per unit length respectively. The above equation indicates that yarn diameter is a significant factor in determining fabric dimensions, contrary to Munden's basic approach.

Smirfitt [12] proposed a model for 1×1 rib structure based on Leaf's equation. He was the first to show that for more practical purposes the dimension properties of wool 1×1 rib structure could also be described by K parameters, which are similar but not identical to those found for the plain knit structure. He defined the repeating unit as the length of the yarn in the knitting loop showing on the face or the back of the fabric. This means that the loop length (ℓ) is associated with any one needle, and he calculated the courses and wales per inch as seen on the face of the fabric. On plotting c and w against 1/ℓ, he reported that intercepts other than zero appeared, suggesting that the structure of the 1×1 rib is more complex than the plain-knitted structure. For more practical work, he also proposed that these intercepts can be ignored, and an accurate prediction of dimensions and fabric weight can be obtained simply by using K values similar to the plain-knitted structure. The values of K as presented by Smirfitt appear in Table 3.

**Table 3.** Values of constants (K) for fabric geometry on 1×1 rib [12]

| Fabric state | Parameter | | | |
|---|---|---|---|---|
| | $K_c$ | $K_w$ | Ks | R |
| Dry-relaxed | 4.53 | 3.34 | 15.1 | 1.35 |
| Wet-relaxed | 5.00 | 3.19 | 16.0 | 1.57 |

Another investigation concerning 1×1 rib fabrics was carried out by Natkanski [14] who attempted a theoretical analysis of the geometric shape of 1×1 rib knitted loop. He considered a two dimensional 'elastica model' of a single rib loop, and his calculations showed completely different values from those obtained by Smirfitt in his experimental work.

A subsequent paper by Knapton et al. [15] introduced a new concept called the 'structural knitted cell' (SKC), that is, the smallest repeating unit of structure, and suggested the following definitions. The effective loop length should be the length of yarn in one SKC, defined as the structural-cell stitch length ($\ell_u$), and the depth and width respectively of the SKC were defined as $1/C_u$ and $1/W_u$ where $C_u$ is equal to courses units/unit fabric length and $W_u$ equal to wale units/unit fabric width. Therefore, Knapton et al. modified Munden's equations (1-4) as follows:

$$u_c = C_u \times \ell_u \qquad (8)$$

$$u_w = W_u \times \ell_u \qquad (9)$$

$$u_s = S_u \times \ell_u^{\ 2} = C_u \times W_u \times \ell_u^{\ 2} \qquad (10)$$

$$\frac{u_c}{u_w} = \frac{C_u}{W_u} \qquad (11)$$

In other words, the SKC of the 1×1 rib structure consists of two single loops and that of interlock of four, etc. According to this logic, the values found in the fully relaxed state by Knapton et al. are recalculated and presented in Table 4, together with Natkanski [14] and Smirfitt's experimental values.

**Table 4.** Values of constants (K) for fabric geometry on 1×1 rib fully relaxed

| | Parameter | | | |
|---|---|---|---|---|
| | $K_c$ | $K_w$ | Ks | R |
| Knapton et al. | 5.30 | 3.00 | 15.9 | 1.76 |
| Smirfitt | 5.30 | 3.14 | 16.5 | 1.69 |
| Natkanski experimental | 5.35 | 3.16 | 17.0 | 1.69 |

Knapton et al. [15] also made a preliminary study of the dimensional behaviour of 2×2 rib wool structure, albeit without giving any details on the knitting process. This is an important omission, since a 2×2 rib fabric can be knitted using either a 2/3 needle arrangement or a 2/4 needle arrangement; in other words, in a 2/3 needle arrangement there are two active needles for loop formation out of three (Fig. 7b). Therefore, the inactive needle arrangement must be specified, because the fabric then displays different properties and its behaviour during subsequent treatments is completely different. Their general conclusion was that the tighter fabric structures, i.e. those with a small loop length, exhibit the larger area shrinkage in the fully-relaxed state. For practical purposes, it was suggested that for increased contraction properties, a small loop length or an increase in the cover factor is advisable. A series of constant values (K) is obtained, which are then recalculated in order to be comparable with the results obtained by the authors (Table 5).

**Table 5.** Values of constants (K) for fabric geometry on 2×2 rib [15]

| Fabric state | Parameter | | | |
|---|---|---|---|---|
| | $K_c$ | $K_w$ | Ks | R |
| Dry-relaxed | 4.84 | 3.66 | 17.69 | 1.32 |
| Wet-relaxed | 5.12 | 3.51 | 17.97 | 1.46 |
| Fully-relaxed | 5.57 | 3.16 | 17.59 | 1.76 |

A further study by Knapton & Fong [21] on interlock fabric, using wool yarns with three different ranges of loop length or structural cell-stitch length (SCSL), as they call it, has shown that the K values are not constant in dry and wet relaxed states, but are significantly dependent on loop length. However, in the fully relaxed state, no significant dependency of K values on SCSL was observed. They also observed that the standard deviations of K values in the fully relaxed state were surprisingly large, suggesting that some felting occurs in tumble-drying. The different K values which they obtained have also been recalculated, and are presented in Table 6.

**Table 6.** Values of constants (K) for fabric geometry on interlock [21]

| Fabric state | Parameter | | | |
|---|---|---|---|---|
| | $K_c$ | $K_w$ | Ks | R |
| Dry-relaxed | 4.23 | 2.57 | 10.87 | 1.65 |
| Wet-relaxed | 4.44 | 2.58 | 11.45 | 1.73 |
| Fully-relaxed | 5.12 | 2.45 | 12.54 | 2.10 |

## Discussion

Following the above survey of weft-knitted fabric geometrical analyses, a number of deductions can be made:

1. It is generally recognised that there are certain relaxing conditions as fabrics are subjected to a variety of ‘relaxation’ treatments. These are defined as dry- and wet- relaxed conditions, which cause dimensional differences between the subjected fabrics.
2. Consolidation and felting shrinkage were defined by Munden and Knapton and described as fully-relaxed conditions.
3. Different fibres often react in different ways, so that the equilibrium values of the geometry constants vary (Munden).
4. Equations 1-4 and 9-11 are identical, giving the same results when applied to plain-knitted as well as to rib or interlock structures.
5. Tightness Factor or Cover Factor present the same arithmetical constant value, and can be applied to both plain, rib and interlock structures.
6. The loop length can be defined as the average value of the existing needles.
7. Using a combination of the existing K values above and the appropriate loop length, it is possible to calculate courses and wales per unit length or width, as well as the loop density.
8. The calculations of courses and wales per unit length and width respectively can be made in three different states, dry, wet and fully relaxed.

The assumptions presented above have guided the authors to the following considerations:

a. The fabric weight can be predicted in the different relaxed conditions using the above constant values. The weight per unit area of a fabric is again related to a host of other properties, and is determined by two factors that interact on the above-mentioned equations, namely the loop size and the yarn size. Therefore, the calculation for fabric weight in grams per square metre can be easily confirmed by combining the equation for loop density and the equation for cover factor.
b. Using all the mathematical models from the existing literature, it is possible to set up a sequence of estimations through appropriate software which can provide reliable calculations of the final fabric weight per unit area in the different relaxing conditions for single and double jersey fabrics.
c. In producing the software, a simple and effective programming language should be used that can operate in a Windows environment.

## ProKNIT- a simple but effective system for making fabric weight predictions

Using the proKNIT system, it is possible to estimate with substantial accuracy what the weight per unit area of different basic knitted structures, such as single jersey (plain and purl) and double jerseys (ribs and interlock), will be when these fabrics come out of the knitting machine, by following a certain relaxation procedure, and when are completely finished.

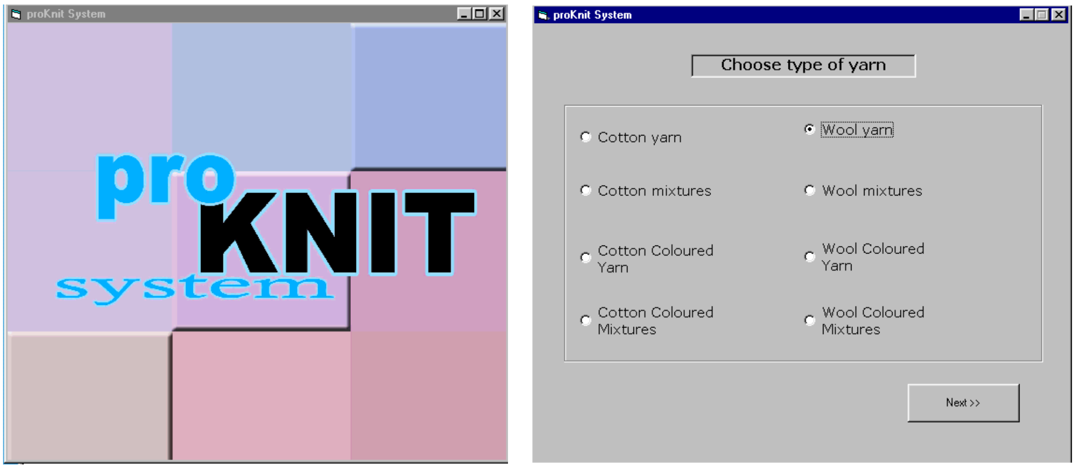



**Figure 1.** First and third pages of the proKNIT software

The first two pages of the program contain the title and general information concerning the use of the system. By moving the cursor onto the ‘proKNIT system’ button and left-clicking, the second page appears. The program will function as soon as the ‘Start’ button is pressed. On the third page a table of different yarn characteristics appears. The yarns have been classified into eight categories for the two most widely used natural fibres, which are cotton and wool. The user has the choice between dyed and undyed yarns and their mixtures. If ‘wool’ yarn is selected, this refers to an undyed natural colour worsted yarn. In the case of ‘cotton’, it is a combed yarn of natural colour. These mixtures cover the most popular combinations existing in the market, such as cotton/polyester, cotton/viscose, cotton/nylon, wool/acrylic and wool/nylon (Figure 1).

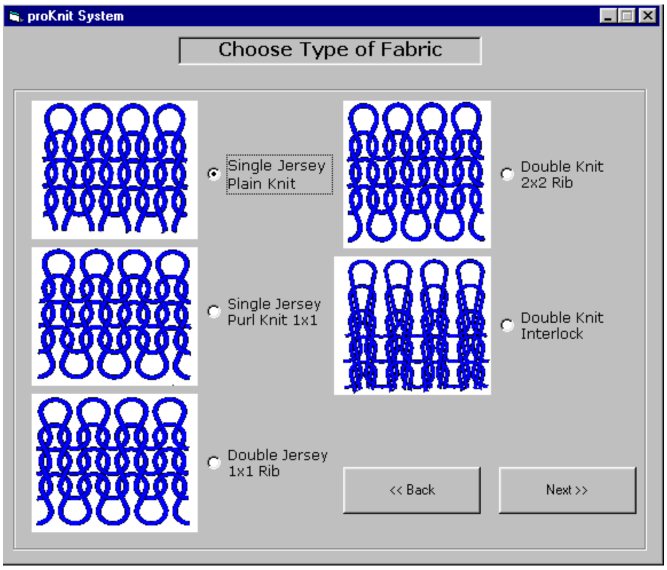



**Figure 2.** Fourth page of the proKnit software

On an experimental level, we attempted to predict the fabric weight per square metre of wool mixture yarns. By choosing the right category of yarn and pressing ‘Next>>’, the fourth page appears wherein the type of knitted fabric has to be chosen. Plain knit, 1×1 rib and interlock fabrics have been chosen due to the extent of the literature concerning them which already exists, so that the estimation of our K values can be compared with those predicted by other researchers. The purl structure has been chosen because it is a single needle fabric with certain wales containing both face- and reverse-meshed loops. Finally, the 2×2 rib structures were selected because very little work has been done in predicting K values for them. From the fourth page to the last one, it is possible for the user to go back to the previous page using the ‘<<Back’ button, to make alterations, or to move forward by pressing ‘Next>>’ (Figure 2).

**Table 7.** Machine gauge (n.p.i.) and linear density of yarn count, tex

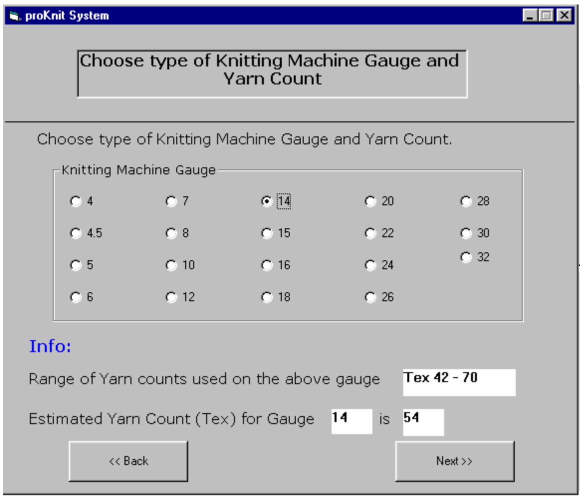
| Gauge n.p.i. | Single Knits, tex | | Double Knits, tex | |
|---|---|---|---|---|
| | Range | Estimated | Range | Estimated |
| 7 | 260 – 100 | 217 | 240 – 150 | 180 |
| 8 | 169 – 84 | 166 | 180 – 120 | 138 |
| 9 | 140 –72 | 131 | 140 - 80 | 109 |
| 10 | 113 – 56 | 106 | 120 – 60 | 88.5 |
| 12 | 84 – 50 | 73 | 75 – 45 | 61.5 |
| 14 | 70 – 42 | 54 | 49 – 36 | 45.0 |
| 15 | 56 – 36 | 47 | 42 – 31 | 39.5 |

The fifth page will appear on the screen as soon as ‘Next>>’ has been pressed. Here, the user is able to select the type of knitting machine gauge according to the variety of the knitting machines available for production, and the proKNIT system will present the range of yarn counts suitable for the chosen gauge as well as the estimate (Figure 3). All the available data has been based on information presented by different knitting machine producers. Inside the software, the data is tabulated as shown on the sample of ranges presented in Table 7, where the yarn count suitable for each machine gauge is written as a total value of tex, and not in the commercial form, i.e. Tex 50/2. Since there is no basic equation to predict the appropriate yarn count for each knitting machine gauge, the estimated value for each machine gauge presented in Table 5 also appears on the fifth page of the proKNIT software, based on equations (12) and (13), which are generally recognised by knitters [16].

$$N_{Tex} = \frac{10630}{G^2} \quad \text{.........................................(12)}$$

$$N_{Tex} = \frac{8860}{G^2} \quad \text{.........................................(13)}$$

where N is the yarn count in Tex and G is the knitting machine gauge (needles per inch).



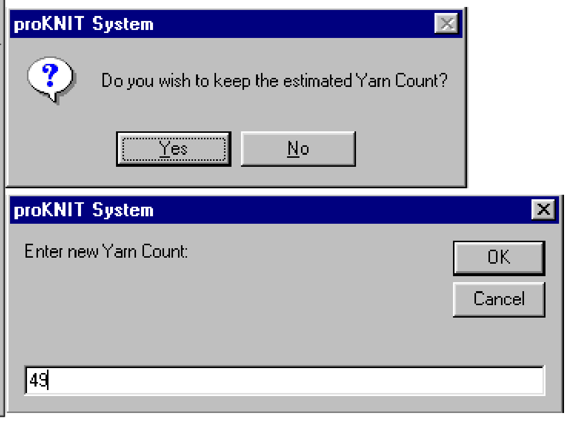




**Figure 3.** Fifth page of the proKNIT software

**Figure 3.1.** Fifth page of the proKNIT software

Let us assume that a gauge of 14 has been chosen; in order to continue the procedure, the estimated yarn count for gauge 14 is 54 tex, while the range of yarns suitable for this gauge is 42 to 70 tex. Now the user has two options: the first is to keep the reference yarn count, or alternatively to alter it according to the schedule of production. By pressing 'Next>>' the screen shown in Figure 3.1 appears and alterations can take place. If the user responds 'No' to the question "Do you wish to keep the estimated yarn count?" then a new window opens with the title "Enter new yarn count". By entering the required new yarn count and pressing 'OK', the system moves to the sixth page.

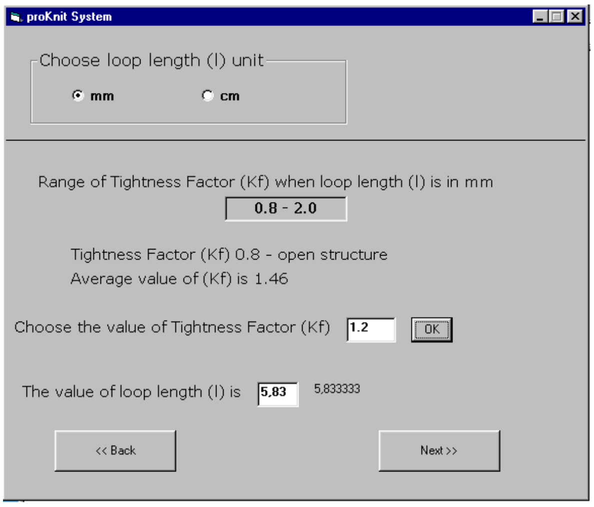



**Figure 4.** Sixth page of the proKNIT software

By pressing 'OK' the new page appears, as already mentioned, as do the new values required in order for the system to cover the puzzle of information (Figure 4). In this new window, the unit of loop length must be selected first. As soon as the unit of loop length has been chosen (mm or cm), the information below the line appears where the tightness factor has to be provided according to the available range. The choice of loop length in mm presents a range of tightness factor starting from 0.8 and going up to 2.0 with an average value of 1.46 [17], and when choosing loop length in cm this range increases by 10 with an average value of 14-14.70 [9, 10, 16]. The loop length has been estimated according to yarn count and the chosen tightness factor using equation (6). By choosing the value of tightness factors and by pressing 'OK', the last line appears indicating the size of the loop length value, in millimetres or centimetres according to the selected unit above.


**Figure 5.** Seventh page of the proKNIT software

The next page is concerned justifying the relaxed state of the knitted fabric where the estimations of the fabric weight/$m^2$ will be made (Fig. 5). In order to predict the weight of a fabric after knitting, three different and realistic relaxed conditions were selected in such a way that they would reflect, more or less, those existing in the knitting industry. The three relaxed conditions are defined as follows, according to standard procedures used in quality control sections:

- *Dry relaxed state*: Knitted fabrics conditioned for 48 hours in a standard atmosphere of 65% ± 2% RH and 20° ± 2°C.
- *Wet relaxed state*: knitted fabrics are soaked in water at 40°C for 2 hours, hydro-extracted in a domestic washing machine and left flat to dry (ISO 6330, procedure C). The fabrics are then conditioned for 24 hours in a standard atmosphere.
- *Finished and full-relaxed state*: Wool knitted fabrics and their mixtures are steamed flat in an industrial conveyor belt steamer, and are then hand-washed with a household mild detergent for 15 minutes at 30°C. The excess water is hydro-extracted and the fabrics left flat to dry (ISO 6330, procedure C). The fabrics are conditioned for 24 hours in a standard atmosphere.
  Cotton knitted fabrics and their mixtures are washed and tumbled-dried according to standard ISO 6330, and washed at 60°C (procedure No $3A^h$), using a non-phosphate ECE reference detergent A (without optical brightener). Tumble-drying is done at 60°C until the fabrics are dried. Finally, conditioning takes place in a standard laboratory atmosphere for 24 hours.

By pressing 'Next>>' the eighth page appears, where the estimations of courses per cm, wales per cm, loop density and loop shape in the chosen relaxed state appear after pressing Calculate (Fig. 6). Exactly the same procedure applies with the ninth page, where the estimations are presented for the fabric in a wet or a finished state respectively, according to the selections made on page seven. Page ten shows the estimations of weight of the chosen knitted fabric, in the given relaxed state, in grams per square metre, while their percentage difference is also estimated. On the last page, a full list of the values is finally given, so that the knitter has an overall view of the data he has chosen (Fig 6). This page can be printed and/or kept on file for reference. The user can also go back to page seven and alter the chosen relaxing states by pressing <<Back, or to go further back in order to add new values.

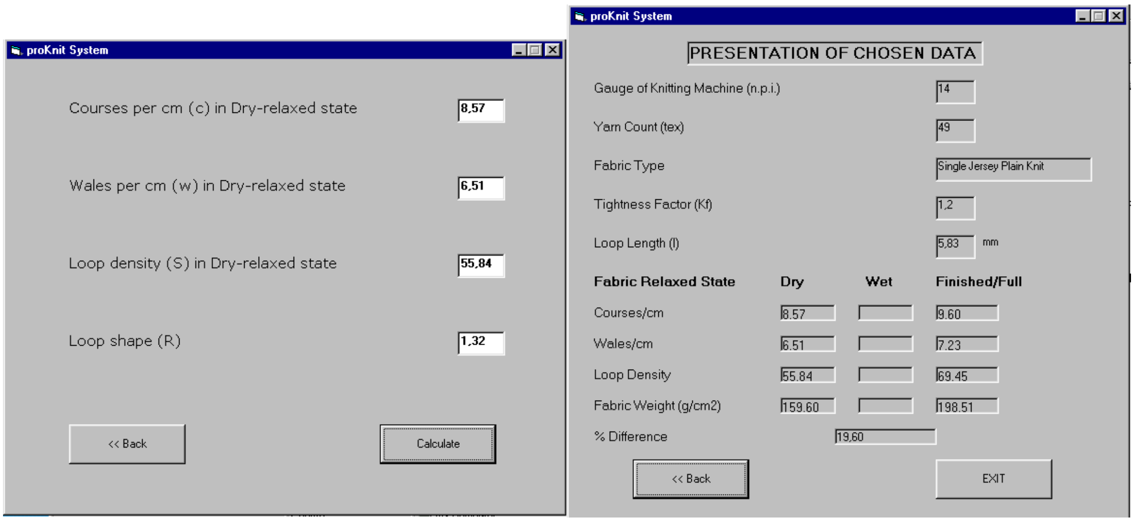



**Figure 6.** Eight and last page of the proKNIT software

## Experimental details

In order to calculate the fabric weight per unit area to a substantial degree of accuracy, it is important to have our own database of K values. To do this it was considered extremely important to produce knitted fabrics which would be subjected to the selected treatments. By analysing the fabrics produced, the required results would be obtained; these would be input into the proKNIT system, thus making it more accurate and realistic.

However, due to the enormous amounts of data required in order to make the system work while remaining as realistic as possible, it was decided to test and make predictions about wool mixture fabrics only in dry and wet relaxed states.

### Yarns used

The yarns used in this experiment were taken from industry, and cover the most popular mixtures and yarn sizes used in the production of knitted goods. The yarns were tested only for yarn count, while the results obtained together with their specifications are listed in Table 8. When knitting fabrics using a thinner yarn count, it is common practice to combine two or three separate ends of the fine yarn, rather than to use a single multi-folded yarn. The difference in K values for the fabrics produced by separate ends and those produced by multi-folded yarn are fairly small, provided that the total number of ends knitting singles and multi-fold yarns is the same [12]. It is seen from Table 8 that according to the yarn count, two- and three-parallel ends were used to produce the required fabrics.

**Table 8.** Yarn specifications

| Yarn composition | Yarn count | | Number of yarns used | Total count used, tex (theoretical) | Total count used, tex (actual) |
|---|---|---|---|---|---|
| | Nm | tex | | | |
| 50% acrylic / 50% wool extra fine (undyed) | 2/28 | 2/36 | 3 | 215 | 218.4 |
| 70% acrylic /30% wool (undyed) | 2/28 | 2/36 | 3 | 215 | 218.1 |
| 50% acrylic / 25% viscose / 25% wool (undyed) | 2/17 | 2/59 | 2 | 235 | 234.4 |
| 50% wool merinos / 50% Dralon (dyed blue) | 2/28 | 2/36 | 3 | 215 | 219.6 |
| dry relaxed 70% wool / 30% acrylic (dyed brown) | 2/28 | 2/36 | 3 | 215 | 218.4 |
| 50% acrylic 25% viscose 25% wool (dyed beige) | 2/17 | 2/59 | 2 | 235 | 256.8 |

### Knitting details

The five fabrics (plain knit, purl, 1×1 rib, 2×2 rib and interlock) were knitted from all the yarns listed in Table 8 on a Stoll C.M.S. 411 Selectanit electronic V-bed knitting machine, with 7 needles per inch. The machine has two knitting systems, which can work together or independently. However, the knitting process of all the fabrics tested involved only one knitting system. The knitting speed was controlled electronically at 1.2 metres/second using the same knitting system for the production of all fabrics. Two or three parallel yarns were fed to the front yarn feeder, which was used throughout the whole knitting process. The take-down tension and the yarn input tension were kept constant for each type of fabric by programming the knitting machine's software.

Sample fabrics from each yarn were knitted at three different loop lengths, so as to cover a range of three different cover factors which are very close to the average value of 1.46 according to equation (6). Table 9 presents the values used for stitch cam setting. The values shown do not correlate to stitch length or cover factor; however, 12.5 will create a smaller loop length than 13.5 value, and so on.

**Table 9.** Stitch cam details

| Type of knitted fabric | Yarn size, tex | Stitch cam setting | | |
|---|---|---|---|---|
| Plain knit and purl fabric | 215 | 12.5 | 13.5 | 14.5 |
| | 235 | 13.5 | 14.5 | 15.5 |
| 1×1 rib knit | 215 | 10.5 | 11.5 | 12.5 |
| | 235 | 11.5 | 12.5 | 13.5 |
| 2×2 rib knit | 215 | 11.2 | 12.2 | 13.2 |
| | 235 | 11.2 | 12.2 | 13.2 |
| Interlock | 215 | 11.5 | 12.5 | 12.5 |
| | 235 | 11.5 | 12.5 | 12.5 |

Plain knit, purl and 1×1 rib were produced without needle selection, but directly from the cam system. During the production of plain knit only, the front bed needles were active, with the back bed needles out of action. The purl structure was produced on the principle that the loops are transferred from one bed to another in order to draw reverse loops through the face loops and vice versa. A full sequence of loop production is illustrated in the four notation lines in Figure 7a. For the production of simple 1×1 rib structure, both cam boxes were activated to knit with all needles on both beds. Interlock fabric was knitted by selected needles on both needle beds and using half-racking to bring the needles' alignment from the front and back bed. Finally, the 2×2 rib structure was knitted using needle selection. As can be observed from the notation in Fig. 7b, only two of every three needles are active in the front and the rear needle bed. All the knitting machine details have been saved for the production of the predicted fabric weight samples.

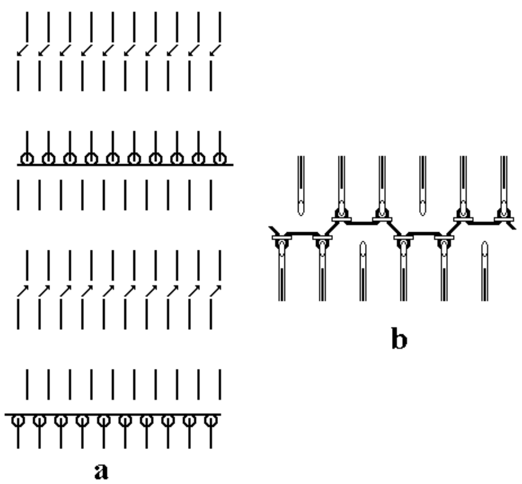



**Figure 7.** Details of the structure

## Fabric analysis

This investigation was concerned solely with predicting fabric weight per unit area of wool mixture fabrics, while consolidation and felting conditions were not considered. The static wet treatment was, therefore, used throughout, and agitation of the samples was specifically excluded.

Two sets of knitted samples were produced successively for all the categories of fabrics, yarns and stitch cam settings. One sample was placed directly in a testing laboratory for conditioning and relaxing for a period of 48 hours before measurements were begun. The other sample was placed flat for two hours inside a large stain steel tub containing water at $40^0$C. The excess water was hydro-extracted in a domestic washing machine, and the sample was left flat to dry. After drying, the fabric was placed in a controlled atmosphere and brought back to standard conditions for a period of over 24 hours before measurements commenced.

After conditioning the knitted fabrics, courses and wales per centimetre were counted using a magnifying glass with a 3×3cm viewing area. Ten random measurements from the three-centimetre viewer were taken, and the values tabulated for estimation of the mean value.

Unravelling the knitting yarn from a 15 cm-wide fabric and using a crimp tester 1500mm long, the course length of each fabric width was calculated. From each type of fabric, ten random course lengths were taken and their average value was calculated. However, it was found that course length variation rarely exceeded 1%. The loop length in mm was calculated simply by dividing the average course length found in each fabric by the amount of wales present in the 15-cm knitted fabric.

## Results and Discussion

According to the values obtained for courses and wales per centimetre and loop length in millimetres, the values of $K_c$, $K_w$, $K_s$ and R were calculated. Some of the results obtained have been tabulated in Table 10.

At this point, it is necessary to make some comments on the K values obtained. In SI units, the recommended length unit for courses and wales per unit length is the centimetre, and that of the stitch length is the millimetre. This causes the values of $K_s$ found in previous works to be multiplied by 100, and those of $K_c$ and $K_w$ by 10, in order to be compared with the values presented in Table 10. The ratio value R is naturally unaffected. For double jersey fabrics (1×1 rib, 2×2 rib and interlock) the values of wales per unit length are given with a slash and a value of 2 (i.e. 4.0/2). This value refers to the number of wales on the back of the fabric. The K values have been estimated by multiplying the courses & wales per centimetre shown on the face of the fabric by the loop length respectively. The logic of the structural knitted cell (SKC) used by Knapton et al. has not been adopted in the calculations of K values. The small differences (in tenths of a hundredth) found in loop length between dry and wet relaxed states must be ignored because they do not affect the final values of K, nor the cover factor of the fabrics (Table 11). According to the stitch cam settings used, the cover factor was kept within the range of ±18% of the recommended average value of 1.46, since various authors [3, 10, 18, 19] have commented that the so-called 'constants' $K_c$, $K_w$ and $K_s$ do not in fact remain constant over a wide range of tightness factors. The values presented in Table 11 indicate the above-mentioned percentage variation of the tightness factor.

**Table 10.** Dimensional values

| Type of fabric | c.p.c. | w.p.c | Loop length, mm | $K_c$ | $K_w$ | $K_s$ | $R=K_c/K_w$ |
|---|---|---|---|---|---|---|---|
| Plain knit 12.5 undyed (dry relaxed) | 5.3 | 4.1 | 9.50 | 50.3 | 39.0 | 1950 | 1.29 |
| Plain knit 12.5 undyed (wet relaxed) | 5.7 | 4.3 | 9.50 | 54.1 | 40.9 | 2213 | 1.32 |
| Purl knit 14.5 undyed (dry relaxed) | 5.6 | 2.9 | 12.20 | 68.3 | 35.4 | 2418 | 1.93 |
| Purl knit 14.5 undyed (wet relaxed) | 5.6 | 3.0 | 12.28 | 68.8 | 36.9 | 2539 | 1.87 |
| 1X1 rib 10.5 undyed (dry relaxed) | 5.3 | 4.0/2 | 8.52 | 45.2 | 34.1 | 1541 | 1.33 |
| 1X1 rib 10.5 undyed (wet relaxed) | 5.9 | 3.7/2 | 8.51 | 50.2 | 31.5 | 1581 | 1.59 |
| 2X2 rib 13.2 undyed (dry relaxed) | 4.0 | 3.1/2 | 12.25 | 49.0 | 37.9 | 1857 | 1.29 |
| 2X2 rib 13.2 undyed (wet relaxed) | 4.3 | 2.9/2 | 12.21 | 52.5 | 35.4 | 1859 | 1.48 |
| Interlock 12.5 undyed (dry relaxed) | 4.2 | 3.9/2 | 11.57 | 48.6 | 45.0 | 2187 | 1.08 |
| Interlock 12.5 undyed (wet relaxed) | 4.5 | 3.7/2 | 11.60 | 52.2 | 42.9 | 2239 | 1.22 |

The values of constant (K) that were achieved with 95% confidence limits for all the fabrics produced, from dyed and undyed yarns in dry and wet relaxed states, have been tabulated in Table 12. The non-dimensional parameters of Table 12 have been fed into the proKNIT system in order to make it operational. The prediction of fabric weight per unit area is a result of these non-dimensional parameters (constant K values) in conjunction with yarn linear density, loop length and/or tightness factor.

**Table 11.** Variation of tightness factors

| Type of fabric | Yarn count, tex | Loop length, mm | Tightness factor |
|---|---|---|---|
| Plain knit 12.5 undyed (dry relaxed) | 218.4 | 9.50 | 1.56 |
| Plain knit 12.5 undyed (wet relaxed) | 218.4 | 9.50 | 1.56 |
| Purl knit 14.5 undyed (dry relaxed) | 218.4 | 12.20 | 1.21 |
| Purl knit 14.5 undyed (wet relaxed) | 218.4 | 12.28 | 1.21 |
| 1X1 rib 10.5 undyed (dry relaxed) | 218.4 | 8.52 | 1.74 |
| 1X1 rib 10.5 undyed (wet relaxed) | 218.4 | 8.51 | 1.74 |
| 2X2 rib 13.2 undyed (dry relaxed) | 218.4 | 12.25 | 1.21 |
| 2X2 rib 13.2 undyed (wet relaxed) | 218.4 | 12.21 | 1.21 |
| Interlock 12.5 undyed (dry relaxed) | 218.1 | 11.57 | 1.27 |
| Interlock 12.5 undyed (wet relaxed) | 218.1 | 11.60 | 1.27 |

The values of the non-dimensional parameters ($K_C$, $K_w$, $K_s$ and R) presented in Table 12 are significantly dependent on the relaxing condition (dry, wet) as well as the type of yarn used, dyed or undyed. Comparing the authors' K values with those presented by Munden (Table 1), it becomes clear that the general conclusion is that there is no significant difference between them. In a dry relaxed state for undyed wool the values of K are about the same. In a wet relaxed state, the authors have estimated separate K values for dyed and undyed yarns in order to have a greater accuracy or small deviations when determining fabric weight in correlation with real fabric weight. When determining the average K values which result from both dyed and undyed yarns, it is apparent that there is a very close correlation with the K values presented by Munden. In trial testing conducted by applying Munden's K values to the proKNIT system, it was demonstrated that the results produced did not differentiate greatly from those obtained by measuring the real fabric weight in both states of relaxation (dry and wet).

Moreover, in plain-knitted fabrics in a dry relaxed state, the K values presented by Postle do not approach either those obtained by Munden or those presented in Table 12. On the contrary, in a wet relaxed state there is a clearer picture as far as the constant values are concerned. Postle's K values are very close to those presented by the authors for undyed yarns; however, the ratio of $K_c$ to $K_w$ presented is lower, which is probably connected to the tightness factors used by Postle.

**Table 12.** Non-dimensional parameters used on the proKNIT' system

| Type of fabric | Process | Kc | Kw | Ks | R |
|---|---|---|---|---|---|
| Plain knit undyed yarn | Dry | 50.0±0.3 | 38.8±0.2 | 1940 | 1.29 |
| Plain knit dyed yarn | Dry | 50.0±0.3 | 39.5±0.2 | 1975 | 1.27 |
| Plain knit undyed yarn | Wet | 54.0±0.3 | 41.0±0.2 | 2214 | 1.32 |
| Plain knit dyed yarn | Wet | 53.0±0.3 | 40.0±0.2 | 2120 | 1.32 |
| Purl fabric undyed yarn | Dry | 68.8±0.7 | 36.2±0.4 | 2490 | 1.90 |
| Purl fabric dyed yarn | Dry | 70.2±0.7 | 37.0±0.4 | 2585 | 1.90 |
| Purl fabric undyed yarn | Wet | 70.0±0.7 | 37.0±0.4 | 2590 | 1.89 |
| Purl fabric dyed yarn | Wet | 72.4±0.7 | 38.3±0.4 | 2773 | 1.89 |
| 1x1 Rib undyed yarn | Dry | 44.0±0.6 | 34.0±0.3 | 1500 | 1.30 |
| 1x1 Rib dyed yarn | Dry | 45.0±0.6 | 34.0±0.3 | 1530 | 1.32 |
| 1x1 Rib undyed yarn | Wet | 50.0±0.6 | 31.5±0.3 | 1575 | 1.58 |
| 1x1 Rib dyed yarn | Wet | 50.0±0.6 | 32.5±0.3 | 1625 | 1.54 |
| 2x2 Rib undyed yarn | Dry | 49.0±0.2 | 38.0±0.2 | 1862 | 1.29 |
| 2x2 Rib dyed yarn | Dry | 50.0±0.2 | 38.0±0.2 | 1900 | 1.31 |
| 2x2 Rib undyed yarn | Wet | 52.4±0.2 | 35.5±0.2 | 1860 | 1.50 |
| 2x2 Rib dyed yarn | Wet | 53.0±0.2 | 36.0±0.2 | 1908 | 1.47 |
| Interlock undyed yarn | Dry | 48.0±0.2 | 45.0±0.2 | 2160 | 1.06 |
| Interlock dyed yarn | Dry | 48.8±0.2 | 45.8±0.2 | 2235 | 1.07 |
| Interlock undyed yarn | Wet | 51.6±0.2 | 42.7±0.2 | 2203 | 1.21 |
| Interlock dyed yarn | Wet | 52.4±0.2 | 43.3±0.2 | 2270 | 1.21 |

Regarding double knitted fabrics, and 1×1 Rib in particular, Smirfitt analysed this structure using the logical path of plain-knitted fabrics and thus produced the non-dimensional parameters of K values presented in Table 3. Comparing these values with those obtained by the authors, it seems clear that there is a very close correlation between them. Knapton et al. also presented a set of K values for dry and wet relaxed states using the logic of structural knitted cell (SKC) for 1×1 rib structure. The results as presented do not agree with those listed in Table 12 because the logic behind the calculation is different. By recalculating the values presented by Knapton et al. so that they may be more easily compared to those in Table 12, it appears that there is still a great difference between them. When applying Smirfitt's values to the proKNIT system for determining the fabric weight per unit area of 1×1 rib, it is obvious that the predictions of fabric weight are more realistic than those of Knapton et al.

Looking at the $K_s$ values obtained for the dry and wet states of double knit structures (1×1 rib, 2×2 rib and interlock) as presented in Table 12, it becomes apparent that there is no substantial increase in the values as the state of relaxation passes from dry to wet. This is due to the fact that the loops inside the structure rearrange themselves, giving approximately the same total $K_s$ value. However, an increase in the $K_c$ value for 1×1 rib structure, particularly in the wet state, does not necessarily mean that there will be a proportionate increase in $K_w$ value, which in fact decreases. The same behaviour is also characteristic of the rest of the structures of 2×2 rib, and interlock where the rearrangement of loop position inside the structure results in very small differences in $K_s$ values. This rearranging behaviour of the courses and wales per unit length inside the structure is indicated by the value of R, which is directly affected and determined by the increase in differences between courses and wales per unit length and width respectively. However, the values obtained for the interlock fabric in a dry relaxed state are of particular interest since, while the ratio between courses and wales per centimetre is about equal (1.06 or 1.07), this ratio increases as the process of relaxation moves from the dry to the wet state. The same behaviour is also true of 2×2 rib structures.

Knapton et al. have also demonstrated this tendency to loop rearrangement in 2×2 rib structure (Table 5). The $K_s$ values which they obtained in two relaxed states, dry and wet, do not change distinctively, but remain more or less about the same, while at the same time there is an increase in ratio values. All the constant values presented by Knapton et al. are lower than those recorded by the authors in Table 12, and so it is precarious to use any of these values for determining fabric weight.

For interlock fabrics, Knapton & Fong presented a set of K values in dry and wet relaxed states (Table 6), which are completely different from those presented by the authors in the above table.

## Estimations of fabric weight per unit area using proKNIT software

All the above values of $K_c$, $K_w$, $K_s$ and R presented in Table 12 were fed into the software of the proKNIT system so as to set it up with the necessary data. In order to compare the theoretical fabric weight predicted by the proKNIT system with that of actual fabric weight, new samples were knitted by the same knitting machine, a Stoll CMS 411 Selectanit electronic V-bed knitting machine with a gauge of 7 needles per inch. The new knitting machine was programmed with the data obtained from experimental trials which also used the same types of yarns. All the new knitted fabrics produced were relaxed in dry and wet states, and then the fabric weight in grams per square metre as well as the loop length of each fabric were determined. The tightness factor for each fabric was calculated using the values of loop length and yarn count.

Next, the values of machine gauge, yarn count and tightness factor were entered into proKNIT, which processed the data given and produced the estimated loop length, courses and wales per centimetre and theoretical fabric weight. Some of the results obtained by both procedures are presented in Table 13.

By making a simple overall comparison of the figures presented in Table 13, it appears that the proKNIT system has predicted the fabric weight per unit area with a variation of less than ±3.8%. The small differences presented in the loop length values between actual and theoretical fabric weight have to do with diversion in calculations. The system always starts predicting the theoretical fabric weight by determining the fabric loop length through the variables of yarn count and tightness factor.

In Table 13, the interlock values of fabric weight represent an undyed fabric knitted at a 13.5 stitch cam setting, in both dry and wet relaxed states. According to the values obtained, the increase in mass weight from a dry to wet relaxed state is $26 gr/m^2$ for the tested fabric and $22.5 gr/m^2$ for the estimation values of the proKNIT system. In other words, the increase in weight for dry to wet relaxation of the tested fabric is 3.5%, and 3.1% for the theoretical values predicted by proKNIT. The difference between the two percentage values is 0.5%, a value that can be considered as negligible.

After a closer look at the other estimated values in Table 13, it becomes clear that the proKNIT software is indeed capable of making predictions of fabric weight per unit area with substantial accuracy, provided, of course, that the values of non-dimensional parameters ($K_C$, $K_w$, $K_s$ and R) at different states of relaxation fed into the system are realistic.

**Table 13.** Comparison between actual fabric weight and predictions of proKNIT system

| Fabric type | c.p.c. | w.p.c. | Loop density | Loop length, mm | Actual fabric weight, g/m$^2$ | Theoretical fabric weight, g/m$^2$ | Tightness factor | Yarn count, tex |
|---|---|---|---|---|---|---|---|---|
| Plain knit undyed dry 12.5 | - | - | - | 9.72 | 440 | - | 1.52 | 218.1 |
| proKNIT estimation plain undyed dry 12.5 | 5.15 | 3.99 | 20.55 | 9.71 | - | 435.20 | 1.52 | 218.1 |
| Plain knit undyed wet 13.5 | - | - | - | 11.02 | 475 | - | 1.39 | 234.4 |
| proKNIT estimation plain undyed wet 13.5 | 4.91 | 3.70 | 18.17 | 11.00 | - | 468.15 | 1.39 | 234.4 |
| Purl dyed dry 14.5 | - | - | - | 12.74 | 432 | - | 1.16 | 218.4 |
| proKNIT estimation purl dyed dry 14.5 | 5.51 | 2.9 | 15.98 | 12.74 | - | 444.63 | 1.16 | 218.4 |
| 1X1 rib undyed dry 11.5 | - | - | - | 10.45 | 699 | - | 1.47 | 234.4 |
| proKNIT estimation 1X1 rib undyed dry 11.5 | 4.22 | 3.26 | 13.76 | 10.42 | - | 672.16 | 1.47 | 234.4 |
| 1X1 rib dyed wet 11.5 | - | - | - | 10.80 | 768 | - | 1.48 | 256.8 |
| proKNIT estimation 1X1 rib dyed wet 11.5 | 4.62 | 3.00 | 13.86 | 10.83 | - | 770.93 | 1.48 | 256.8 |
| 2X2 rib dyed dry 13.2 | - | - | - | 12.40 | 759 | - | 1.29 | 256.8 |
| proKNIT estimation 2X2 rib dyed dry 13.2 | 4.02 | 3.05 | 12.26 | 12.42 | - | 782.05 | 1.29 | 256.8 |
| 2X2 rib dyed wet 12.2 | - | - | - | 10.35 | 814 | - | 1.43 | 218.4 |
| proKNIT estimation 2X2 rib dyed dry 12.2 | 5.13 | 3.48 | 17.88 | 10.33 | - | 806.77 | 1.43 | 218.4 |
| Interlock undyed dry 13.5 | - | - | - | 12.95 | 725 | - | 1.14 | 218.4 |
| proKNIT estimation interlock undyed dry 13.5 | 3.70 | 3.47 | 12.84 | 12.96 | - | 726.86 | 1.14 | 218.4 |
| Interlock undyed wet 13.5 | - | - | - | 12.87 | 751 | - | 1.15 | 218.4 |
| proKNIT estimation interlock undyed wet 13.5 | 4.02 | 3.32 | 13.35 | 12.85 | - | 749.32 | 1.15 | 218.4 |

## Conclusion

After a close study of the results given, the following conclusions can be drawn:

- The ProKNIT system has been created on the basis of the existing literature on the geometric and dimensional properties of weft-knitted fabrics.
- The first attempt to predict fabric weight for wool mixture yarns was successful, and the predictions did not show significant differences from the actual fabric weight.
- The whole system is constantly being replenished with more data, in order to cover a much wider variety of yarns and thus make it more flexible and minimise errors.

At the moment, the system is being tested with a considerable degree of success by two knitting factories, one of which produces cotton knitted fabrics and the other one woollen knitted goods.

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