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Investigation of an innovative plating process in weft knitting

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ABSTRACT

In a previous R&D project funded by the European Regional Development Fund (EFRE – 0400310), an innovative yarn feeding technology for weft knitting machines was validated. This technology employs three yarn carriers to create unique fabric structures: one carrier inserts yarn Y3 into both needle beds to produce a 1x1 rib pattern, while the other two carriers insert yarns exclusively into either the cylinder Y1 or dial needles Y2, resulting in a single jersey structure on each needle bed. This study investigates the effects of various machine settings on the plating results of knitted fabrics using this technology. Experiments were conducted to evaluate the impact of timing (synchronized and delayed), yarn tension, and cam depth on the fabric's appearance. Color components of blue, yellow, and red were analyzed through stitch color counting and image processing with Matlab. Results indicated that synchronized timing increased the visibility of Y3, while delayed timing enhanced the prominence of Y1 on the technical front of the fabric. Increasing yarn tension of Y3 resulted in a noticeable color gradient. Adjustments in cam depth led to minor color changes. The study concluded that timing significantly affects the knitting result, with increased yarn tension of Y3 reducing its visibility on both sides of the fabric, while cam depth had less effect. These findings highlight the importance of precise machine settings in determining the final appearance of knitted fabrics, providing valuable insights for the textile industry in fabric design and production.

Keywords

knitting,
plating,
multiply fabric,
innovative yarn supply,
layering,
novel structures,
synchronized and delayed timing,
yarn tension,
cam depth

1 Introduction

The continuous growth in demand for technical textiles asks for the development of innovations and accelerated processes. Improving the properties of technical textiles requires novel approaches and the development of innovative manufacturing processes.

A promising approach in this regard is the utilization of multi-layered knitted structures. Knitted fabrics offer a versatile platform for various technical applications in numerous fields, such as medical [1,2], sports [3-6], automotive [7,8], composite materials [7,9], construction [10], or textile electronics [11–13]. To enhance the performance of knitted fabrics, they can incorporate areas with various knitting structures. For instance, some zones can be reinforced through different structures that change the fabrics' properties [6,14] or weft insertion either in course and wale direction or at specific angles [15,16]. Multi-layered fabrics like weft-knitted spacer fabrics [17,18], formed by interconnecting both sides with yarns or walls, offer a wide range of different applications, such as thermal insulation [19,20], composites [21], stab resistance [22], sound absorption [23,24] or capacitive sensors [25,26].

Despite the versatile applications of multi-layered knitted structures, simultaneous insertion of different structures, i.e. single and double jersey in the same knitting cycle is not widely used. There is limited information on the manufacturing processes of such knitted fabrics and a lack of data on their properties and potential applications. In a previous study [28], we analyzed the implementation of such a technology on flat and circular knitting machines. The trials on the circular knitting machine showed promising results with an interesting plating effect. Therefore, in this study, we investigate the factors influencing the knitting result. The yarn carrier development for circular knitting machines used in this study enables knitting single and double jersey in the same system with the same needles. Three yarn carriers are needed. When the needles are at their highest position (Fig. 1a), the three yarns (Y1 blue, Y2 yellow and Y3 red) are inserted at different positions. SY3 is in the standard position and inserts its yarn (Y3) in the middle above the needle cross (L). CY1 is positioned in front of the cylinder needles underneath the needles of the dial. When the needles raise, the latches (Z) open and CY1 inserts yarn Y1 on the opened latches of the cylinder needles. As the yarn is underneath the needles of the dial, Y1 is only inserted in the cylinder needles. DY2 is positioned on the dial behind the cylinder needles. It lays its yarn Y2 on the opened latches of the dial needles. As the yarn carrier is positioned behind the cylinder needles, Y2 is only inserted in the needles of the dial. After lowering and therefore closing the needles (Fig. 1b), there are two yarns in each needle hook (K). Y1 and Y3 are in the cylinder needles and Y2 and Y3 are in the dial needles.

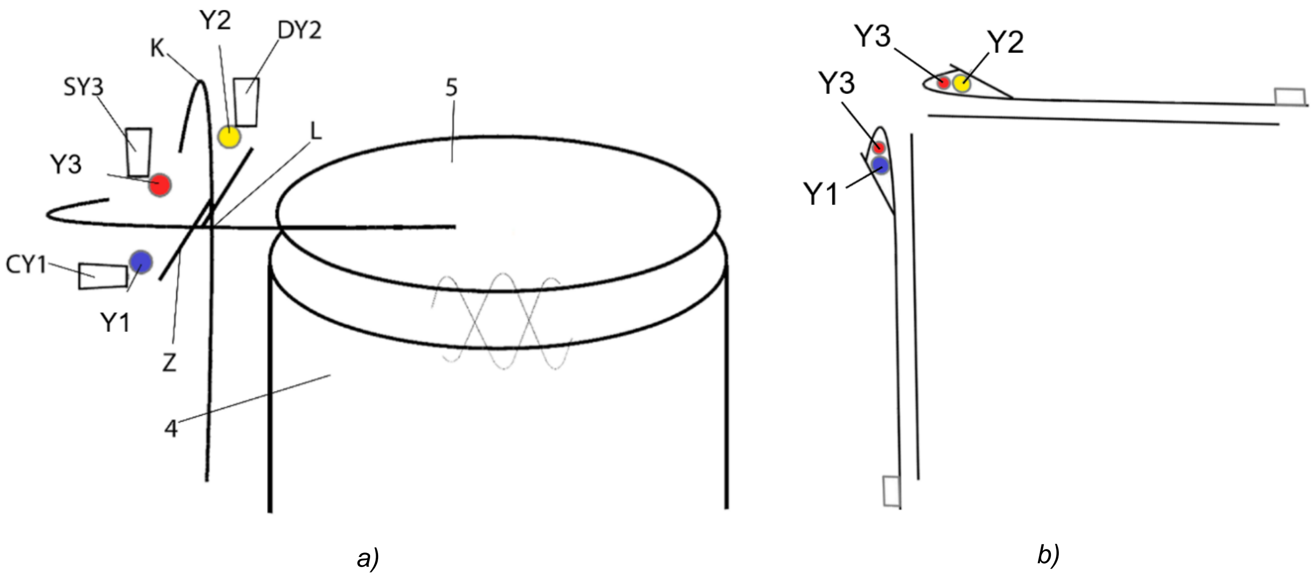


Fig. 1 Machine set-up for the innovative technology on a circular knitting machine with the needles a) in raised position, b) in lowered position, source: adapted from [27].

Thereby, new possibilities for knitted constructions and expanding potential application areas are opened up. Furthermore, the integration of plating technology with the novel yarn feeding represents an innovation in knitting production. By combining these techniques, the resulting fabrics exhibit multi-layered structures, offering new fabric design and properties.

2 Materials and Methods

2.1 Machine and machine set-up

The knitting machine used for this study is a large diameter circular knitting machine by Mayer & Cie. GmbH & Co. KG type FV2.0. It has a gauge of E10 and 432 needles on each cylinder and dial. Only one system is activated. The machine is running at a speed of 30 revolutions per minute (rpm).

Yarn feeders (Memminger EFS 920 [29]) are installed to the machine in order to ensure consistent yarn tensions with positive yarn feeding [30]. In contrast to positive yarn feeders with length-control, thus delivering a constant yarn length per unit of time, these yarn feeders are tension-controlled, meaning they always maintain a constant yarn tension.

2.2 Yarn features

A texturized 100% polyester filament yarn named “Waffle” by Filati Di.Vè [31] is used. It has 40 filaments and a yarn count of Nm 1/45 which corresponds to 22 tex. According to the manufacturer, they are usually used on knitting machines with a gauge of E 16/18. Therefore, the yarns are too fine for the before mentioned machine with gauge E 10. However, with the innovative technology, two yarns are placed in each needle (Y1 and Y3 in the front needle bed or cylinder and Y2 and Y3 in the back needle bed or dial). This effectively doubles the yarn count to approx. 44 tex, which suits to a machine with a gauge of E 10. Three different colors are used: blue, yellow and red. Y1 (knitting only on the cylinder) is blue, Y2 (only knitting on the dial) is yellow, and Y3 (knitting on cylinder and dial) is red.

2.3 Yarn carrier prototypes

Yarn carrier prototypes are developed and built by Pinkert machines UG & Co. KG [32] to insert Y1 and Y2. In contrast to the magnetic stands used in the previous study [28], these yarn carriers are not as easily adjustable in their position, but they offer the advantage to insert the yarn closer to the needle and offer more stable and reproducible position.

The positions of the three yarn carriers in circular knitting are exactly defined, each by three distances:

d1: Distance from yarn carrier tip to top of cylinder system (for CY1 and SY3) and to dial needles (for DY2) (in mm);

d2: Distance from yarn carrier tip to cylinder (for CY1) and to plate of the dial system (for DY2 and SY3) (in mm);

d3: Distance from yarn carrier tip to the first closed knitting needle (for CY1, DY2 and SY3) (in mm).

2.4 Evaluation methods

To analyze the knitted fabrics, microscope images are taken from each sample. Images of the knitted fabrics are captured on five areas of each sample, front and back, respectively, using a Keyence microscope at a magnification of 30. To avoid reflections, a polarization filter is used. As blue, yellow, and red yarns reflect differently, the filter is individually adjusted for each pattern.

To quantify the inaccuracies in the plating of the knitted fabrics, the samples are analyzed in two different ways to determine the proportion of each color presents on external front and back.

2.4.1 Evaluation by counting the color components

Initially, the number of complete stitches shown in the image is tallied. Following this, the distribution of blue, yellow, or red within the left leg of the stitches is estimated. The same process is repeated for the right leg of the stitches. This counting is performed for all five images per knitted fabric and for each front and back. Subsequently, the percentage of each color per image is calculated, followed by the calculation of the mean value. This mean indicates the percentage of each color present on the front and back of the knitted fabric:

- For the front side of the sample shown in Fig. 2a it gives: Blue = 97.3%, Red = 2.7%, Yellow = 0%;
- For the back side of the sample shown in Fig. 2b it gives: Blue = 0%, Red = 91%, Yellow = 9%.

a) b)

Fig. 2 Microscopic image of the external front taken at a 30x magnification a) on the external front, the estimated values of the sample result in a blue component of 97.3% and a red component of 2.7%. Since none of the front stitches contain yellow, the yellow component is 0%, b) on the external back, the estimated values of the sample result in a red component of 91% and a yellow component of 9%. Since none of the back stitches contain blue, the blue component is 0%.

The higher the percentages of one color, the fewer plating defects there are in the knitted fabric, thereby determining the most impeccable plating achieved by each fabric.

In this procedure, only the stitches of each sample, i.e. the color visible on the front stitches, are considered. If a color is visible between the stitch wales, i.e. back stitches, it is not included in the count (yellow between the blue stitch wales in Fig. 2.14a. However, this method is subjective due to the estimated values.

2.4.2 Evaluation by image processing

In the second approach, the images of the knitted fabrics are processed using Matlab. The color assessment is carried out through an analysis of colors. An algorithm is developed with Matlab to calculate the respective proportions of the three colors individually and output them as percentage values (Fig. 3). The algorithm distinguishes between blue, red, and yellow, calculating the respective proportions of each color in the microscope images. In this method, all colors visible on the sides of the fabric are evaluated, including those that are visible between the stitch wales and therefore not truly on the surface. That gives the following color components for Fig. 3:

- Front side: Blue = 72.6%, Red = 19.2%, Yellow: 8.1%;

Like in the “manually counted results”, all five samples are analyzed and a mean value for each color is calculated. The mean values for all five images of the shown sample are calculated for the front and back side.

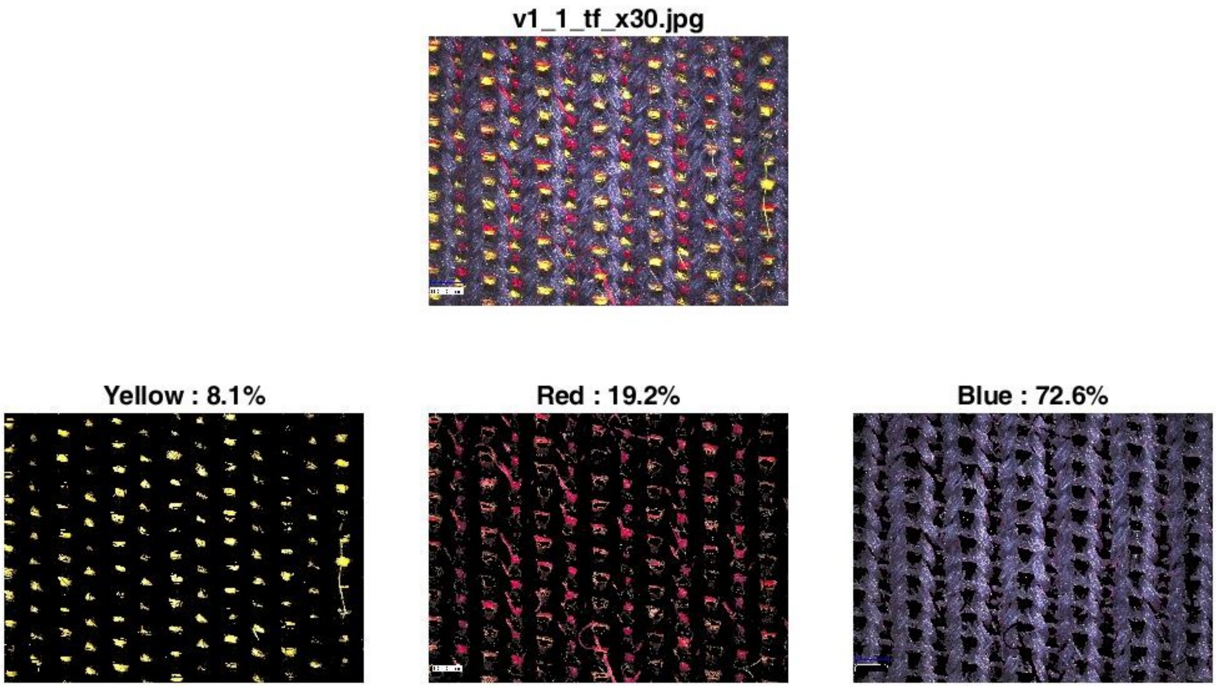


Fig. 3 Analysis of the three colors using Matlab. Even though yellow is not knitting on the surface, the sample has a yellow component of 8.1%.

2.5 Yarn position nomenclature

To define the position of each yarn more precisely, a theoretical nomenclature of the possible yarn positions is created.

Each stitch consists of two yarns that are regarded as different layers. As the innovative fabrics are knitted on cylinder and dial, respectively, they are regarded as a knitted fabric with four layers: one external and one internal front layer and one external and one internal back layer (Figure 4).

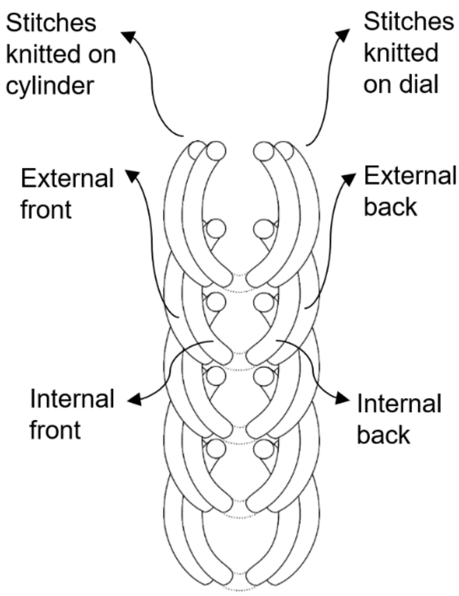
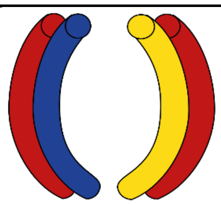
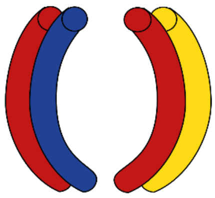
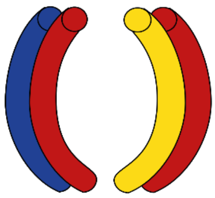
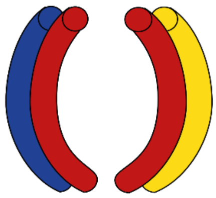


Fig. 4 Side cross section of a plated 1x1 rib fabric with four layers external and internal front and external and internal back. The dashed line symbolizes the connection between the cylinder and dial of the 1 x 1 rib

The dashed line symbolizes the connection between the cylinder and dial of the 1 x 1 rib structure. It should be noted that the connection made by Y3 (SY3) does not necessarily have to be between the internal front and back. Each of the three yarn carriers (CY1, DY2 and SY3) can insert their yarns to take different positions in the fabric. As CY1 is only knitting on the cylinder needles, Y1 (blue) can only take the external and internal front of the fabric. DY2 is only knitting on the dial needles; therefore, Y2 (yellow) can only take the external and internal back, while Y3 (red) can take all four possible positions. By these positions, four theoretical different combinations of possible positions of the innovative knitted fabrics can be defined, as shown in Table 1. These four options are regarded as error-free plating results, i.e. when there is only one yarn visible on the external front and one yarn visible on the external back.

Table 1. Four theoretical layer combinations for the innovative knitted fabrics.

Back Front	DY2 internal SY3 external	DY2 external SY3 internal
CY1 internal SY3 external		
CY1 external SY3 internal		

3 Results and Discussion

3.1 Parameters adjusted

There are several parameters affecting the plating results. In this study, the influence of the yarn tension, the timing and the cam depth is investigated. The aim is to find out how these parameters affect the knitting results and how to achieve an error-free plating on the external front and back of the innovative knitted fabrics.

3.2 Yarn tension

The yarn tension of each yarn has an influence on the plating results [33,34]. To avoid plating defects, a minimum tension should be ensured [35]. Literature gives different opinions on how the yarn tension should be set to achieve good plating. Some researchers [33,36-38] report the yarn which is fed with a higher tension goes to the back of the stitch, i.e. the internal in the case of the innovative knitted fabrics. Therefore, the plating yarn (external) should be knitted with a lower yarn tension than the ground yarn (internal). According to Wiedmaier and Bühler [35], the yarn tension for the plating yarn is typically adjusted to be higher than that of the ground yarn.

The first trials are conducted in synchronized timing which is usually the standard setting of a circular knitting machine. They are named ST1-ST6 (synchronized timing 1-6) according to Table 2. The yarn tension of Y1 (blue) is reduced to 1 cN and the yarn tension of Y2 (yellow) is reduced to 5 cN. The tensions are chosen differently to see if there is a difference when the yarn tensions of Y1 and Y2 are adjusted differently. It should be noted that “yarn tension” refers to the tension (cN) that is set at the yarn feeders, not the measured yarn tension. Therefore, the tension does not change during the knitting process.

The yarn tension of Y3 (red) is gradually increased from 10 cN to 40 cN (maximum setting). From Table 2, it is obvious that the yarn consumption of Y1 and Y2 hardly changes while the yarn consumption of Y3 decreases with the increase in yarn tension. These results are expected, as the yarn tension of Y1 and Y2 remains unchanged, while an increase in yarn tension results in less material being delivered, therefore lower yarn consumption and lower loop length [39].

*Table 2. Machine set-up: Change from yarn tension of Y3. *The yarn tension is changed on the yarn feeder of SY3, i.e. Y3, i.e. red.*

Timing		**Synchronized**					
Trial no.		ST1	ST2	ST3	ST4	ST5	ST6
Cam depth	Cylinder	2	2	2	2	2	2
	Dial	10	10	10	10	10	10
Yarn tension (cN) (set.)	Cylinder Y1	1 cN	1 cN	1 cN	1 cN	1 cN	1 cN
	Dial Y2	5 cN	5 cN	5 cN	5 cN	5 cN	5 cN
	Standard Y3	10 cN*	15 cN*	20 cN*	25 cN*	30 cN*	40 cN*
Yarn consumption (m/rev)	Cylinder Y1	2.4 m/rev	2.4 m/rev	2.3 m/rev	2.3 m/rev	2.4 m/rev	2.4 m/rev
	Dial Y2	1.9 m/rev	2.0 m/rev	1.8 m/rev	1.8 m/rev	1.8 m/rev	1.8 m/rev
	Standard Y3	4.2 m/rev	4.2 m/rev	4.0 m/rev	3.9 m/rev	3.8 m/rev	3.7 m/rev

Increasing the yarn tension of Y3 clearly demonstrates a color gradient from red to blue on the front of the fabric (Table 3). In ST1, it is visible that only some left sides of the stitches are plated in blue. In ST6, the complete left side of each stitch is plated in blue. However, even in ST6, the sample with the maximum yarn tension of 40 cN, only on the left side of the stitch blue is on the external front; on the rest of the stitch, red is on the external front. On the external back, there is no such obvious color gradient from red to yellow. However, it seems yellow becomes more visible between the red stitch wales with an increase in yarn tension of Y3.

Table 3 shows the results of the color components of blue, yellow and red manually counted and analyzed with Matlab, both for the external front and back of the fabrics. The results show that an increase of the yarn tension of Y3 increases the blue component and decreases the red component on the external front according to both, the Matlab and counted results. The yellow component remains low in all results with a slight increase with increasing yarn tension on Y3. On the external back, the red component is the most prominent in all trials, having higher color components for the counted results with an increase in the yarn tension of Y3 while the yellow component is decreasing. For the Matlab results, none of the color components change significantly with an increase of yarn tension of Y3.

The results clearly show that the proportion of red on the external front (Figure 5.a) decreases with an increase in the tension of the standard yarn. Conversely, the proportion of blue increases, while the proportion of yellow experiences only a minor elevation. The correlations between the tension of the standard yarn and the proportion of red and blue are very high; the coefficient of determination R^2 is respectively -0.95 and 0.94. Higher yarn tension corresponds to lower red component and higher blue component. However, even at the highest yarn tension of 40 cN, the blue component remains only around 30% and the red content close to 70%.

On the external back (Fig. 5b), the component of red increases slightly from a yarn tension of 10 cN to 20 cN, and then decreases again to a yarn tension of 40 cN. Conversely, the opposite is observed for the yellow component. Therefore, a definite relationship between yarn tension and the proportion of red or yellow cannot be conclusively established.

According to plating theory [34,40], the yarn being put on the latch should be the ground yarn (i.e. internal layer). As Y1 (blue) and Y2 (yellow) are placed onto the latches, it is expected that they take the internal position on the front and back. According to the theory, they should be lifted in the upper position in the needle hook. However, the recordings depict a different sequence of processes (Fig. 6a-d).

The stitch formation process is explained on the dial because Y2 (yellow) and Y3 (red) are clearly visible compared to Y1 (blue).

Table 3. Knitting results and color components: Change from yarn tension of Y3.

	External front				External back		
			Matlab (%)	Counted (%)		Matlab (%)	Counted (%)
ST1		Blue	6.3	19.9		0.1	0
		Yellow	1.7	0		5.3	19.3
		Red	92	80.1		94.5	80.7
ST2		Blue	9.4	28.9		0.3	0
		Yellow	1.8	0		3	20.6
		Red	88.8	71.1		96.8	79.4
ST3		Blue	13.9	36.9		0.2	0
		Yellow	2.0	0		3.1	15
		Red	84.1	63.1		96.6	85
ST4		Blue	16.8	39		0.3	0
		Yellow	2.8	0		3.8	10.1
		Red	80.4	61		96	89.9
ST5		Blue	27.7	44.8		0.3	0
		Yellow	3.6	0		4.3	10.3
		Red	73.7	55.2		95.5	89.7
ST6		Blue	28.5	52.4		0.2	0
		Yellow	3.7	0		6.1	7.3
		Red	67.8	47.6		93.7	92.7

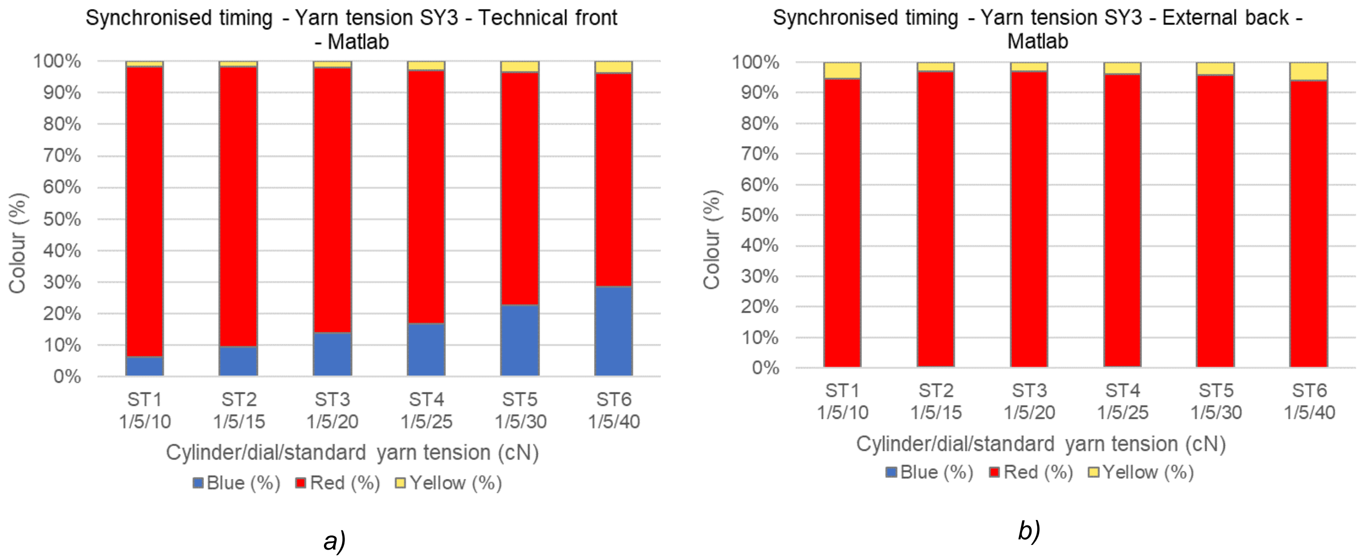


Fig. 5 Distribution of the percentage shares of the respective colors on the a) external front and b) external back of the trials conducted with synchronized timing and changing standard yarn (Y3) tension.

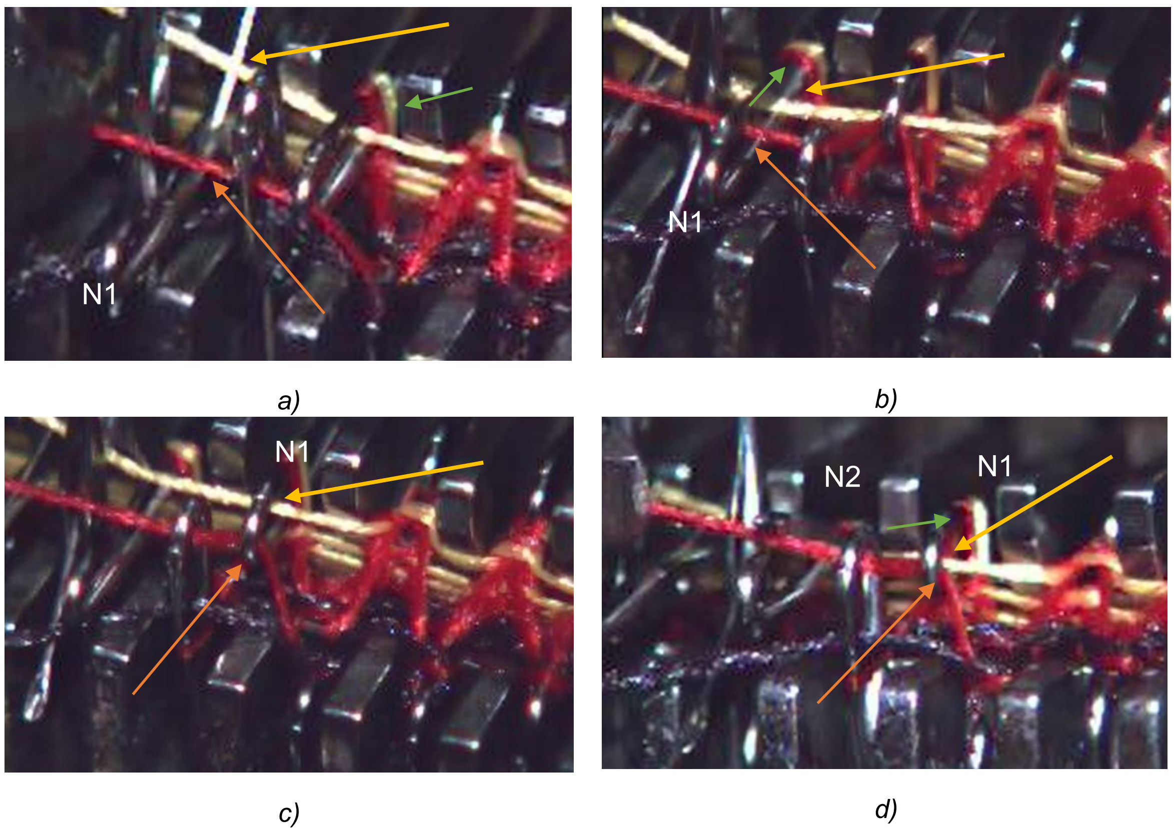


Fig. 6 Sequences of the process during the knitting of ST2. a) Y1 (blue) and Y2 (yellow) are laid on the needle latches, while Y3 (red) is directly inserted in the needle hook. b) Y3 is positioned at the top and back of the needle hook because due to its yarn insertion and its insertion into cylinder and dial needles; Y1 and Y2 are pulled towards the needle latch. c) When the latch of the subsequent needle closes, Y1 and Y2 are pushed from the latch into the back part of the needle, close to the needle stem; since Y3 is already positioned high in the needle hook, Y1 and Y2 are placed lower than Y3. d) During knock-over, Y1 and Y3 and Y2 and Y3 change their positions in a way that Y1 and Y2 take the ground yarn position and Y3 takes the plating yarn position.

Y2 (yellow) is fed to needle N1 and laid on the closing latch (yellow arrow in Fig. 6a). Y3, supplied in standard position, is inserted in the opened needle hook (orange arrow in Fig. 6a). When the latch is closed (Fig. 6b), Y2 is positioned lower in the needle than Y3, i.e. Y2 is in the plating yarn or external layer position. Because Y3 is knitted by both, cylinder and dial needles, it tends to be pulled towards the back (i.e. the side of the needle stem) and hook of the needle (orange arrow in Fig. 6c). Y2 however, is drawn more to the front of the needle, i.e. to the latch, due to the position of the dial yarn carrier (DY2). During needle sinking of N1, Y2 is guided upward along the latch, i.e. the front of the needle (yellow arrow in Fig. 6c). When the subsequent needle (N2) is closing, Y2 is drawn to the back of the needle (yellow arrow in Fig. 6d). According to plating theory [34,40,41], Y2 is in the position of the plating yarn, i.e. the lower position is the hook and then on the external layer. From the green arrows in Fig. 6a,b,d, it can be observed that Y2 is still in the plating position, i.e. on the upper position in the hook, on the previously formed stitch loop, which is the position of the external back layer, while red is in the position of the internal layer.

However, the knitting results show mostly red on the external front and back sides in synchronized timing. On the external back, only one part of the stitches is yellow, i.e. the right leg of the stitch; the rest of the stitch is red. This phenomenon is explained in the following on sample ST1.

Figure 7 shows the knitting process on sample ST1, Y2 (yellow) and Y3 (red) lay next to each other on the closed latch, with Y2 positioned "below" (i.e. closer to the needle foot) Y3, thereby taking the external yarn position on the external back (1). During knock-over, Y2 partly slips over Y3 (2). During loop formation, Y3 slides partly under Y2, in a way that Y2 remains visible only on one side on the external side of the fabric, while Y3 becomes visible on the other side (3). When turning the fabric, the part where red is the external front on Figure 7, is the left leg of the stitch, and yellow is on the external back on the right leg of the stitch.

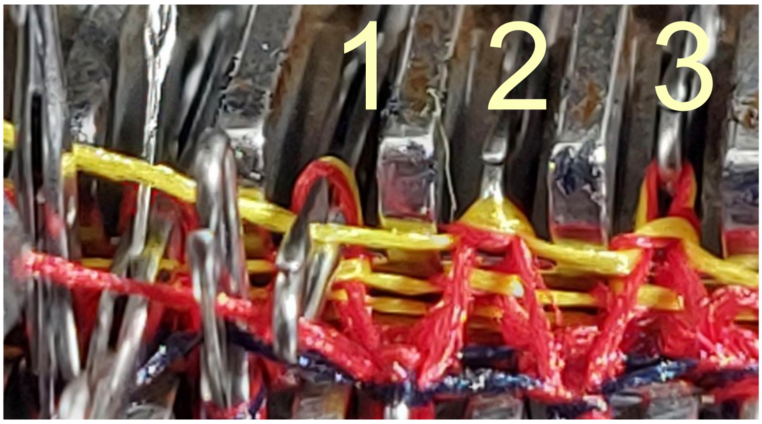


Fig. 7 Change of positions in ST1 from Y2 (yellow) and Y3 (red) during knock-over and loop formation.

Summarized, the influence of the yarn tension is clearly visible and measurable. However, in all samples there is no error-free plating achieved according to the four options described in section 2.5.

3.3 Timing

In the second series, one trial is conducted in synchronized timing (ST7) and another trial is conducted in delayed timing (DT1) with the other parameters remaining unchanged. The settings are changed to delayed timing with a delay of three needles. A delay of three needles is chosen because according to the machine manual of the circular knitting machine, a delay of three needles is referred to as the standard setting for delayed timing [42].

To convert the machine from synchronized to delayed timing, various modifications need to be made. Therefore, it is not accurate to say that only one parameter has been altered. On the one hand, the dial cam movement is shifted by three needles; the cylinder and dial cam curves are not running simultaneously, which increases the distance from DY2 to the first knitting needle (distance 3) (Table 4). On the other hand, the ring to which the yarn carriers are attached must be shifted by one millimeter. This is necessary to prevent the now later opening dial needles from colliding with the standard yarn carrier. Therefore, the distances (d3) between CY1 and SY3 and their corresponding first knitting needle is one millimeter longer. Additionally, with the same cam depth and yarn tension, the yarn consumption of Y1 increases, the yarn consumption of Y2 remains the same and the yarn consumption of Y3 decreases. The positions of the yarn carriers are not changed, therefore their positions relative to each other remain unchanged.

*Table 4. Machine set-up: Change from synchronized timing (ST7) to delayed timing (DT1). *Due to the delay of the cam curve, the distance of DY2 to the first knitting needle (d3) is higher in delayed than in synchronized timing.*

Timing			**Synchronized***	**Delayed***
Trial no.			ST7	DT1
Cam depth	Cylinder		2	2
	Dial		10	10
Yarn carrier position	CY1	d1	14	14
		d2	17	17
		d3	29	30*
	DY2	d1	9	9
		d2	11	11
		d3	31*	39*
	SY3	d1	20	20
		d2	10	10
		d3	3	4*
Yarn tension (cN)	Cylinder Y1		5 cN	5 cN
	Dial Y2		5 cN	5 cN
	Standard Y3		10 cN	10 cN
Yarn consumption (m/revolution)	Cylinder Y1		2 m/rev	2.3 m/rev
	Dial Y2		1.9 m/rev	1.9 m/rev
	Standard Y3		4.2 m/rev	3.5 m/rev

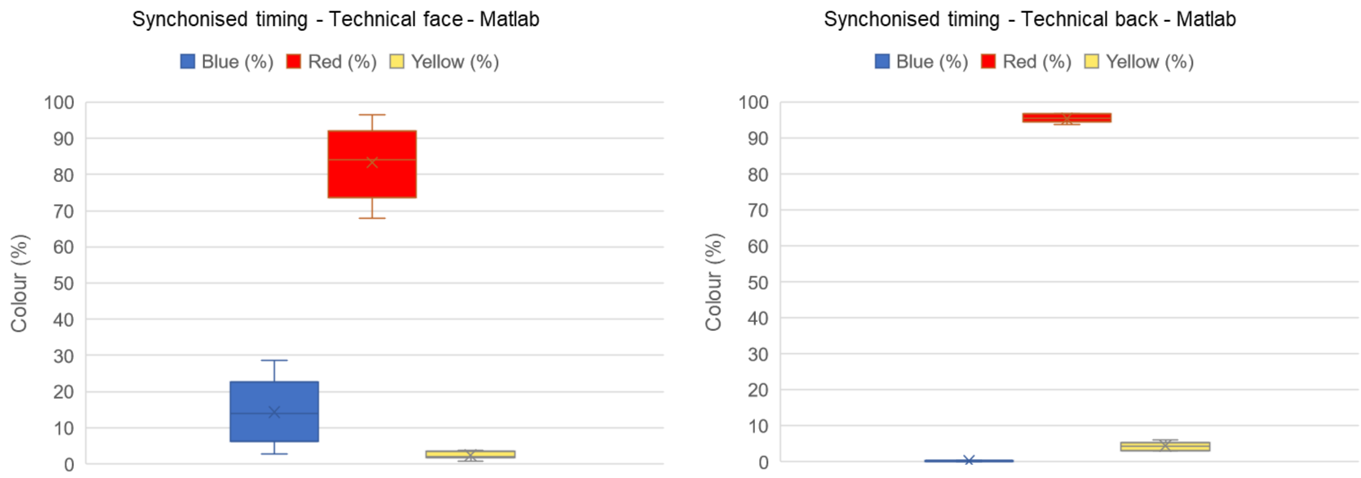
The knitting results presented in Table 5 indicate that the plating on the external front reverses with the change from delayed to synchronized timing. While in delayed timing, Y1 (blue) is on the external of the front, whereas it is Y3 (red) that is on the external front in synchronized timing. On the back side in both, synchronized and delayed timing, it is noticeable that plating, where the yellow yarn is on the external back, almost exclusively occurs on the right half of the stitches. Additionally, yellow is more prominent between adjacent stitch wales in delayed timing.

Table 5. Knitting results and color components: Change from synchronized timing ST7 to delayed timing DT1.

	External front				External back		
			Matlab (%)	Counted (%)		Matlab (%)	Counted (%)
ST7		Blue	2.7	4.3		0.1	0
		Yellow	0.9	0		5.2	13
		Red	96.4	95.7		94.7	87
DT1		Blue	67.3	100		0.3	0
		Yellow	10.9	0		14.8	17.1
		Red	21.8	0		84.9	82.9

Table 5 shows the color components for external front and back of the Matlab image processing and counted results in percentages. On the external front in synchronized timing (ST7), the red color component dominates in both, Matlab and counted results, while blue and yellow only hold small shares. On the external back of ST7, red is the most visible, with yellow having a small share and no blue. On the external front of delayed timing (DT1) however, blue is the most dominant. In the counted result, i.e. only the front of the stitches, there is blue exclusively. From the Matlab results, there is approximately 22% of red and 11% of yellow visible. These yarns are laying between the stitch wales. It can be seen that the difference between the Matlab and counted results are very different for the external front of DT1. On the external back however, red is the dominant in both, Matlab and counted results, with some yellow and (almost) no blue.

Fig. *8* shows the boxplots of all trials conducted in synchronized timing (ST1-ST7). It becomes evident that the main color component of the external front of the samples made with synchronized timing (Fig. *8*a) is red with between ~ 75% to ~ 95%. The blue component ranges from ~ 5% to ~ 15%, while the yellow component is less than 5%.

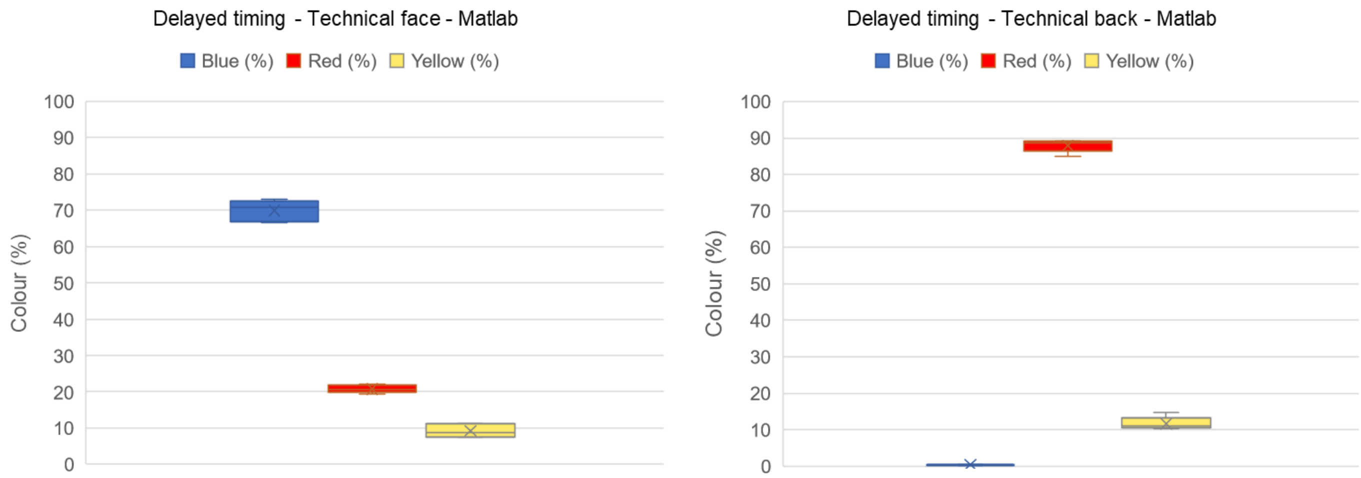


a) b)

Fig. 8 Boxplot of the percentage shares of the respective colors on the a) external front and b) external back of the trials conducted with synchronized timing (ST1-ST7) calculated by Matlab.

On the external back of the fabric (Fig. 8b), the component of red is higher, averaging ~ 95%, while the blue and yellow components are marginal, with nearly 0% and ~ 5%, respectively.

Fig. *9* displays the percentage distribution of colors for the external front and external back of the experiments conducted in delayed timing (DT1 – DT5).



a) b)

Fig. 9 Boxplot of the percentage color components of the respective colors on the a) external front and b) external back of the trials conducted with delayed timing calculated by Matlab.

Fig. 9a shows that the samples produced with delayed timing have a blue component ranging ~ 70% on the external front, indicating a higher blue component compared to the samples produced with synchronized timing. The red component is ~ 20%, and the yellow component is ~ 10%. However, on the back side (Fig. 9b), the blue component is nearly 0%, the red component ranges between 85% - 90%, and the yellow component is between 10%-15%. These results show a clear color change from red in synchronized timing to blue in delayed timing on the external front. On the external back, there is no strong change of the color components. In both, synchronized and delayed timing, red is the main component, followed by a small component of yellow and almost no blue.

The results show that for both, the counted and Matlab results on the external front, the correlation between the timing and the color component is very high. For the external back, there are significant differences between the counted results and the Matlab results. In the counted results, the correlations between the timing and the red and yellow components are very low. In contrast, the correlations in the Matlab results are very high. Therefore, it can be concluded that the correlation between the timing and the external front of fabrics is very high, while the correlation between the timing and the external back cannot conclusively be established.

Fig. 8ure 8 and Fig. 9 illustrate that with delayed timing, blue prevails on the external front of the fabric, while in synchronized timing, red dominates. However, on the external back of the fabric, the red component is always dominant, regardless of whether it is synchronized or delayed timing. The origin of these differences is discussed in the following section.

In synchronized timing (Figure 10), the needle loops of the cylinder and dial are formed simultaneously. Yarn Y3 (red) is therefore drawn from the yarn feeder from both, cylinder and dial needles respectively. This movement is shown as a black arrow in Fig. 11b. Therefore, there is more material per stitch available, resulting in Y3 bulking up between the needles (Fig. 11a). As a result, the yarn consumption is higher (Table 4) than in delayed timing, the stitch wales are wider, leading to a more irregular fabric appearance compared to the delayed timing samples.

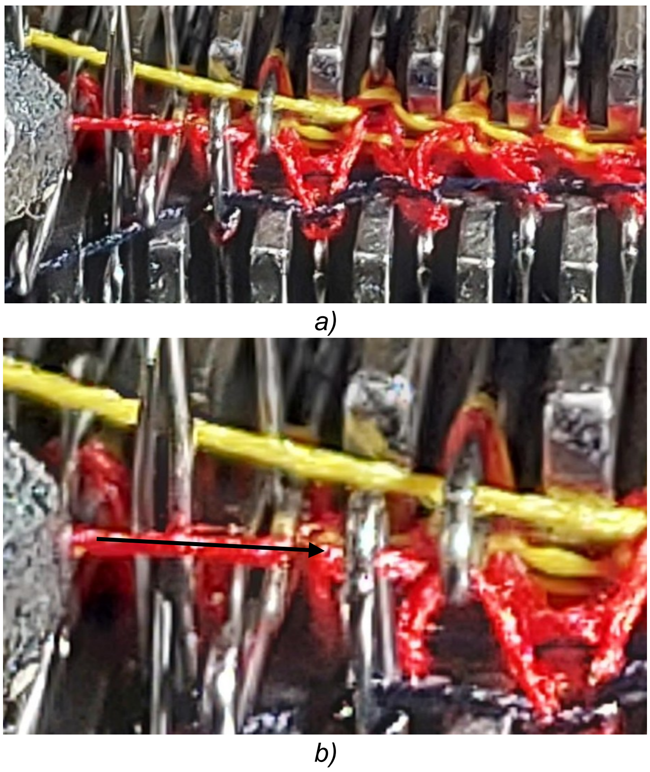


Fig. 10 Yarns on circular knitting machine during a) synchronized timing and b) with the yarn movement represented by a black arrow.

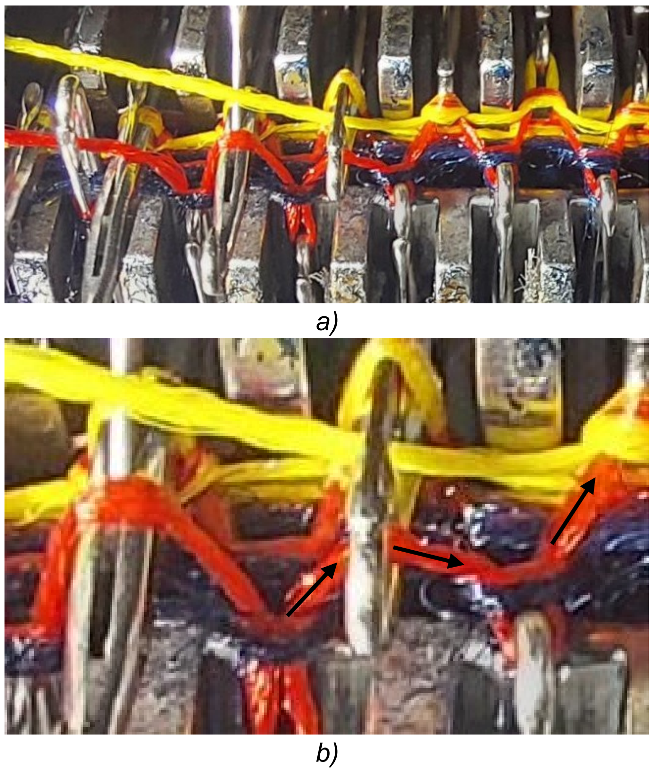


Fig. 11 Yarns on circular knitting machine during a) delayed timing and b) with the yarn movement represented by black arrows.

In delayed timing (Fig.11), the cylinder needles form their stitch loops prior to the dial needles. Therefore, some stitch loops have already been formed in the cylinder and the dial needles cannot draw more Y3 from the yarn feeder. It can be observed from the high-speed videos that when the dial needle sinks, it pulls Y3 out of the needle hook of the cylinder needles, to form a stitch. This yarn movement in delayed timing is visible in the high-speed videos. The movement is represented by black arrows in Fig 11b. Consequently, Y3 is straight between the cylinder and dial needles (Fig.11 a) resulting in narrower stitch wales and a clear fabric appearance. This leads to the assumption that in delayed timing Y3 (red) is being pulled to the internal front of the cylinder stitch and is therefore not visible on the external front.

The phenomenon where a needle pulls yarn from a previously formed loop is known as “robbing back” [43,44]. Yarn tension increases with each friction point [34,45,46]. The force that is needed to pull yarn from the yarn feeder increases quickly, making it easier for yarn to be pulled back from already formed loops when needles start to rise from their lowest position [34]. In this context, the yarn tension in a 1 x 1 rib structure is higher than in a plain knitted structure [47] because there are more friction points and higher wrapping angles.

3.4 Cam depth

According to literature [48], the cam depth affects the properties of a plated knitted fabric. At high and loose density, plating defects occur more frequently compared to a medium density [35]. Therefore, different cam depths are tested to validate their influence on the plating result of the innovative fabrics. Cam depth is a unitless parameter that ranges from 0 to 10 on the used circular knitting machine. It should be noted that the same setting number on cylinder and dial (e.g., 2 on the cylinder and 2 on the dial) does not necessarily produce the same stitch size. It is possible that a setting of 2 on the cylinder doesn’t correspond to a setting of 2 on the dial. In synchronized timing, the cam depth of the cylinder is set on 2 and the cam depth of the dial is set on 10 because with these settings the yarn consumptions of Y1 (only knitting on the cylinder) and Y2 (only knitting on the dial) are the most balanced.

Changing the cam depth on the cylinder may affect the plating result not only on the external front but also on the external back. To analyze the influence of the cam depth on the plating result of the innovative fabrics, not only the cylinder cam depth but also the dial cam depth, is varied. The trials where the cam depth is altered (Trial DT1 – Trial DT5) are conducted with delayed timing. The cam depth on cylinder and dial can be adjusted from 1 to 10. As shown in Table 6, the cam depths are changed which leads to small changes in yarn consumption.

*Table 6. Machine set-up: Change of the cam depths from cylinder and dial in delayed timing. *Only cam depths are changed for the machine settings. The yarn consumption is only changing as a result of the changed cam depth.*

Timing			**Delayed**				
Trial no.			DT1	DT2	DT3	DT4	DT5
Cam depth	Cylinder		2*	3*	5*	7*	10*
	Dial		10*	6*	5*	7*	10*
Yarn carrier position	CY1	d1	14	14	14	14	14
		d2	17	17	17	17	17
		d3	30	30	30	30	30
	DY2	d1	9	9	9	9	9
		d2	11	11	11	11	11
		d3	39	39	39	39	39
	SY3	d1	20	20	20	20	20
		d2	10	10	10	10	10
		d3	4	4	4	4	4
Yarn tension (cN) (set.)	Cylinder Y1		5 cN	5 cN	5 cN	5 cN	5 cN
	Dial Y2		5 cN	5 cN	5 cN	5 cN	5 cN
	Standard Y3		10 cN	10 cN	10 cN	10 cN	10 cN
Yarn consumption (m/revolution)	Cylinder Y1		2.3 m/rev	2.3 m/rev	2.3 m/rev	2.4 m/rev	2.4 m/rev
	Dial Y2		1.9 m/rev	1.8 m/rev	1.8 m/rev	1.9 m/rev	2 m/rev
	Standard Y3		3.5 m/rev	3.3 m/rev	3.3 m/rev	3.4 m/rev	3.5 m/rev

In DT1, the cylinder cam depth is set on 2 and the dial cam depth is set on 6, as in the trials of synchronized and delayed timing. Then, the cylinder cam depth is set on 3 and the dial cam depth is set on 6. In the following trials, both cam depths are set on 5, 7 and 10. Even with strong changes in cam depth, the yarn consumptions are only slightly changing.

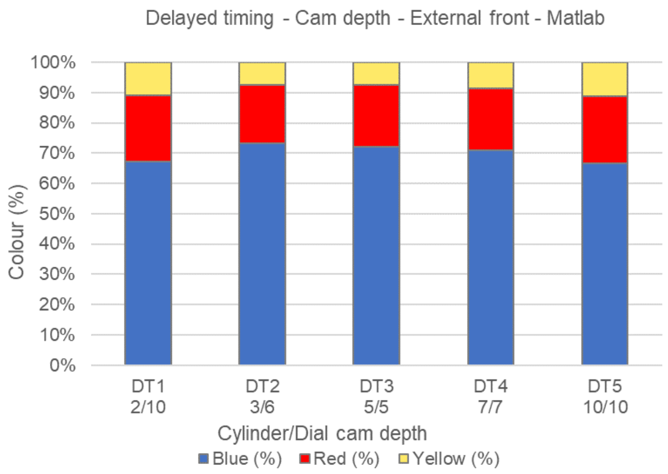
Table 7 shows the knitting results for the changing cam depths. All samples show blue dominantly on the external front and red dominantly on the external back. There is no obviously visible change of the color component with a change in cam depth.

Table 7. Knitting results and color components: Change of the cam depths from cylinder and dial in delayed timing.

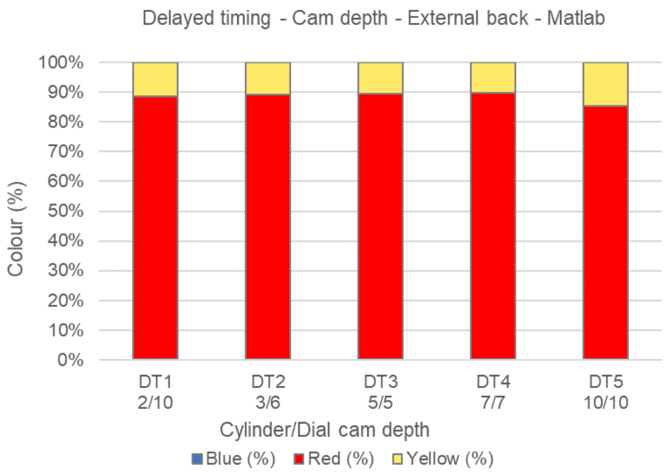
	External front				External back		
			Matlab (%)	Counted (%)		Matlab (%)	Counted (%)
DT1		Blue	67.3	100		0.3	0
		Yellow	10.9	0		14.8	17.1
		Red	21.8	0		84.9	82.9
DT2		Blue	73.1	97.3		0.3	0
		Yellow	7.5	0		11.6	9
		Red	19.3	2.7		88.1	91
DT3		Blue	72.1	97.7		0.4	0
		Yellow	7.6	0		11	9.3
		Red	20.3	2.3		88.6	90.7
DT4		Blue	70.8	98.5		0.4	0
		Yellow	8.6	0		10.6	11.1
		Red	20.5	1.5		88.9	88.9
DT5		Blue	66.5	98.8		0.4	0
		Yellow	11.3	0		10.4	12.4
		Red	22.1	1.2		89.2	87.6

On the external front, from the Matlab results blue has the highest component, followed by red, with yellow having the lowest values. Even the highest change in cam depth (from 2 in DT1 to 10 in DT5), the difference in the color components of the external front is very low. In the counted results, blue is almost exclusively dominant on all samples. On the external back, red is dominant with some yellow components and almost no blue for both, Matlab and counted results respectively. For the counted results, the yellow component increases when the cam depth of the dial is higher. Contrarily, the red component decreases with an increasing cam depth of the dial. However, the changes are minimal.

Increasing the cam depth reduces the blue component of the external front slightly. A greater cam depth corresponds to a larger stitch. Consequently, Y2 and Y3 become more visible between the stitch wales. However, even at the maximum cam depth of 10, the blue component still remains at ~ 65% on the external front (Fig. 12a). On the external back, the red component dominates at all different settings. Regardless of how high the cam depth is adjusted; the value of the red component lies between 85% and 90% (Fig. 12b)



a)



b)

Fig. 12 Percentage shares of the respective colors on the a) external front and b) external back of the trials conducted with delayed timing and changing cam depths

In general, the correlations between the cam depth and the color components range from low to high. However, the results also indicate that even with significant changes in the cam depth settings, the colour components only change marginally. Therefore, the overall influence of cam depth on the plating outcome of the innovative knitted fabrics is considered to be minimal.

4 Conclusion and outlook

The impact of the yarn tension, delayed and synchronized timing, and the cam depth on the visibility on the colors in knitted fabrics on the innovative knitted technology is investigated. The results clearly demonstrate that the timing has the greatest impact on the knitting result as the plating on the external front changes from red in synchronized timing to blue in delayed timing. Increasing the yarn tension of Y3 results in a corresponding decrease in the component of Y3 on both the external front and back of the fabric. Regardless of the settings, there are always at least two colors on both sides of the fabric. Additionally, it should be noted that knitting at such high tensions is uncommon in practice. Changing the cam depth of cylinder and dial respectively, only leads to minor changes in the fabric appearance. However, none of the settings can produce a fabric that displays only one color on the external front or external back side.

In this study, the yarn tension is set on the yarn feeder (tension-controlled positive yarn feeder Memminger EFS 920) and the stitch length is controlled by the cam depth. In this case, the results show that the timing is the most important criterion, followed by the yarn tension. However, with a length-controlled positive yarn feeding, i.e. where the stitch length is set on the yarn feeder and the yarn tension is controlled by the cam depth, it is expected that, again, the timing will be the most important criterion, followed by the cam depth.

Future studies could focus on how different yarn materials and tensions further influence the knitting results. Additionally, it would be interesting to explore how these findings can be applied to other industrial knitting machines.

In conclusion, the results of this study highlight the importance of machine settings for the final appearance and structure of knitted fabrics and provide valuable insights for the textile industry.

Author Contributions

P. Holderied: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, visualization, project administration; M.-A. Bueno: methodology, software, validation, formal analysis, investigation, data curation, review and editing, visualization, supervision; T. Mutschler: supervision, funding acquisition; M.O. Weber: review and editing, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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