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ORIGINAL ARTICLE

Integration of the vertical warp stop motion positioning in the model-based self-optimization of the weaving process

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Abstract The warp tension is a critical variable of the weaving process. If the warp tension is too high or too low, the weaving process will be interrupted. In order to find a suitable setting for the weaving machine, the experience of the operator is needed. Self-optimization routines can support the operator in finding optimal settings. Within this paper, the model-based self-optimization of the weaving process developed at Institut für Textiltechnik der RWTH Aachen University is presented. The self-optimization routine uses an automatic design of experiment to generate data for a full quadratic regression model of the characteristic values of the warp tension. Three weighted quality criteria are used to optimize the machine settings within given boundaries. An improvement is proposed by integrating the vertical warp stop motion position as a factor with high impact on the warp tension. The vertical warp stop motion position is automated and integrated into the optimization process. The adjusted routine is validated on an air jet weaving machine. The test results show that the integration of the warp stop motion position into a self-optimization routine leads to a 35% reduction of tension in the warp yarns. Compared to the existing routine, the integration of the warp stop motion position leads to a 23% higher effect on the warp tension as the target value of the optimization. The statistical validation shows that the quality of the used regression model is high. The described system also reduces the setup time of a weaving machine. Economically, the improvements mean a reduction of production costs by 22%, when producing small lot sizes. The system therefore contributes to the competitiveness of weaving mills in high-wage countries.

Keywords Weaving · Optimization · Warp tension · Modeling

1 Introduction

Weaving is one of the oldest manufacturing technologies known to mankind. Woven fabrics are described as a rectangular crossing of so-called warp and weft yarns. Woven fabrics are produced on weaving machines or so-called looms [1]. The principle of a weaving machine is shown in Fig. 1.

The so-called warp yarns are delivered by the warp beam and redirected by the backrest system. The yarns are led through the warp stop motion. The warp stop motion redirects the warp yarns and detects breaks of the warp yarn. A part of the warp yarn is led through a shaft. The up and down motion of the shafts creates the shed, in which the so-called weft yarn is inserted rectangular to the warp yarns. The reed strikes the inserted weft yarn to the fabric edge and the position of the shafts changes. The produced fabric is taken off and rolled onto the fabric beam [1].

Modern looms process a high number of diverse yarns and fiber materials to various fabrics. Examples are cotton webs for the apparel industry or technical webs made from polyamide for parachutes or carbon for lightweight products. Every combination of yarn and produced article requires its own setting of the loom. There are over two hundred parameters that can be varied on a modern loom. Setup of a weaving machine is done in general by relying on the experience of machine operators. The position of all yarn-guiding elements and many process parameters are adjusted for every new fabric.

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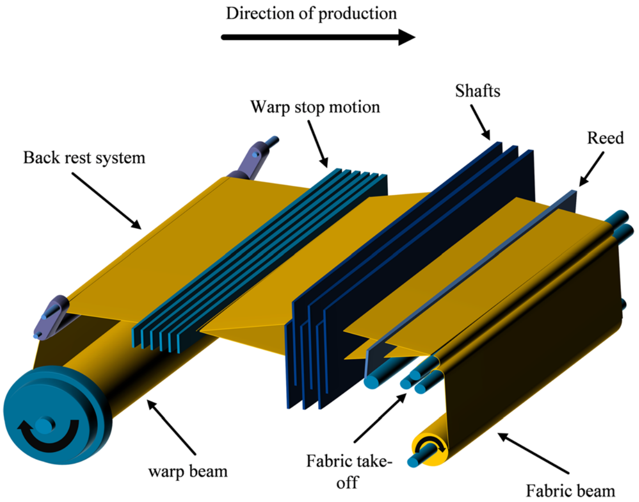


Fig. 1 Principle of a weaving machine (loom)

The setting of the weaving machine aims at having a constant but low stress in the warp yarns. In general, setup of a weaving machine is done by using an in-house operation database. New fabrics require experiments and an iterative improvement of the settings to find a stable setting point. These tests involve costs for the weaving mill. Costs are caused by the downtime of the weaving machine, the consumed material during the tests, and the personnel time needed for the tests. Especially in high-wage countries, the personnel costs for the setup of a weaving machine are high. In addition, the fabrics produced in high-wage countries are generally technical fabrics. The raw materials for technical fabrics are expensive compared to the raw materials used in the clothing industry [2].

In the past, the Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany, successfully automated several factors of modern weaving machines. Within the AutoWarp concept, an active backrest system was developed using simulation of the warp tension and a genetic optimization algorithm [3]. Also, a control for the fabric weight during weaving was developed using an X-ray sensor and a control loop with a Smith predictor [4]. The shed geometry of a loom can be optimized using a warp tension simulation based on geometric parameters [5]. Latest development is a model-based self-optimization of a weaving machine for three important setup parameters. In this paper, an advancement of the model-based self-optimization is made by the integration of the warp stop motion position as a setup parameter [6].

2 State of the art

2.1 Self-optimization

Self-optimization systems are defined as systems, which can apply adoptions of their inner state or structure in case of changes in input conditions or disturbances. Target values of the self-optimization can be, e.g., capacity, lot size, quality, costs, or processing time [7]. Self-optimizing systems are characterized by the following continuous steps:

- Determination of targets
- Analysis of the actual situation
- Adaption of the system behavior in order to reach targets [8]

The application of self-optimization is also known in the use of mechatronic systems, whereas the focus of research deals with the system design. Classical control loops and algorithms are used [9, 10]. Self-optimizing products are developed, which are used for the control of mechatronic systems using sensors and actuators [11].

2.2 Importance and optimization of warp tension in the weaving process

One crucial process variable which is influenced by the setup of the weaving machine is the warp tension. The importance of the warp tension for the weaving process and factors influencing the warp tension have been widely studied [12–17]. Schlichter examined the influence of the single machine elements on the yarn movements and tensions [12].

Figure 2 shows the effects of a wrong tension in the warp yarns.

If the warp tension is too high, the warp yarns will break; if the tension is too low, the warp yarns sag into the weaving shed. The weft yarn then collides with the warp yarn during the weft insertion. Both errors stop the machine immediately and have negative effects on the quality and the mechanical properties of the produced fabric. The fixing of broken warp yarns or the removal of a not correctly inserted weft yarn takes time in which the weaving machine is not producing. The correct setting of the warp tension is therefore crucial for the productivity of the weaving process and therefore has a high effect on the costs of a weaving mill.

The overall setting of a loom aims at producing the desired fabric and increasing productivity of the loom, by designing the process with low yarn breaks and machine stops. The fabric is determined by the following setting parameters:

- The weaving pattern
- The density of warp and weft yarns
- The yarn types used for the fabric

The setting of the weaving machine aims at having a constant but low stress in the warp yarns to increase the productivity of the loom. The setting parameters for the determination of the produced fabric are fixed and will not be changed by the weaver. Nevertheless, these parameters directly affect the warp tension, for example, by the stress-strain behavior and the tribological properties of the yarns. So, the mechanical parameters

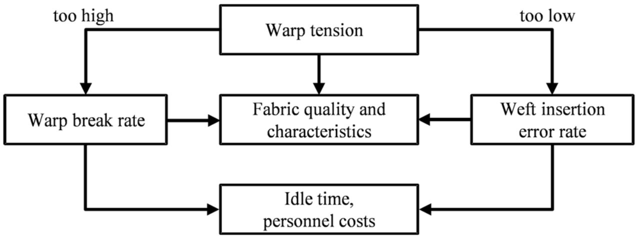


Fig. 2 Effects of the warp tension [18]

of the loom have to be adjusted accordingly to achieve a staple production process with low stress on the yarns.

One parameter group is the setting of the backrest system. There are several different backrest systems on the market including variations in the number, weight, and stiffness of the rolls. Picanol nv, Ieper, Belgium, also offers a regulated air suspended backrest system for highly sensitive yarns. The roll-based backrest system is movable to reduce the variation of the warp tension. This is achieved by a spring-damper suspension of the backrest system and a connection to the main shaft of the loom with a lever. The spring-damper suspension yields under the pressure of the warp yarns. Additionally, the lever connected to the main shaft forces a movement of the backrest roll(s) opposed to the reed movement. By this manner, the peak in the course of the warp tension, when the reed hits the fabric edge, is reduced. To adjust the active and passive movement of the backrest system, several mechanical factors like the lever length, type, length, and characteristics of the springs and dampers and the positions of the suspension mounting can be adjusted.

An active backrest system using servo drives including a simulation for the necessary movement has been developed at ITA but has not been established at the market because the additional price of the drives was too high compared to the achievements in process stability [3, 5]. Nevertheless, a working simulation for the necessary movement of the backrest system is available and can be used by weaving mills. Therefore, it is not necessary to develop a self-optimization for the setting parameters of the backrest system.

The second parameter group is the setting of the warp system consisting of the shed geometry and the warp let-off. The warp let-off provides the necessary length of the warp yarns to produce the fabric. Beside that, the warp let-off controls the warp tension using the servo drives in the warp and fabric beam. The most important setting parameter for the warp let-off is the basic warp tension, which can be set directly at the user panel. There are several setting parameters for the adjustment of the closed loop control, which can be adjusted to. Usually, this is not done by the weaver but just by the machine producer, as this requires special know-how of the behavior of the control loop.

The shed geometry can be adjusted by the position of all yarn guiding elements, most importantly, the movement of the shafts and the position of the warp stop motion. The vertical position of the warp stop motion directly affects the tension in the warp yarns, by the minimum and maximum elongation of the warp yarns (see Sect. 3.2). The vertical warp stop motion position therefore varied in the setting routine.

The movement of the shafts also affects the course of the tension in the warp yarns. The necessary amplitude of the shaft movement is predetermined by the weaving pattern, and machine geometry is therefore not varied in a setting routine, although it directly affects the shed geometry. Also that time, the shed rests in the open shed position and the shed closing angle of the main shaft is predetermined by the weaving pattern. Beyond that, the movement style of the shafts does not affect the minimum and maximum warp tension.

It has been studied that the machine speed also has a significant effect on the warp tension. As this influence is not linear, it is suggested that this is resulting from the vibration of the machine elements and the oscillation of the yarns [6, 18]. The machine speed therefore needs to be varied in a setting routine to improve the warp tension.

There are two other parameter groups which will not be discussed in this paper. One large group contains all parameters for the weft insertion. These parameters do not influence the tension in the warp yarns significantly [12]. Therefore, the weaver does not vary these parameters to affect the warp tension. The second remaining parameter group contains the surrounding conditions like the temperature and the humidity in the weaving mill. If these parameters are controlled, they are not adjusted for one product but for a whole weaving mill. Therefore, the surrounding conditions are not subject of an optimization routine in this work.

In order to support the weaver in the setting procedure, the machine builders have developed own systems to shorten the time needed to find suitable parameters. Picanol nv, Ieper, Belgium, offers the so-called EasyStyle-System for weaving machines. The EasyStyle-System is a database in which setup parameters of good running weaving machines are stored. The operator receives statistically averaged setting parameters from this database after inserting material and article data. For material and article data, which are not stored in the database, optimal setting parameters are calculated based on the existing data. The so-called Weave Assist System from Toyota Industries Cooperation, Kariya, Japan, and so-called Weave Navigation System from Firma Tsudakoma Corp., Kanazawa, Japan, work in a same manner [19, 20].

The support systems by the machine builders only rely on the statistical effects of good running machines. There is no real optimization done. In practice, the settings of the machines differ obviously from the settings suggested by the systems. This results from the fact that every weaving machine is different in praxis because of different additional equipment used and different production charges.

It is therefore necessary to establish a model-based self-optimization routine to optimize the setting concerning the warp tension based on measurements made exactly on the machine that the setting is applied on.

2.3 Model-based self-optimization of the weaving process

The model-based self-optimization of the weaving process was developed at Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany. The aim of the concept is the automatic optimization of the warp tension during weaving using three parameters [6]:

Basic warp tension
Machine speed
Weft density

The model-based self-optimization uses warp tension sensors, which are implemented in the weaving machine, and calculates optimal setting parameters within the boundaries given by the machine operator. The concept consists of the following four steps [6]:

Generation of the experimental design
Test procedure
Modeling
Determination of optimal settings

In the first step, an experimental design is calculated based on the boundaries (minimum and maximum) of the setting parameters given by the machine operator. A central composite-bisected design is generated for the test procedure. The experimental design ensures suitable data generation to calculate a regression model with a high coefficient of determination even for quadratic coherences and linear interaction of parameters [6].

In the second step of the test procedure, the weaving machine realizes every test point and the warp tension is being recorded for each point. After reaching one test point, the warp tension is measured for 20 pattern repeats in order to achieve a high statistic security. The course of the warp tension can be characterized by six characteristic values [6]:

W_{max}: highest warp tension during one pattern repeat, value as arithmetic median of measurement of 20 pattern repeats
$\mathrm{SD}_{\mathrm{max}}$: standard deviation of W_{max} of measurement of 20 pattern repeats
W_{min}: lowest warp tension during one pattern repeat, value as arithmetic median of measurement of 20 pattern repeats
$\mathrm{SD}_{\mathrm{min}}$: standard deviation of W_{min} of measurement of 20 pattern repeats
W_{med}: medium warp tension during one pattern repeat, value as arithmetic median of measurement of 20 pattern repeats
$\mathrm{SD}_{\mathrm{total}}$: standard deviation of W_{med} of measurement of 20 pattern repeats

The characteristic values of the warp tension are shown in Fig. 3 .

In the third step, full quadratic regression models are calculated with the obtained data from the test procedure. Every model consists of a quadratic equation, which one describes the dependency of the characteristic values and the varied setting parameter.

$$W_{\mathrm{max}} = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_1^2 + a_5x_2^2 + a_6x_3^2 \quad (1)$$

$$\mathrm{SD}_{\mathrm{max}} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1^2 + b_5x_2^2 + b_6x_3^2 \quad (2)$$

$$W_{\mathrm{min}} = c_0 + c_1x_1 + c_2x_2 + c_3x_3 + c_4x_1^2 + c_5x_2^2 + c_6x_3^2 \quad (3)$$

$$\mathrm{SD}_{\mathrm{min}} = d_0 + d_1x_1 + d_2x_2 + d_3x_3 + d_4x_1^2 + d_5x_2^2 + d_6x_3^2 \quad (4)$$

$$\mathrm{SD}_{\mathrm{total}} = e_0 + e_1x_1 + e_2x_2 + e_3x_3 + e_4x_1^2 + e_5x_2^2 + e_6x_3^2 \quad (5)$$

Coefficients α_i,$\alpha \in$ [a,b,c,d,e], $i \in$ [0,1,2,3,4,5,6] state the influence of the parameters x_i, $i \in$ [1, 3, 18] on the according characteristic value of the warp tension [6].

In the last step, optimized setting values are calculated based on three weighted quality criteria. In order to determine the optimal setting parameters, boundary condition of the optimization needs to be known. On the one hand, boundary condition arise from the fact that with a tension higher than $W_{\mathrm{max,allowed}}$, the warp would break. On the other hand, a warp tension below $W_{\mathrm{min,allowed}}$ is not allowed so that the weft insertion can be achieved [6].

A first quality criterion G_1 covers the maximum warp tension. Since stress on the warp has to be kept low, the maximal warp tension has to be minimized and to be below $W_{\mathrm{max,allowed}}$. Therefore, the first quality criterion is set to the following [6]:

$$G_1 : \Delta_{\mathrm{max,limit}} - \Delta_{\mathrm{max}} \rightarrow 0 \quad (6)$$

With

$$\Delta_{\mathrm{max,limit}} = W_{\mathrm{max,limit}} - \mathrm{MIN}\{(W_{\mathrm{max}} + \mathrm{SD}_{\mathrm{max}})\} \quad (7)$$

$$W_{\mathrm{max,limit}} = \mathrm{MIN}\{\mathrm{MAX}\{(W_{\mathrm{max}} + \mathrm{SD}_{\mathrm{max}})\}, W_{\mathrm{max,allowed}}\} \quad (8)$$

$$\Delta_{\mathrm{max}} = W_{\mathrm{max,limit}} - (W_{\mathrm{max}} + \mathrm{SD}_{\mathrm{max}}) \quad (9)$$

The second quality criterion G_2 covers the minimum warp tension. Since stress on the warp has to be kept low, the minimal warp tension has to be minimized as well but has to be kept above $W_{\mathrm{min,allowed}}$ in order to guarantee a stable weft insertion. Therefore, the second quality criterion is set to the following [6]:

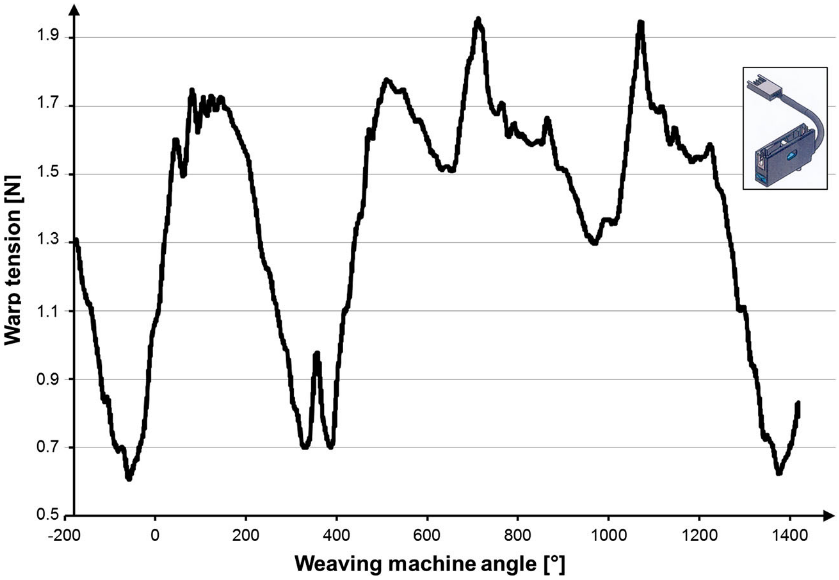


Fig. 3 Characteristic values of the warp tension [6]

$$G_2 : \Delta_{\min} \rightarrow 0 \tag{10}$$

With

$$\begin{aligned}\Delta_{\min} &= (W_{\min} - \mathrm{SD}_{\min}) - W_{\min,\mathrm{limit}}\\ W_{\min,\mathrm{limit}} &= \mathrm{MAX}\{W_{\min,\mathrm{allowed}}, \mathrm{MIN}\{(W_{\min} - \mathrm{SD}_{\min})\}\}\end{aligned} \tag{11}$$

For the third quality criterion, G_3, the standard deviation of warp tension according to W_{med} is analyzed. W_{med} indicates how smooth the warp yarns are stressed at a setting point and therefore is a value for the dynamic stress on the warp yarns. Since the dynamic stress on the warp thread should also be low in this case, the third quality criterion is set to the following [6]:

$$G_3 : \Delta_{\mathrm{SD,total}} \rightarrow 0 \tag{12}$$

With

$$\Delta_{\mathrm{SD,total}} = \mathrm{SD}_{\ \mathrm{total}} - \mathrm{MIN}\{\mathrm{SD}_{\ \mathrm{total}}\} \tag{13}$$

In order to weigh the quality criteria, they are normalized within the interval [0,1]. Normalization is achieved by taking into account the theoretical range of warp tension. As an example, normalization of G_1 is shown in (14).

$$\frac{\Delta_{\max,\mathrm{limit}} - \Delta_{\max}}{\Delta_{\max,\mathrm{limit}}} \in [0, 1] \tag{14}$$

A total quality criterion G_{total} is calculated according to (15). The weight factors R_1, R_2, and R_3 indicate how strong the quality criteria G_1, G_2, and G_3 are taking into account [6].

$$G_{\mathrm{total}} = \frac{R_1}{R_{\mathrm{total}}} \frac{\Delta_{\max,\mathrm{limit}} - \Delta_{\max}}{\Delta_{\max,\mathrm{limit}}} + \frac{R_2}{R_{\mathrm{total}}} \frac{\Delta_{\min}}{\Delta_{\min,\mathrm{limit}}} + \frac{R_3}{R_{\mathrm{total}}} \frac{\Delta_{\mathrm{SD,total}}}{\Delta_{\mathrm{SD,total,limit}}} \tag{15}$$

With

$$R_{\mathrm{total}} = R_1 + R_2 + R_3 \text{ and } G_{\mathrm{total}} \in [0, 1] \tag{16}$$

The optimal setting point can be found, whereas G_{total} is minimized. The optimized setting point in this case is characterized by a minimal maximum and minimum warp tension and a low total standard deviation of the warp tension in one pattern repeat. This is equal to a minimal stress on the warp yarns and, therefore, an optimal setting concerning the warp tension [6].

The model-based self-optimization was tested on an air-jet weaving machine and reduced the warp tension by 13% compared to a setting point without using the self-optimization (Fig. 4) [6].

3 Parameter analysis

3.1 Existing parameters

The existing model-based self-optimization of the weaving process uses the basic warp tension, the machine speed, and the weft density as setting parameters. Compared to the basic warp tension and the machine speed, the weft density has a smaller impact on the course of the warp tension.

The weft density has a big influence on the optical characteristics and the surface weight of the produced fabric. Hence, the weft density is often set by the customer so that it must not be changed. The use of the weft density as a parameter for the model-based self-optimization therefore is limited. Thus, the model-based self-optimization is getting further developed. Instead of the weft density, the vertical warp stop motion position is being implemented in the self-optimization process. The warp stop motion functions as a redirector for the warp yarns and, in this way, influences the warp tension using the shed geometry.

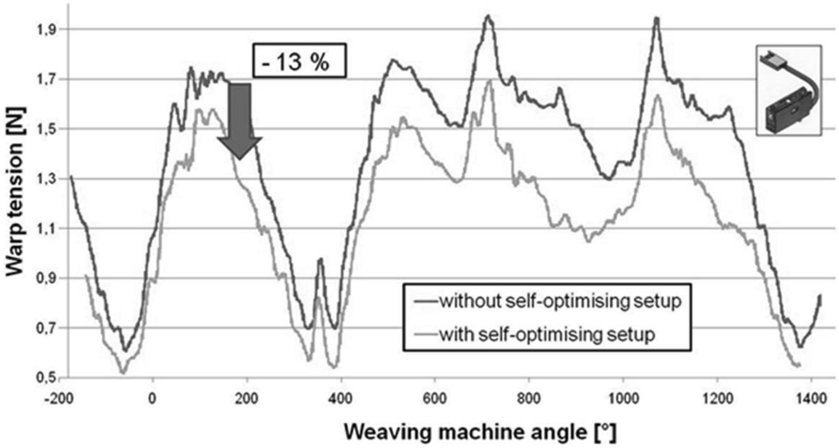


Fig. 4 Comparison of warp tension with and without self-optimization using the parameters basic warp tension, machine speed, and weft density [6]

3.2 Effect of the vertical warp stop motion position for the warp tension

The main function of the warp stop motion is to detect breaks of the warp yarns. If a break of any warp yarn is detected, the weaving machine stops immediately. The weaver can repair the warp yarn break before the open end of the broken yarn gets stuck in moving machine parts. Beside this security feature, the warp stop motion redirects the warp yarns. The position of the warp stop motion therefore influences the appearance of the produced web and the tension in the warp yarns.

Figure 5 shows a schematic weaving shed and that the elongation of the warp yarns in the different shed positions is different depending on the vertical warp stop motion position.

The amount of yarn delivered by the warp beam is equal for all warp yarns. Between the warp beam and the warp stop motion, the yarn length of all yarns is the same. Depending on the position of the warp stop motion, the warp yarns get differently elongated between the warp stop motion and the shafts. In the upper weaving shed geometry in Fig. 2, angle α is greater than angle β.

$$\alpha > \beta \tag{17}$$

The different lengths of the warp yarns between the warp stop motion and the shafts can be described using the back shed length (BSL) and angles α and β.

$$\frac{\mathrm{BSL}}{\cos\alpha} > \frac{\mathrm{BSL}}{\cos\beta} \tag{18}$$

Therefore, the elongation of the warp yarns in the different shed positions is different. Hooke's law states that the tension σ depends on the E modulus and the elongation ε [7].

$$\sigma = E^{*}\varepsilon \tag{19}$$

As the E modulus of the yarn is constant, the different elongation of the yarns, and therefore the vertical position of the warp stop motion, directly affects the tension in the yarn. As the sheds change their position frequently depending on the weaving pattern, the vertical warp stop motion position not only affects the minimum and maximum but also the standard deviation of the warp tension. Therefore, the vertical warp stop motion is integrated into the model-based self-optimization of the weaving process.

4 Integration of the automated warp stop motion positioning in the model-based self-optimization

4.1 Automation of the vertical warp stop motion positioning

To integrate the warp stop motion position into the model-based self-optimization of the weaving process, the warp stop motion position has to be adjustable during the weaving process. The automated variation of the vertical warp stop motion position was realized at Institut für Textiltechnik der RWTH Aachen University.

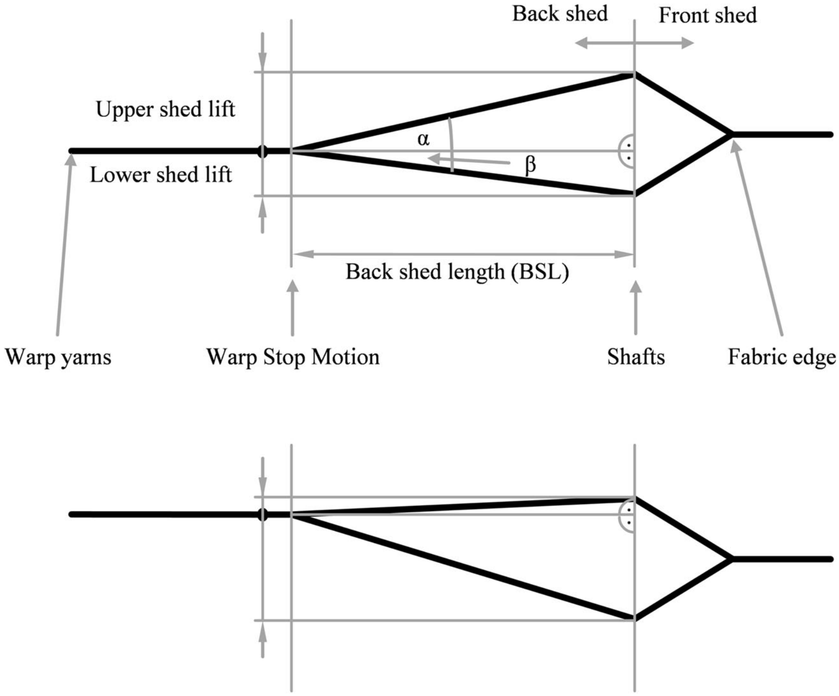
Stepper motors were chosen as suitable actuators. The motors are driven by special stepper controllers by WAGO Kontakttechnik GmbH & Co. KG, Minden, Germany. A program for a programmable logic controller (PLC) was designed to communicate with the stepper controllers.

Figure 6 shows the structure of the structure of the PLC program [21].

At the beginning, the stepper controllers are initialized. The initializing task confirms old errors, resets the stepper motors, and switches them on. After the initializing process, the configuration of the stepper motors is started automatically. The configuration task writes the configuration into the stepper controller and sets parameters like the acceleration and deceleration type and value, the driving speed, and the reference offset. After the configuration is successfully completed, the stepper controllers are able to accept driving commands [21].

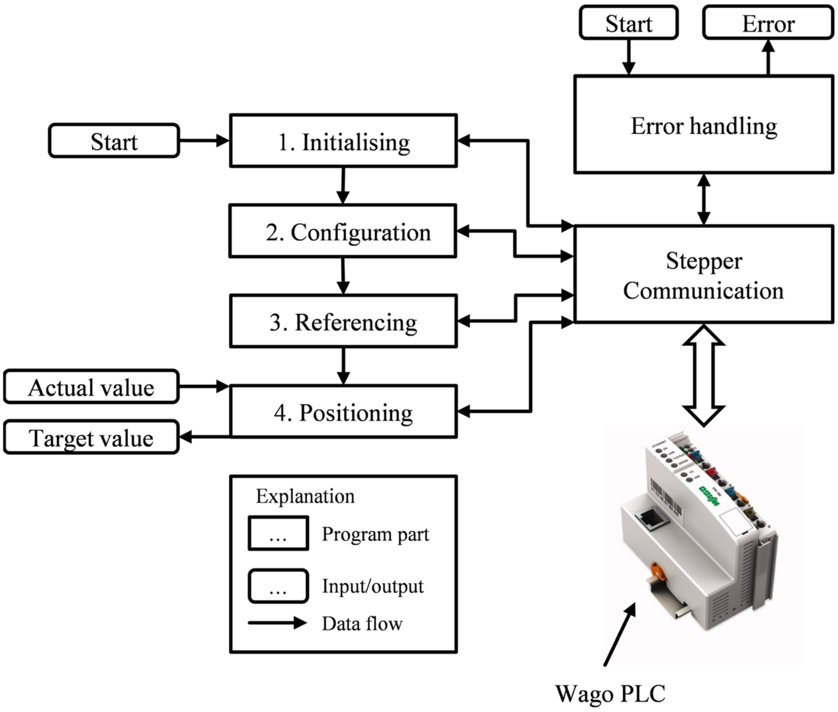
The motion system for the warp stop motion does not use a position sensor. The actual position of the warp stop motion is calculated by the number of steps that the motors made and

Fig. 5 Two schematic weaving shed geometries



the safe assumption that the movement happens without a significant loss of the steps. At the beginning of the positioning process, it is necessary to drive the warp stop motion to a known position to initially set the correct position. From then on, all other positions can be calculated by the number of steps that the motors have made. To do so, the reference mode of the stepper controllers is used. The upmost position of the driving range is limited by an end switch. During the reference mode, the stepper control drives the warp stop motion as long in the upward direction until the end switch is triggered. The position of the end switch is known and written into the stepper controllers during the configuration. After the warp stop motion has reached the end position, the controller sets the position of the end switch as the actual position. This reference

Fig. 6 Structure of the programmable logic controller program [21]



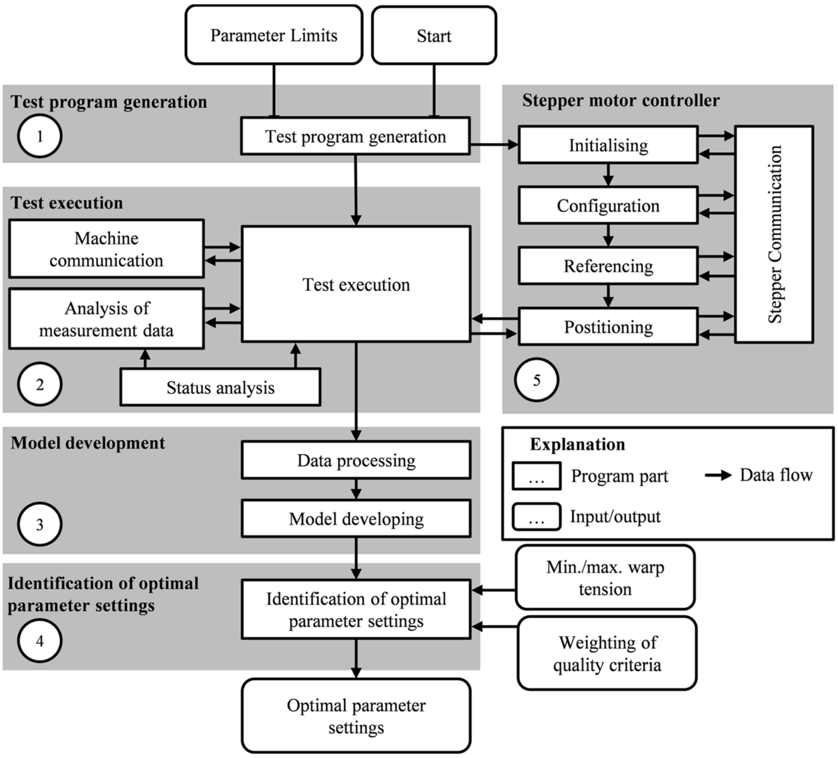


Fig. 7 Improved model-based self-optimization including the automated warp stop motion positioning

procedure also ensures an absolute even positioning of the warp stop motion. After the reference procedure is completed or skipped, the positioning task starts. As soon as the desired position is unequal to the actual position, the positioning task creates the process image to command the stepper controllers to drive the warp stop motion in the correct position [21].

4.2 Adjustment of the model-based self-optimization

The concept of the model-based self-optimization was implemented using components from the company iba AG, Fürth, Germany. In this work, the automated vertical warp stop motion positioning was implemented into the program of the PLC instead of the weft density.

Figure 7 shows the structure of the complete program.

As soon as the user has started the self-optimization of the weaving process, the starting signal gets transmitted to the program part "initializing." After that, the stepper motors successively get initialized, configured, and referenced. Finally, the program part "positioning" starts. The program part "test execution" is only started if the experimental design is generated and the program part positioning is ready. During the self-optimization process, the program part test execution sends the new target position to the part positioning as soon as a new test point is reached. The positioning part continuously sends the actual position of the motors to the test execution. The test execution compares the actual position with the target position and starts measuring the warp tension if all three parameters reached their target value. After the measurement series is complete, the optimal parameter values are calculated and put out.

5 Validation

5.1 Validation of the improved model-based self-optimization

The validation of the improved model-based self-optimization was conducted on an OmniPlus 800 air jet weaving machine from Picanol nv, Ieper, Belgium. The warp was 740 dtex polyester and the weft a 150 dtex polyester yarn. The produced web had a warp density of 20 threads/cm and a weft density of 33 threads/cm. The limit values of the setting parameters static warp tension (x_1), machine speed (x_2) and warp stop motion position (x_3) are shown in Table 1.

The limits of the warp tension, the machine speed, and the warp stop motion position were empirically determined prior to the test runs in a way that the operation of the loom with adverse settings is just stable enough for the test procedure. During the

Table 1 Limit values of model input parameters

Parameter	Basic warp tension (kN)	Machine speed (rpm)	Warp stop motion position (mm)
Min	3.25	600	−10
Max	5	1000	15

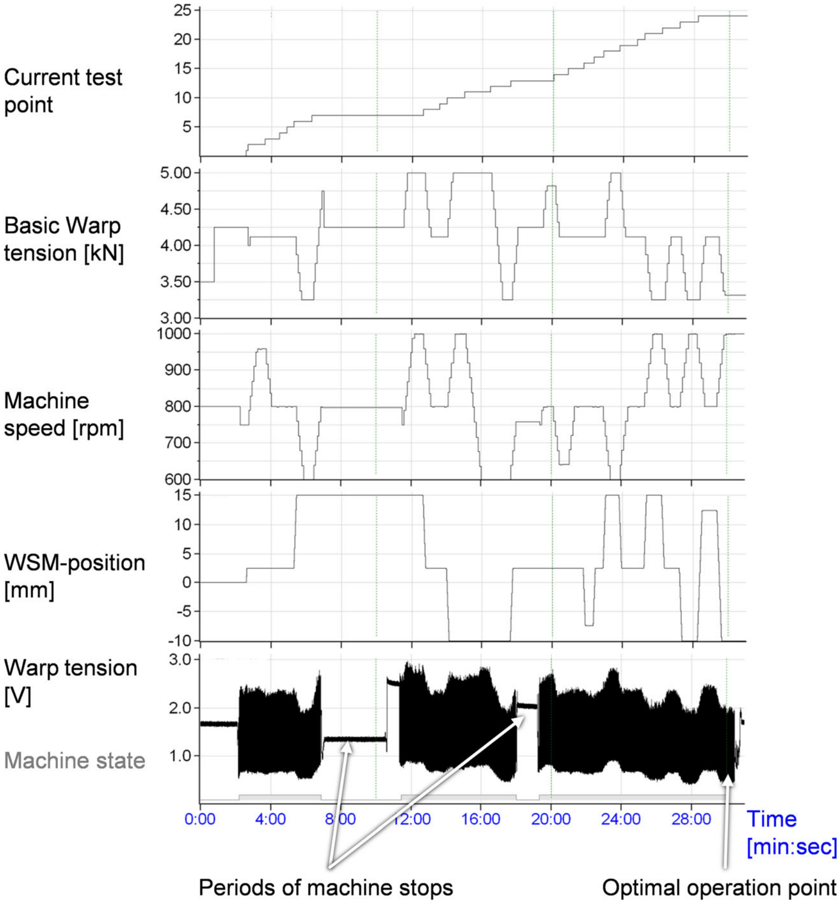


Fig. 8 Recorded parameters and warp tension during validation (*WSM* warp stop motion)

testing procedure, machine stops occurred because of weft errors while operating in the limit areas of the testing space.

The weft errors indicate that the limit values of the parameters were chosen correctly because the warp tension in the test points with machine stops was too low for a stable weft insertion. The whole test procedure took around 34 min including a 4.5-min machine stop because of a filling bobbin change. Figure 8 shows the recorded target values and the recorded warp tension.

In the bottom graph, the periods during the machine stops are clearly visible. The warp tension in the single operating points differs and spreads differently. The upper graph shows that all 24 test points were successfully completed. The three graphs in the middle show the adjustments of the three parameters to the target values of the actual setting point. At the end of the testing run, the optimal setting point is set and held statically during the production process. The parameters are not varied during the process, as a change would always affect the produced quality. The recorded

Table 2 Setting, productivity, and machine stops during the validation in the production process

		Optimized setting according to model	Worst setting according to model
Settings	Basic warp tension (kN)	3.25	5
	Machine speed (rpm)	1000	6000
	Warp stop motion position (mm)	−10	15
Productivity	Machine efficiency	98.4%	98.6%
	Weft insertions	59.986	39.000
	Produced article length in 1 h	18.18 m	11.82 m
Machine stops	Weft-related stops	1	1
	Warp-related stops	0	0
	Other	0	0

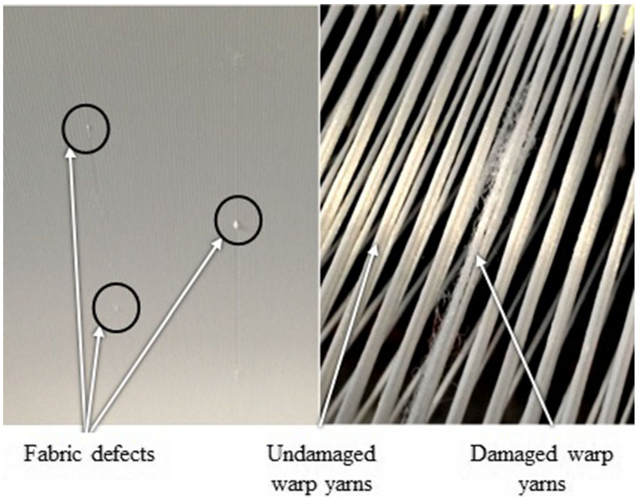


Fig. 9 Fabric defects and damaged warp yarn

values for $W_{\max}$, $W_{\min}$, $\mathrm{SD}_{\min}$, $\mathrm{SD}_{\max}$, and $\mathrm{SD}_{\mathrm{total}}$ of a test run can be found in Appendix Tables 8, 9, and 10.

5.2 Effects of the improved settings on the production process

The effects of the improved settings on the production process are examined. Therefore, the improved model-based self-optimization is performed on a loom. Afterward, the machine is operated with the best and worst settings determined by the routine for 1 h each. All machine stops are documented. The produced amount and quality are compared. Table 2 shows the settings used for the two production periods as well as the effects of the settings on the productivity and on machine stops.

During each test run, one weft-related stop occurred. In one case, a bobbin went empty; in the other, the weft yarn broke between bobbin and prewinder. The occurred machine stops are not logically related with the different settings of the machine. The machine efficiency indicates the amount of time during which the machine produced fabric. The small differences in the machine efficiency can be traced back to different times in the cause fixing. To obtain exact data on the impact of the improved self-optimization on the machine efficiency, a long-time test has to be performed or the test shall be repeated with more break-sensitive material than texturized polyester threads.

In the quality control of the produced fabric, no defects could be found in the fabric produced with the optimized settings. The fabric, produced with the worst settings, contained many defects as shown in Fig. 9.

Table 3 Optimal parameter values

Basic warp tension (kN)	Machine speed (rpm)	Warp stop motion position (mm)
3.25	1000	−10

The damage types shown in Fig. 9 occur when there is a high friction between warp yarns and guiding machine elements. The damaged yarn is included in the fabric and generates several knots. Using more sensitive material, the high friction would have led to several warp breaks.

Due to the higher machine speed in the optimized setting, the machine could produce more fabric at the same time. This equals a productivity increase of 54% between the two settings. It has to be stated that the model-based self-optimization only aims at optimizing the course of the warp tension and not the productivity of the machine. Therefore, the productivity of the machine is increased, and at the same time, a higher quality is produced.

6 Results

6.1 Effects of the adjusted model-based self-optimization

The best settings of the loom according to the model-based self-optimization were determined by the program. These settings match with all tests that were made and are shown in Tables 2 and 3.

Table 4 shows the characteristic values of the warp tension for settings before and after the self-optimization. The mean warp tension can be reduced by approximately 35%, and also, the standard deviation is reduced by 30%. This means a significant improvement compared to the unmodified model-based self-optimization containing that gained a reduction of 13%. Figure 10 visualizes the reduced and more even course of the warp tension with the settings determined by the improved model-based self-optimization.

6.2 Quality of the model

In order to describe the quality of the regression, the corrected coefficient of determination R^2 is calculated.

$$\overline{R}^2 = 1\text{-}\frac{\mathrm{SS}_{\mathrm{error}}}{\mathrm{SS}_{\mathrm{total}}} \tag{20}$$

$$\mathrm{SS}_{\mathrm{error}} = \frac{1}{n\text{-}p\text{-}1}\sum_{i=1}^{\mathrm{n}}\left(Y_i\text{-}Y_i\right)^2 \tag{21}$$

$$\mathrm{SS}_{\mathrm{total}} = \frac{1}{n\text{-}1}\sum_{i=1}^{n}\left(Y_i\text{-}\overline{Y}_i\right)^2 \tag{22}$$

Whereas $\mathrm{SS}_{\mathrm{error}}$ describes the ratio of the square error, $\mathrm{SS}_{\mathrm{total}}$ describes the absolute sum of the squares and p describes the amount of parameters. R^2 describes the part of the target value change that is described by the regression. The higher is the corrected coefficient of determination, the

Table 4 Characteristic values of the warp tension with and without self-optimization

Setting	Min. tension (N)	Max. tension (N)	Difference (N)	Average warp tension (N)	Standard deviation warp tension (N)
With self-optimization	0.437	2.109	1.671	1.233	0.325
Without self-optimization	0.840	2.935	2.095	1.903	0.464
Reduction	47.94%	28.15%	20.22%	35.19	29.91%

more precise is the regression model [22]. The corrected coefficient of determination is calculated with the help of the Software Minitab from Minitab Ltd. Coventry, UK. Table 5 shows the results for three test runs. For the model-based self-optimization, a sufficient quality is reached if the corrected coefficient of determination is higher than 0.9. Hence, the used models show a more than sufficient quality.

6.3 Expected economic effect

Beside the technical benefits described in Sect. 6.1, the economic effect of the test is considered. The development is expected to have an impact on the production costs. For the following considerations, an increase of the machine efficiency from 95 to 97% and a waste reduction from 2 to 1% are used. For the simplification, a single loom is considered. The lot size is defined to 1.000 m^2. A reduction of the setup time of 15 min is assumed. Furthermore, the conditions in Table 6 are used. The wage for machine tenders was set to 20.5 \$/h as an average value between multiple high-wage countries. For example, the hourly wage for machine tenders is 26.85 \$/h in Italy and 16.9 \$/h in the USA [23].

The Software "EcoWeave," developed at Institut für Textiltechnik was used to determine variable and fixed costs of the process. The costs for resources (e.g., energy, lubricants) were set constant to 200 \$ for ten lots, as the effect of the self-optimization on the resource costs is negligible. The calculated costs for the production of ten lots are stated in Table 7.

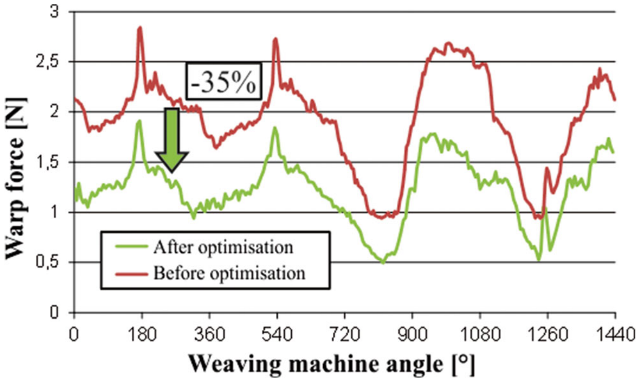


Fig. 10 Comparison of the warp tension with and without self-optimization

It is visible that in a high-wage country, the costs for producing ten lots with a lot size of 1000 m^2 are expected to drop approximately 22% or 14.41 \$/m^2. The relevance of this achievement is explained by the German weaving industry: 81.7523.969 m^2 web was produced only in Germany [24]. If estimating that only 10% of the webs are produced in lots and not continuously, the self-optimization would result in 1.178,052 million \$ cost savings in the German industry, if all looms, which produce small lots, were equipped with the proposed self-optimization. If looking at a mill, which is not

Table 5 Corrected coefficients of determination

Characteristic value	Corrected coefficient of determination R^2		
	Test run 1	Test run 2	Test run 3
W_{max} + SD_{max}	0.9935	0.9668	0.9921
W_{min} + SD_{min}	0.9956	0.9863	0.9812
SD_{total}	0.9846	0.9723	0.9924

Table 6 Conditions for the calculation of the economic impact

Parameter	Value
Amount of looms	100
Machine Speed	500 U/min
Production time per year	5840 h/a
Average number of article changes per machine and year	40
Average time for setup	3 h
Average warp length	500 m
Machine efficiency	95%
Waste production	2%
Material costs	11.37 \$/kg
Weft density	20 threads/cm
Kettdichte	15 threads/cm
Edge trim	10 mm
Weaving width	1900 mm
Yarn fineness	100 tex
Wage	20.5 \$/h
Personnel changeover	4
Personnel weaving	10
Lot size	1000 m^2
Warehousing costs	0.2 €-ct/m^2

Table 7 Calculated production costs for producing with and without self-optimization

Cost type	Value	
	Without self-optimization	With self-optimization
Setup costs (hardware)	81.95 $	81.95 $
Planning costs	335.84 $	192.23 $
Resources	200 $	200 $
Personnel for production	11.23 \$-ct/m^2	10.89 \$-ct/m^2
Material costs	4.60 \$/m^2	4.60 \$/m^2
Waste costs	11 \$-ct/m^2	6 \$-ct/m^2
Cost for 1 m^2	66.60 $	52.19 $

producing small lots, but continuous, an implementation of the system in the weaving machine might not be economical. This is due to the fact that the setting only needs to be optimized once. For those mills, the self-optimization could be offered as a service by third-party companies.

7 Conclusions and future works

In this paper, the authors described the model-based self-optimization of a weaving loom and proposed an improvement by changing a parameter. The objective was the objectification of the machine settings and the reduction of setup times. The weft density is an often predetermined setting parameter, which cannot be changed. Therefore, it is insufficient for the self-optimization of the weaving process. Instead, the vertical warp stop motion position was automatized and integrated into the program. Several test runs validated the adjusted self-optimization. The improved self-optimization reduces the warp tension by 35% and therefore outperforms the existing methods.

The self-optimization reduces the setup time of a weaving machine. In addition, the personnel costs are reduced because the automated routine does not require a constant supervision by the worker. Economically, this means an estimated cost reduction of 22% or 14.41 \$/m^2. The described system therefore contributes to the competitiveness of weaving mills in high-wage countries. In the future. more setting parameters might get integrated into the self-optimization. The algorithm model-based self-optimization can also be used to optimize other target values than the warp tension such as energy consumption or product quality.

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Appendix

Table 8 Characteristic values of the warp tension development in test run 1

Parameter settings			Characteristic values of the warp tension development (N)				
BWT (kN)	MSP (rpm)	WSP (mm)	$W_{\max}$	$\mathrm{SD}_{\max}$	$W_{\min}$	$\mathrm{SD}_{\min}$	$\mathrm{SD}_{\mathrm{total}}$
3.25	600	−10	1.93446	0.0298	0.49809	0.01014	0.348585
5	600	−10	2.65294	0.03585	0.83202	0.01532	0.46648
3.25	1000	−10	1.88275	0.0545	0.46788	0.01606	0.31426
5	1000	−10	2.57045	0.05975	0.74809	0.02026	0.440255
3.25	600	15	1.92171	0.02632	0.54333	0.015503	0.326705
5	600	15	2.73009	0.03177	0.91258	0.01471	0.444619
3.25	1000	15	1.99463	0.05918	0.53569	0.02027	0.332039
5	1000	15	2.71616	0.05584	0.88354	0.01786	0.454968
3.43025	800	2.5	2.00609	0.03636	0.56796	0.01529	0.36511
4.81975	800	2.5	2.53407	0.06967	0.81166	0.01604	0.450136
4.125	641.2	2.5	2.28815	0.03035	0.69232	0.013756	0.41237
4.125	958.8	2.5	2.32202	0.037325	0.67302	0.01833	0.39939
4.125	800	−7.425	2.28181	0.04056	0.64059	0.013327	0.39981
4.125	800	12.43	2.40071	0.04571	0.729233	0.026365	0.41403
4.125	800	2.5	2.312407	0.04408	0.69058	0.015195	0.41541

Table 9 Characteristic values of the warp tension development in test run 2

Parameter settings			Characteristic values of the warp tension development (N)				
BWT (kN)	MSP (rpm)	WSM (mm)	W_{max}	SD_{max}	W_{min}	SD_{min}	SD_{total}
3.25	600	−10	1.967030	0.062901	0.503983	0.017919	0.352236
5	600	−10	2.742740	0.042802	0.828201	0.014407	0.465965
3.25	1000	−10	1.898770	0.080601	0.453857	0.023274	0.312465
5	1000	−10	2.528240	0.044684	0.743408	0.028695	0.434516
3.25	600	15	1.915340	0.036992	0.532974	0.015602	0.325119
5	600	15	2.694080	0.035971	0.898636	0.015042	0.446227
3.25	1000	15	1.967970	0.069535	0.528046	0.025253	0.326638
5	1000	15	2.727460	0.030974	0.925064	0.015909	0.452090
3.43025	800	2.5	2.020720	0.027968	0.540024	0.016582	0.346654
4.81975	800	2.5	2.536710	0.042024	0.823761	0.017551	0.451736
4.125	641.2	2.5	2.218830	0.036149	0.673416	0.015663	0.391553
4.125	958.8	2.5	2.258410	0.039642	0.636215	0.017761	0.401604
4.125	800	−7.425	2.224880	0.031437	0.638489	0.013150	0.400608
4.125	800	12.43	2.349560	0.067949	0.690536	0.019190	0.406004
4.125	800	2.5	2.304710	0.039563	0.680836	0.014660	0.411868

Table 10 Characteristic values of the warp tension development in test run 3

Parameter settings			Characteristic values of the warp tension development (N)				
BWT (kN)	MSP (rpm)	WSM (mm)	W_{max}	SD_{max}	W_{min}	SD_{min}	SD_{total}
3.25	600	−10	1.916050	0.027085	0.493469	0.011639	0.361854
5	600	−10	2.807310	0.026165	0.850189	0.013670	0.478837
3.25	1000	−10	1.877470	0.038245	0.459412	0.015078	0.312615
5	1000	−10	2.574220	0.053196	0.745209	0.017486	0.436956
3.25	600	15	1.909940	0.024063	0.561798	0.011623	0.326617
5	600	15	2.739200	0.032368	0.917664	0.015996	0.451886
3.25	1000	15	1.978670	0.049704	0.539856	0.016824	0.326188
5	1000	15	2.740160	0.051090	0.891266	0.020448	0.457665
3.43025	800	2.5	1.962720	0.033659	0.551193	0.010521	0.356256
4.81975	800	2.5	2.645260	0.042644	0.863754	0.016028	0.463986
4.125	641.2	2.5	2.317380	0.026766	0.699432	0.010141	0.415745
4.125	958.8	2.5	2.290050	0.059846	0.668488	0.014624	0.386038
4.125	800	−7.425	2.320690	0.040305	0.674362	0.011683	0.416044
4.125	800	12.43	2.406220	0.038846	0.713028	0.012312	0.411163
4.125	800	2.5	2.303590	0.036372	0.684566	0.014300	0.414765

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