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Functional Model of a Warp-Knitted Machine for Producing 3D Technical Knitted Fabrics

DOI: 10.5604/01.3001.0014.2393

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Abstract

The article describes the construction and testing of a functional model of an innovative warp – knitting machine for technical spatial knitted fabrics with an original structure. Design assumptions regarding the geometrical, kinematic and driving characteristics of the machine are described. The functional model as well as its physical implementation as a research stand are presented. The production phases of the 3D knitted fabric are also demonstrated. The research results are described and their importance for the construction of a machine prototype of the production version are emphasised.

Key words: *warp-knitting machine, 3D knitted fabric, machine functional model.*

Introduction

The technology of 3D technical textile products developed, as well as the idea of a warp-knitting machine for their production are of an innovative character [1, 2]. Similar technologies for spacer and multilayer knitted fabrics are popular and widely used. However, they only refer to fabrics whose walls do not form a closed shape in the cross section, which results in their relatively low stability and limits their application in composite construction products. This publication presents selected results of application-oriented research work on a model of a machine for producing knitted fabrics in the form of solids, with the cross-section forming a closed shape, e.g. a square (***Figure 1.a***). It can be supposed that the stability of such structures is sufficient and that they can be applied as a reinforcement in composite beams, which can be used, for example, in landscape architecture or machine construction (***Figure 1.b***).

Literature survey on the technology of 3D knitted fabrics

There is a small number of literature sources concerning the technology of 3D spacer knitted fabrics, as it is a relatively novel research field. The concept of innovative technology and some general assumptions concerning the warp-knitting machine developed by the team of the Department of Knitting Technology and Textile Machinery of TUL are presented in the patent description [1] and several related publications, mainly [2]. These sources were used to develop the design assumptions of the functional model presented in ***Figure 3*** of this article. The concept described, as indicated by the authors, is fully realistic, at least in relation to the simplest geometric forms of knitted fabrics. Article [2] describes a physical model in which a fragment of a knitted fabric in the form of a solid with a square cross-section and side length of two inches was obtained manually, which confirms the thesis above. The literature references cited above constitute the starting point for the development of works, in particular the construction of a functional model of a warp-knitting machine of a new type.

The few literature sources available describe well-known and frequently applied technological and constructional solutions with respect to distance knitted fabrics, which are closest to the model considered. The latest collection of articles by representatives of various textile technologies, entitled “Advances in 3D Textiles” [3], provides a comprehensive overview of the current state of knowledge in the field of 3D textiles. It presents spacer knitted fabrics produced on both weft-knitting (flat and circular) and warp-knitting machines. The warp-knitting machines described in the articles are double-needle bed machines from Karl Mayer (***Figure 2***).

Technology for distance knitted fabrics intended for the production of mattresses is also presented in articles by J. Grębowski, e.g. [4], where the author compares individual machine models in terms of the thickness of knitted fabrics produced on them. The author also presents a *Highdistance* machine specially constructed for maximum thicknesses (40-65 mm). A theoretical study of the structure of such knitted fabrics in terms of strength optimisation is presented by B. Supeł in [5].

Comparative conclusions were drawn from the literature analysis. In the case of the designed warp-knitting machine, fabric thickness in both directions of the cross section is to equal 100 mm, and potentially even up to 200 mm. This means that the stroke of the guide bar guiding the warp thread of the inner layer of the knitted fabric in this machine is several times larger than in the case of machines for manufacturing distance fabrics. This implies a different type of motion of the

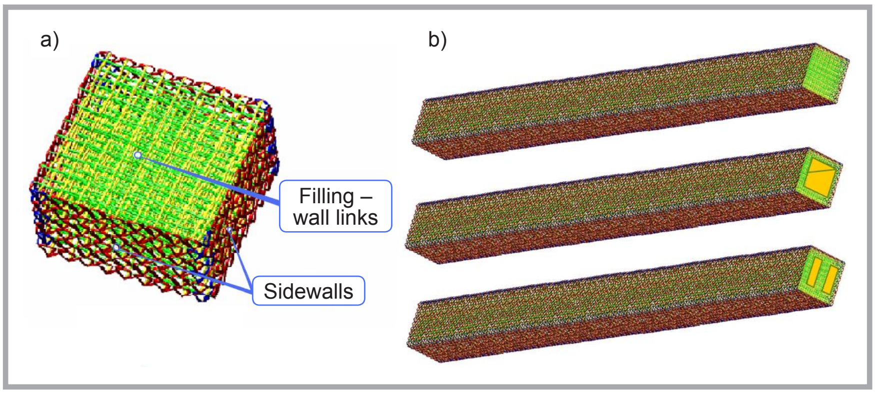

Figure 1. *Innovative 3D knitted fabric: a) – layers of knitted fabric with a square base, outer – sidewalls and inner – filling, b) – knitted fabric applied as a reinforcement of composite beams.*

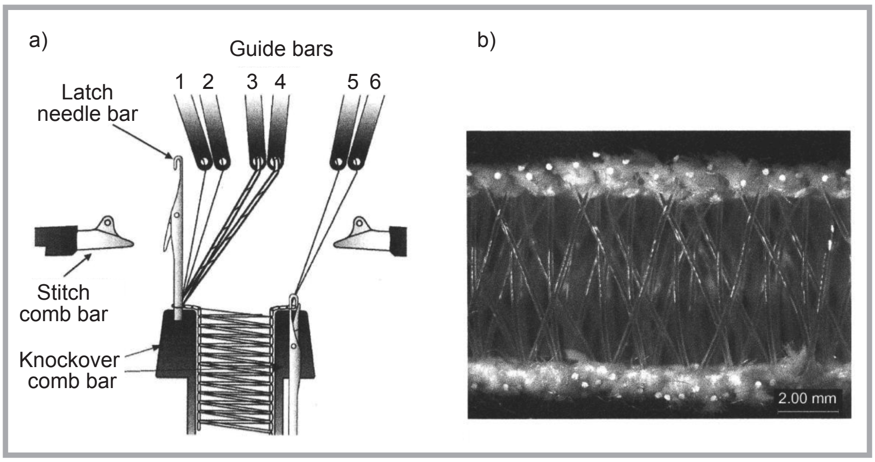

Figure 2. *Distance knitted fabric: a) Loop-forming elements of a double-needle bed warp knitting machine: needles, sinkers, knockover combs, guide bars (1, 2, 5, 6 – for threads of the outer layers, 3, 4 – for threads of the inner layer), b) Cross-section of knitted fabric, visible outer layers and inner layer (filling)[3].*

guide bars guiding the warp threads (rectilinear instead of swinging) and significant differences in the construction of the machine.

General assumptions and conceptual design of the functional model of the warp-knitting machine

General assumptions and the conceptual design of the machine model derive primarily from the concept of 3D knitting technology. The main difference between the construction of distance knitted fabrics and 3D knitted fabrics according to [1, 2] is the sidewall structure of the cross-section. In the case of distance knitted fabrics, it does not constitute a closed circumference, and the two opposite walls of the outer layers are connected by thread loops (connectors) of the filling layer (***Figure 1.b***). In the case of the innovative knitted fabric, the sidewalls form a closed circumference, and the filling is built of successive layers of connectors perpendicular to each other, and not one-way as in distance fabrics. It can be said that such a knitted structure consists of two crossed distance knitted fabrics, or that it constitutes a common part, where the two fabrics perpendicular to each other penetrate. Regarding the manufacturing process, distance knitted fabrics are produced on two needle combs, whereas the innovative fabric, as can be concluded from the above, has to be formed on a four-comb warp-knitting machine. Each of the combs corresponds to one sidewall or outer layer to which it is parallel. General assumptions and the associated conceptual design of the four-comb warp-knitting machine constitute the first stage in the process of constructing the functional model (***Figure 3***). Activities related to the construction and testing of the functional model are the subject of an application-oriented scientific work [6].

The conceptual design was developed on the basis of preliminary assumptions and basic technical features which have to be considered for each newly designed machine [14]. These technical features are first formulated in general terms, then further elaborated (i.e. simulation models, including the initial one, geometric and structural one [7, 8], and then the

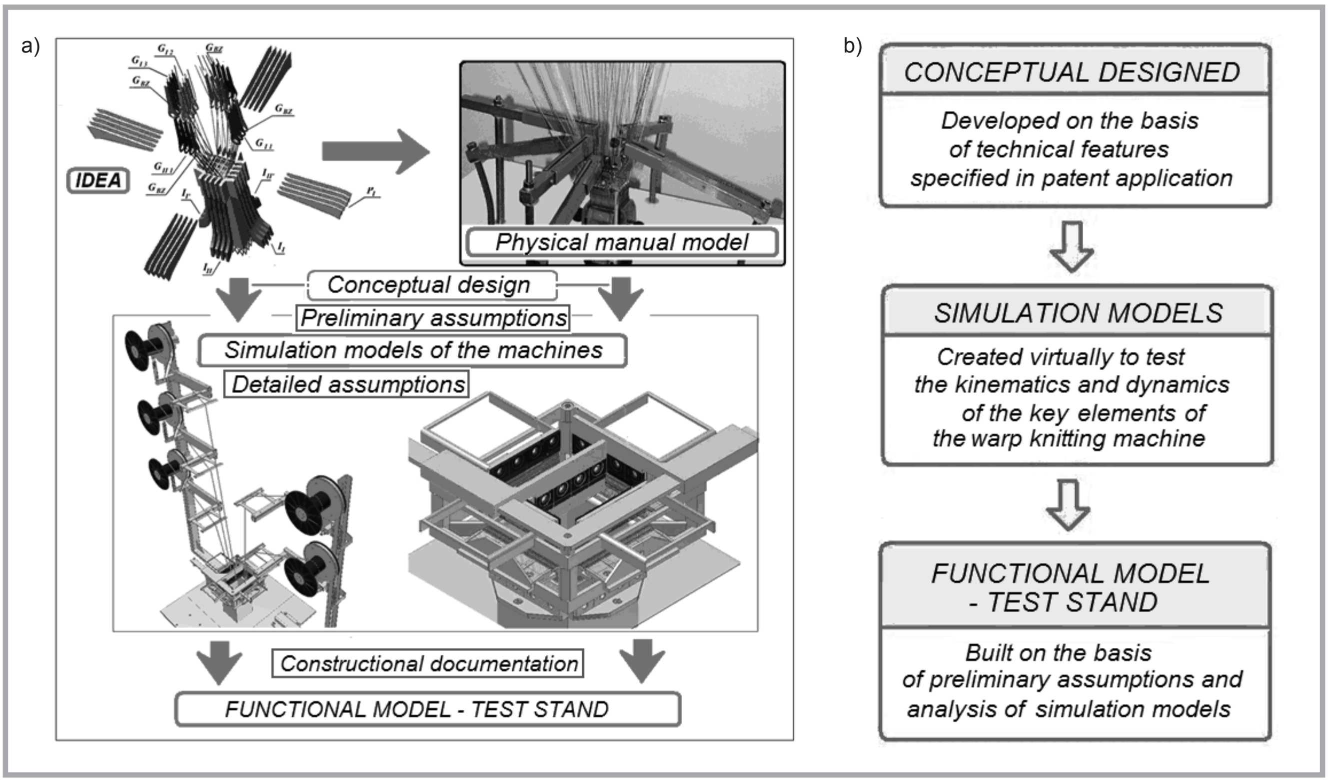

Figure 3. *Diagram of research activities: a) from the general concept of the warp knitting machine to detailed construction documentation of its functional model, b) algorithm of simulation modeling preceding construction of the physical model.*

dynamic one [9, 10]), until the construction of the functional model is completed. The functionality of the model results from the implementation of the main technological functions of the machine, which in the case of a warp knitting machine is connected with the three main zones: the feeding zone (warp feeding), loop forming zone (formation of the 3D structure) and take-up zone. The basic technical features of the model are its geometry, kinematics and forces.

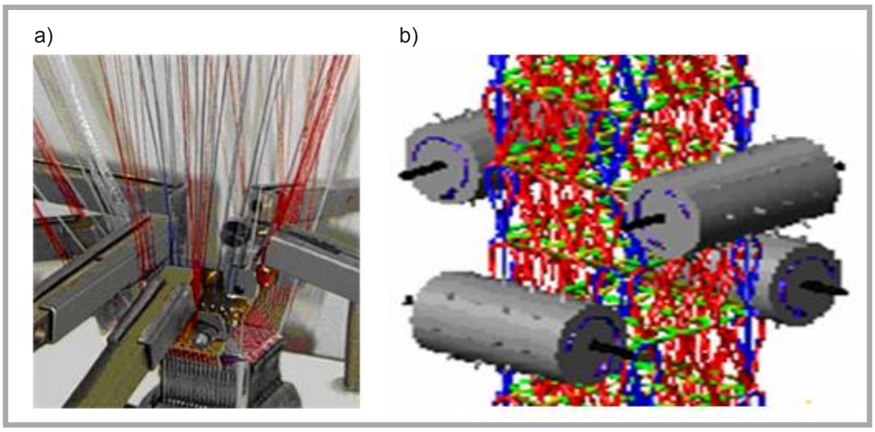

Figure 4. *Feeding and take-up zones of the warp knitting machine at the stage of conceptual design: a) high density of threads supplied (according to manual model [2]), b) take-up (spiked rollers [1]).*

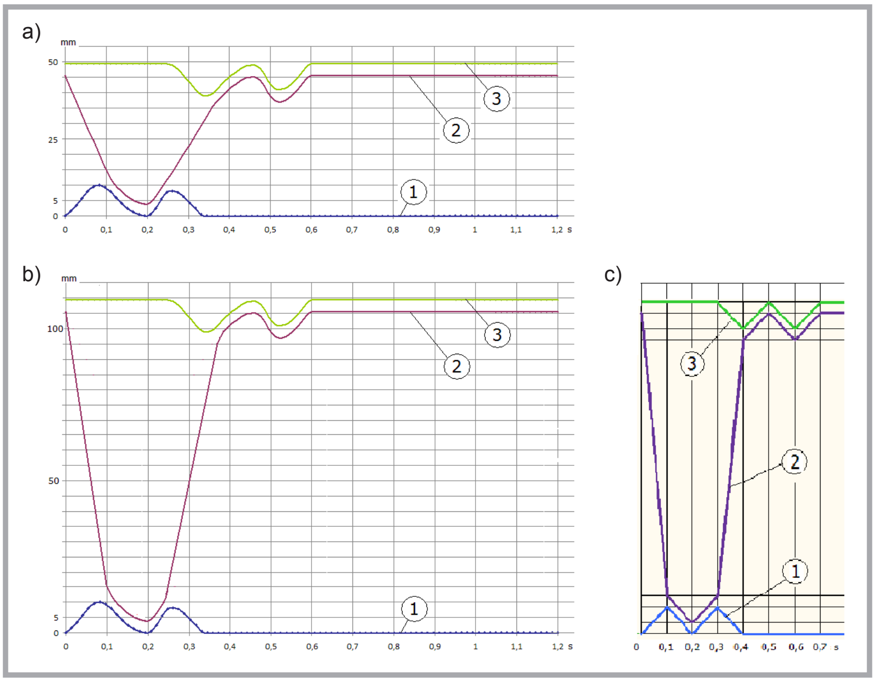

Figure 5. *Guide bars paths: 1.3 – sidewall warp, 2 – filling warp, a) for 2” spacing of needle combs (distance fabric), b) for 4” spacing of needle combs (functional model assumptions) c) graph (b) modified for animation of structural-geometric model.*

The geometry is understood as a system of loop-forming elements, including their dimensions and technological features (shape), as well as the spatial distribution of the elements (arrangement).

Geometric assumptions of the model:

- needle combs – 4 identical ones (thus the innovative warp knitting machine is defined as a four-comb machine) with a length of 101.6 mm (4”) arranged in a square configuration. The needle gauge adopted was 6, corresponding to the thickness of the processed technical warps. Latch needles were used, which do not require a press bar.
- knock-over combs- for the innovative 3D knitted fabric, they form a closed square channel.
- guide bars – the model initially assumed that the walls were produced of a single tricot stitch, which, however, is not very stable and requires additional joining of the walls at the edges. In order to avoid that, it was eventually decided that the walls should be formed of a stable double tricot, which eliminated the need for edge joining. In this case, however, two guide bars are necessary for each wall of the outer layer. Adding one for both directions of forming the inner layer, we have a total of 10 guide bars.
- structural restrictions – the feeding zone (above the loop-forming area), due to the high density of threads supplied (***Figure 4.a***), cannot constitute the location for the moving parts and drives,
- feeding and take-up systems.

The functional model assumes negative feeding of the warp threads of the outer layers from small beams, and positive feeding from large beams (supported by individual drive) of the warp threads of the inner layer of the knitted fabric. In the case of the inner layer, the warp demand is about 40 times greater than for the outer layer, hence the difference in the size of the beams. These size differences were sufficient for testing, but for continuous operation another way of feeding the filling warp was considered, e.g. directly from the creel. In the model constructed the knitted fabric is taken-up by spiked rollers (***Figure 4.b***), which, acting multi-pointedly on the knitted fabric, due to the dispersion of the force required (which is also necessary to ensure the necessary technological tension of the threads), shall not cause fabric deformation.

Kinematic assumptions and model drive: The starting point is the movement of the loop forming elements in the warp-knitting machine for distance knitted fabrics. During the tests described in [2], kinematic courses of needle bars were recorded for a distance of 50 mm between the fabric walls (***Figure 5.a***). This quantity also represents the approximate spacing of the opposite needle combs, and at the same time the approximate thickness of the spacer fabric. Typical values given by the producers of distance fabrics are several mm, with the exception of the *high distance* machine from Karl Mayer (65 mm).

In the case of the conceptual design of the functional model, the stroke of the guide bar leading the warp threads of the inner layer is at least twice as large as on tra-

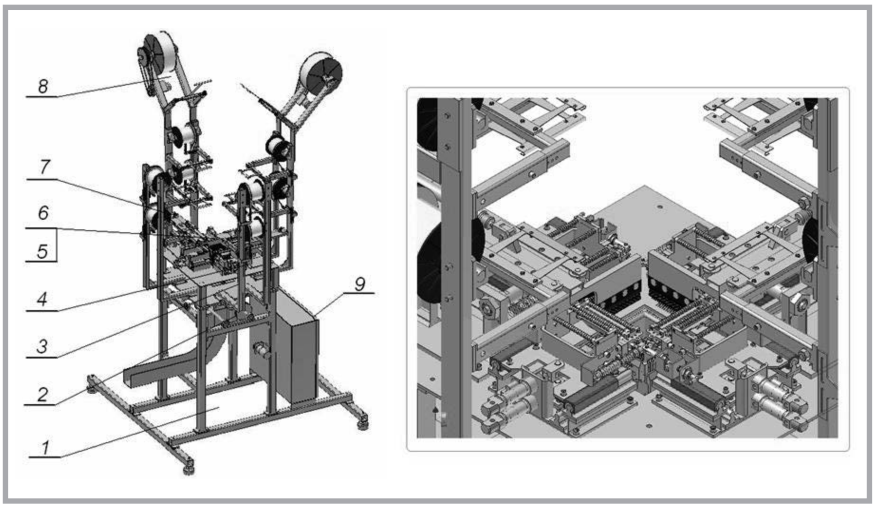

__Figure 6.__ Design of complete functional model of warp knitting machine (left). Individual machine assemblies have been distinguished, including 3 to 6 – elements of loop forming zone. On the right – enlarged loop forming zone; two perpendicular working planes, two opposite needle combs within each of them.

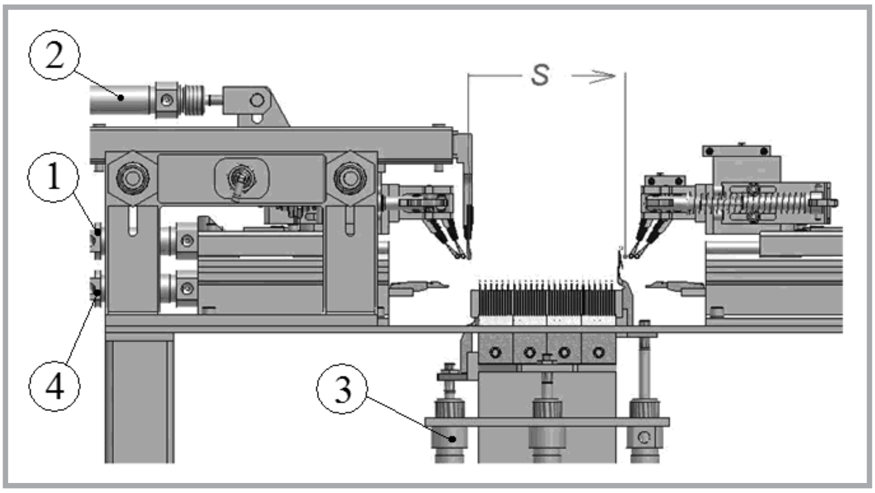

__Figure 7.__ Loop-forming zone (view for one of two working planes) with pneumatic linear drives: side wall guide bars (1), filling layer guide bars (2), needles (3) and sinkers (4), S – stroke of filling layer guide bars.

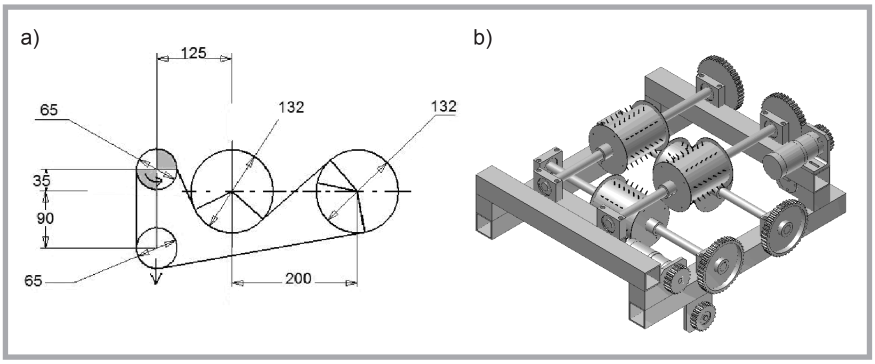

__Figure 8.__ Drive diagram (a) and 3D model of spiked take up rollers (b).

ditional distance warp knitting machines. However, the same cycle duration was assumed for the distance of 4” between two of the four walls of the 3D knitted fabric (***Figure 5.b***) and for the distance of 2” between the walls of the distance fabric (***Figure 5.a***). At the conceptual design stage , adopting such an assumption seems reasonable, because the double increase in the stroke length means smaller masses of the moving elements (shorter guide bars), which improves their dynamic properties. The correctness of this assumption in relation to the 100 mm stroke is confirmed by the analyses of virtual dynamic models of the feeding system conducted (including the beam, back rest roller, and slide with a guide bar) – described in [9, 10].

The cycle duration for one pair of needle combs is then 0.6 s, and the full cycle (for two pairs) lasts 1.2 s. The average speed of the filling layer guide bar (2) in its main stroke increases twice, to approx. 1 m/s. Accelerations at the initial and final moment of this movement also increase. Time limits of the filling layer guide bar stroke are at a level of 0.1 s. The strokes of the other loop-forming elements, such as warp guide bars of the fabric sidewalls, needle combs, and sinkers, were adopted at the level of 20-25 mm, and the laps (guide bar strokes along the needle comb) by one pitch (for needle gauge 6, 4.2 mm). The assumptions above gave rise to kinematic simulations of the structural-geometric model [7, 8] – ***Figure 5.c***.

The reason for such a nature of guide bar movement in the innovative warp knitting machine, which is different from that in classic and distance machines, is, apart from the large spacing of sidewalls in the 3D fabric, the lack of possibility of placing classic drive mechanisms in the feeding zone. This results from the point-like rather than linear (as in classic warp knitting machine) character of the working space, which results in a high concentration of warp threads supplied (***Figure 5.a***). Increasing the distance between the combs beyond the range used in classic warp knitting machines makes it necessary to reject the swinging movement of the guide bars in favor of a rectilinear motion.

The conceptual design assumes that the linear drives for all bars are individual and synchronised, mechanical as well as pneumatic, with electronic control. This solution (different to the branched drive from a single source, used in classic warp knitting machines) provides the regulation possibilities necessary for model testing. Due to the large, and at the same time occurring in very short intervals, strokes of the filling layer guide bars, pneumatic drive is the most suitable. For structural homogeneity of the model, the same type of drive was also adopted for the other loop forming elements.

Functional model of the warp-knitting machine

The functional model physically implemented enabled experimental verification of preliminary assumptions and previous simulation models (structural-geometric and dynamic) and preceded the construction of the machine prototype.

Model design

The results of testing virtual models, including the dynamic ones [9-11], which preceded the construction of the functional model, significantly contributed to the preparation of construction documentation (covering more than a hundred detailed drawings) for the technological size of 4”– ***Figure 6***.

The simulations made it more likely that the solutions developed would be suitable, and significant corrections could be avoided after the elements had been made ‘in metal’.

The construction of individual machine zones was developed, including ones for loop formation (***Figure 7***) and fabric take-up (***Figure 8***).

An original solution of the arrangement of guide bars forming the double tricot stitch of the fabric sidewalls was also proposed (***Figure 9***).

Functional model of the warp-knitting machine – test stand

The functional model was designed (***Figure 10.a***) and implemented (***Figures 10.b*** and ***11***) in a simplified version, with one working plane, without any drives in the fabric take-up zone, and with a negative warp feeding system.

When the functional model is physically constructed, and not only virtually, as sometimes happens, [12, 13] attempts are often made to reduce costs by using rapid prototyping methods and cheaper materials which can replace the original ones (without losing the characteristics required, such as strength or dimensional accuracy). In the construction of the warp knitting machine model, it was attempted to introduce 3D printing of selected details (***Figures 12*** and ***13***), in the case of which rigidity or strength characteristics of the substitute material do not constitute a significant limitation during tests.

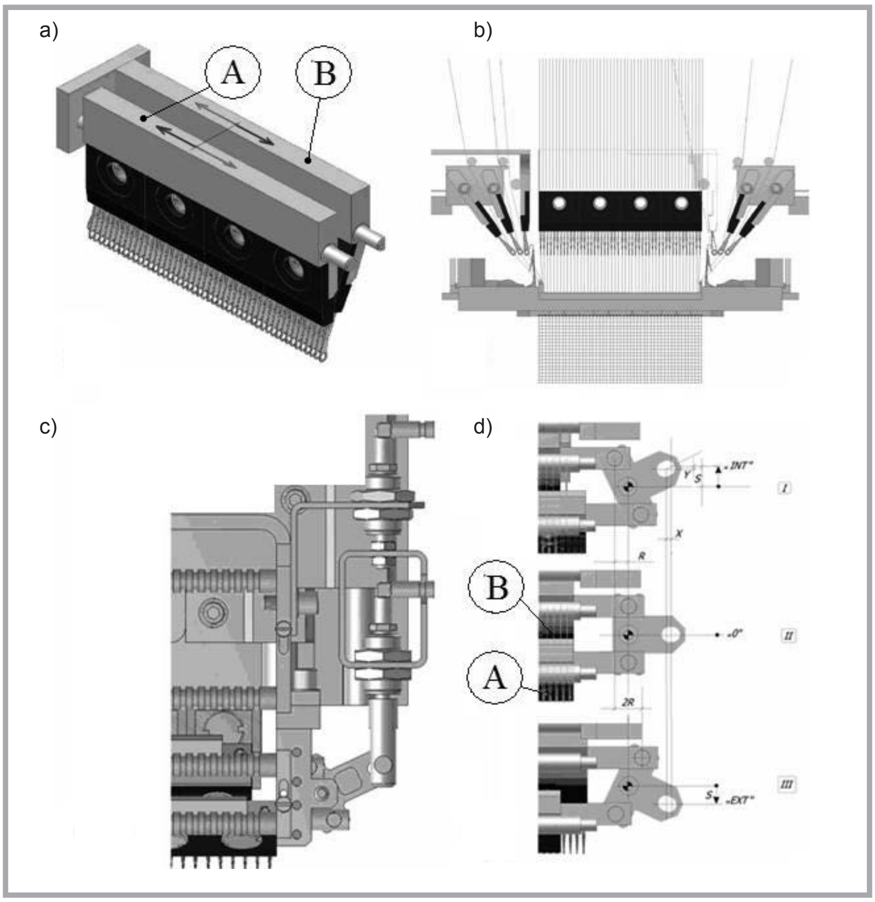

Figure 9. *Warp guide bars of the fabric sidewalls, kinematically coupled: a) diagram of the reverse motion of the bars: front (A) and rear (B), b) bars arranged on the fabric face and back; on the back the bar of the inner layer (vertical) is also visible, c) drive mechanism of the reverse motion of the bars, enabling their precise positioning in three technological positions, d) bar positions: middle, the so-called zero, meaning that bars A and B are exactly one after the other.*

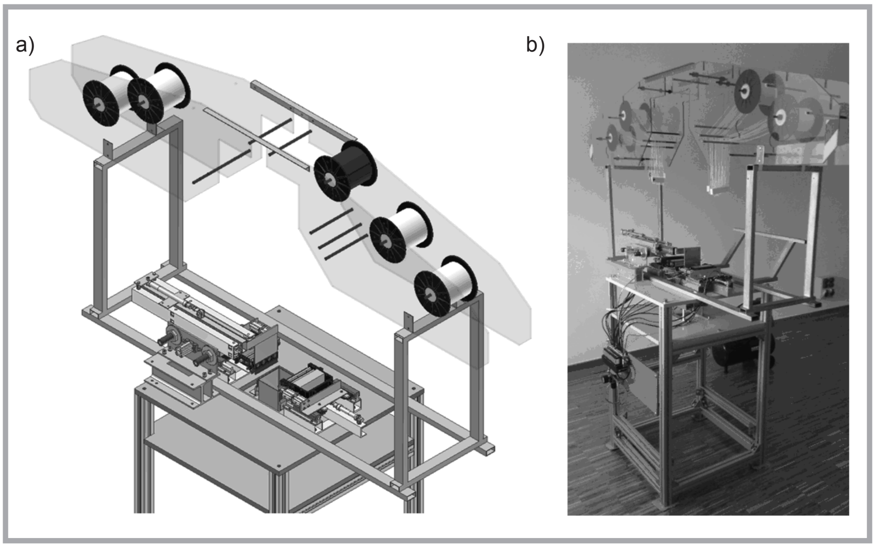

Figure 10. *Functional model: a) 3D design, b) physical implementation (test stand).*

The implementation of the assumptions concerning model drives is shown in ***Figure 14***. The system of pneumatic linear drives is based on the diagram (***Figure 14.a***), whereas synchronisation, necessary for the efficient manufacturing of the knitted fabric, is ensured by the cyclogram developed (***Figure 14.b***), according to which the control program operates. The kinematics of the actuators shown on the cyclogram also correspond to the paths of the loop forming elements.

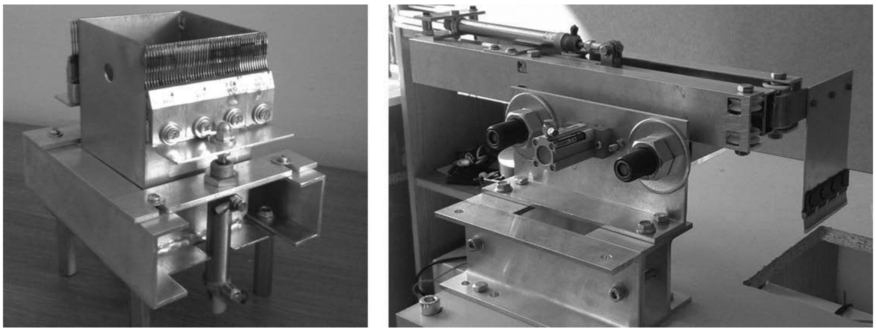

Figure 11. Set of needle combs with drive and fabric forming tube (left) and set of guide bars of the filling layer of 3D fabric – implemented 'in metal'.

mesh scale 1.000
mesh rotation z 0.00
mesh rotation x 0.00
mesh rotation y 0.00
mesh position z 0.000

Figure 12. Elements of warp guide bars of fabric sidewall – programming the 3D printing process (Voxelizer software).

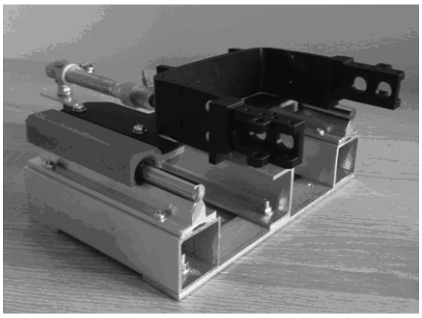

Figure 13. Set of warp guide bars of fabric sidewall during assembly (thrust bearing mountings marked in red and bar holder marked in black – 3D printing).

Model tests

The tests carried out on the functional model made it possible to draw some important conclusions as to the technological efficiency of the machine, which was confirmed by the experiments. The following tests were performed:

1 – Organoleptic testing of the rigidity of the structure elements: both component parts and their connections (actual clearances), including rigidity tests for the elements made of alternative materials, such as light alloys (aluminum) or printed from ABS. Before the final assembly of the functional model, while constructing some of its elements, important structural features were revealed which confirmed both the correctness of the solutions adopted and some shortcomings that should be eliminated. That is why model optimisation was necessary before constructing a prototype of the industrial version of the machine. In the case of the sidewall guide bars, the key role for movement precision and accuracy is played by the rigidity of the bar system in the direction of its main motion, as well as in the perpendicular direction (lap direction). The relatively long linear bearings are to ensure the rigidity required in the direction of the main motion. Bearing mountings are made of ABS plastic on a 3D printer.

In the case of the guide bars of the filling layer, organoleptic tests and manual trials without side loading confirmed sufficiently smooth and stable movement of the slider along the bar. A slight deflection of the bar was observed after applying a small load simulating lateral forces from warp tensions.

In the whole structure, motion resistance of the elements guiding individual needle combs and guide bars was tested manually after the functional model had been assembled. The accuracy of bar arrangement in extreme positions, corresponding to full strokes of the driving actuators, was also tested. It was found that the functional model meets the threshold requirements in terms of structural strength, rigidity and kinematic accuracy,

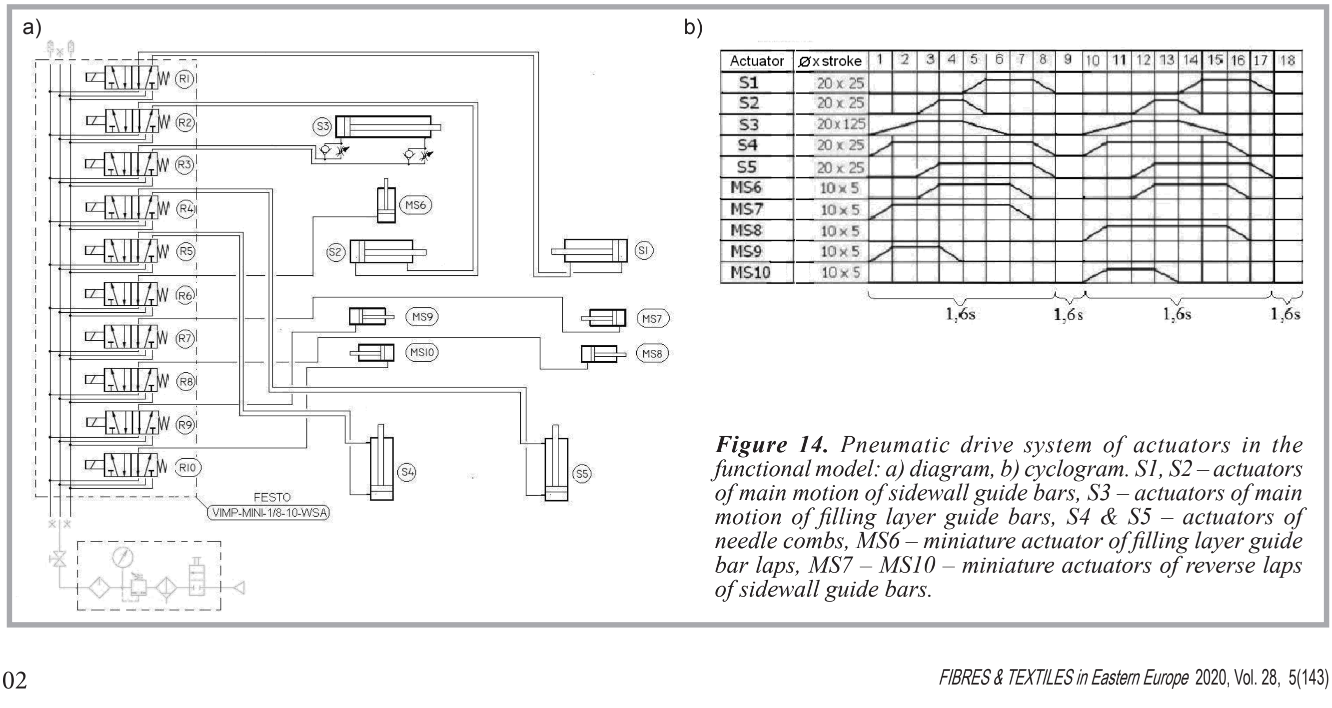

Figure 14. Pneumatic drive system of actuators in the functional model: a) diagram, b) cyclogram. S1, S2 – actuators of main motion of sidewall guide bars, S3 – actuators of main motion of filling layer guide bars, S4 & S5 – actuators of needle combs, MS6 – miniature actuator of filling layer guide bar laps, MS7 – MS10 – miniature actuators of reverse laps of sidewall guide bars.

and can be subjected to further technological tests.

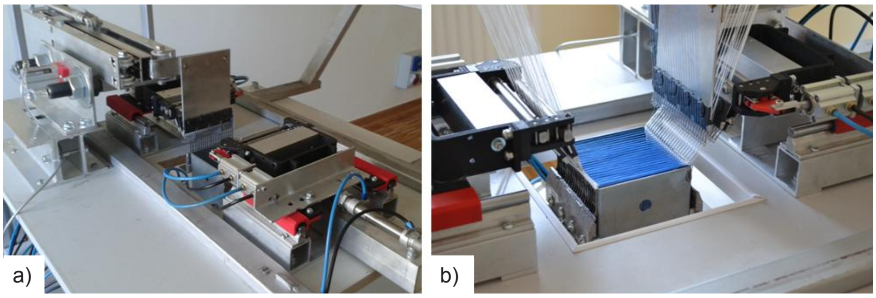

__Figure 15.__ Functional model of warp knitting machine during tests: a) loop forming zone without warp, b) loop forming zone with warp.

2 – Testing the movement of loop forming elements and their drives without a technological load (***Figure 15.a***) at minimum speeds, and then when the speeds gradually increased, the accuracy and precision of the movement of the needle combs and guide bars in relation to each other were observed.

Kinematic and dynamic tests were carried out without loading the needle combs and guide bars with warp. All pneumatic drives were switched on successively, starting from the lower levels of air speed and pressure. The operation of the actuators was considered appropriate. With a gradual increase in speed up to fast strokes at a pressure of 6 bar, it was observed that the nature of actuator operation changed to more percussive at reversal points. The conclusion is that the actuators need to be slowed by increasing damping in extreme positions. It is difficult to predict how the warp is going to affect actuator operation.

3 – Testing the behaviour of the loop forming system with warp introduced (***Figure 15.b***) and the conditions of the manufacturing process of the 3D knitted fabric- test of the technological efficiency of the machine.

In order to determine the technological efficiency of the machine, preliminary tests of the functional model with warp were carried out at relatively low speeds of the loop-forming elements. It was assumed that the speed would be gradually increased if there were no disturbances during the process. It was also assumed, for fear of possible collision of the elements whose kinematic paths intersect, that the tests should consist of individual switching on of pneumatic drives, so as to ensure the correct movement sequence and control of the position of the needle combs and guide bars at any time. Switching on all the drives in full synchronisation according to the cyclogram (***Figure 14***) was planned at a later stage, after making sure that each element of the complex system worked properly, or that after necessary corrections it was going to function without risk of collision, which would have been destructive.

Process of creating 3D knitted fabric in the functional model studied.

Before the process of forming the 3D knitted fabric started, appropriate fragments of the side walls were prepared in order to create a stable base (even loops and even distribution of thread loads) for fixing the first loops of the filling layer.

Characteristic locations of the loop-forming elements in the subsequent phases of producing a spacer fabric – in this case a distance fabric (two needle combs) but with twice the maximum spacing of the sidewalls – are shown in ***Figure 17***.

In the description of the motion of the loop-forming elements in the subsequent stages of the knitting process, the following terms have been adopted: *main motion* – stroke in the direction perpendicular to the needle comb, equivalent to the swinging motion in classic warp knitting machines, *lap* – stroke parallel to the needle comb – as in classic warp-knitting machines, where it is also called longitudinal movement (along the needles), *zero position* – where the front and rear guide bars performing the reverse motion are situated exactly one after the other, *'in front of' and 'behind'* positions – in front of and behind the needles (in front of the needles on the side of the latches).

Description of phases 1 to 4, identical for the right (P) and left (L) wall – ***Figure 17***:

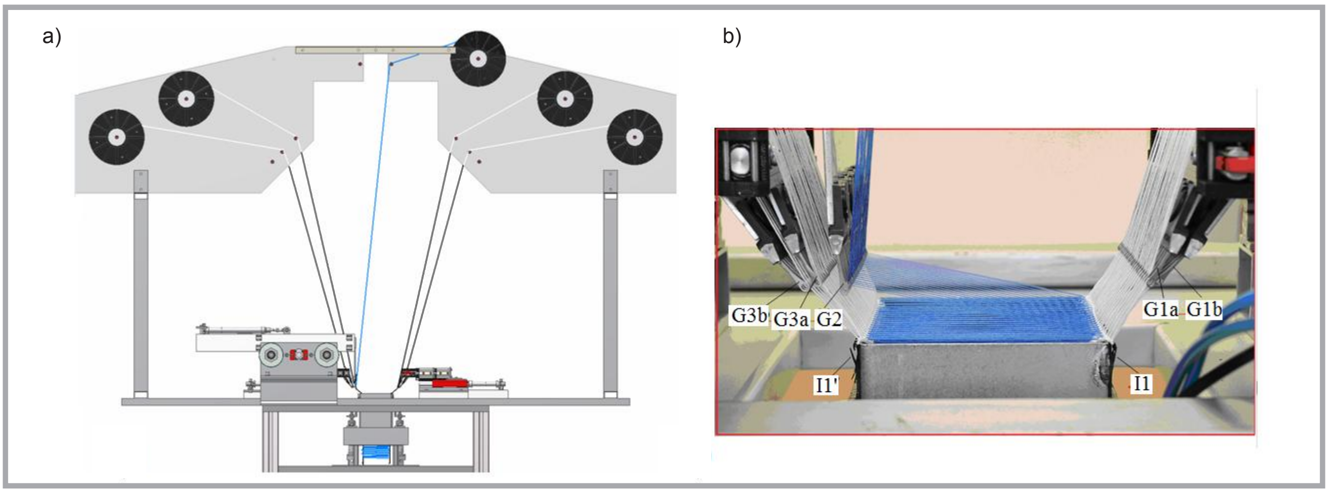

__Figure 16.__ Forming a 3D knitted fabric: a) diagram, b) loop forming zone. Designation of loop-forming elements: __Right wall__ of 3D fabric (according to the position in the drawing): G1a – front guide bar ,G1b – rear guide bar, I1 – needle comb; __Left wall__ of 3D fabric: G3a – front guide bar , G3b – rear guide bar , I1'– needle comb; __Inner layer__ of 3D fabric (blue): G2 – guide bar of filling layer.

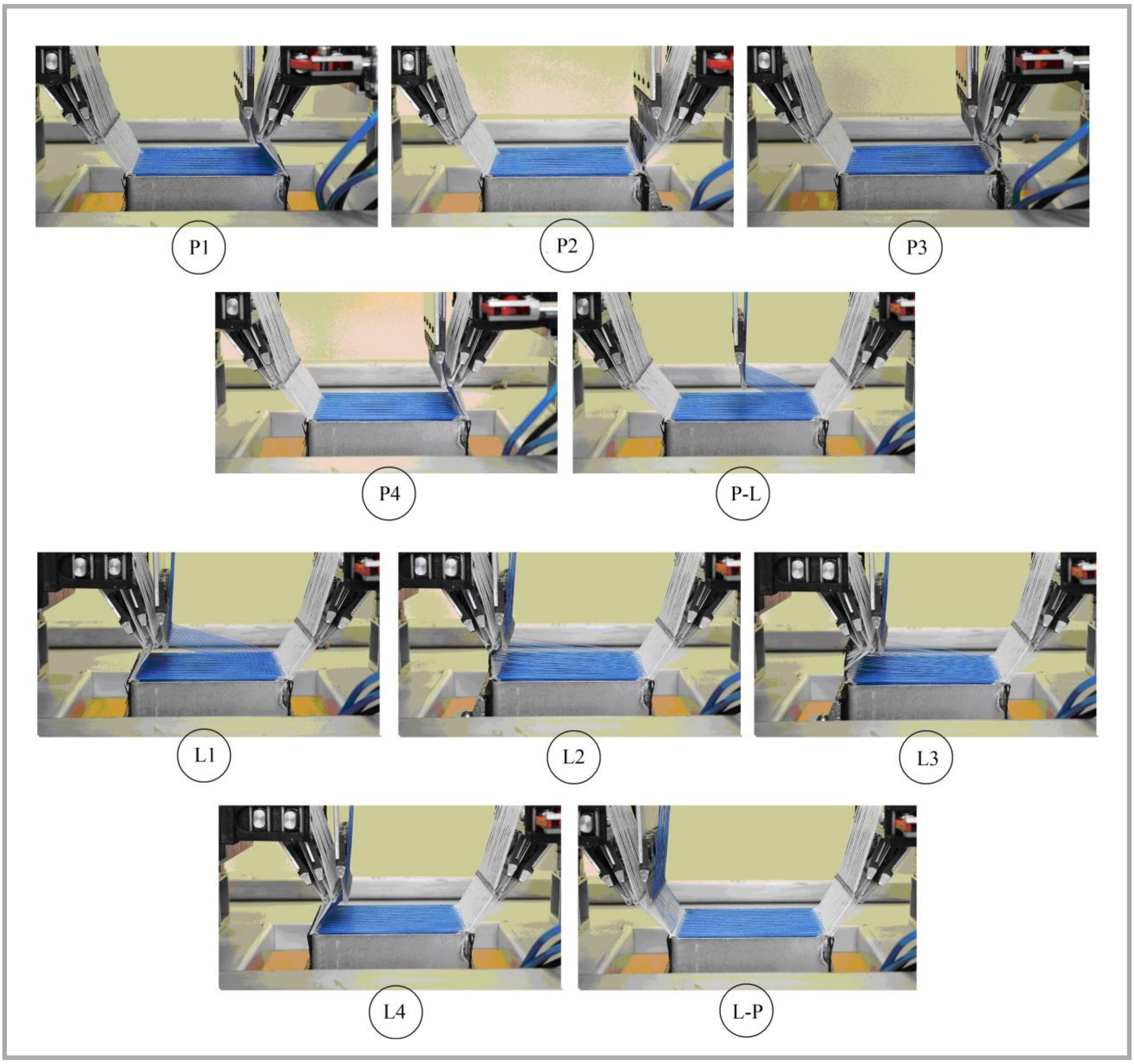

Figure 17. *Stages of knitted fabric formation. P1 to P4 – forming a course of the right wall, P-L – forming half of the loop connecting the walls, when the guide bar of the filling layer shifts from the right to the left, L1 to L4 – forming a course of the left wall, L-P – after the course has been formed the middle bar (of the filling) starts to shift towards the opposite (right) wall, forming the second half of the loop connecting the fabric walls.*

- Phases P1 and L1 – The guide bars of walls Ga and Gb and the warp guide bars of the filling layer G2 are situated behind the needles and make a lap to the zero position. The needles are in the lowest position.
- Phases P2 and L2 – The guide bars pass between the needles to the ’in front of’ position. The threads are prepared to feed the needles.
- Phases P3 and L3 – Feeding the needle is completed. Guide bars in the ’behind’ position.
- Phases P4 and L4 – Needles in the lowest position; a course has been formed.

Transitional phases, P-L and L-P, – forming the filling layer, (creating loops between the walls, main motion (stroke of 120 mm) of bar G2 towards the opposite wall of the knitted fabric; at the same time needle bars Ga and Gb move to the position ’in front of’ the needles.

Conclusions

The main purpose of the scientific and application work was to construct and examine a physical functional model of a warp knitting machine for 3D knitted fabrics. The functional model was used to perform tests confirming the technological efficiency of the machine. Before the model was constructed, the following stages had to be completed:

- preliminary assumptions based on the concept presented in relevant publications,
- geometric, structural and dynamic models of the main zones of the warp knitting machine, together with cyclograms of the drives for the loop-forming elements,
- construction documentation of the model in a full four-needle-comb version,
- 3D model of the simplified double-needle-comb version.

The functional model of a warp knitting machine constructed consists of feeding units with negative warp feeding, loop forming units with original design solutions (which are the subject of patent applications), as well as drive and control systems.

The technological and experimental tests carried out on the physical functional model confirmed the possibility of producing 3D knitted fabrics according to the innovative concept, on a new type of four-needle-comb warp knitting machine.

References

1. Mikołajczyk Z, Pieklak K, Golczyk A, Wiater Z. *Knitted Spacer Product (in Polish)* Patent P-386074. Patent Office of the Republic of Poland 25.09.2014.
2. Pieklak K., Mikołajczyk Z. Original Concept of a New Multicomb Warp-knitting Machine for Manufacturing Spatial Knitted Fabrics. *FIBRES & TEXTILES in Eastern Europe* 2009; 17, 3(74): 76-80.
3. Xiaogang C. *Advances in 3D Textiles*. Woodhead Publishing is an Imprint of Elsevier 2015, Series in Textiles Number 167.
4. Grębowski J. Distance Fabrics in Mattresses, (in Polish) *Przegląd WOS* 10/2006.
5. Supeł B, Mikołajczyk Z. Model of the Compressing Process of a One- and Two-Side Fastened Connector of a 3D Distance Knitted Fabric. *FIBRES & TEXTILES in Eastern Europe* 2008; 16, 6B(71): 44-48.
6. Michalak A. *Analysis of the original functional model of a warp-knitting machine for 3D fabrics* (in polish). Doctoral dissertation, Lodz University of Technology, 2019.
7. Michalak A, Mikołajczyk Z. The Concept of a Warp-Knitting Machine for Spatial Knitted Fabrics. Design and Constructional Assumptions, (in polish) paper for *XVI Scientific Conference of the Faculty of Material Technologies and Textile Design 2013*, Lodz University of Technology.
8. Michalak A, Kuchar M, Mikołajczyk Z. Constructive Assumptions of a New Four-Comb Warp – Knitting Machine, paper for *47th IFKT Congress*, 2014, Izmir/Turkey.
9. Michalak A, Kuchar M, Mikołajczyk Z. Simulation Tests of the Feeding System Dynamics on a Warp Knitting Machine with Four Needle Bars. *FIBRES & TEXTILES in Eastern Europe* 2015; 23, 4(112): 127-133. DOI: 10.5604/12303666.1152744.
10. Michalak A, Kuchar M, Mikołajczyk Z. Dynamic Analysis of a Warp-Knitting Machine with Pneumatic Drive for Producing 3D Knitted Fabrics. *Indian Journal of Fibre & Textile Research* 2017; 42, December: 502-505.
11. Michalak A, Kuchar M, Mikołajczyk Z. Impact of Whip Roller Parameters on Warp Dynamic Loads For 3D Fabrics Made on a Four-Comb Warp-Knitting Machine. *AUTEX Research Journal*, DOI 10.2478/aut-2019.
12. Pater Z, Tofil A. *Virtual Prototyping iIn Mechanical Engineering*. (in Polish), Lublin University of Technology, The State School of Higher Education in Chełm.
13. Herbuś K, Świder J. *The Use of Virtual Reality Technology in Machine Design* (in Polish), Silesian University of Technology.
14. Dietrych J. *System and Construction*. (in Polish), Warsaw: WNT, 1978.

Received 25.02.2020 **Reviewed 22.05.2020**