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Innovation in Weaving at ITMA 2023 Lights the Road to Industry 4.0

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Introduction

The textile industries are major contributors to environmental pollution that is caused by high water and energy consumption, use of harmful chemicals, create waste of high disposable cost, and generate petroleum-based microfibers/microplastics that end up in stream & ocean water and even air and can be transferred to the bodies of living things causing serious health issues. Today's consumers are increasingly knowledgeable of textile products impact on the environment which directs their purchase behavior toward products with low carbon footprints. In some cases, even willing to pay higher prices to protect the environment. For these reasons and the mounting regulations from environmental agencies around the world, research was directed toward the development of recycled fibers and fibers from natural resources that are biodegradable and environmentally friendly. Responding to the concerns and consumers' demand, the machine manufacturers are developing technologies addressing sustainability in terms of reduction in manufacturing waste, saving in energy and water consumption, and formation of yarns and fabrics from recycled and bio fibers. The technologies exhibited at ITMA 2023 revealed the continued commitment of the machine manufacturers, which started at the previous ITMA show, to focusing on sustainability and digitization that light the road to Industry 4.0. It should be noted that sustainability and digitization are highly interrelated.

This paper critically covers the most notable innovations in weaving technologies exhibited at ITMA 2023. As previous shows, machine manufacturers continued to develop and improve their equipment to form diversified products for apparel, home, and technical textiles' markets. Several exhibitors demonstrated weaving yarns from recycled fibers at high-speed. At the previous ITMA show, machine manufacturers marketed their technologies as Industry 4.0 ready, which has continued at this ITMA with more development in digitization.

Preparation for Weaving

The last three decades have witnessed a dramatic increase in automation, control, monitoring of production and performance, and data storage in supercomputers and cloud and communication to access the data using electronic devices. The advances in the yarn preparation for weaving technologies (warping, sizing, tying-in, and drawing-in) since ITMA 2007 are covered by the author in previous publications in the Textile World

Magazine (Seyam 2020, 1016, 2011, 2080). This section addresses the improvement of preparation for weaving technologies exhibited at ITMA 2023.

Sample preparation technologies were developed for rapid prototyping. Small samples are produced and assessed before bulk production. Prior to the development of sample technologies, weavers used their production machines to develop prototypes that led to significant loss of production and raw materials.

Sample warpers were advanced to not only produce prototypes but also short and medium orders for diversified line of production. Due to their numerous advantages, today, sample warpers are used not only by weavers but also by universities for teaching and research and research institutions. The two companies that contributed the most notable advancement of sample warpers are CCI and Karl Mayer. CCI did not participate in this ITMA.

The **KARL MAYER GROUP** exhibited a compact version of the automatic sample warping machine MULTI-MATIC® 32 Compact with creel capacity 32 wound packages for short and medium length warps. The machine was producing an intricate stripped warp depicted in Figure 1. The MULTI-MATIC® 32 Compact is characterized by its high production (as its productivity is much higher than their GIR-O-MATIC® of the same space and number of colors in the warp), interactive multi-flexible movable creel, fast pattern change, and short setup times. The increase in productivity is achieved by eliminating the stop for leasing and sizing separation. Figure 2 shows a comparison between GIR-O-MATIC® and MULTI-MATIC® 32 for solid-color, 3-color, and 6-color warps.

Figure 1. Multi-Matic® 32 Compact Sample Waring Machine

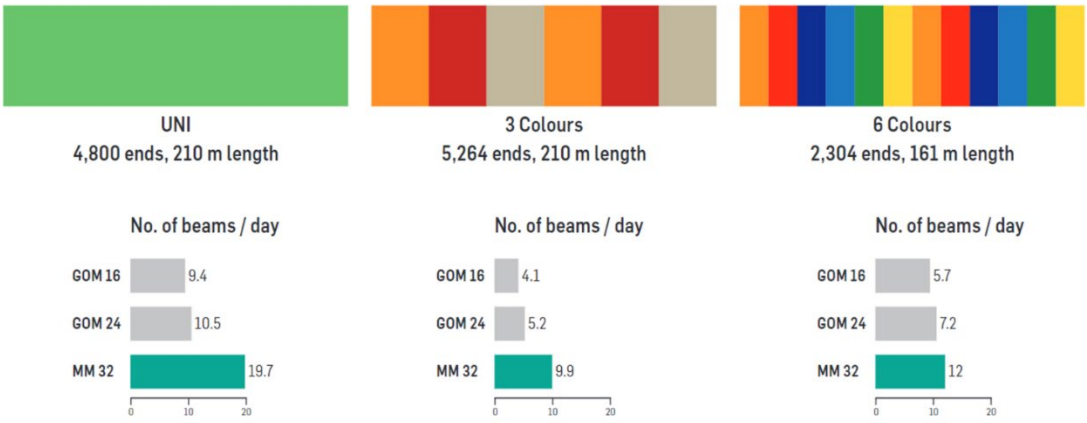

Figure 2. Comparison between GIR-O-MATIC® (GOM) and MULTI-MATIC® 32 (MM) for Solid-Color, 3-Color, and 6-Color Warps (Source: MULTI-MATIC_32_Compact_en_0523)

The company offers LINK-MATIC® automatic systems to increase the productivity of up to 30% of indigo and sizing machines. After completing a warp beam set, the system is used for tying-in the warp yarns from the new warp beam set to the set just completed. The LINK-MATIC® is designed to be managed by only one operator and reduce material waste.

Karl Mayer's machines, including warp preparation systems, are networked via cloud for efficient access to machine data and remote service. Production and quality management reports stored in the cloud can be accessed by electronic devices (such as mobile, laptop computers, desktop computers, etc.). Their software company KM.ON offers customers individual solutions that include production data analysis tools for flexibility and efficiency.

VANDEWIELE demonstrated their "Smart Creel" that was shown at the previous show. The creel is very compact compared to a traditional creel as the large wound packages are replaced with much smaller cells/holders arranged in rows and columns. Robots are used to wind the pile yarns from large wound packages with the exact length needed per carpet pattern. The author provided detailed assessment on a paper published in the Textile World Magazine (Seyam 2020) covering ITMA 2019.

Groz-Beckert continued to have a presence in the tying-in and drawing-in domain. The company showed one of their KnotMaster that were shown at the previous ITMA shows. They also exhibited their drawing-in machine WarpMasterPlus, which was shown at ITMA 2019. The machine is equipped with a computer system with a swivel monitor of touch screen user-interface with operator guided visualization that provides instructions on operation and troubleshooting via videos. Two monitors are available as an option to facilitate the operator monitoring as the machine length is long (2.4-4.0 meters). The machine consists of the drawing-in needle, drop wires, heddle wires, reed, and a single yarn from a wound package and their associated modular mechanisms. The yarn is fed to the machine by a feeder that is similar to weft yarn feeder in weaving. The heddle wires and drop wires, which are loaded by an operator, are fed automatically to the drawing-in zone. The single yarn is fed to the drawing-in needle that threads the yarn through a drop wire eye, a heddle wire eye, and a reed dent. Then the yarn is cut, and the procedure is repeated at up to 150 times/min depending on the yarn type. After the drawing-in is completed, the drop wires are

transferred to drop wire bars and the heddle wires to harnesses. The harnesses, drop wire bars, and reed are moved on a trolley to a storage area. When a weaver's beam is ready, the drawn-in warp from a single yarn is knotted to the corresponding warp yarns using a tying-in machine. Then warp beam, read, harnesses, drop wires bars are moved to the weaving area to supply a new warp to a weaving machine according to production planning. Due to the absence of the weaver's beam because of using a single yarn, the drawing-in machine occupies less space. However, space is required at the next step for the weaver's beam and tying-in process post drawing-in. While the drawing-in process is faster and setup time is shorter as a result of the simplicity of drawing from a single yarn, additional time is needed for knotting the weaver's beam yarns to the drawn-in yarns. To the author's knowledge, there are no time studies available in the public domain to compare between drawing-in from a wound package and from a warp beam.

Staubli showed their newest tying-in machine TIEPRO that was unveiled at ITMA 2019. More information is revealed at this ITMA including images (Figure 3). As can be seen from the figure, the machine employes a new method of yarn separation from the upper and lower warp sheets. Two conically shaped separators (see Figure 3) are used instead of the traditional method of yarn separation. The traditional tying-in requires, range of needles depending on yarn type and size. It may take the tying-in operator several trials to identify suitable needles for a given warp yarn type. The TIEPRO conical yarn separation mechanism is independent of yarn type and size. Additional features of the TIEPRO include tying-in with or without lease, yarn count range 3-100 Ne, suitable for staple yarns, 100% cotton yarns, and cotton blends, double end detection, short knot fringes, and up to 600 knots/minute depending on yarn characteristics and size. The TIEPRO is equipped with Auto-Reverse function (Figure 4) that is associated with detecting double-end: the machine repeats on its own the yarn separating process before tying and it does not cut the yarn. The operator intervention is required to separate the double end and then the tying-in resume from where it was stopped.

At this ITMA, **Staubli** continued to exhibit its SAFIR 60 automatic drawing-in machines for stripped warp. The features of different types of SAFIR (S30, S40, S60, and S80) drawing-in machines along with their applications are reported in (Seyam 2016). The company's new version of Active Warp Control 0.2 (AWC 2.0) allows the SAFIR machines to detect double-end and manage color/twist (S or Z) sequence in case of drawing-in warps without lease. If a double-end is detected, the two yarns are returned to the warp sheet and the system tries again for picking one yarn. As for the color/twist sequence, the AWC 2.0 checks the yarn color against the color repeat sequence and if the yarn is out of sequence, it will be kept in a storage area. Yarn in storage will be picked up later and placed in the correct sequence. The color detection system is designed to detect small differences in color to meet the demand of using the same color of different shade and depth.

Figure 3. Staubli TIEPRO Automatic Tying-in Machine (Source: https://www.staubli.com/gb/en/textile/products/weaving-preparation/tiepro-warp-tying-machine.html)

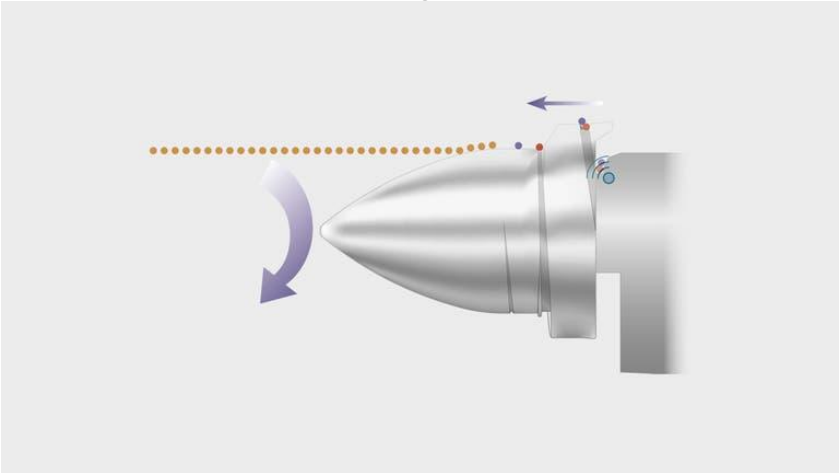

Figure 4. Conical Yarn Separator in Auto-Revers when Detecting Double End (Source: https://www.staubli.com/gb/en/textile/products/weaving-preparation/tiepro-warp-tying-machine.html)

Weaving

Dornier exhibited a total of 2 air jet A2 (new) and 2 rapier P2 weaving machines with one A2 and one P2 machines at their stand, one A2 at Staubli stand and one P2 at VANDEWIELE/Bonas stand weaving a diverse range of fabrics. The P2 rapier weaving machines were shown at ITMA 2015 before commercialization and at ITMA 2019 post commercialization. At their both, one P2 Type TGV 8/S G20/360 cm with 339 cm width in reed (WIR) machine was weaving plain weave sailcloth fabric at 320 picks/min or 1,085 m/min rate of filling

insertion (RFI). At VANDEWIELE/Bonas booth, the other P2 Type TKN 8/J G/220 cm with 171 cm WIR machine was weaving intricate Jacquard scarf fabric at 400-450 picks/min or 684-770 m/min RFI. At Dornier booth, the A2 Type AWS 4/E D 10/280 cm with 266 cm WIR was weaving plain woven Awning fabric at 900 picks/min or 2,394 m/min RFI. At Staubli stand, the other A2 Type AWS 6/J G/240 cm with 226.5 cm WIR machine was forming Jacquard high stretch sportswear fabric from warp and weft yarns containing spandex at 1,000 picks/min or 2,265 m/min RFI.

The A2 air jet machines, which is the successor of A1 series that was introduced in 1989, were shown for the first time at this ITMA. The A2 machines are highly digitized. The ErgoWeave® operating panel was redesigned with optimal continuous fabric production parameters overview. The more user-friendly high-resolution interface permits monitoring and shortens changeover of woven fabric parameters.

In the vein of digitization, weaving machines may be networked via the Dornier DoXNet software that provides a user-friendly production overview. Networking does not require the internet; hence weavers have full control over their proprietary production, optimum machine settings and fabrics' specifications data. With DoXNet optimum machine settings for a given type of fabric can be shared with other machines weaving the same fabric. Furthermore, Dornier DoXWeave, which centrally manages weaving machine data in a plant(s)control desk, allows remote access, if so desired, to weaving machines' production data. The Dornier myDoX is a portal that allows customers 24/7 online shop and provides direct Industry 4.0 connection to experts and information from Dornier. Figure 5 visually illustrates the data flow and the relationship between the weaving machines, DoXNet, DoXWeave and myDoX.

Discussion with technical personnel at the show revealed that Dornier's most contribution to sustainability is designing sturdy machines that have worked for many years. Dornier is still supporting spare parts for machines produced in 1978. It is a well-known fact that weavers have to surplus their machines or seek machine shops for support at extremely high cost for the lack of spare parts of early machines. The question that comes to mind is "Can such machines be digitized at reasonable cost to benefit from digitization and readiness for Industry 4.0?"

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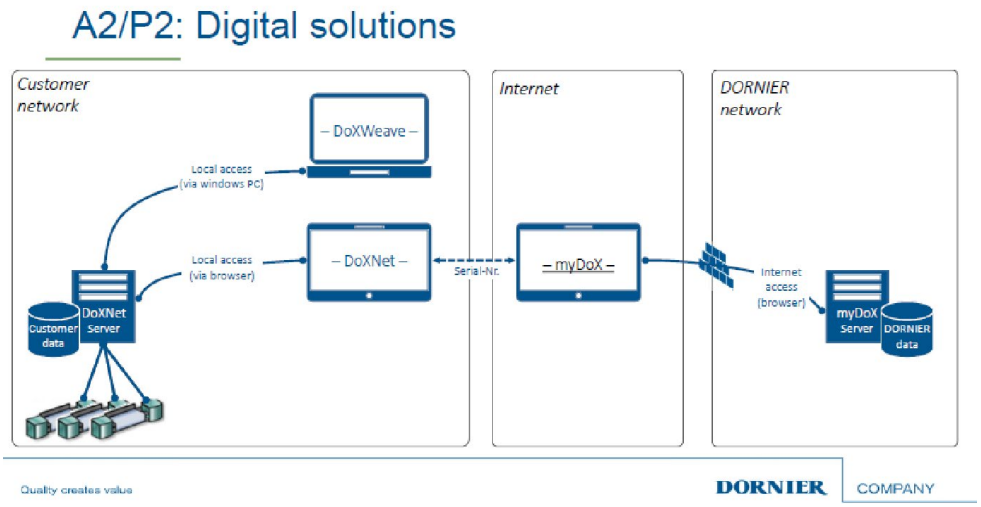

Figure 5. Weaving Machines, DoXNet, DoXWeave and myDoX Systems Data Flow (Source: Press Release ITMA2023_VDMA)

Itema Group unveiled their new EVO Series rapier machines (R9500EVO) and an air jet (A9500EVO) machine. A total of 12 machines (10 EVO 1 R9500-2 and 1 Hercules) were shown; 7 machines at their booth and 5 machines at other stands covering formation of diversified fabrics for apparel, home textiles and technical textiles from natural and high-performance fibers. At their stand, Itema exhibited R9500EVO/220 cm weaving wool fabric at 600 picks/min or 1,320 m/min RFI, R9500EVO/220 cm weaving denim fabric at 750 picks/min or 1,650 RFI, R9500EVO/190 cm weaving Jacquard Tapestry fabric at 600 picks/min or 1,140 RFI, R9500EVO/260 cm weaving Jacquard terry fabric, R9500EVO/220 cm weaving reinforced sail fabric at 600 picks/min or 1,320 RFI, A9500EVO/190 cm weaving bottom weight fabric, and Hercules/380 cm weaving heavyweight filter fabric.

The 5 machines exhibited at other stands include R9500EVO at Staubli booth weaving Jacquard high fashion apparel, R9500EVO at VANDEWIELE booth weaving Jacquard decoration fabric, R9500EVO at MEI stand weaving label fabric, R9500EVO at Julibao booth weaving label fabric and R90002 weaving shoe fabric.

In terms of sustainability, Itema developed the new mechatronic device iSAVER®, which was expanded to several fabric types after its success in denim weaving, with the target to reduce raw material waste. At their booth three machines were equipped with the iSAVER® forming wool, denim, and sails reinforced fabrics mentioned above. The device eliminated the need for auxiliary selvage yarns and cutter and minimized the fringes at the fabric left-hand side; only short filling fringe left as it can be seen from Figure 6. The iSAVER® is available in up to 6 filling yarns (color/type).

Figure 6. R9500EVO Machine Equipped the iSAVER® forming Denim Fabric

In terms of digitization, Itema offers iKNOW™ and MyWeave™ systems. The iKNOW™ is an expert system loaded with collected information from the field over years. It is claimed that the system enhances the user experience and optimizes production. Such systems are useful based on previous experience and may be limited when it comes to developing new fabrics using new materials, especially fabric from recycled and bio-based fibers. The system needs continuous updates that require commitment from Itema and their customers. MyWeave™ is a new system that provides monitoring and management production data for a plant(s). The EVO series is equipped with an EVOConsole of 15.6-inch-wide touch screen and can be connected to Wi-Fi and Bluetooth. It is also ready for data analysis and IoT. The EVOConsole allows access to the brand-new customer portal HelloItema, which allows customers to request service, access data and documents, and order spare parts.

Picanol unveiled new rapier Ultimax weaving machines that build on their successor the OptiMax machines. The Ultimax machines are designed with a high degree of digitization to facilitate operation and communication with each other as well as PicConnect. Picanol continued to exhibit their OptiMax-i rapier and OmniPlus-i air jet machines that were shown at previous ITMA. A total of 10 machines were shown at the Picanol stand and one machine was exhibited at VANDEWIELE/Bonas stand and another at Staubli booth forming diversified fabrics for apparel, home textiles, and technical textiles. The list of machines along with fabric type, weaving speed and RFI are listed below:

Ultimax-4-R-220 weaving denim fabric at 730 picks/min (1,600 m/min RFI)

Ultimax-8-R-360 weaving voile fabric at 400 picks/min (1,440 m/min RFI)

Ultimax Terry-8-J-260 weaving Jacquard terry towel at 545 picks/min (1,417 RFI)

Ultimax-12-J-340 Jacquard flat carpet at 300 picks/min (1,020 m/min RFI)

OptiMax-i Connect-4-R-430 weaving anti hail fabric at 330 picks/min (1,419 m/min RFI)

OptiMax-i Connect-4-R-540 weaving coating fabric at 275 picks/min (1,485 m/min RFI)

TerryPlus-i Connect-6-D-260 weaving Jacquard terry towel at 600 picks/min (1,560 m/min RFI)

OmniPlus-i Connect-4-D-340 weaving sheeting fabric at 1,000 picks/min (2x3,400 m/min RFI)

OmniPlus-i Connect-4-D-190 weaving car seat fabric at 1,200 picks/min (2,280 m/min RFI)

OmniPlus-i Connect-4-P-190 weaving bottom weight fabric from 100% recycled yarns at 1,500 picks/min (2,850 m/min RFI).

OmniPlus-i Connect-4-J-220 weaving Jacquard African damask at Staubli stand

OptiMax-i Connect-12-J-190 weaving a Jacquard fabric at VANDEWIELE/Bonas booth

The OmniPlus-i Connect-4-P-190 weaving machine was weaving bottom weight fabric from 100% recycled warp and weft yarns with fiber content 67%/33% polyester/cotton at an impressive high-speed 1,500 picks/min (2,850 m/min RFI). The performance and hence weavability of yarns from recycled fibers is lower and contains short fibers. Despite this, Picanol demonstrated the commitment to develop high-speed machines to handle such yarns and support sustainability. In their brochure, Picanol reported that the Ultimax-4-R-220 is recycled yarn ready. Another notable achievement is weaving sheeting from fine cotton yarns Nm 102/1 warp and Nm 68/1 weft with fabric count (72x41x2) at 1,000 picks/min weaving speed or 2x3,400 m/min RFI (the 2 for double-pick insertion). As a result of high short fiber content in recycled yarns, they generated higher fly that settled on the

machine, warp sheet and fabric, this will require blowing system to remove the fly that are handled by air suction system, Blowers and suction system are not unusual in weaving sheds.

The Ultimax-8-R-360 and OmniPlus-i Connect-4-P-190 machines were equipped with newly developed leno motion O-Leno. The O-Leno yarns are driven by a timing belt and two time gears that can be programmed to form half-turn or full-turn leno weaves to secure the fabric selvages. It may be programmed to vary form half- or full-turn leno for individual weft yarns depending on their surface characteristics.

Picanol highly digitized machines are Industry 4.0 ready. The company developed their PicConnect to access data stored in the cloud. It is the gateway to all Picanol digital information access such as Picanol applications, IoT, AI, and customer service.

Itema and Picanol exhibited the highest number of weaving machines (12 each) at this ITMA.

Smit exhibited 3 of their rapier machines; 2FAST 220 C8 D (new), GS980 260 F8 J (shown at ITMA 2019) and CONCEPT 190 C8 D (new conceptual machine underdevelopment). 2FAST machine was weaving denim fabric at 700 picks/min with WIR 222 or 1,554 m/min RFI, GS980 machine was weaving Jacquard terry towel at 500 picks/min with WIR 244.4 cm or 1,222 RFI, and CONCEPT machine was weaving shirting fabric at 800 picks/min with WIR 172 cm or 1376 m/min RFI. The 2FAST and the CONCEPT machines are designed for Quick Style Change. The warp stop motion in CONCEPT machine is monitored by a laser device to eliminate the drop wires. Monitoring warp breaks using laser may be challenging with high warp density that causes the broken yarn to be supported by neighboring yarns. With such a support, the yarn will not fall to cut the laser light and avoid detection of break. The 2FAST machine is equipped with 2SAVE that was shown for the first time at ITMA 2019. It eliminates auxiliary selvages from both sides and cut weft fringes collected for recycling. Figure 7 shows the waste saving with the 2SAVE system. Figure 8 shows the left-hand selvage of a fabric using the 2SAVE. While the machine at the show was weaving denim fabric, it is designed for versatility to weave fabrics for fashion, home textiles, and technical fabrics using a range of yarns from different fibers and counts. The rapier is a free flight system (no guide is required to support the rapier during weft insertion) that was developed and shown at previous shows.

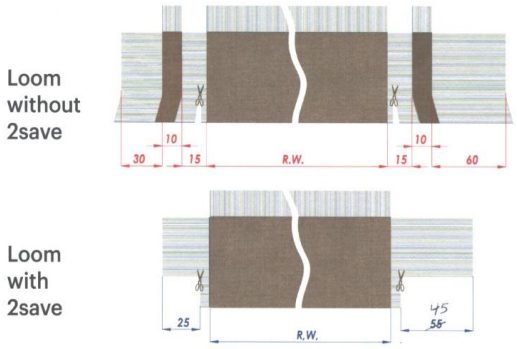

Figure 7. Weft and Auxiliary Warp Yarns Saving using 2SAVE Mechanism (Source: Smit 2SAVE Brochure)

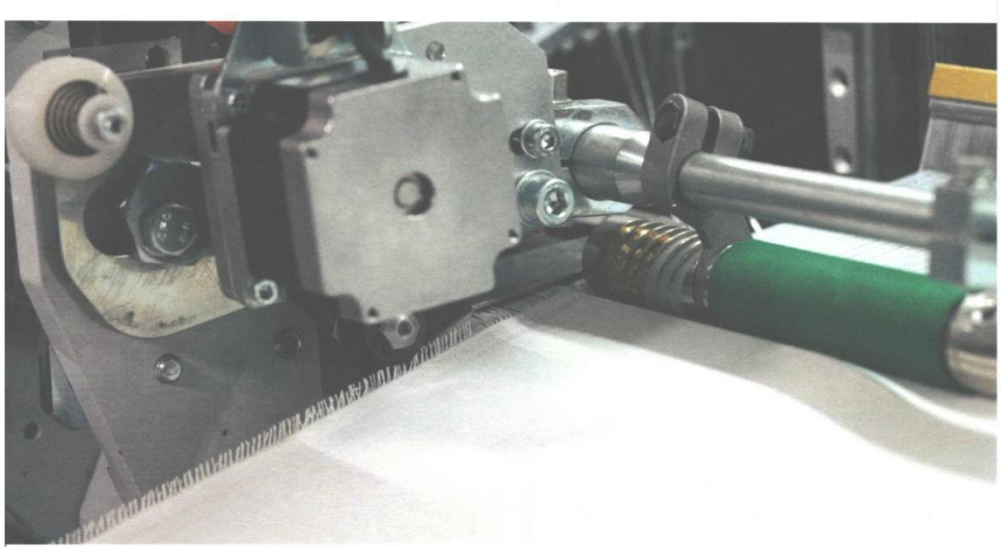

Figure 8. 2SAVE Mechanism (Source: Smit 2SAVE Brochure)

Toyota showed 3 of their new JAT 910 air jet series. JAT910 4F-230ES-EF was weaving high fabric count (274x526) double face fabric at 1,000 picks/min with WIR 210 cm (2,100 RFI), JAT910 2S-340LM-ET weaving side-by-side 261 cm wide sheeting and 20 cm wide pillow fabrics at 900 picks/min (3,060 m/min RFI), and JAT910 8T-280JE-EH weaving 4-panel of different Jacquard patterns terry towel at 950 picks/min with 269 WIR (2555.5 m/min RFI). Toyota's approach of sustainability is reduction of air consumption/energy. This is done by i-SENSOR located to monitor the leading weft yarn during insertion inside the shed prior to arrival at the right-side selvage. Early arrival (takes place as the weft package diameter is reduced due to the known fact that the weft yarn gets more air friendly with higher traction with air) will be detected and insertion timing is adjusted accordingly. Toyoda reported a 20% reduction in air consumption compared to the conventional model. There are no studies in the public domain that compared air consumption using adaptive control systems by different machine manufacturers. Toyota factory management support system FACT has been evolved to FACT-plus. The system collects data in real time from weaving preparation (warping and sizing) weaving machines and inspection room and proposes actions to machines and operators. It monitors different sensors (speed, pressure, temperature, compressor pressure data, etc.) and provides instructions for machine maintenance and the next assignments for operators.

Tsudakoma exhibited a new air jet weaving machine series ZAX001neo that was successfully commercialized and sold in 2021. At their stand they exhibited two machines ZAX001neo-190-2C-Cam weaving lining fabric at 1,200 picks/min (2,280 m/min RFI) and ZAX001neo-390-4C-Cam weaving awning fabric at 820 picks/min (3,198 m/min). A new weft insertion system was designed as a standard for the ZAX001neo machines with optimized auxiliary nozzles positions leading to a reduction of 35% in air consumption corresponding to 20% reduction in air pressure compared to their existing model. Additionally, a direct drive high-efficiency IPM motor, developed for this series, reduces stop marks. The company upgraded their weaving support system to Weave Navigation® System II. The system has different functions: Weave Vavi® provides user support to best weaving conditions for a given situation, Tune Navigation delivers best machine setting (loom timing, tension, easing amount, air pressure, etc.) for a given fabric type, and i-start that eliminates stop

marks via controlling the let-off and take-up to adjust cloth fell position and the warp tension back to its pre-set levels.

Three-Dimensional (3D) Weaving

3D weaving for fiber-reinforced composites and other innovative applications continued to be one of the highlights at this ITMA. At the previous shows several companies (Optima 3D, Staubli, VANDEWIELE, and VUTS) displayed 3D woven products including 3D orthogonal, 3D variable thickness, distance (spacer), stitched multilayer, and unstitched/stitched double cloth for insertion of electronics and ceramic for ballistic protection. At this show VANDEWIELE displayed on a large screen several distance/spacer fabrics for automotive and boat applications to demonstrate their weaving technologies' capabilities. They also showed samples on a table display.

Optima 3D continued to have a presence for two ITMA shows in a row. The company exhibited one machine of Series SJ-600-4, 3D weaving machine equipped with 4 shuttles for weft insertion and SX Staubli Jacquard shedding system. The machine forms one shed at a time and the shuttle is transferred by a magnetized arm (rapier) for weft insertion. The arm is designed with magnetized conical space to hold the metal nose of the shuttle. The machine is equipped with a linear fabric take-up motion, as thick 3D preforms cannot be taken-up on rollers, and touchscreen controls for user interface. The warp yarns are supplied from a compact creel with rotating flanged spools that allows parallel winding for longer yarn and hence longer runs to reduce creel change. The creel capacity is 576 spools, and two or more creels can be set behind the machine if needed. The company product line also includes spool winding machines. Shuttle weaving combined with Jacquard shedding system allows the formation of 3D orthogonal and angle interlocking, stitched/unstitched multi-layer along with a variety of shaped 3D preforms including I, T, Truss, cellular, etc. for fiber-reinforced composites and other applications.

VUTS (Liberec, Czech Republic) Company exhibited an air jet weaving machine DIFA weaving 3D distance fabric. The machine can be programmed to form fabrics with variable distances between the top and bottom base (ground) fabrics to obtain the target shape of the inflatable structure after coating. This type of distance fabric requires a minimum of two warp beams; one dedicated for the warp sheet for the top and bottom ground fabrics and the other is assigned for the pile warp sheet. Applications for the distance fabrics include inflatable structures such as boats of different types, dock, mats, flood protection, lifting bags, etc. Figure 9 shows an inflated boat that was displayed at the booth. The company showed their CAMEL ADAPTIVE air jet machine for formation of leno fabrics. VUTS marketed their machine as Industry 4.0 ready without providing supporting data on their brochures or website on the level of digitization of their machines.

Figure 9. Inflated Boat from Variable Height Distance Fabric

Narrow Weaving for Smart and High-Performance Applications

Jakob Müller has been developing narrow weaving machines for innovative smart textiles applications since ITMA 2011. Then they showed a wireless smart label, which consists of a woven antenna from electrically conductive yarn and a chip with integrated circuit, for antifraud identification using radio frequency (RF) technology. At ITMA 2019, the company showed their NFM®MDW® machine weaving narrow fabric containing electrically conductive e-yarns from PES/Cu/Ag with aid of e-yarn guides that move the yarns out of the open reed and place them as desired to form fabric-based electronic circuits, heating as well as anti-bacterial applications. At this ITMA, Jakob Müller showed their NFM® 53 2/84 MDW® (where MDW stands for Multi Directional Weaving) machine. Unlike the NFM®MDW® shown in 2019 that works using open reed technology, the new version MDW® technology is using a different methodology of laying-in effect/functional yarn(s) at strategic places to form a desired pattern. The MDW® is equipped with effect/functional yarn(s) guides. Up to four guide bars are available. The effect/functional yarn(s) are moved downward by the aid of the guide bar(s). The weft yarn is then inserted and held down the effect/functional yarn(s) in place, then the effect/functional yarn(s) are incorporated to the fabric following the beat-up. A strategic motion can be electronically preprogrammed to move the effect/functional yarn(s) to either side a specified distance, lower the yarn(s) to interlace with weft yarn and the steps are repeated to complete the target design. The calculated movement of the effect/functional yarn(s) guides results in the formation of area covered with the effect/functional yarn(s) distributed with the desired pattern. The NFM® 53 2/84 MDW® machine was forming e-textile with base fabric from polyester filament yarns and two conductive yarns containing copper-nickel controlled independently by two guide bars (Figure 10). Potential applications for this technology include e-textiles (heating, electronic circuit, anti-bacterial, RFID, etc.), fashionable textiles using colored and fancy yarns, and multidirectional yarns for enhanced performance in different directions other than the main directions of wrap and weft. Currently, formation of 3D multidirectional preforms for fiber-reinforced composites is achieved by manually stacking of 2D woven fabrics at different angles to form semi-isotropic and other structures with enhanced properties at different directions, which is time consuming, subjected to labor errors, and costly. The MDW® technology can be expanded for broad weaving to benefit the fiber-reinforced composite industry for forming wide preforms with laid-in multidirectional high-performance yarns.

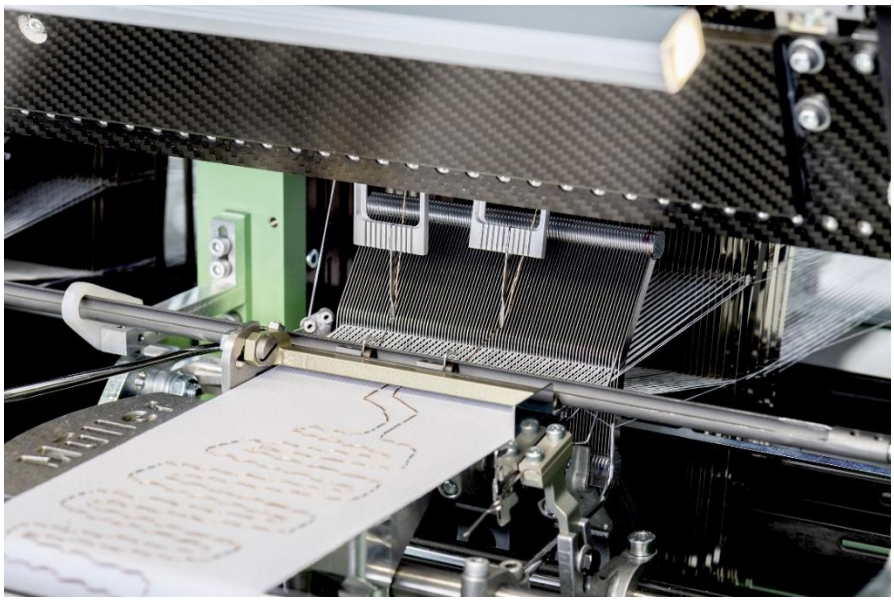

Figure 10. NFM® 53 2/84 MDW® machine forming e-textile with two conductive yarns containing copper-nickel (Source: Jakob Müller)

On-Loom Fabric Inspection

On-loom fabric inspection systems have been developed to detect defects at the loom stage and trouble shoot the root cause of defects and thus avoiding the production of off quality fabrics that leads to reduction in fabric waste and increase in profit. One of the early systems was Batch Motion. It consists of an off-loom fabric take-up, platform/stage for operator/inspector, and inspection station. The batch motion is situated between the front fabric rest and off-loom take-up rolls. The inspection station is similar to post-weaving manual inspection and relay on the weaver/inspector's eye to detect defects. There are several drawbacks associated with the batch motion, including the distance between the cloth fill and the inspection station is several meters and hence defects may pass without detection, reduction of machine assignment/weaver, and requires more space compared to post weaving inspection. To eliminate the manual post-weaving and Batch Motion inspection, several automated on-loom fabric inspection systems with high-speed image capturing (cameras/scanners) were developed. Examples of these include LOOM-TEX by Elbit Vision System or EVS (shown at ITMA 1999 and 2003), Cyclops by Barco, and Fabricscan by **USTER**. These systems can capture and store fabric defects' images, identify and classify defects, report defects map, and if desired stop the weaving process based on the severity of the defect. These systems are installed between the front fabric rest and take-up rolls, which is an improvement over the manual post-weaving and Batch Motion inspection. However, more than one meter of fabric passes the system without detection which leads to late detection of fabric defects, second quality products and waste. To avoid this serious disadvantage, **USTER** (acquired EVS company in 2018) developed the Q-BAR 2 on-loom automatic fabric inspection system (Figure 11) that was exhibited at this ITMA. As can be noticed from the figure the scanner is installed right above the fabric formation area. The scanner covers the entire width, including the cloth fell, as well as the fabric length as the fabric is taken up (100% fabric quality monitoring). With such scanner location, the fabric is scanned right after each weft insertion that leaves no room for delayed fabric inspection. The Q-BAR 2 is equipped with a touchscreen visualization system (Figure 12). As the quality is defined

differently according to the end use of the fabric (such as safety, high fashion, commodity fabrics), the system offers a range of grading of fabric rolls based on defect type, size, and location.

Figure 11. USTER Q-BAR On-Loom Fabric Inspection System (Source: USTER)

Figure 12. USTER Q-BAR 2 Visualization System (Source: USTER)

While there are high volume instrument (HVI) systems to measure fiber quality data that spinners are making use of to optimize bale layout for production of high-quality and consistent yarn batches and monitoring quality of yarn of individual positions on winding machines, these data are not utilized by the weavers due to lack of available systems. Wound packages are used to form warps and used as weft yarns at preparation stages for weaving. This seems to be challenging as it is difficult to identify locations along yarn length that may negatively impact weaving efficiency and fabric quality. However, this is not trivial. It is envisioned that during winding, markers

could be placed on yarn at intervals to allow tracing and adaptive control systems to mitigate efficiency and quality issues. Obviously, monitoring a few weft yarns during weaving would be much easier than the large number of warp yarns. In this vein At ITMA 2015, **USTER** (Acquired by Toyota in 2012) showed ALPIN, which is an Adaptive Control System targeting reduction in air consumption. **USTER** sensor is positioned between weft package and weft feeder to monitor filling yarn air friendliness, which depends on yarn hairiness and surface texturing, and accordingly adjusts air blowing. The monitoring and adeptness could be expanded to include other key quality yarn parameters that influence weaving efficiency and fabric quality. As mentioned earlier, warp yarns are numerous and extremely difficulty to make use of their quality data captured during the winding process at the weaving process. It is envisioned that the **USTER** Q-BAR 2 system may be used to monitor the warp yarns. Two monitoring locations may be feasible: (1) monitor the warp sheet between the warp take off point from the warp beam and web roll using additional unit or (2) monitor the warp and fabric quality at the location shown in Figure 11 using one unit. The latter approach is less expensive but more challenging as the read moves (from the beat-up position to the most back position) and comes between the scanner and the warp sheet up to 1,500 times (equals to loom speed in picks/min). However, this may be accounted for since the system uses high-speed cameras.

Road to Industry 4.0 for the Weaving Industry

The ultimate goal of Industry 4.0 is to maximize productivity, efficiency, and product quality through automation and digitization of technologies that allows communication between machines, software systems, and people via IoT (Internet of Things), throughout different stages of the pipeline required to manufacture a product. This can be achieved by cyber-physical systems and big data (storage in cloud) to collect data from sensors and integrate them for analytics and AI. In terms of automation, the weaving machine manufactures developed numerous automated systems including warp stop motion, weft stop motion and automatic repair, monitoring stops and efficiency, adaptive weft control systems for air jet weaving for saving energy, automatic weave/pattern change, pre-programmed weft selection for intricacy and hybridization, pre-programmed variable machine speed, pre-programmed variable weft density, automatic on-loom fabric inspection, automatic smart drawing-in and tying-in machines, individual warp yarn control in Jacquard, individual harness control in dobby, etc. More affordable automations are still required to achieve the goal of Industry 4.0, including automatic repair of broken warp yarns, multiphase weaving that triple or quadruple productivity with dobby/Jacquard shedding systems, and automated style change system. There is a need for integration of the entire technologies required to manufacture woven-based products from fibers since the productivity and quality are influenced by all the steps required to form them.

The weaving (and other textiles) and its allied industries are far more complex than many other industries considering that they deal with manufacturing diversified products starting from fibers and ending with products driven by consumer demand. . There are numerous processes to convert fibers to end products; the fibers undergo 7-9 processes to make spun yarns, 4 processes to prepare the yarns for weaving, weaving, several processes (variable depending on the end use of products) to color and finish the fabrics, several processes (variable depending on end use) for converting fabrics to apparel, home textiles, or industrial textiles products. There are suites of machines and procedures within each stage of conversion with the apparel being the most complex and lowest level of automation. Globally, there are several companies' structures. There are vertically integrated companies with varying degrees of integration (fiber to apparel products, yarn to apparel products, and yarn to dyed and finished fabric), companies convert yarns to

greige fabrics, companies on commission for dyeing and finishing of greige fabric, and others are commissioned for warping and sizing, etc. It is a fact that the machines (even within a spinning plant, weaving shed, etc.) used by a company are not from the same manufacturer. At this ITMA and 2019 shows, weaving machine manufacturers advanced their technologies with high degree of digitization that allow machines to communicate and store big data relevant to the production and fabric quality that are accessible to users via intuitive user-friendly interface. It can be seen from the above review; the machine manufacturers' software products are broad and varied and that poses challenges to companies housing machines from different manufacturers. Machines are driven digitally by proprietary and elaborate low-level computer code. A company with machines from different manufactures cannot integrate their production and quality data without adding significant cost. The integration must be done by collaboration between machine manufacturers to standardize data access and user interface or by a third party. The demand from customers may lead government agencies to regulation of standardization. Collaboration between companies that are not fully vertically integrated, greige fabric producers, etc. are in need to collaborate with their suppliers and customers to take full advantage of digitization and Industry 4.0.

Machine manufacturers demonstrated high levels of digitization and large capacity systems for accessing big data storage that facilitates big data analytics and AI. Due to the complexity of the textile industry stated above, there is a need to prepare a technical team with collective skills in textile technology and engineering, machine learning, AI models, computer programming language, mathematics, and statistics to achieve the goals of Industry 4.0. Vertically integrated companies may afford to build such a team. Those who cannot afford such a team may collaborate with their business partners or retain consultant firms in the field. How fast the textile Industry completes the road to Industry 4.0 depends on the factors discussed above and perhaps more importantly on the economy.

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