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# Development of innovative inlay-insertion technologies for warp-knitting machines

Thomas Mutschler

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## **Abstract**

The technology of warp-knitting is one of the more recently developed processes in knitting technology. Complex machine technology and highly productive production machines characterize the process. This principle allows obtaining fabrics with various characteristics and for various applications. It is possible to insert straight inlay yarns into the textile structure. The inlay yarn can be inserted either over the entire width of the textile surface or only over a specific area of the textile. This is the limiting factor in respect of process speed. Different methods for traversing yarn positioning in the textile industry, with the potential to increase the inlay-insertion speed, had been introduced to the warp-knitting industry. Over the timeline of the developments, the Magazine insertion system (MIS) has been established with the state-of-the-art technology.

Consequently, the results of this study present and discuss possibilities to increase the velocity and efficiency of the process of warp-knitting with inlay yarn. This will allow the future to increase the production efficiency, reduce the stress on the inlay yarn due to acceleration and deceleration, and reduce the lateral and longitudinal vibrations of the inlay yarn.

Several main obstacles are determined to establish a valid new and alternative inlay-insertion system. Major technical challenges will be first to cope with the given machine cycle and use the given time window for the inlay yarn insertion as effectively as possible. Secondly, to control the yarn speed and tensile force and the actual position during the highly dynamical inlay process.

The design, assembly, and testing from two prototype units with different inlay yarn presentation systems show the advantage and necessity of an intermediate store unit for selected textile applications and the effectiveness of the process. As a technical alternative, it also shows the potential from the possibility of an electronically triggered individual inlay yarn insertion.

However, the potential of increasing speed, creating higher process flexibility, reducing energy consumption, and a reduction of moving parts required for the inlay technique can be achieved working at a smaller width. To adapt these technologies to machines with a bigger working width requires further research and design efforts. Innovative applications and design possibilities are suggested.



## **Personal acknowledgements**

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I would like to take this opportunity to thank my friends and family, all those who have supported and accompanied me in writing this thesis over the last months and years, and all those who have suffered with me.

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The desire to write this thesis arose from the memory of the person without whom I would not have become what I have become. Therefore, I dedicate this work.....to my father Helmut Mutschler, who passed away on 3 December 1981.

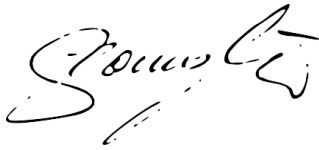
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## Statutory declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources /resources, and that I have explicitly marked all material that has been quoted either literally or by content from the used sources.

Mönchengladbach, 29.October 2022

Signatur

A handwritten signature in black ink, appearing to read 'T. Mutschler', written in a cursive style.

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## Nomenclature

Variable	Unit	Description
HSNR		University of Applied Science Niederrhein
rpm	1/min	Revolutions per minute
rps	1/sec	Revolutions per second
POR		Point of return
SMPS		Standardized Machine Setting Parameters
$W_M$	m	Machine width (inlay area)
$W_W$	m	Waste yarn width
n	yarn ends	Number of simultaneously inserted yarn ends
$\alpha_i$	°	Angle window for yarn insertion
$\alpha_g$	°	Angle for one complete machine revolution
$t_i$	s	Theoretical inlay insertion time
$t_r$	s	Time for one machine revolution
$v_t$	m/s	Theoretical yarn speed
$v_i$	m/s	Individual inlay yarn speed
$v_a$	m/s	Inlay yarn speed gripper method
$v_b$	m/s	Inlay yarn speed traversing yarn pos. eyelet
$v_c$	m/s	Inlay yarn speed rotating yarn guide rod
$v_d$	m/s	Inlay yarn speed rotating yarn cones
$v_e$	m/s	Inlay yarn speed Magazine Insertion System
$v_f$	m/s	Inlay yarn speed double belt system
$v_g$	m/s	Inlay yarn speed string bar technology
m	kg	Mass
$v_0$	m/s	Initial linear speed
v	m/s	Maximum system speed inlay system
$E_{kin}$	J	Kinetic energy
$E_{kini}$	J	Individual kinetic energy
$\Delta E_{kin}$	J	Difference kinetic energy
$W_y$	J	Mechanical counter acting yarn tensile force
S	m	Inlay width
$F_y$	N	Force in line
$E_{rot}$	J	Rotational energy
$E_{roti}$	(kgxm <sup>2</sup> )/s <sup>2</sup>	Individual rotational energy
$\omega_0$	rad/s	Initial angular velocity
$\omega$	rad/s	Maximum angular velocity inlay system
f	rad/s	Rotation frequency

$E_{ti}$	J	Complete energy consumption/yarn end
$E_{lt}$	J	Complete energy lost during the process
$t_a$	s	Time to insert yarn gripper method
$v_a$	m/s	Insertion speed gripper method
tex	g/km	Yarn count
$E_{ta}$	J	Approximate energy consumption gripper method
$E_{ya}$	J	Energy consumption/weft insertion gripper method
$E_a$	J	Total energy consumption gripper method
$E_{ia}$	J	Energy consumption gripper method
Swi	%	Share of Energy for inlay insertion in %
$E_a^*$	J	Total est. energy consumption based on $E_{inst}$
TYPE		Traversing Yarn Positioning Eyelet
$t_b$	s	Insertion time TYPE
$v_b$	m/s	Insertion speed TYPE
$E_{tb}$	J	Approximate energy consumption TYPE
$E_{yb}$	J	Energy consumption/weft insertion TYPE
$E_{yt}$	J	Energy consumption tensile force compensation TYPE
$E_{yib}$	J	Energy consumption/weft insertion tensile force compensation. TYPE
$E_b$	J	Total energy consumption TYPE
$E_{ib}$	J	energy consumption/weft insertion TYPE
RYGR		Rotating Yarn Guide Rod
$t_c$	s	Insertion time RYGR
$\omega_c$	rad/s	Angular velocity RYGR
$v_c$	m/s	Insertion speed RYGR
$I_r$	kgxm <sup>2</sup>	Moment of inertia RYGR
$L_r$	m	Length from the rod RYGR
$m_r$	kg	Mass from the rod
$E_{tc}$	J	Approximate energy consumption RYGR
$E_{yic}$	J	Energy consumption /weft ins. tensile force compensation RYGR
$E_c$	J	Total energy consumption RYGR
$E_{ic}$	J	Energy consumption/ weft insertion RYGR
RYC		Rotating Yarn Cone

S		Center of gravity
$T_d$	s	Insertion time RYC
$\omega_d$	rad/s	Angular velocity RYC
$v_d$	m/s	Insertion speed RYC
$J_s$	$\text{kgxm}^2$	Moment of inertia concerning centre of gravity
s	m	distance point S to point A (rotating centre)
$J_a$	$\text{kgxm}^2$	Moment of inertia concerning centre of gravity
$E_{cd}$	J	Approximate rotary energy per yarn cone RYC
$E_{cdt}$	J	Approximate rotary energy all cones RYC
$E_d$	J	Total energy consumption RYC
$E_{id}$	J	Energy consumption/ weft insertion RYC
MIS		Magazine insertion system
TBS		Two belt system
SBS		String bar system
$E_{te}$	J	Approximate energy consumption MIS
$E_{ye}$	J	Energy consumption/weft insertion MIS
$E_{yte}$	J	Energy consumption tensile force MIS
$E_{yie}$	J	Energy consumption/weft insertion tensile force compensation MIS
$E_e$	J	Total energy consumption MIS
$E_{ie}$	J	Energy consumption/ weft insertion MIS
$E_{tf}$	J	Approximate energy consumption TBS
$E_{yf}$	J	Energy consumption/weft insertion TBS
$E_{ytf}$	J	Energy consumption tensile force. TBS
$E_{yif}$	J	Energy consumption /weft insertion tensile force compensation TBS
$E_f$	J	Total energy consumption TBS
$E_{if}$	J	Energy consumption/ weft insertion TBS
$E_{lbf}$	J	Power transmission efficiency losses TBS
$E_{dg}$	J	Continuous power consumption SBS
$E_{tg}$	J	Approximate energy consumption SBS
$E_{yg}$	J	Energy consumption/weft insertion SBS
$E_g$	J	Total energy consumption SBS
$E_{ig}$	J	Energy consumption/ weft insertion SBS

$E_{lbg}$	J	Power transmission efficiency losses SBS
WIWK		Inlay insertion warp-knitting system
$t_i$	s	Time frame for one inly cycle
$n_{es}$		Number of evaluated solutions
$T_s$	s	Period of a complete yarn carriage cycle
$\Phi$	°	Wrapping angle
$\alpha$	°	Deflection angle
$T_0$	N	Yarn tensile force before the eyelet
$T_i$	N	Yarn tensile force after the eyelet
$\mu$	dimensionless	Coefficient of friction between yarn and eyelet
$T_{init}$	N	Starting value yarn tensile force
$T_{final}$	N	Ending value yarn tensile force
$\alpha_i$	°	Wrapping angle at the eyelet i
$t_i$	s	Insertion time
$v_i$	m/s	Insertion speed
$n_{es}$		Number of evaluated solutions
$T_s$	s	Period of a complete yarn carriage cycle
MP1	N	Yarn tensile force measuring at P1
MP2	N	Yarn tensile force measuring at P1
MP3	N	Yarn tensile force measuring at P4
J	kgxm <sup>2</sup>	Moment of inertia
$E_{bl}$	J	Theoretical rotary energy
$E_{blr}$	J	Energy consumption rotary blade system
$\beta$	°	Drag angle
r	m	The inlay width
$A_1$	m	The distance rotor blade to needle bar
$A_2$	m	The distance guiding rail to needle bar
$A_3$	m	The distance thread origin to needle bar
$S_1$	m	The thread section rotor plane to needle bar
$S_2$	m	The thread section guiding rail to rotor plane
$S_3$	m	The thread section thread origin to guiding rail
$L_{(t)}$	m	Yarn length relative to time
WP		Work package
$E_M$	J	Energy consumption torque motor
$E_{Mi}$	J	Energy consumption torque motor/weft insertion

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## Introduction

The technology of warp-knitting was more recently developed, in comparison to the other methods for fabric production. The processes and machines of warp knitting are characterized by a loop-forming process. In addition to the loop-forming threads, straight inlay yarns can be inserted into the warp-knitted fabric.

The inserted weft threads in warp knitting often represent the process limitation in terms of machine speed, as the feeding of the weft threads requires thread guidance with high masses and accelerations and the available time window in the loop forming machine cycle from the warp-knitting machine is limited. Previous insertion processes are characterized by machine elements that have to perform an acceleration and braking movement for each insertion in the shortest possible time. The state-of-the-art magazine weft insertion systems attempt to increase the processing speed and thus the efficiency of the warp knitting machine by simultaneously inserting several weft yarns. The second aim is to prepare stretched-out inlay yarn in an intermediate storage system to enlarge the time window for weft insertion. This makes the machine systems very large and requires a lot of installation space.

Innovative developments during the last decades have greatly advanced fields of application such as the production of spacer fabrics for use in automobile seats or mattress fabrics. Also because it is possible to insert straight yarns in the textile structure, it can be used either to manufacture textile fabrics presenting very low or no elongation, i.e. lower than a woven fabric. These fabrics are especially useful in composite reinforcements for structural mechanical parts, or for inserting yarns that don't support curvature because they are very delicate, like carbon or optical fibres, or rigid, like metallic yarns. In this case, the inserted yarn improves the mechanical/physical properties of the fabric. It is also common to insert inlay yarn in the cross direction<sup>1</sup>. The inlay yarn can be inserted either over the entire width of the textile surface (full inlay-insertion) or only over a specific area of the textile (partial inlay-insertion)<sup>1</sup>.

The base for a new innovative weft insertion system is to realize a high insertion speed of the weft yarn, utilizing constantly moving yarn guiding elements. In addition to an increase in the productivity of the warp knitting machine, lower energy consumption and a shortened installation space of the machine are also achieved. This principle allows to obtain fabrics with various characteristics and for various applications. In many new and also proven areas of application, such as nets, reinforcement textiles, agricultural - and geotextiles, lace can benefit from the possibilities offered by the new process.

Warp-knitting machines work with jointly moved needles and synchronous loop formation of all needles. Each needle is assigned an individual thread to form the loops. Complex machine technology and highly productive production machines characterize the process.

The aims and specific objectives of this Ph.D. project were as follows:

(1) To do a technological review on the methods of fabric production focusing on the loop forming process in different knitting technologies.

- Basics of fabric design,
- Manufacturing possibilities of textile structures,
- Knitwear production technologies,
- Technical construction of knitted fabrics.

This work is presented in Chapter 1

(2) To review inlay yarn insertion technologies along their timeline of development to determine and evaluate the positive and negative aspects of the technological approaches.

- Inlay-yarn insertion in inlay-knitting machines
- Inlay-yarn insertion in warp-knitting machines
- Inlay-yarn insertion cycle in warp-knitting machines
- Timeline of inlay yarn insertion technologies in warp-knitting machines
- Evaluation from the known inlay-insertion systems

This analytical review is presented in Chapters 1 to 2.

(3) To evaluate and determine the technological requirements of a new and innovative inlay yarn insertion system.

- Holistic and systematic product or process development,
- Problem definition alternative inlay-insertion system,
- Innovation process,
- Innovative technical solution for an inlay system for warp-knitting machines.

This analytical review is presented in Chapter 3.

(4) To evaluate the technological parameters which are influencing the inlay yarn and the resulting fabric during the dynamic process itself:

- Basics related to the yarn speed and tensile force during the knitting process,

- Measurements at the MIS System,
- Analysis from the MIS machine cycle,
- Conclusion from the measurements.

This analysis is described and presented in Chapter 4.

(5) To build up a development approach based on the method of systematic innovation and then derive the most beneficial development approaches from it. Moreover, to design and set up two prototypes from innovative weft insertion systems into warp-knitting machines of smaller width.

- General definition prototype unit,
- Analysis of rotary blade process,
- Analysis of the traversing process in warp knitting machines,
- Important requirements for an innovative system in warp knitting machines,
- Thread laying systems in cone winding machines,
- Preliminary modelling rotary blade system, observations, and prototype definition,
- Project structure, development steps prototype unit rotary blade system,
- Design and set up prototype unit rotary blade system,
- Suggested improvements to rotary blade system,
- The prototype with rotating eyelet,
- Preliminary modelling rotating eyelet system, observations, and prototype definition,
- Project structure, development steps prototype unit rotating eyelet system,
- The torque motor drive unit,
- Design and set up prototype unit rotating eyelet system,
- Suggested improvements rotating eyelet system,
- Conclusions and suggested improvements.

This analysis is described and presented in Chapter 5 for the rotary blade system and in Chapter 6 for the rotating eyelet system.

(6) To finally conclude the results from the research and design of the two prototypes and to determine a technical outlook.

.

# 1 State of art

## 1.1 Technology of knitting

Knitting is a technique of making fabric made with yarn on a single or more needles. The word “knitting” comes from the word “knot”<sup>2</sup>. Knitted products are commonly made of yarns which can be made of wool, cotton, silk, or other materials. The first pieces of clothing made a technique similar to knitting were socks.



Figure 1.1: Knitter in ancient Egypt<sup>3</sup>

The oldest knitted items have been found in Egypt (Figure 1.1). Spanish Christian royal families employed Muslim knitters and their works are the earliest known knitted items in Europe. Archaeological findings from the many cities of Europe show that knitting spread throughout Europe in the 14th century<sup>4</sup>.

From the first beginnings of hand knitting in Italy around the middle of the 13<sup>th</sup> century, the English priest William Lee developed in 1589 his hand warp-knitting apparatus equipped with spring beard needles. This enabled a considerable increase in the performance of manual work with approximately 100 loops per minute. It was further developed to 600 loops per minute and later even 1,500 loops per minute<sup>4</sup>.

When and by whom the first weft-knitting apparatus was invented cannot be said with certainty. Possible inventors are the English inventor Crane around 1775, other sources date the invention around 1780 in France or also in Holland<sup>4</sup>. In 1836, W. Lamb's first flat knitting machine was invented. This simplified the loop formation process; each needle was individually mounted in a slot and moved individually. Loops were formed one after the other, one needle after the other in an ongoing continuing process. In the year 1856 in England William Townsend invented the tongue needle.

In 1876, a needle is placed inside a second needle bed and put in a gap to the needles in the opposite first needle bed. This made it possible to produce a type of fabric with face loops on both sides (Figure 1.2). It is highly elastic and does not tend to curl at the fabric



edges. A further milestone in the development of a crossed right/right knitted fabric (interlock) in 1910 by the American Walter Scott<sup>5</sup>.



Figure 1.2: Knitter at a hand knitting machine<sup>6</sup>

### 1.1.1 Basics

The development of a knitted textile product begins with the assessment of the properties required for the final product.

Requirements for textile products can be:

- Structure (kind of knit),
- Morphological properties (structure, weight per surface unit, thickness),
- Optical properties (colour, pattern, transparency, brightness),
- Physical properties (water permeability, wash ability, wicking, conductivity),
- Mechanical properties (stretch, durability,...),
- Chemical properties (colour resistance, smelliness),
- Tactile properties, haptics,
- Comfort,
- Price and availability,
- Sustainability in production and logistics,
- Sustainability of the final product.

### 1.1.2 Morphology of textile surfaces

Based on the requirements for the final textile product like described in chapter 1.1.1, the product layout starts with the definition and selection of the fibre raw material. The morphological structure of surface textile production is described in Figure 1.3.

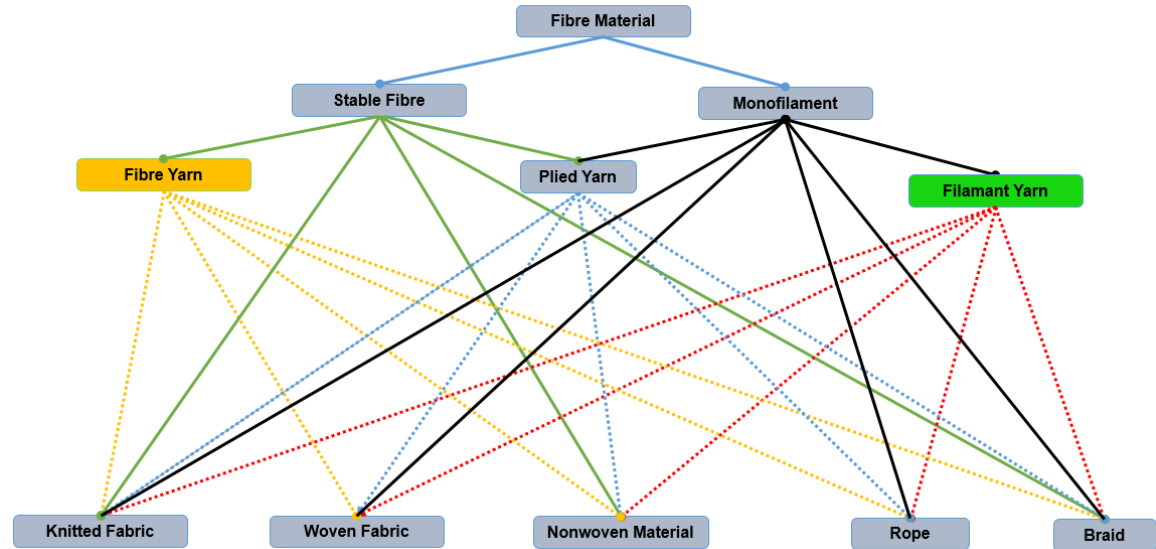


Figure 1.3: Morphological structure of surface textile production inspired from<sup>7</sup>

### 1.1.3 Development process chain for textile products

The fibre raw material is transformed by a spinning process into a multifilament filament or staple fibre yarn. These yarns are the basis to produce knitted textile fabrics. The desired mechanical, optical, or physical properties of the fabric are either defined by the raw material, the structure, or by downstream finishing and dyeing processes. Depending on the technology used and the objective of the product, certain steps can be skipped or adjusted along the production process.

The fibre material defines by

- The chemical structure,
- The physical structure,
- The cross-section, the length,
- The topographical characteristics,
- The mechanical properties

the resulting roving.

The roving defines by:

- The fibre type,
  - The fibre length,
  - The fibre length distribution (stack),
  - The fibre diameter,
  - Fibre cross section,
  - Fibre structure (fibre yarns),
  - Raw material,
  - Filament count,
  - Filament diameter,
  - Filament cross section (filament yarns)
- the resulting raw fabric.

Directly or via the intermediate stages of twine or pleated yarn, the properties of the raw fabric are defined by:

- Raw material type, i.e. yarns,
- Fabric weight per surface unit,
- Manufacturing techniques,
- Textile structure,
- Mechanical properties,
- Physical/chemical properties,
- Surface properties,
- Optical properties,
- The final textile structure.

The respective suitability and usability for the applications of the textile in the final technical component or product in assemblies or applications are defined by:

- Shape,
- Chemical/biological properties,
- Physical properties,
- Mechanical properties,
- Thermal properties,
- Tactile, haptics,
- Smell,
- Sustainability,
- Recyclability,

- Price and availability,
- Fashion/Trends,
- Colour,
- Shape and shape resistance,
- Functionality to braiding,

## 1.2 Manufacturing technologies for textile structures

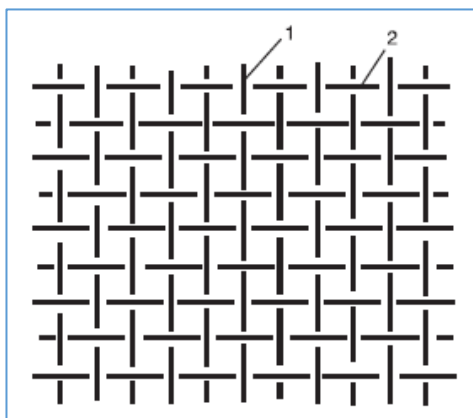
There are four principally different technologies used to produce textile structures:

- Weaving to produce woven fabric,
- Braiding to produce braided textile,
- Loop forming to produce knitted goods,
- Nonwovens and clutches

### 1.2.1 Woven material

During the weaving process, the warp threads run from the warp beam through the healds of the heald frames and through the reed to the cloth beam. The heald frames control the type of weave, the reed determines the density of the fabric. In weaving machines the up and down movements of the heald frames form the shed into which the weft is inserted using shuttles<sup>8</sup>. Further systems to insert the inlay are used in rapier, air jet, water jet and projectile weaving machines. Woven fabrics are made by the interleaving of two sets of yarns (Figure 1.4), disposed at right angles<sup>9</sup>.

- the warp thread system
- inlay- thread



1: Warp direction

2: Weft direction

Figure 1.4: Structure of a plain woven fabric<sup>1</sup>

## 1.2.2 Nonwovens

The nonwovens are consisting of natural and synthetic fibres, very often with the addition of other fibrous components of different types and lengths. The type and quality of the nonwovens are not only determined by the raw material itself but also essentially by the fact that they are a random arrangement of not oriented fibres that characterizes the structure from the fabric.<sup>8</sup>

This fibre layer is stabilized by mechanical (needle punching, air jet, water jet), chemical, or thermal processes. The individual fibres are connected or linked to each other in a detachable or non-detachable way (Figure 1.5).

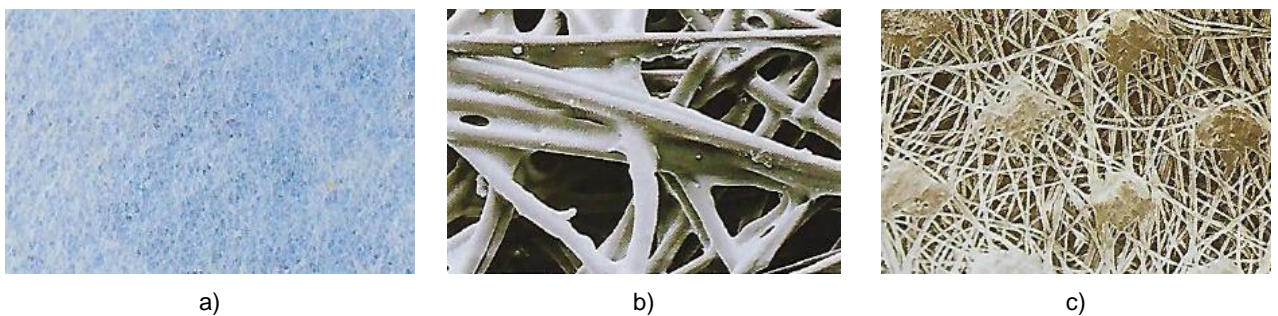


Figure 1.5: Structure of nonwoven fabric<sup>9</sup> a) random air laid, b) adhesive bonded, c)

## 1.2.3 Braided structures

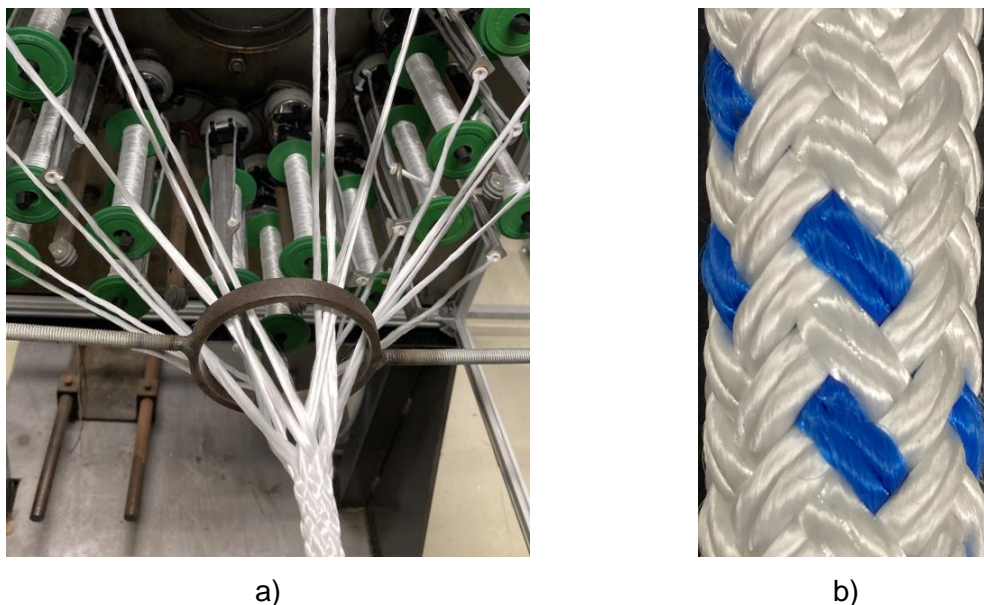


Figure 1.6: a) Braiding point in a braiding machine, b) braided rope

Braiding is a process of interlacing three or more threads diagonally to the product axis (parallel to the longest dimension of the resulting product) in order to obtain a thicker, wider or stronger product (Figure 1.6) or in order to cover (over-braid) some profile. Braids can

be linear products (ropes), curved or plane shell or solid structures (one, two or three-dimensional fabrics) with constant or variable cross-section, and of closed or open appearance<sup>10</sup>. DIN 60000 defines the term braids as:

Flat or solid structures with a regular thread density and a closed fabric appearance, the braiding threads of which intersect in an oblique direction to the fabric edges<sup>11</sup>.

#### 1.2.4 Knitted fabrics

Knitted fabrics are made by the interlocking of loops. In weft knitted fabrics the loops are formed by yarns traversing across the fabric width. In warp knitted fabrics the loops are formed by a set of yarns disposed along the fabric length<sup>9</sup>. The basic element of knitwear is the single loop which is containing no straight yarn elements. The loop is a true yarn reservoir and therefore a knitted piece of fabric can stretch in all directions.

### 1.3 Knitwear production technologies

#### 1.3.1 Basics

Knitted fabrics are textile fabrics in which a loop formed by a yarn is looped into another loop. The fabric produced in this way can be formed using one or more yarns. It is the generic term for textile fabrics in which at least one yarn is formed into knitted loops and the knitted loops interlock in loops<sup>12</sup>. Knitted fabric is specified as an indivisible yarn unit and, depending on the technology<sup>12</sup>.



Generic term for knitted fabrics in which loops made from each yarn are formed essentially over the width of the fabric<sup>12</sup>

Inlay-knitting machines (single yarn in course like Figure 1.7 a)

Generic term for knitted fabrics in which the loops produced from each warp are formed essentially over the length of the fabric<sup>12</sup>

Warp-knitting machines (each warp yarn is fed in wale with the direction of production like Figure 1.7 b)



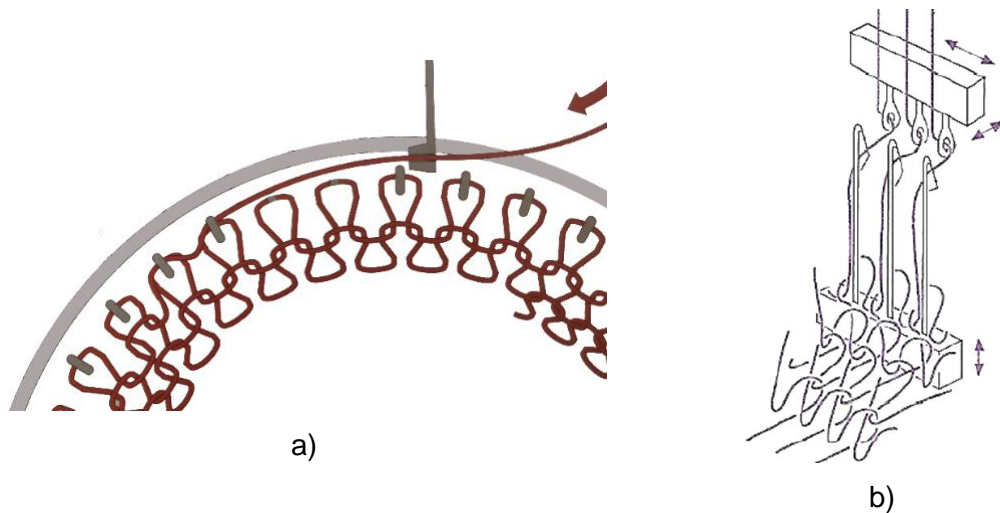


Figure 1.7: Sequence of loop formation during the knitting process for a) weft knitting process<sup>13</sup> and b) the warp-knitting process<sup>8</sup>

### 1.3.2 Inlay-thread technologies

Flat knitting machines:

- Single face,
- Double face,
- Purl knit (two individual single beds at 180 ° angle)

Circular knitting machines (large diameter)

Single jersey (cylinder),

- Double jersey (cylinder and dial),
- Purl knit (two cylinders single in alignment)

Circular knitting (small diameter):

- Single-cylinder socks machines,
- Body-size machines,
- Pantyhose machines,
- Double cylinder socks machines.

Technologies with multiple thread yarn beams, named wrap, (warp-knitting technologies).

Warp-knitting machines:

- Circular warp-knitting machines,
- Raschel machines,
- Crochet machines,
- Tricot machines.

## 1.4 Technical design of knitted fabrics

Knitted fabrics are made from interlocking loops or loops, formed from a single yarn or from multiple yarn ends<sup>8</sup>. The structure of a knitted fabric is built up from the various basic binding elements. The properties and the functionality of the knitted fabric are resulting from the arrangement of the individual structural elements within the area of the textile surface. The target of the technical product development of knitted products is to gain product satisfaction by combining the structural elements with the yarn properties.

### 1.4.1 Loop warp knitting

In warp knitting, a distinction is made between closed loops and open loops. If the underlaps before and after the considered loop are in opposite direction it is called a closed loop (Figure 1.8 a and b), if the underlaps are in the same direction it is called an open loop (Figure 1.8 c and d). Each loop has a face side (loop) and a back side (underlap). The side with loop legs is the technical face and the side with the underlaps is the technical back<sup>14</sup>.

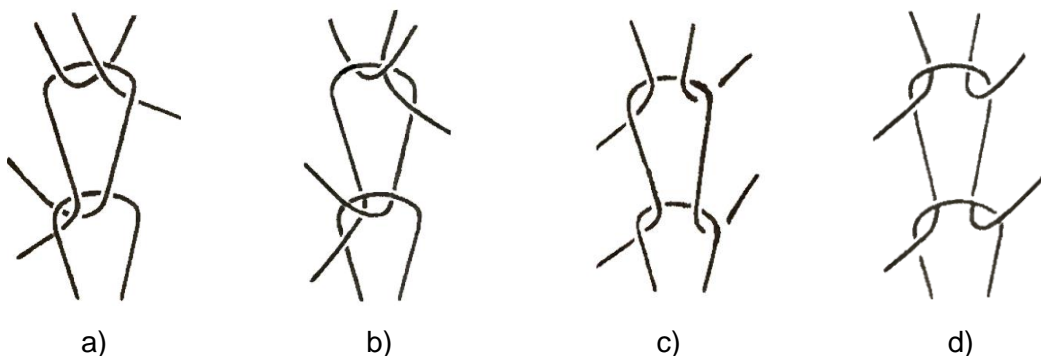


Figure 1.8: warp knitting basic structures: a) closed loop, technical face side, b) closed loop, technical back side, c) open loop, technical face side, d) open loop, technical back side<sup>14</sup>

The warp knitted loop structure is made of two parts. The first one is the loop itself, which is formed by the yarn being wrapped around the needle and drawn through the previous loop. This part of the structure is called an overlap. The second part is the length of yarn connecting the loops, which is called an underlap. It is formed by the shogging movements of the ends across the needles<sup>15</sup>. The loop is the basic structural element. It comprises a head (the needle loop), two legs, and two feet. The feet joining two adjacent loops form the sinker loop. Fabric is formed by intermeshing loops. Each loop has four intermeshing points in two pairs. The legs as a pair must always intermesh in the same sense; both legs lying either under or over the head of the preceding loop (Figure 1.9 a and b).



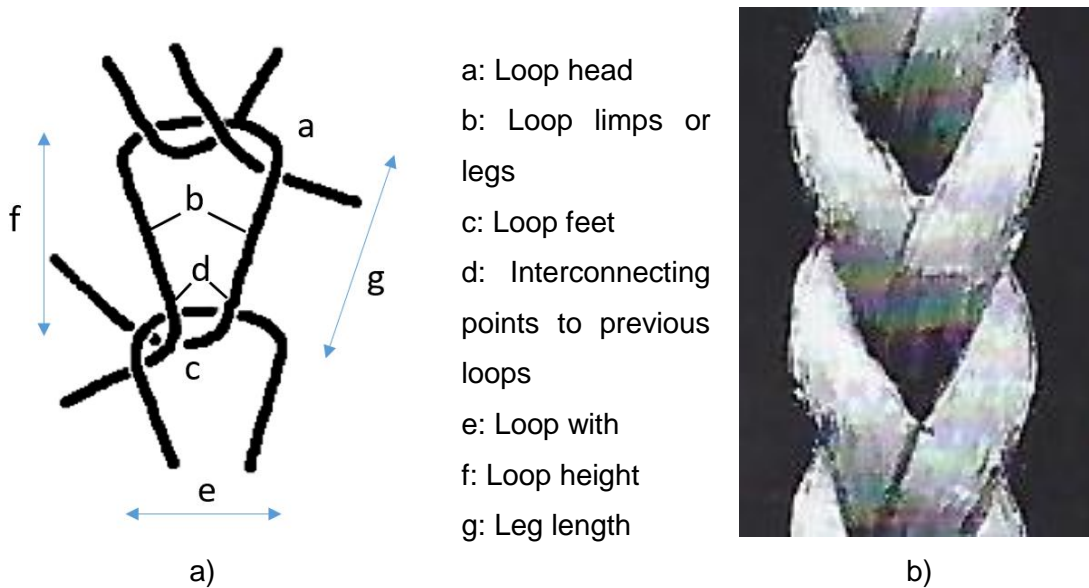


Figure 1.9: a) Warp knit closed loop face side<sup>14</sup> b) Large scale warp knit closed loop technical face side<sup>1</sup>

The dimensions in knitted fabrics are defined in courses and wales. A course is a horizontal row of loops formed by the needles during one knitting cycle. In warp knitting, all the needles perform the knitting action simultaneously, so that one knitted course is formed across the whole width of the knitting machine for every turn of the main shaft. A wale can be defined as a vertical column of loops formed by a single needle. The number of wales in the fabric equals the number of needles across the width of the machine<sup>15</sup>(Figure 1.10<sup>9</sup>).

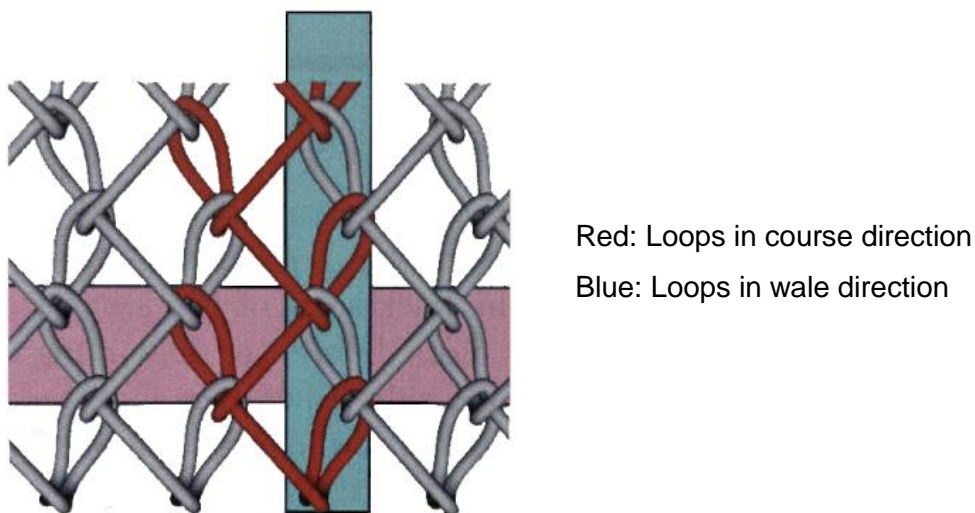


Figure 1.10: Warp knitted structure horizontal cours, vertical loops arranged in wales<sup>16</sup>

### 1.4.2 Tuck loop warp knitting

A tuck loop, comprises a held loop and a tuck loop, both intermeshed in the same course (Figure 1.11). The tuck loop is a thread loop with four binding points in different loop wales<sup>1</sup>.

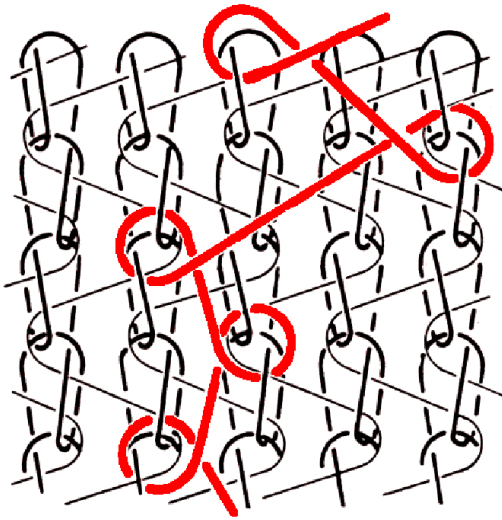


Figure 1.11: Tuck loop in warp knit<sup>1</sup>

### 1.4.3 Inlay yarn warp knitting

Float (miss) loop, a length of yarn not received by a needle and connecting two loops of the same course that are not in adjacent wales<sup>9</sup>. So it can also be described as a binding or non-binding yarn section between reversal points, tied in a loop course direction and held by right or left loops.<sup>7</sup>

A longitude of floats is leading to an inlay-yarn sequence. An extra (inlay) yarn is floated on the technical back possibly tucking at regular intervals. Usually, the inlay yarn is much coarser than the ground yarn<sup>9</sup>. Inlay yarns can extend over the knitted fabric width or only over limited areas.

It is specified either as full inlay-insertion Figure 1.12 a) or partial inlay-insertion (Figure 1.12 b). In the knitting sector, the terms float and partial inlay are overlapping. The term float is preferably used for a small number of needles, whereas inlay covers a larger fabric width.

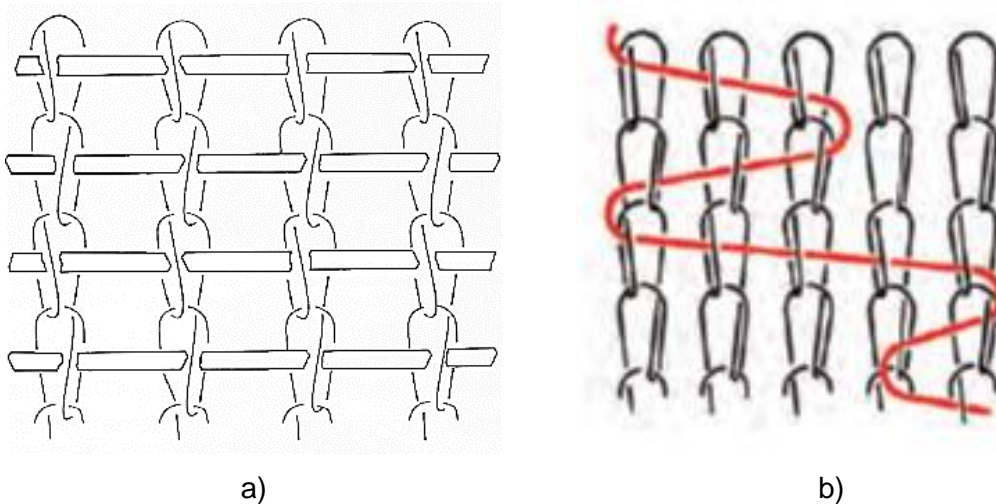


Figure 1.12: Single face warp knit a) full inlay-yarn insertion, b) Partial inlay insertion<sup>1</sup>

#### 1.4.4 Continuous miss lap

The miss lap as a mono-axial binding element is usually inserted by guide needles of a laying bar, whereby this laying bar only executes swinging movements without under lapping and over lapping<sup>1</sup>. Also defined as binding or non-binding yarn-bound in the wale direction held by right or left loops (Figure 1.13).<sup>1,6</sup>

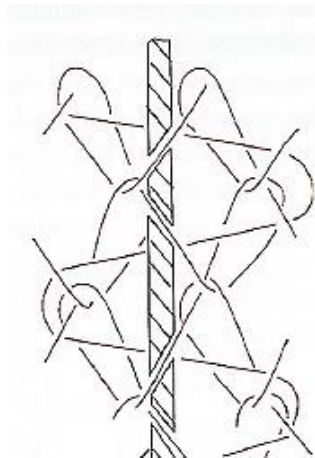


Figure 1.13: Continuous miss lap as mono-axial element in a single face warp knitted structure<sup>1</sup>

As an alternative to the subdivision previously described, the differentiation between the different structural elements in knitting are described by the principle process flow. Figure 1.14 illustrates this in the four basic working steps outlined below.

- laying-in
- loop forming
- forming bridges
- joining (creating binding units)

The principle of loop formation described in the four basic steps like yarn preparation, loop-formation, bridge building and connecting for the knitting, crochet and warp knitting process like described in Figure 1.14<sup>12</sup>.

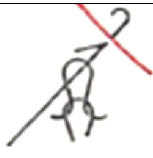







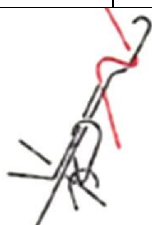

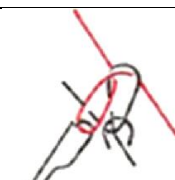
	Yarn preparation	Loop-formation	Bridge building	Connecting
Weft-knitting				
Crochet				
Warp-knitting				

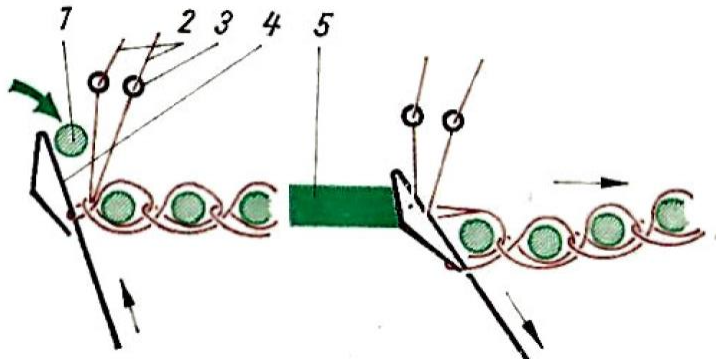
Figure 1.14: Principle of loop forming by the principle process flow<sup>17</sup>

## 1.5 Weft insertion in warp knitting machines

### 1.5.1 Basics

Laying-in technique is advantageous in technical, design, and commercial aspects. From the technical viewpoint, it allows yarns that otherwise cannot be knitted to be used. Yarn count is usually limited by the size of the needle hook and the space between the needle and the trick plates. By using laying-in techniques, any yarn capable of passing freely through the eyelet of the guides and between the needles during the swing can be inserted into the fabric<sup>15</sup>. The technical feature to place inlay yarns into the knitted structure is known to the weft- and warp-knitting industry.

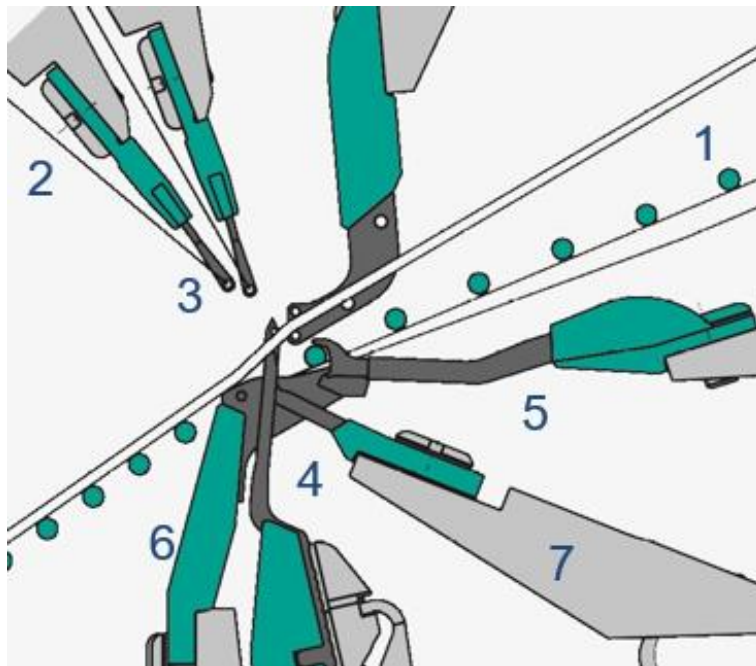
Warp knitted fabrics are made with at least one sheet of warp yarns. Each individual warp yarn is drawn through a guide needle (number 2 and 3 in Figure 1.15<sup>12,17</sup>). Which is mounted on a guide bar. Movements of the guide bar containing the guide needles (lapping) cause the yarn to be lapped around the needle (number 4 in Figure 1.15<sup>12,17</sup>). After the yarns are lapped, the needle bar is moved to cause loops to be formed simultaneously at all needles, resulting in a whole knitted course.



- 1: Inlay insertion yarn
- 2: Warp yarns
- 3: Guide needle
- 4: Bearded needle
- 5: Presser bar

Figure 1.15: Warp-knitting inlay-yarn system with special case of bearded needles<sup>17</sup>

The sideways movement from the guide needle bar (number 2, 3 in Figure 1.15 and Figure 1.16) by one or more needles before the next cycle produces another course. The shogging of the guide bar determines the structure of the fabric<sup>9</sup>.



- 1: Inlay yarn
- 2: Warp yarn
- 3: Guide
- 4: Compound needle
- 5: Inlay element/ feeder
- 6: Sinker
- 7: Stitch comb

Figure 1.16: View into a inlay- insertion warp-knitting machine<sup>18</sup>

It is possible for a weft yarn (number 1 in Figure 1.16), laid across the full width of the machine, to be carried forward by special weft insertion bits (number 5 in Figure 1.16) over the needle hooks and deposited on top of the overlaps on the needles (number 4 in Figure 1.15 and Figure 1.16) and against the yarn passing down to them from the guide bars. In this way, the inserted inlay will become trapped between the overlaps and underlaps as an inlay yarn when the needles rise and will run horizontally across the complete course of loops<sup>19</sup>. Then the inlay thread is fixed into the warp knitted fabric when the following loop is made<sup>4,17</sup>.



The inlay yarn is stretched out and motionless when it is inserted in the knitting area as it is preplaced in the intermediate storage system.

To allow a parallel inlay-yarn insertion (number 1 in Figure 1.17), the placing systems need to perform a movement pattern along the machine axis and perpendicular to it. This transportation chain includes their yarn supply and placing components for example a carriage is working independently driven from the machine cycle. The transportation speed from the magazine chain needs to be directly synchronized to the production speed from the machine to have a prepared inlay yarn for every knitting cycle required.

The remaining inlay yarn, as waste yarn, which is wrapped around the transportation hooks is automatically cut and disposed of (number 2 in Figure 1.17).



Figure 1.17: Inlay-yarn feeding in a warp-knitting machine

This technique (Figure 1.16 and Figure 1.17) is less restrictive for fancy and irregular yarns as inlay (Figure 1.12) and, as a weft covers the full fabric width, yarn can be supplied from individual packages. It has the major advantage that weft can be prepared and laid in advance of the timing of the insertion, so that it has less effect on the knitting machine speed. Inlay threads are inserted perpendicularly to the loop forming warp thread systems at a 90° angle to the machine axis. This results in a unidirectional influence on the fabric parameters for example higher fabric stability or elasticity achieved in the weft direction<sup>19</sup>. Technical applications for inlay fabrics are for example in the medical textiles elastic warp knitted bands<sup>20</sup>, medical corsets<sup>21</sup> or multi-layered fabrics of different layers which has the ability to complement and maximize the essential comfort properties for a bed linen<sup>22</sup>.

### 1.5.2 Production cycle of inlay-yarn insertion in warp-knitting

The loop forming process from a warp-knitting machine is cyclical. The machine cycle from a warp-knitting machine is defined by a 360° rotation from the main machine drive shaft. The speed of a warp knitting machine is defined by the number of main shaft rotations per minute (rpm). Each revolution creates one course of loops. The machine

cycle from a warp-knitting can be split up into the following - constantly and contiguous repeating - sequential operational steps:

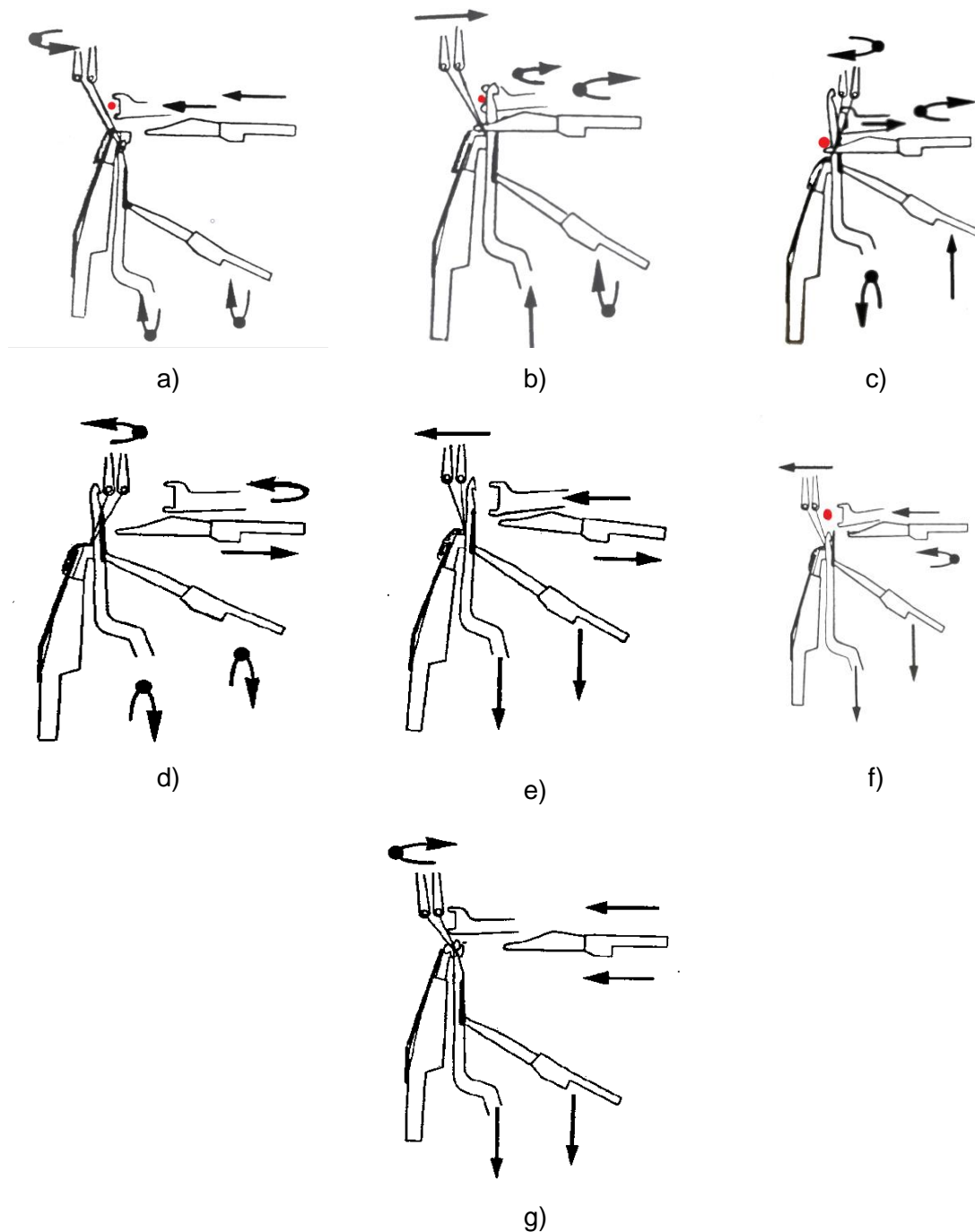


Figure 1.18: Production cycle inlay-yarn insertion warp-knitting machine with a) Preparation/Underlap, b) Enclosing loop/Placement weft yarn, c) Swinging in/Overlap, d). Swinging back/Sinkers retreat, e) Swinging back/weft yarn preparation, f) Casting on, g) Loop formation/New weft placement<sup>15</sup>

a) Preparation/Underlap

The needles are in a knock-over position. The guide bars are at the back of the needles, performing the underlap shogging movement. The sinker bar is moving forward to secure the fabric and the weft yarn inserting device is in its foremost position (Figure 1.18 a)<sup>15</sup>.

The inlay yarn, held in position by the placing element (number 5 in Figure 1.16) is placed on the back side of the needles<sup>15</sup>.

b) Enclosing loop/Placement weft yarn

The needles rise while the closing elements stay down to allow the hooks to open. The sinkers are in the forward position, securing the fabric, which is held by the take-up tension. The guide bars begin their forward swing movement into the lines of the needles (Figure 1.18 b)<sup>15</sup>. The weft yarn is at the back of the needles<sup>15</sup>

c) Swinging in/Overlap

The needles are in the clearing position. The closing elements rise slightly but do not close the hooks. The guide bars on the hook side of the needle shog sideways to produce the overlap. The weft inserting element is moving backward to collect a new weft yarn (Figure 1.18 c)<sup>15</sup>. The inserted weft yarn is now locked between the back of the needles and the warp yarns<sup>15</sup>.

d) Swinging back/Sinkers retreat

The guides start to swing back, and the needles descend. The sinkers retreat and the inserting elements turn forward (Figure 1.18 d)<sup>15</sup>. The inserted weft yarn is now locked.

e) Swinging back/weft yarn preparation

The guides swing back to the front of the machine, wrapping their yarn around the needles which start to descend (Figure 1.18 e)<sup>15</sup>. The weft yarn inserting element moves the new weft yarn towards the knitting zone<sup>15</sup>.

f) Casting on

The compound needles descend so that the closing elements close the hooks. The newly wrapped yarns are within the hook, while the loops of the previous course slide outside the closing elements. The needles and closing elements continue to descend simultaneously (Figure 1.18 f)<sup>15</sup>. The weft inserting elements continue to deliver the next weft yarn towards the knitting zone<sup>15</sup>.

g) Loop formation/New weft placement

The needles and needle slides are in the lowest position and draw the newly wrapped yarns into loops. The sinkers start to move forward<sup>15</sup>. The weft inserting elements place the yarn behind the line of the needles (Figure 1.18 g)<sup>15</sup>.



## **1.6 Time line of developments inlay-yarn insertion technologies**

The technology of warp-knitting is the youngest developed process in knitting technology, especially if compared with weaving or weft-knitting<sup>15</sup>. However, devices to insert an inlay thread in warp-knitting machines were already existing between the first and the second world war<sup>23</sup>. Various complex inlay-yarn insertion technologies combined with highly productive production warp-knitting machines had been developed. Partial inlay-yarn insertions over a limited number of needles are realized by the pattern thread guide systems like string bars<sup>1</sup>. The incorporation of continuous weft insertions over larger widths requires a different method of yarn feed into the knitting point<sup>4,17</sup>.

The preparation from the inlay-yarn insertion is carried out preoperational for all insertion technologies besides the gripper technology. The thread is placed into the holding elements (clamps or hooks) from a constantly moving transporting device like a chain.

In the following major technologies used for weft insertion independently of the process, i.e. weaving or knitting are discussed

### **1.6.1 Gripper or rapier method**

A constant forth and back moving mechanical yarn guide gripper transports the inlay yarn along the machine axis over the width of the fabric. The inlay yarn is inserted by the gripper into a yarn fixing (holding) device at each side of the fabric, additional support to hold and fix the inlay yarn at the fabric edges is required. The following two systems have been realized in different technological versions depending on machine builder and application.

#### **1.6.1.1 Single rapier loom**

The single rapier loom is using only one rapier to insert the weft yarn in the shed. Before entering the shed, the gripper (feeder gripper), while moving to the right, grasps the yarn presented by the selector lever with its open clamp (number 1 in Figure 1.19). Scissors cut the yarn from the fabric edge. The transfer of the yarn from the left to the right hook takes place in the centre of the machine. After transfer, the pick-up gripper brings the weft to the right edge of the fabric<sup>24</sup>.

The travelled distance of the rapier gets equal to the reed space used in the loom. This kind of loom works at a very low speed. The warp yarn exerts high pressure on the rapier.

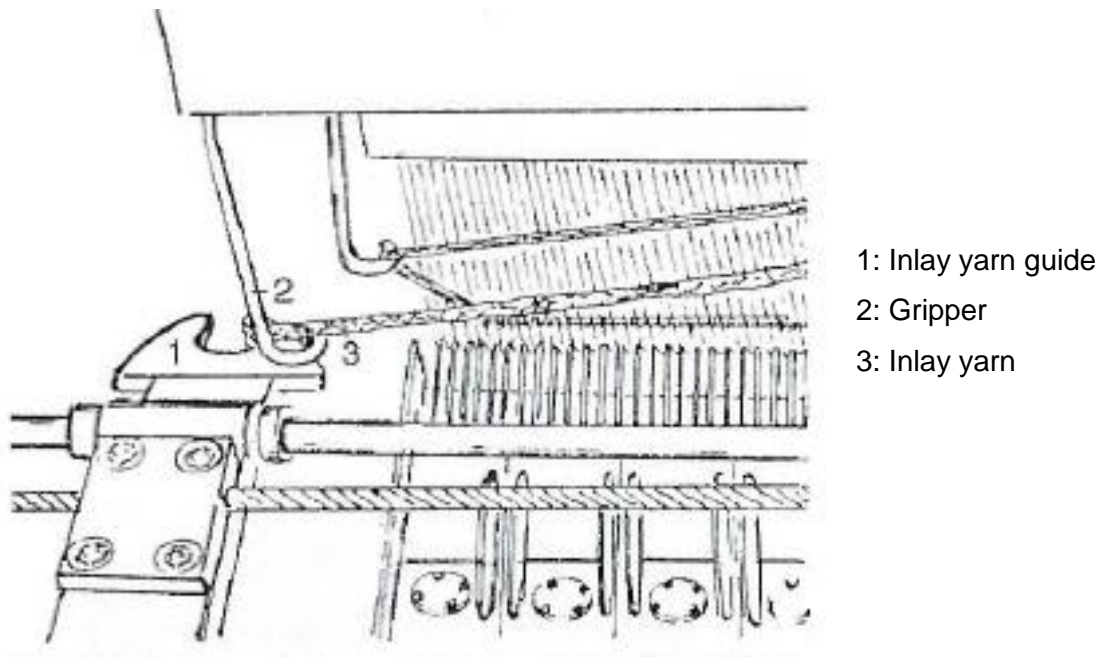
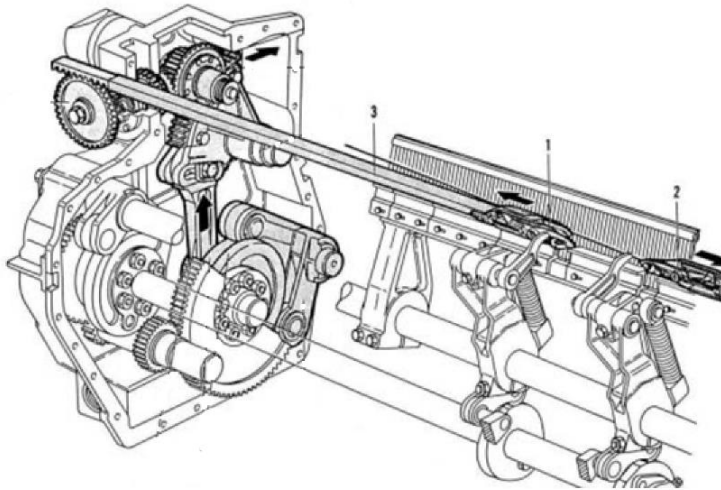


Figure 1.19: Gripper inlay-yarn insertion single rapier loom<sup>17</sup>

### 1.6.1.2 Double rapier loom

The double rapier loom in which the weft insertion in the shed is carried out with the help of two rapiers. The left-hand gripper (number 3 in Figure 1.20) grips the yarn presented by the filling selector needle with an open clamp; the clamp then closes immediately while scissors cut off the filling at the fabric side. The “handing-over” gripper then moves to the centre of the weaving shed to transfer the yarn to the right-hand rapier (number 2 in Figure 1.20). This active transfer is controlled positively, that is, say the gripper clamps are each opened briefly for the yarn transfer, but the “handing-over” gripper does not release the filler yarn until the yarn is securely clamped in the “taking over” gripper. The yarn is then transported to the right-hand edge of the fabric. There, the gripper clamp releases it again after it has been firmly secured by the catch selvedge. The weaving shed remains open throughout the entire insertion phase<sup>24</sup>. Double rapier looms run at very high speed. The pressure of the warp yarn on the rapiers gets reduced up to a maximum extent. The stretched-out yarn segment is pushed into the knitting elements to be fixed from the loops made with the warp yarns. This process can be either directly synchronized with the machine cycle or can feed the weft yarn into a transportation chain system.



- 1: Grab bar
- 2: Gripper (taking over)
- 3: Gripper (handing over)

Figure 1.20: Gripper system with double rapier grab bar in a weaving machine (System Sulzer)<sup>25</sup>  
 The yarn feeding is done directly from an individual yarn package.

### 1.6.2 Traversing yarn positioning eyelet

The positive or frictional connection between the yarn guide and its drive is rigid. The design requirement is that the force acting on the yarn guide should be at least equal to, or greater than, the respective yarn resistance. The task is solved by arranging a means of transport to take the yarn guide along a path parallel to the yarn storage (Figure 1.21).

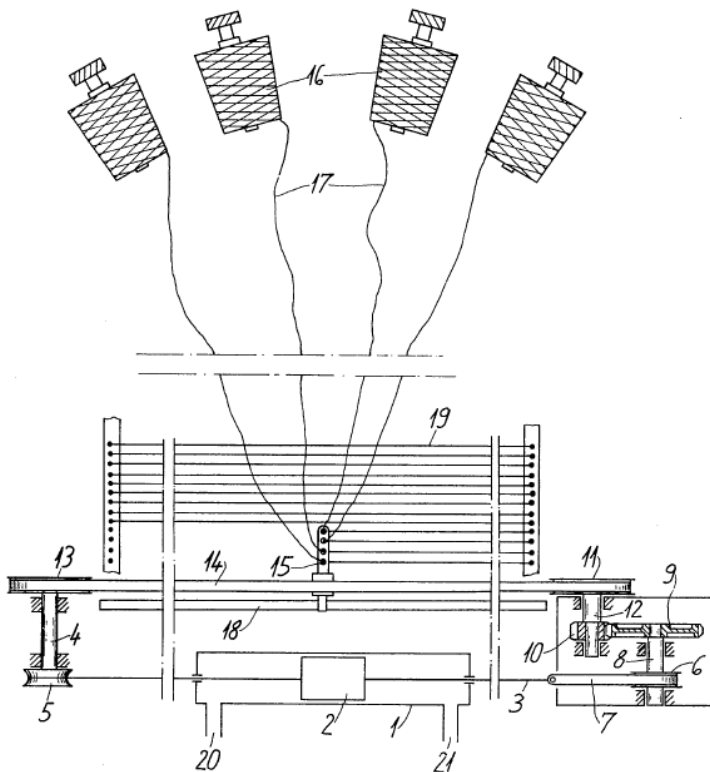


Figure 1.21: Pneumatically driven inlay-yarn insertion<sup>26</sup>

This can be achieved by a pneumatic-mechanical drive for inlay-yarn insertion. The transport means is a piston that moves back and forth in a cylinder and which is pneumatically, preferably compressed air-operated. The piston is fixed synchronized with the yarn guide by mechanical transmission means.

A mechanical drive for inlay yarn insertion using an endless traction element can be provided by a lever system via a toothed segment and a two-part toothed wheel stage, which is driven by the main machine shaft (Figure 1.22). The lever system consists of a crank, a swing arm, and a coupler as well as an angle lever, whereby the gear elements are assigned articulation points and a coupling point. The coupling point of the coupler connected to a swing arm describes a cinematically defined coupling curve.

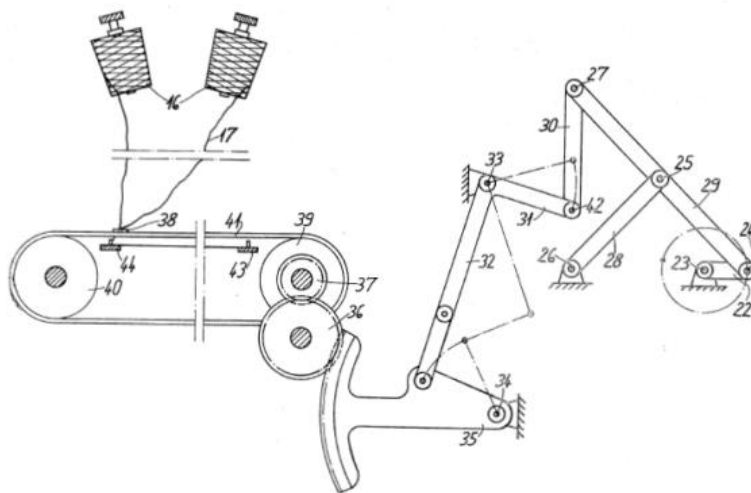


Figure 1.22: Mechanical inlay-yarn insertion via toothed segment<sup>26</sup>

A further development is based on a gear coupling gear for driving the traction element for the yarn guide, whereby the coupling gear is designed as a multi-part lever system consisting of a crank, a lever arm, and a rocker (Figure 1.23).

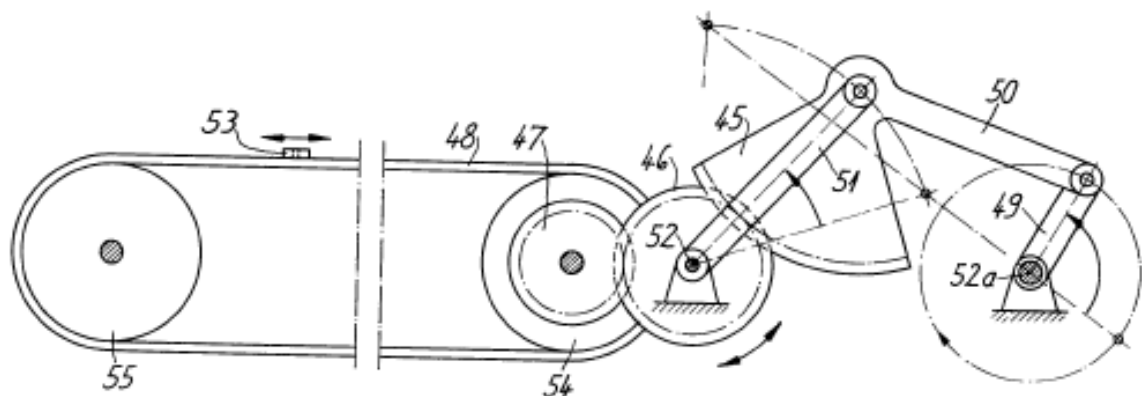


Figure 1.23: Mechanical inlay-yarn insertion via a gear coupling<sup>26</sup>

There is no fixed connection between the rocker arm, which is mounted in a moving bearing, and the pinion. In this case, too, the endless traction element carrying the yarn guide runs over a driven and a non-driven pulley.<sup>27</sup>

### 1.6.3 Rotating yarn guide rod

The inlay yarn is placed by a rotating yarn guide rod into hooks from a moving chain or a rotating wheel with fixing elements. The rod is rotating parallel to the machine axis (Figure 1.24). This chain or the wheel leads the threads into the knitting elements. The rod rotates at a constant distance circular around the thread transporting chain or wheel. Due to the matching rotation speed, the continuously moving transport chain and the speed of the warp-knitting machine, the out-stretched and parallel inlay-insertion thread reaches the knitting elements in time<sup>17</sup>.

The yarn feeding is done directly from an individual yarn cone.

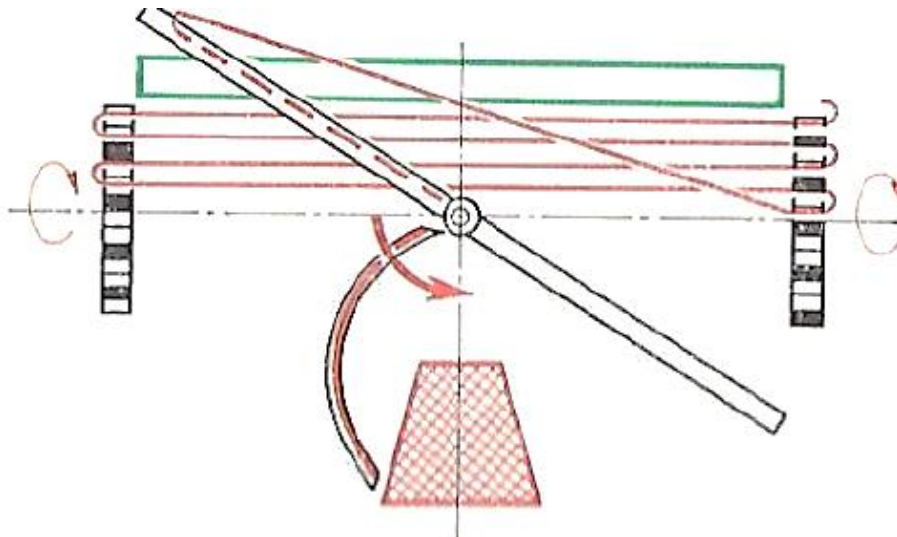


Figure 1.24: Inlay- insertion rotation thread guide bar<sup>17</sup>

### 1.6.4 System of moving (rotating) yarn cones.

The inlay yarn is withdrawn simultaneously from several, but phase-shifted moving, yarn cones (Figure 1.25 a). The cones move at a constant distance in an ellipse shape around the thread transporting chain. The yarns are supplied directly from the rotation cones without any intermediate storage feeder. Due to the matching speed of the yarn cones, the continuously moving transport chain and the speed of the warp-knitting machine the out-stretched and parallel inlay-insertion thread reaches the knitting elements in time.

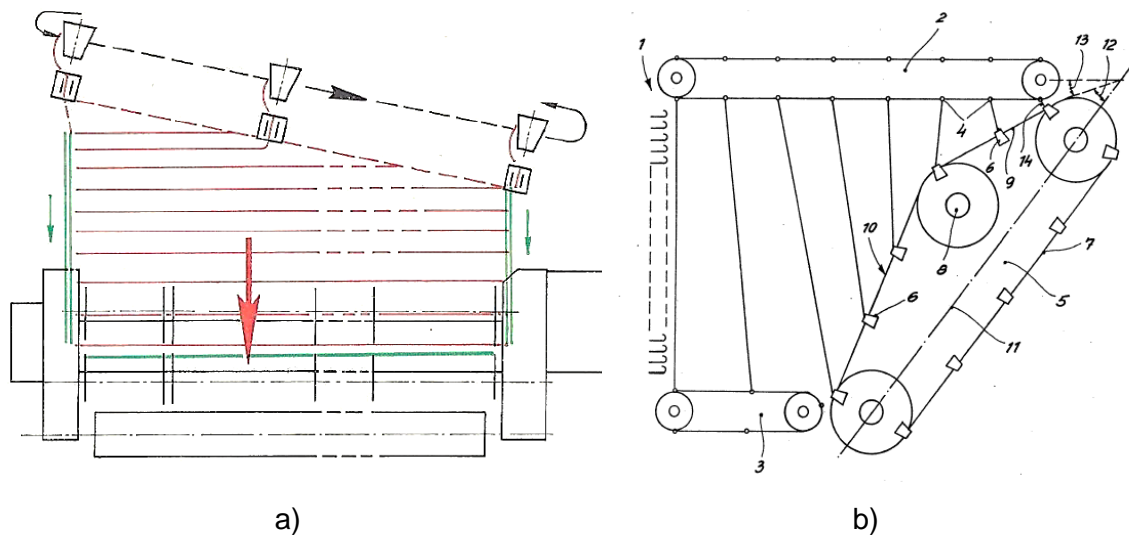


Figure 1.25: Inlay-inserting a) by rotating cones parallel to the machine axis<sup>17</sup>, b) by rotating cones<sup>28</sup>.

The inlay yarns must be placed in an additional intermediate storage mechanism such as transportation and placing chain. It is important to maintain the yarn separation from each other and the yarn tensile force level to achieve that (Figure 1.25 b). As soon as the yarns have been spread to their full length, they are already located near the needle bar. Then utilizing a conventional cutting device the yarns are cut and, by using a conventional gripping device, they are transferred towards the needle bar<sup>29</sup>.

### 1.6.5 Simultaneous withdrawal of inlay yarns from fixed bobbins "Magazine Weft Insertion Warp Knitting system" (MIS)

A yarn magazine for the cones from the inlay yarns is arranged on a warp-knitting machine. The yarn supply is done directly from the yarn cones on the fixe creel, via storage feeders. First developments show the fixed arranged yarn cones and the simultaneous inlay-yarn preparation and supply means of a direct chain storage system (Figure 1.26). The inlay yarn had to be cut on both sides of the fabric and inlay insertion was only possible over the whole width from the machine.

Later developments result in an inlay-yarn laying carriage (Figure 1.27) that moves transversely, reciprocates between the holding devices/clamps and transports the inlay yarns from one edge of the transportation chain to the other (Figure 1.28 a). It inserts a group of inlay yarns (current state-of-the-art is up to 30) simultaneously into the hooks/clamps from the constantly moving and transporting storage magazine.

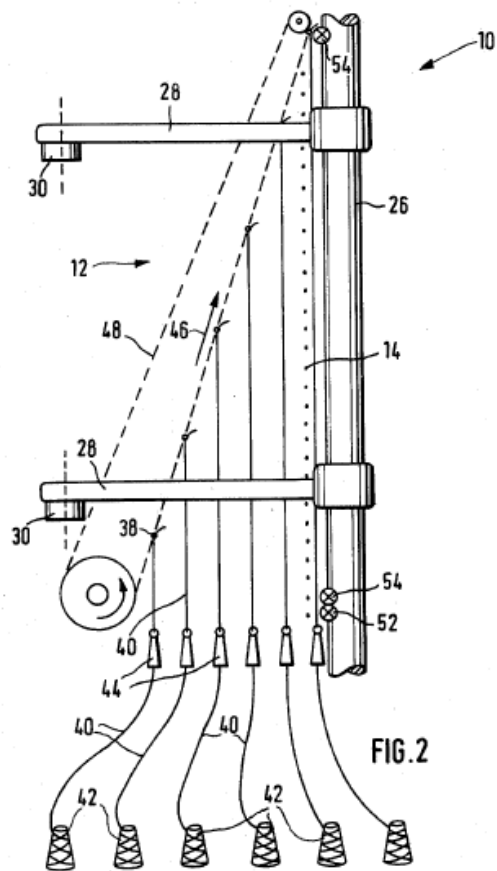


Figure 1.26: Inlay- inserting by rotating cones<sup>30</sup>

This magazine includes a pair of endless transportation means like chains or belts, each having holding devices for retaining inlay yarns in a parallel manner and delivering them to the knitting area (Figure 1.28 b). Therefore, the yarn movement is slow and smooth but this system needs large, complex, and heavy equipment to operate around the machine. When the transfer chains and the carriage continue to move, this has the desired effect that a group of inlay yarns is either laid or not laid, that the inlay yarns can be laid with different diagonal angles, or that the inlay yarns can be laid, by choice, parallel or diagonally<sup>31</sup>.

Moreover, it is impossible to change the width of insertion, which is fixed to the width of the machine. This chain brings the stretched-out insertion threads continuously towards the knitting elements (Figure 1.28 b). The MIS system represents the current state-of-the-art weft insertion warp knitting machine technology.



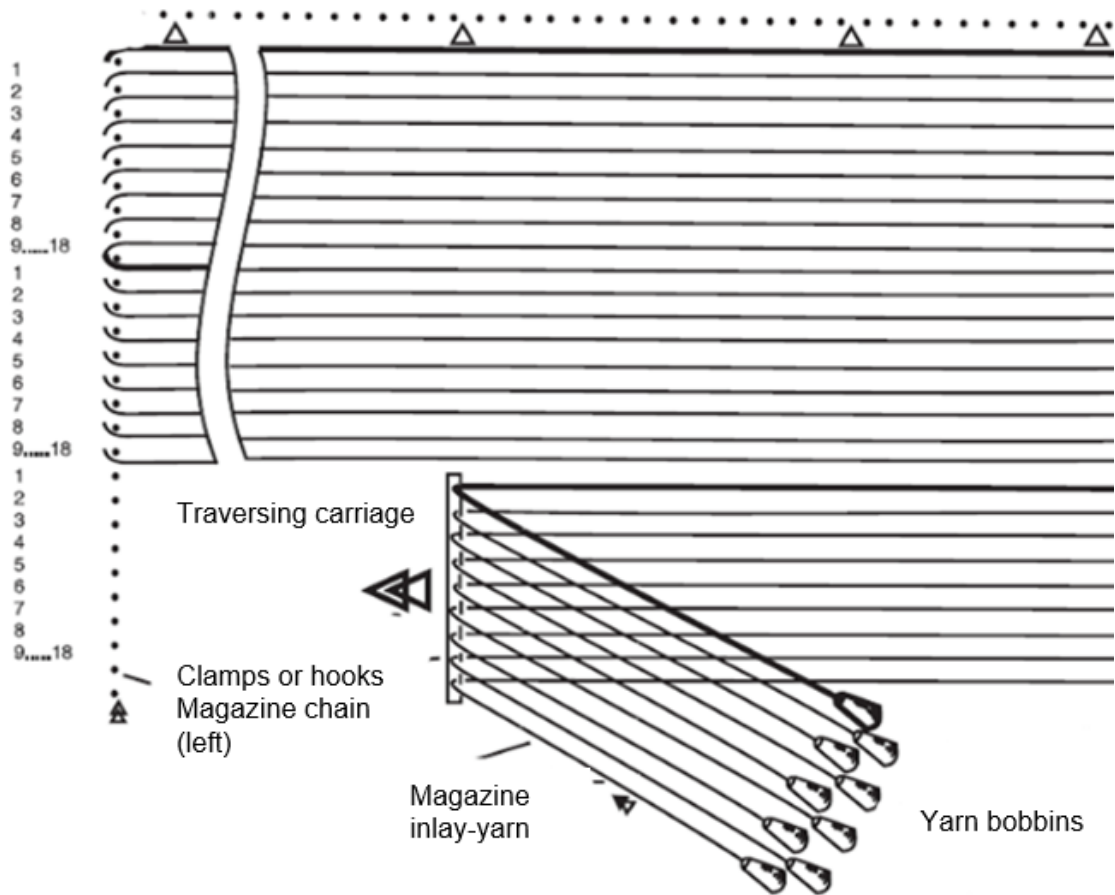


Figure 1.27: Magazine insertion system layout<sup>32</sup>

The group of yarn guides attached to the yarn carriage (Figure 1.27 and Figure 1.28 a) is performing a diabolo-shaped movement.

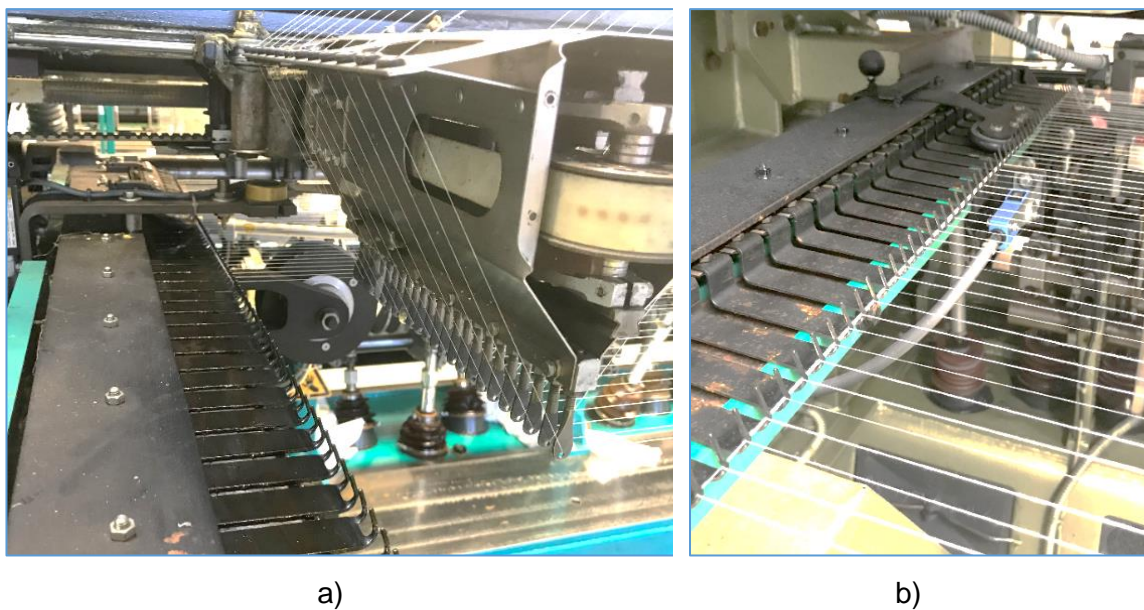


Figure 1.28: a) Yarn placing carriage Karl Mayer MSU Company Rökona, Tübingen b) Inlay-yarns in the transportation chain Karl Mayer RS-4 MSU at University of Applied Science



In the direction from the machine axis during the insertion of the inlay thread and for the preparation of the thread. Transversally it moves to compensate for the offset movement from the transportation chain. This offset and the continuous withdrawal of the thread from the yarn cones result in cut waste from the inlay yarn. This cut waste is getting bigger the more yarns are prepared simultaneously. Based on the coordination of the speed from the feeding carriage with the speed of the warp-knitting machine, an inlay-thread course that is inclined relative to the warp yarn alignment, can also be achieved (Malimo technology)<sup>1</sup>.

### 1.6.6 Two belt drive system

It is a transport system for weft yarns in the machine axis direction. The weft yarn transport comprises transport devices that are spaced apart from one another and which comprise, in the machine direction, two constantly moving belts (Figure 1.29 a and b)<sup>33</sup>. They are equipped with transportation hooks which are used to grab the inlay yarn from a fixed bobbin on a creel and to insert it in the transportation means from a constantly moving chain. The two belts are driven by two independent motors. The traversing element is feeding one yarn end at a time.<sup>34</sup>

The transportation chain is then presenting the stretched-out inlay yarns to the knitting elements.

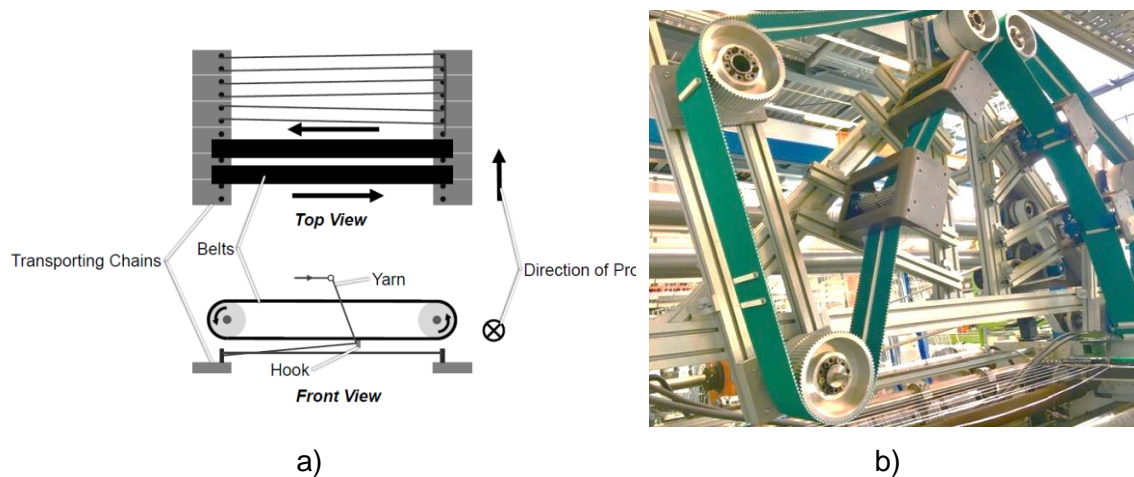


Figure 1.29: a) Inlay yarn insertion principle with two belts in opposite direction<sup>34</sup>. b) prototype unit<sup>33,34</sup>

Figure 1.30 and 1.31 a)-h) show the cyclical process flow in subsequent steps. Both belts are constantly moving. In Figure 1.31 a) the transportation hook from the right belt is grabbing the inlay yarn. It is handed over to the holdings means from the right transportation chain in Figure 1.31 e). In Figure 1.31 f) the hook from the left belt is grabbing the inlay yarn and transporting it to the corresponding holding means from the left chain (Figure 1.31 e-h). The cycle is repeating itself. Figure 1.31 b) shows the prototype unit for the two belt system.

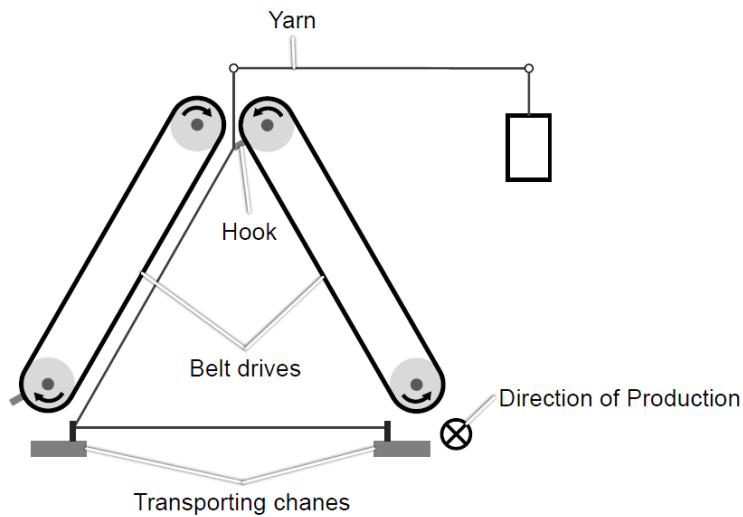


Figure 1.30: Set-up two belt drives running in opposite directions<sup>34</sup>

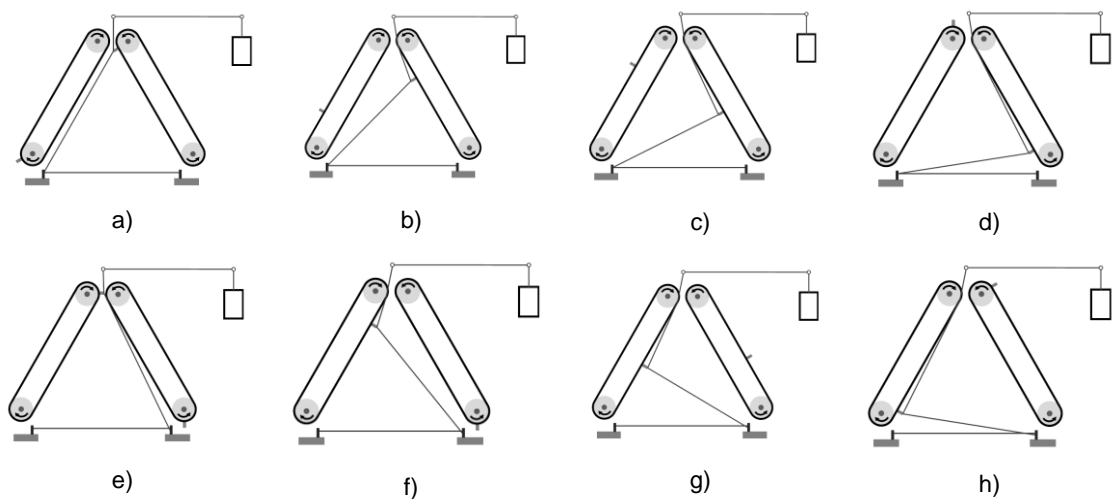


Figure 1.31: a-h) Movement diagram two belt drives running in opposite directions<sup>34</sup>

### 1.6.7 Stringbar Technology

The string bar technology is developed for the simultaneous use of many different, in pattern arranged, yarns. In this technology, the individual pattern guide bars are replaced by thin wires and the yarn guides are glued on where needed (Figure 1.32). A string bar unit can consist of 12 wires in two offset levels.

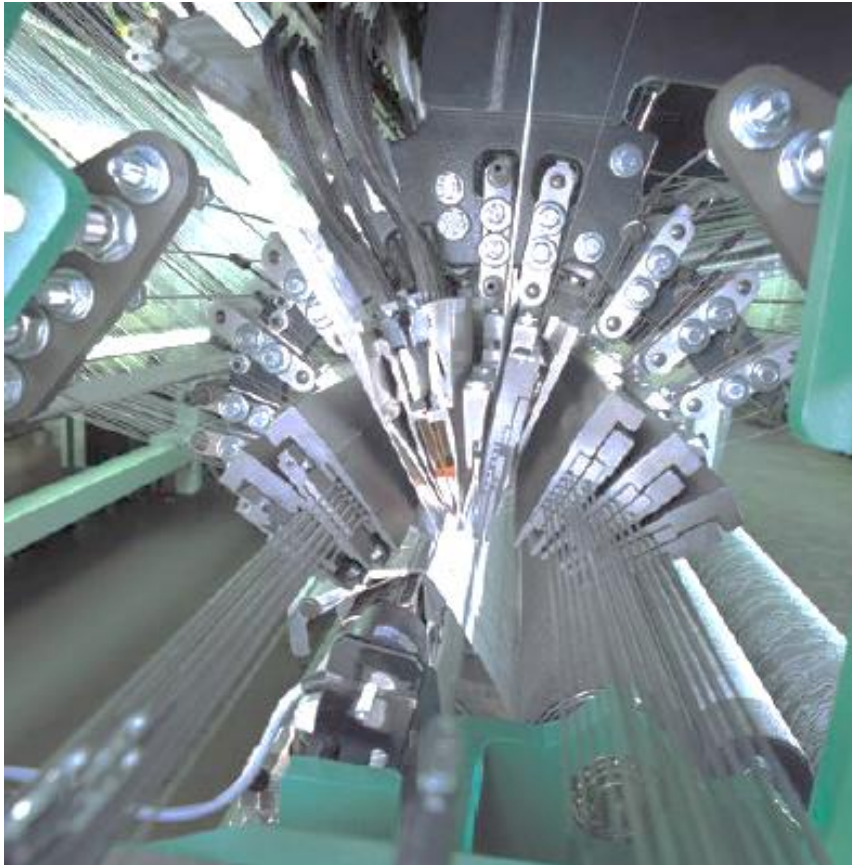


Figure 1.32: Arrangement from string bars in a warp-knitting machine<sup>35</sup>

The total wrap angle of the strand from the wire to the mesh-forming area is approximately  $300^\circ$  and increases the yarn tensile force and increases the risk of yarn damage or breakage.

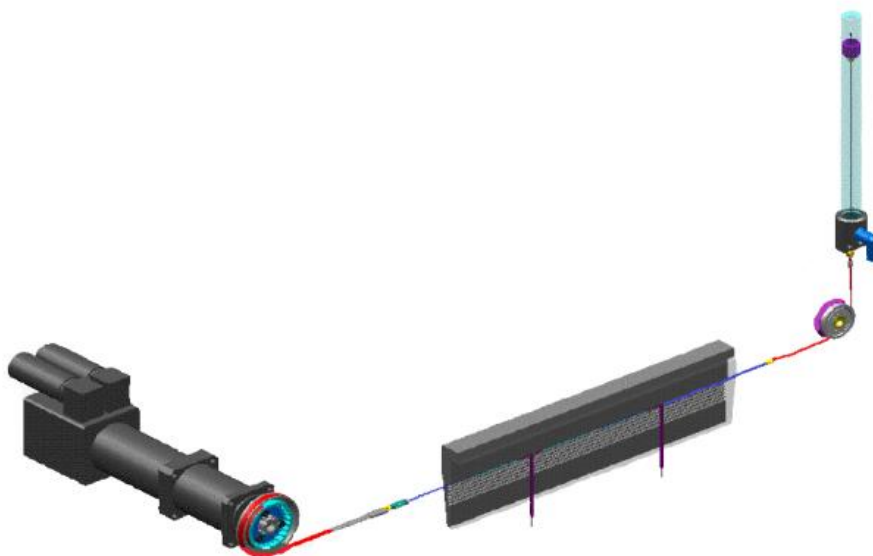


Figure 1.33: Principle set-up string bar technology<sup>35</sup>

By using different string bar units, up to 92 pattern guide bars can be used on these machines. The drive and thus the positioning of the wires (strings) is done by laterally arranged stepper motors with a counteracting gas pressure spring at the other end (Figure 1.33)<sup>1</sup>. The string bar is tensioned with uniform force over the entire offset range component. Each string is controlled by a single motor (energy consumption)<sup>36</sup>.

## **2. Comparative analysis of the available systems for possible weft insertion**

The various inlay-yarn insertion systems known from literature and the state-of-the-art are evaluated, assessed, and compared according to various criteria. The task of all developments in the past was always to increase the production speed (defined by the increase of the number of placed inlay yarns per minute) and by maintaining or increasing the stability of the insertion process. To control the warp insertion process it is very important to control the insertion yarn in its:

- Movement,
- Vibration (lateral and longitudinal),
- Positioning.

All initial attempts to change the insertion technology away from alternating transversal movements from the yarn supply units failed or never made inroads into the industry. Either the yarn bobbins had to be moved or large, complex, and heavy equipment had to operate around the machine. The magazine inlay process requires a carriage system that traverses in the form of a diablo. The carriage is inserting the inlay yarn into the transportation system with clamps or hooks at both edges of the fabric (transportation chain). This transportation and storage chain is constantly moving and presents the prepared and stretched inlay yarn to the knitting zone. The stretched-out inlay yarn is inserted into the knitting area utilizing additional insertion elements. These insertion elements are directly driven from the machine's main drive shaft and are synchronized to the knitting cycle. The insertion elements also dampen the transversal and longitudinal vibrations from the prepared inlay yarn. The elements are placed in a separate bar at a distance of approximately 12 cm to each other over the whole width of the machine.

An increase of speed for this technology was achieved by increasing in the transportation chain the number of simultaneously inserted yarns. However, the possible maximum speed from the inlay process defines the maximum possible machine speed from the warp knitting machine.

The string bar technology is used to place an individual inlay yarn in the designated parts of the fabric according to the given pattern. The movement from the inlay carrier is individually controlled for every course of the fabric. There is no additional transportation system required.

## 2.1 Evaluation of the criteria used

The criteria are selected to evaluate the multiple different technical approaches from the historical developments which had not been followed up to the actual state-of-the-art, which is the magazine storage system. These criteria are assessing all major impacting factors of the inlay process in warp-knitting machines in respect of stability, reliability, process costing, sustainability, and environmental protection.

For the technical comparison, overseeing the technical solutions described in chapter 1.6, the following parameters are chosen because their significance in the warp knitting process:

- Number of yarns,
- Yarn speed,
- Moved masses/inertia,
- Energy consumption,
- Process stability/ Complexity.

### 2.1.1 Number of yarn ends

The magazine insertion system in state-of-the-art warp-knitting machines works with up to 30 ends of yarn simultaneously. For the research and comparison, the Karl Mayer RS 4 MSU N with 18 yarn ends used at the laboratory from the University of Applied Science is used. The other systems are counted in respect of the figures found in the literature (Table 2.1).

	Number of simultaneous inserted yarn ends
Gripper method	1
Traversing yarn positioning eyelet	4
Rotating yarn guide rod	6
Rotating yarn cones	6
Magazine Insertion	24
Double belt system	4
String bar technology	1

Table 2.1: Number of yarn ends

### 2.1.2 Yarn speed

The supply speed to present inlay yarn under the above-mentioned conditions is limiting the speed of the warp-knitting machine. To ensure a constant yarn speed under a controlled tensile force level the yarn supply is made via individual storage feeders

between the creel and the warp knitting machine. These feeders eliminate firstly all negative influences on the inlay-insertion process caused by irregularities in the condition of the yarn cone or bobbin. They also equalize all added yarn tensile force, due to friction at deflection angles, in the yarn path from the cone to the warp-knitting machine.

The inlay yarn must be supplied to the warp-knitting machine:

- In the proper timing to the machine cycle,
- Straightened out over the required insertion area,
- Parallel to the machine axis,
- In the proper length,
- With the correct yarn tensile force,
- Damped, without transversal or longitudinal vibrations.

The number of simultaneously inserted yarn ends is characterizing the different insertion technologies, this is affecting the speed from the individual yarn end.

The overview of the simultaneously handled inlay yarn ends from different inlay methods is described in Table 2.1.

For all yarn speed calculations and to make the results comparable the standardized machine setting parameters (SMSP) described in Table 2.2 are estimated and used for the yarn speed determination.

Machine width ( $W_M$ )	300cm
Waste at fabric edges ( $W_w$ )	10cm
rpm main machine shaft	1.000rpm
Number of yarn ends	1

Table 2.2: Standardized machine setting parameters (SMSP)

During the warp knitting process, the machine's main drive axis is rotating constantly. As the inlay yarn needs to be placed directly behind the raising needles there is only a defined time window available. According to measurements at the Karl Mayer MSUS machine with MIS system in the laboratory from the Niederrhein University of Applied Science the time window for the insertion of the inlay yarn is only approximately  $\alpha_i = 47^\circ$  main drive revolution angle out of the complete machine revolution corresponding to angle  $360^\circ$  main shaft revolution.

Yarn speed calculation from different methods:

The theoretical yarn speed ( $v_t$ ) is calculated based on the machine speed and the available time frame (angle of revolution  $\alpha_i = 47^\circ$ ) to insert the yarn in relation to the complete revolution ( $\alpha_g = 360^\circ$ ) of the main shaft.

The theoretical available insertion time for one inlay-yarn is calculated according to Equation 1.

$$t_i = t_r \cdot \frac{\alpha_i}{\alpha_g} \quad (1)$$

With:

$t_i$ : theoretical inlay insertion time in s,

$t_r$ : time for one machine revolution, in the present case the machine has 1.000 rpm, therefore it is 0.06 s,

$\alpha_g$ : angle for a complete machine revolution, set to 360°,

$\alpha_i$ : available angle of revolution for the inlay-yarn insertion, in the present set-up set to 47°.

According to Equation 1 and the given parameters the time  $t_i = 0.008$  s/revolution:

$$v_t = \frac{(W_W + W_M)}{t_i \cdot n} \quad (2)$$

With:

$v_t$ : theoretical insertion yarn speed in m/s,

$W_M$ : working width from the warp-knitting machine in m,

$W_W$ : waste yarn in m,

$n$ : number of simultaneously inserted yarn ends (dimensionless).

Based on the values from Table 2.4 and Equation 2  $v_t$  results in 400 m/s.

The individual yarn speed for the inlay insertion system depends on the number of yarn ends  $n$  supplied simultaneously into the warp-knitting machine (Equation 3):

$$v_i = \frac{v_t}{n} \quad (3)$$

With:

$v_i$ : Individual inlay yarn speed in m/s for the different cases from a to f described below and g for string bar technology.

This value represents the average yarn speed based on the assumption a single yarn end only, is inserted in one traversal movement.

#### a. The gripper method and the string bar system

The gripper method and the string bar system are working with one end of yarn at a time to be inserted into the machine ( $n=1$ ).

Based on  $n=1$  and the Equation 3 the individual yarn speed for the gripper system named  $v_a$ , for the present case, can be calculated to  $v_a= 400$  m/s.

The string bar system is neither designed nor able, to supply an inlay-yarn over a width of 300 cm. The current maximum width from this technology is limited to approximately 60-70cm. It is included for comparison and evaluation for a possible improving development.



However, based on  $n=1$  and the Equation 3 the individual yarn speed for the string bar can be calculated to  $v_g= 400\text{m/s}$ .

**b. The traversing yarn positioning eyelet system**

The traversing yarn positioning eyelet system is working with  $n=4$  yarn cones simultaneously.

The yarn speed per individual end for the same amount of weft yarns inserted, is therefore reduced according to Equation 3 to  $v_b = 100 \text{ m/s}$ .

**c. The rotating yarn guide rod system:**

The rotating yarn guide rod system is working with one rotating rod. For every complete  $360^\circ$  rotation two inlay yarns can be inserted, therefore  $n = 2$ . The yarn speed per individual end for the same amount of weft yarns inserted is therefore reduced according to Equation 3 to  $v_c = 200 \text{ m/s}$ .

**d. The rotating yarn cone system**

The rotating yarn cone system is working with six revolving yarn cones simultaneously, the amount of simultaneously inserted yarn ends is therefore  $n=6$ .

The knitting cycle is identical to the gripper machine; therefore, the time window for the inlay- insertion remains the same. The yarn speed per single end for the same amount of weft yarns inserted is therefore according to Equation 3 to  $v_d = 66.7 \text{ m/s}$ .

**e. The Magazine Insertion System**

The magazine insertion system (MIS) is working (like Karl Mayer Weft fashion TM3 warp knitting machine) with a carriage with  $n=24$  ends simultaneously<sup>37</sup>. This particular machine is used for comparison even when the current state-of-the-art is supplying 30 yarn ends simultaneously. The deeper research in the following chapters is also made on this machine, this is allowing a consistent data basis for the whole research paper. The knitting cycle is identical to the gripper machine; therefore, the time window for the inlay- insertion remains the same.

The yarn speed per individual end for the same amount of weft yarns inserted is therefore according to Equation 3 to  $v_e = 16.7 \text{ m/s}$ .

## f. Two belt drive system

The two belt system is working with  $n = 4$  yarn cones inserted simultaneously.

The yarn speed per individual end for the same amount of weft yarns inserted is therefore according to Equation 3 to  $v_f = 100$  m/s.

The calculated theoretical yarn speeds from the different weft inlay technologies are brought together in Table 2.3:

	Number of yarn ends	Speed (m/s)	Speed value (m/s)
Gripper method	1	$v_a = v_t$	400
Traversing yarn positioning. eyelet	4	$v_b = \frac{v_t}{4}$	100
Rotating yarn guide rod	6	$v_c = \frac{v_t}{6}$	66.7
Rotating. yarn cones	6	$v_d = \frac{v_t}{6}$	66.7
Magazine Insertion	24	$v_e = \frac{v_t}{24}$	16.7
Double belt system	1	$v_f = \frac{v_t}{4}$	100
String bar technology	1	$v_g = v_t$	400

Table 2.3: Summary of yarn speeds

### 2.1.3 Moved masses/inertia

The gripper method is the only system which is feeding the inlay yarn directly to the warp-knitting machine without intermediate transportation or storage system. It is feeding one yarn end at a time. It is to differentiate an inlay-yarn preparation process that is cyclically simultaneously connected to the production cycle from the warp-knitting machine and constantly moving without stops and restarts or, like the magazine insertion, the traversing yarn positioning eyelet system and the double belt system are traversing along the machine axis supplying in an intermediate storage unit. The rotation rod and the rotating yarn cones rotate at a constant speed around the intermediate storage unit and do not need to be stopped and reaccelerated. For comparison the moment of inertia for the rotating systems based on a machine width of 0.5m are included in (Table 2.17 and Table 2.22). The relevant parameters and estimations are listed in Table 2.4.

	Constant yarn supply	Moved mass inlay supply unit (kg)	Moment of inertia in kg·m <sup>2</sup>	Transport system
Gripper method	No	5		No
Traversing yarn positioning. eyelet	No	5		Yes
Rotating yarn guide rod	Yes- rotating	5	0.1	Yes
Rotating yarn cones	Yes- rotating	50	0.0675	Yes
Magazine Insertion	No	30		Yes
Double belt system	Yes- traversing	10		Yes
String bar technology	No	8		no

Table 2.4: Moving masses/inertia different inly-yarn placing systems

#### 2.1.4 Energy consumption

The technological process of inlay yarn in warp-knitting machines requires energy in the following process steps:

- During the insertion,
- For the preparation of the inlay yarn,
- For the transportation of the inlay yarn to the knitting zone,
- For the knitting process itself.

As the warp-knitting machine with the loop forming process is considered identical for all different systems their energy consumption is not taken into account when comparing the different inlay yarn systems. Kinetic energy is the energy that an object contains due to its movement. It corresponds to the work that must be expended to move the object from rest to the current motion. It depends on the mass ( $m$  in kg) and initial speed ( $v_0$  in m/s) and the final speed ( $v$  in m/s) of the moving body<sup>38</sup>. In a traversing system the direction change requires a complete stop from the insertion speed, therefore  $v_0=0$  m/s and a reacceleration to the maximum traversing speed. The energy consumption is indicated by the build-up of kinetic energy ( $E_{kin}$ ). For each inlay-yarn insertion, linear acceleration and decelerating from components is required<sup>39</sup>. In the following calculations  $v_0$  is set to 0 m/s. Additional mechanical work ( $W_y$ ) has to be spent by the yarn inserting system due to the counter-directional yarn tensile force of the insertion yarns. The kinetic energy can be expressed as:

$$E_{kin} = \frac{1}{2} m \cdot (v_1^2 - v_0^2) \quad (4)$$

With:

$E_{kin}$ : kinetic energy in J

M: mass in kg

$v_0$ : initial linear speed, in this case set to 0 m/s

$v_1$ : maximum system speed inlay system in m/s

The weight of the yarn (estimated yarn with 167 dtex with the length of 4·3.71 m, which is the machine width) is 0.00025 kg and therefore compared to the mass of the systems involved negligible.

$$W_y = F_y \cdot s \cdot n \quad (5)$$

With:

$W_y$ : mechanical work to be spent due to the counter-directional acting yarn tensile force in J

$F_y$ : yarn tensile force in line in N

s: inlay width in m

n: number of yarn ends (dimensionless)

In order to determine the values per individual yarn end it applies:

$$E_{kini} = \frac{E_{kin}}{n} \quad (6)$$

With:

$E_{kini}$ : individual kinetic energy in J.

In rotating systems, the energy consumption is indicated by the build-up of rotational energy ( $E_{rot}$ ). In traversing systems, for each inlay-yarn insertion, linear acceleration and decelerating from components is required<sup>39</sup>.

The value  $E_{rot}$  is set to zero when the system is permanently rotating. It is still calculated, as the estimated losses are calculated as a percentage of the energy required to accelerate the system.

The energy consumption per inlay-yarn insertion for the rotary acceleration and decelerating from components:

$$E_{rot} = \frac{1}{2} \cdot I \cdot (\omega^2 - \omega_0^2) \quad (7)$$

With:

$E_{rot}$  : rotational energy J,

I: moment of inertia in kg·m<sup>2</sup>

$\omega_0$ : initial angular velocity, in this case set to value 0 rad/s

$\omega$ : Maximum angular velocity inlay system in rad/s

$$\omega = 2 \cdot \pi \cdot f \quad (8)$$

With:

f: rotation frequency in rotations/s

In order to determine the values per individual yarn end it applies:

$$E_{\text{rot}i} = \frac{E_{\text{rot}}}{n} \quad (9)$$

When comparing yarn speeds of different systems, the average speed will be used as a benchmark and calculation basis. The moving masses taken into account and were estimated on the basis of empirical values.

Complete energy consumption  $E_{ti}$  per individual yarn end, therefore, consists of the following components:

$$E_{ti} = E_{it} + E_{\text{kin}t} + E_y \quad (10)$$

With:

- $E_{\text{kin}t}$ : energy used to accelerate or deaccelerate mechanical components (J),
- $E_{it}$ : energy lost during the process (J),
- $E_y$ : energy lost due to counter-acting to the yarn tensile force (J)

The energy  $E_{it}$  during the inlay cycle is lost due to:

- Yarn/yarn friction,
- Yarn friction against machine components,
- Yarn/air friction,
- Working against yarn tensile force,
- Mechanical component friction

To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M + W_W = 0.5\text{m}$  ( $W_M = 0.3\text{ m}$  plus double  $W_W$ ) and  $W_M + W_W = 3.7\text{ m}$  ( $W_M = 3.5\text{ m}$  inlay width plus double  $W_W$ ) with a standardized speed of 1.000 rpm.

A yarn end is placed inside the fabric for each cycle, to insert 1.000 inlay-yarns/min the speed is set to rpm=1.000 rpm. Therefore the standardized values referenced in Table 2.5 are taken for evaluation.

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_a = \text{insertion time (s)}$	0.06	0.06
$v_a = \frac{(M_w + M_w)}{t_a}$ in m/s	8.3	61.7

Table 2.5: Insertion time and insertion speed gripper method

For the comparison of the different inlay systems presented in the state of art, a weaving machine for which the dimensions are precisely known is considered as reference.

**a. The gripper method (rapier machines)**

In the weaving industry there are two gripper movements applied:

- Single gripper (over the whole width from the machine),
- Double gripper (simultaneous from both sides with the handover from the weft in the middle)

Double gripper weaving machines work with a speed up to 700 rpm and a maximum weft insertion rate of 1620 m/min<sup>31</sup>. For comparison, an estimated machine width of 350 cm results in approximately 400 machines cycles/min is used (Table 2.6). The yarn mass is, in comparison with the mass from the gripper unit, negligible.

Machine width ( $W_M$ ) in cm	350
Waste at fabric edges ( $W_W$ ) in cm	10
rpm main machine shaft in rpm/rps	400/6.7
Number of yarn ends	1
Mass from the gripper unit in kg	5

Table 2.6: Technical details gripper method

The gripper method cycle requires each weft insertion to accelerate the gripper mechanics and the yarn to the average speed  $v_a$ . As the grippers meet in the middle of the fabric, the distance is set to 185 cm half distance including the waste on one side.

Based on the values from Table 2.6 the cycle time to place one inlay-yarn ( $t_a$ ) is 0.15 s and the resulting average yarn speed  $v_a$  is 24.7 m/s.

To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M+W_W = 0.5$  m ( $W_M= 0.3$  m plus double  $W_W$ ) and  $W_M+W_W = 3.7$  m ( $W_M= 3.5$  m inlay width plus double  $W_W$ ) with a standardized speed of 1.000 rpm.

One single yarn end is placed inside the fabric for each cycle, to insert 1000 inlay-yarns/min the speed is set to 1.000 rpm. Therefore the standardized values referenced in Table 2.7 are taken for evaluation.

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_a$ = insertion time (s)	0.06	0.06
$v_a = \frac{(M_w+M_w)}{t_a}$ in m/s	8.3	61.7

Table 2.7: Insertion time and insertion speed gripper method

The mass from the gripper unit is estimated with totally 5 kg. The weight of the yarn (estimated yarn with 167 dtex with the length of 4x 3.71 m) is 0.00025 kg and therefore

compared to the mass of the system negligible. For a single yarn is a mechanical driven unit the energy to compensate the yarn tensile force will also be neglected in this system. The approximate energy consumption ( $E_{ya}$ ) and the corresponding energy consumption per individual weft insertion ( $E_{yb}$ ) for the gripper method can be calculated according to Equations 4, 5 and 6 and the values in Table 2.6 and Table 2.7 are listed in Table 2.8.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{ta}$ in J	172.2	9508
$E_{ya}$ in J	172.2	9508

Table 2.8: Energy consumption  $E_{tb}$  and  $E_{ba}$  gripper system

An estimated additional 60% of the acceleration energy will be needed to compensate:

- Friction compensation unwinding yarn,
- Yarn/ fixed part friction,
- Yarn/air friction,
- Mechanical friction drive components,
- Compensation yarn tensile force inlay-yarn,
- Friction during the gripper handover.

The approximate energy consumption ( $E_a$ ) and the corresponding energy consumption per individual weft insertion ( $E_{ia}$ ) (Table 2.9) can be calculated according to Equations 4, 5 and 6 and the values in Table 2.8.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_a$ in J	276	15212
$E_{ia}$ in J	276	15212

Table 2.9: Energy consumption  $E_a$  and  $E_{ia}$  system including friction compensation

61% from the energy for machines with 8 heald shafts and 54% for machines with 16 heald shafts from the energy consumed is used for the weft yarn insertion (Figure 2.1)<sup>40</sup>.

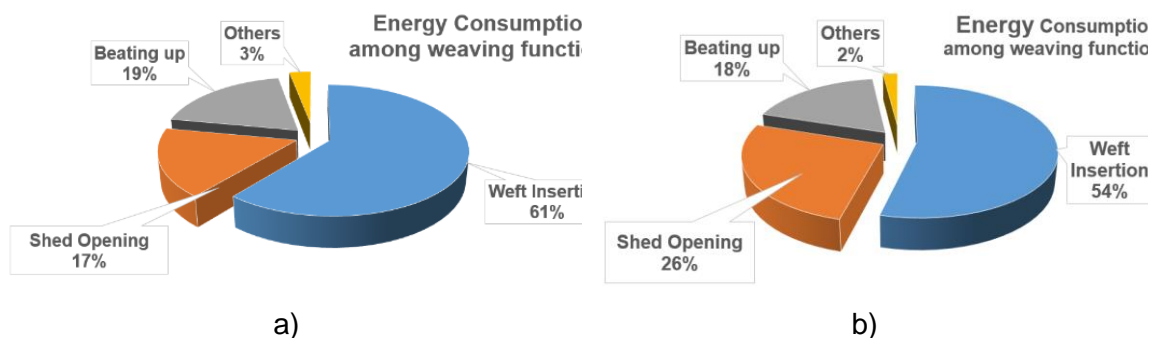


Figure 2.1: Distribution of energy consumption among weaving functions with a) 8 and with b) 16 heald shafts<sup>40</sup>

Estimated total losses of the electrical drive motor consist of the following individual losses:

- Friction losses (sliding or roller bearings),
- Coil winding heating (conductor resistance),
- Motor ventilation (air resistance),
- Iron heating (eddy current losses).

The installed power for a rapier weaving machine for a fabric with  $W_M+W_W=190$  cm is estimated with  $E_{inst}= 3.4$  kW<sup>40</sup>. The process related losses are estimated with additional  $P_L= 20\%$  of the power installed. The full energy consumption  $E_a^*$  based on the estimated losses for the gripper method can be calculated according to Equation 11.

$$E_a^* = E_{inst} \cdot P_l \cdot s_{wi} \quad (11)$$

With:

$E_{inst}$ : installed electrical power rapier machine in J

$P_l$ : process related losses in %,

$s_{wi}$ : share of Energy for inlay insertion in %.

Based on the sample machine in Figure 2.1 with 8 shafts, and the Figure 2.1 the full energy consumption  $E_a^*$  based on the estimated losses for the gripper method can be calculated according to Equation 11 to 2.385J.

The estimations indicated based on Equation 11 are within the range from the values from the estimations made in Table 2.9.

The gripper is positioning the inlay yarn directly to the knitting zone, therefore additional transportation and placement systems are not required and are also to be taken into consideration in respect of energy consumption.

#### b. Traversing yarn positioning eyelet

The traversing yarn positioning (TYPE) eyelet insertion system for 4 inlay insertions requires accelerating the eyelet mechanics and the yarn to the full speed  $v_b$  in addition to the transportation and placement system. With each movement from the carriage system, 4 yarns are placed simultaneously inside the transportation chain.

Machine width ( $W_M$ ) in cm	350
Waste at fabric edges ( $W_W$ ) in cm	10
rpm main machine shaft in rpm/rps	50/0.83
Number of yarn ends	4
Mass from the placing unit in kg	5

Table 2.10: Technical details traversing yarn positioning eyelet



Based on the values from Table 2.10 the cycle time to place one inlay-yarn ( $t_b$ ) is 1.2 s and the resulting average yarn speed  $v_b$  is 3.1 m/s.

To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M+W_W = 0.5$  m ( $W_M= 0.3$  m plus double  $W_W$ ) and  $W_M+W_W = 3.7$  m ( $W_M= 3.5$  m inlay width plus double  $W_W$ ) with a standardized speed of 1.000 rpm. Four yarn ends are placed inside the transportation chain for each revolution of the rod, to insert 1.000 inlay-yarns/m the speed is set to rpm=250. Therefore, the standardized values referenced in Table 2.11 are taken for evaluation.

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_b$ insertion time (s)	0.24	0.24
$v_b = \frac{(M_w+M_w)}{t_b}$ (m/s)	2.1	15.4

Table 2.11: Insertion time and insertion speed TYPE

The approximate energy consumption ( $E_{tb}$ ) and the corresponding energy consumption per individual weft insertion ( $E_{yb}$ ) (Table 2.12) can be calculated according to Equation 6 and the values in Table 2.10 and Table 2.11

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{tb}$ in J	22	1189
$E_{yb}$ in J	5.5	297.2

Table 2.12: Energy consumption  $E_{tb}$  and  $E_{ba}$  traversing yarn positioning eyelet

The energy to compensate the counter-acting yarn tensile force  $E_{y_{tb}}$  and the corresponding energy consumption per individual yarn end  $E_{y_{ib}}$  can be calculated according to Equation 5 and is listed in Table 2.13. The individual yarn end tensile force is estimated with 40 cN according to the tensile force measurements documented in chapter 2.3.4 (Figure 4.15 and Figure 4.16).

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{y_{tb}}$ in J	0.8	2.4
$E_{y_{ib}}$ in J	0.2	0.6

Table 2.13: Compensation to counter-acting yarn tensile force  $E_{y_{tb}}$  and  $E_{y_{ib}}$  TYPE

An estimated additional 30% of the energy will be needed for:

- Friction compensation unwinding yarn,
- Yarn/ fixed part friction,
- Yarn/air friction,

Mechanical friction drive components,

Compensation yarn tensile force inlay-yarn.

Based on the values in Table 2.12 and Table 2.13 and the additional estimated losses of 30%, the total estimated energy consumption ( $E_b$ ) and the corresponding energy consumption per individual weft insertion ( $E_{ib}$ ) can be calculated according to Equation 10 and are displayed in Table 2.14.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_b$ (J)	29.6	1549
$E_{ib}$ (J)	7.4	387.3

Table 2.14: Energy consumption against tensile force  $E_{ta}$  and  $E_{ya}$  TYPE

### c. The rotating yarn guide rod

The rotating yarn guide rod (RYGR) already described in chapter 1.6.3 is constantly revolving and does not need to be permanently accelerated and stopped. It is revolving constantly in addition to the transportation and placement system.

In the literature no specific machine data are available, therefore matching dimensions to the gripper method in weaving machines are taken to have better comparison basics. With each rod rotation, two inlay yarns are placed inside the transportation chain.

Machine width ( $W_M$ ) in cm	351
Waste at fabric edges ( $W_W$ ) in cm	10
rpm main machine shaft in rpm/rps	500/8.3
Number of yarn ends	1
Mass from the rod in kg	5

Table 2.15: Technical details rotating yarn guide rod

Based on the values from Table 2.15 the cycle time to place one inlay-yarn ( $t_c$ ) is 0.12 s. To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M+W_W = 0.5$  m ( $W_M= 0.3$  m plus double  $W_W$ ) and  $W_M+W_W = 3.7$  m ( $W_M= 3.5$ m inlay width plus double  $W_W$ ) with a standardized speed of 1.000 rpm. Two yarn ends are placed inside the transportation chain for each revolution of the rod, to insert 1.000 inlay-yarns/m the speed is set to rpm=500. Therefore the standardized values in Table 2.16 are taken for evaluation.

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_c =$ insertion time (s)	0.12	0.12

$\omega_c = 2 \cdot \pi \cdot f$ in rad/s	52.3	52.3
$v_c = \omega \cdot r$ in m/s	26.2	193.5

Table 2.16: Insertion time and insertion speed RYGR

According to Figure 2.2 characterizing the rotating yarn guide idealistically as a thin rod rotating around its transverse axis<sup>41</sup>.

The formula stated in Equation 12 is an approximation for a cylinder with a length much higher than the other dimensions and by considering the representative rotational axis in the middle of the rod:

$$I_r = \frac{1}{12} \cdot m_r \cdot l_r^2 \quad (12)$$

With:

$I_r$ : moment of inertia in  $\text{kg} \cdot \text{m}^2$ ,

$l_r$ : length from the rod in m,

$m_r$ : mass from the rod in kg.

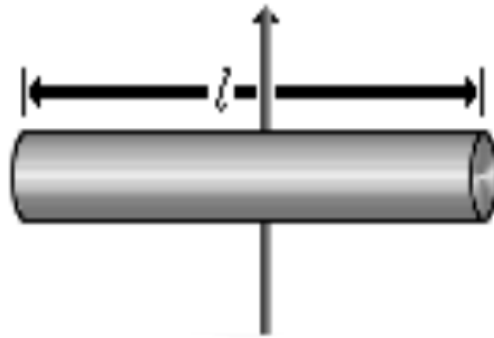


Figure 2.2: Idealistic yarn guide rod<sup>41</sup>

The idealistic moment of inertia  $I$  from the yarn guide rod listed in Table 2.17 can be calculated according to Equation 12 and using the values from Table 2.16

Moment of Inertia	Small (0.5m)	Large (3.7m)
$I_r$ in $\text{kg} \cdot \text{m}^2$	0.1	5.7

Table 2.17: Moment of inertia rotating yarn guide rod<sup>42</sup>

The approximate theoretical rotary energy ( $E_{tct}$ ) and the corresponding rotary energy per individual weft insertion ( $E_{yct}$ ) can be calculated according to Equation 6 and the values from Table 2.15, Table 2.16 and Table 2.17 (Table 2.18).

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{tct}$ (J)	136.8	7796
$E_{yct}$ (J)	68.4	3898

Table 2.18: The theoretical rotary energy  $E_{tct}$  and  $E_{yct}$  rotating yarn guide rod

With the RYGR the energy will be needed for:

Friction compensation unwinding yarn,

- Yarn/ fixed part friction,
- Yarn/air friction,
- Mechanical friction drive components,
- Compensation yarn tensile force inlay-yarn.

Ideally, the system rotates at a constant speed without starting and stopping. To estimate the losses of the system, the energy consumption in the start and stop scenario is estimated and the losses are estimated from this and considered to be the energy consumption for the permanent running system.

Therefore, the estimated energy consumption is set with 10% from the theoretical rotary energy consumption. This results in  $E_{tc}=0.1 \times E_{tct}$  and  $E_{yc}=0.1 \times E_{yct}$ . The values shown in Table 2.19 are based on the values from Table 2.18.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{tc}$ in J	13.7	780
$E_{yc}$ in J	6.8	390

Table 2.19: Energy consumption  $E_{tc}$  and  $E_{yc}$  RYGR

#### d. The rotating yarn cone system

The rotating yarn cone system (RYC) is constantly revolving and does not need to be permanently stopped and reaccelerated (see section 1.6.4). It is revolving constantly in addition to the constant movement from the transportation and placement chain.

In the literature, no specific machine data were available; therefore, matching dimensions to the gripper method in weaving machines are taken to have better comparison basics.

Machine width ( $W_M$ ) in cm	351
Waste at fabric edges ( $W_W$ ) in cm	10
rpm main machine shaft in rpm/rps	20/0.3
Number of yarn ends	1
Mass from the rotating yarn packages in kg	50

Table 2.20: Technical details RYC system

Based on the values from Table 2.20 the realistic cycle time to place a single inlay-yarn ( $t_c$ ) is 3 s.

To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M+W_W = 0.5$  m ( $W_M= 0.3$  m plus double  $W_W$ ) and  $W_M+W_W = 3.7$  m ( $W_M= 3.5$ m inlay width plus double  $W_W$ ) with a standardized speed of 1.000 rpm. Ten yarn ends are placed inside the transportation chain for each revolution of the rod, to insert 1.000 inlay-yarns/m the speed is set to rpm=100. Therefore the standardized values in Table 2.21 are taken for evaluation.

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_d =$ insertion time (s)	0.6	0.6
$\omega_d=2\times\pi\times f$ in rad/s	10.5	10.5
$v_d=\omega\times r$ in m/s	6.3	38.9

Table 2.21: Insertion time and insertion speed RYC system

A yarn bobbin is idealistically a cylinder with radius  $r$  (Figure 2.3). The dimension from the bobbin are estimated with  $r = 0.1$  m and the mass of the cone with  $m=1$  kg.

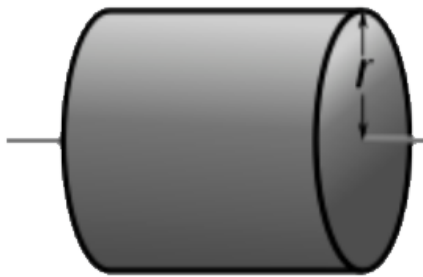


Figure 2.3: Idealistic picture from a yarn bobbin with radius  $r$ <sup>41</sup>

With the geometry indicated in Figure 2.3 the moment of inertia concerning the centre of gravity  $J_s$  can be calculated using Equation 13<sup>41</sup>.

$$J_s = \frac{1}{2} (m \cdot r^2) \quad (13)$$

Using the estimated values the moment of inertia  $J_s$  is calculated to  $0.005$  kg·m<sup>2</sup>

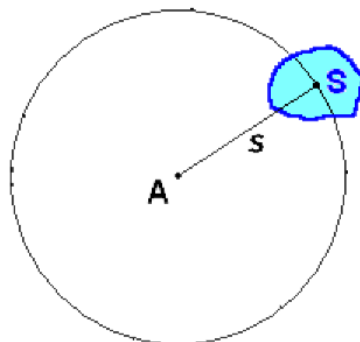


Figure 2.4: Centre of gravity S a rotating mass  $m$  rotating around a point A by passing through with  $s$  the distance between S and A.

According to Equation 14 characterizing the rotating yarn cone system, a cone system is idealistically described as a group of cylindrical bodies rotating about an axis passing through A and perpendicular to the drawing plane. S is an axis parallel to A and passing through the centre of gravity of the body at a distance s. The bodies are idealistically rigid and connected to the axis of rotation A. Then, while each body rotates once around A, it simultaneously rotates exactly once around its centre of gravity axis. It is supposed to be like that to avoid a twist in the yarn end as it is pulled “over the head” from the bobbin. Its moment of inertia concerning the centre of gravity axis is  $J_s$ , and its moment of inertia concerning the axis A is  $J_A$ .

The angular velocity of the two rotations is  $\omega^{43}$ . The kinetic energy of the rotating bodies is composed of the rotational energy concerning the centre of gravity axis and the kinetic energy of the circular motion around A (Equation 13). If the moment of inertia of a body is known concerning an axis passing through the centre of gravity S (Equation 13), its moment of inertia concerning any axis parallel to it can be calculated without further integration (and vice versa)<sup>43,44</sup>.

The mass m from Figure 2.4 has a moment of inertia  $J_s$  with respect to the rotating axis. The parallel axis theorem from Huygens-Steiner<sup>44</sup> states that if the mass m with a moment of inertia  $J_s$  is rotating around a distant (distance s in Figure 2.4) axis (A in Figure 2.4), then the moment of inertia  $J_a$  in relation to the axis A can be calculated using Equation 14; the mass m is not rotating around the axis through point S:

$$J_A = J_s + (m \times s^2) \quad (14)$$

The distance s (Figure 2.4) is set to 0.5 m (fabric width plus single waste length). With the values from Table 2.21 and Equation 13<sup>44</sup> the moment of inertia  $J_A$  from a rotating yarn bobbin which is not rotating around itself can be calculated (Table 2.22).

Moment of inertia	Small (0.5m)	Large (3.7m)
$J_A$ (kg.m <sup>2</sup> )	0.0675	3.43

Table 2.22: Kinetic energy of the yarn bobbin.

The approximate rotary energy per yarn cone ( $E_{cd}$ ) and the corresponding rotary energy for all yarn cones ( $E_{cdt} = n \times E_{cd}$ ) can be calculated according to Equation 7 and the values in Table 2.21 and Table 2.22 and are shown in Table 2.23

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{cd}$ (J)	3.72	189
$E_{cdt}$ (J)	37.2	1980

Table 2.23: Energy consumption the rotating yarn bobbin system

With the RYC the energy will be needed for:

- Friction compensation unwinding yarn,
- Yarn/ fixed part friction,
- Yarn/air friction,
- Mechanical friction drive components,
- Compensation yarn tensile force inlay-yarn.

Ideally, the system rotates at a constant speed without starting and stopping. To estimate these losses, the energy consumption in the start and stop scenario is estimated. The losses are estimated from this scenario and are considered to be the energy consumption for the permanent running system. Therefore, the estimated energy consumption is set with 20% from the theoretical rotary energy consumption in a permanent start/stop scenario. This results in  $E_d = 0.2 \cdot E_{cd}$  and  $E_{id} = 0.2 \cdot E_{cd}$ . The values from Table 2.24 are based on the values from Table 2.23.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_d$ in J	7.4	396
$E_{id}$ in J	0.74	39.6

Table 2.24: Energy consumption  $E_d$  and  $E_{id}$  RYC system

### e. The Magazine Insertion System

The magazine insertion system (MIS) is working (like Karl Mayer Weft fashion TM3) with a carriage with  $n=24$  ends simultaneously<sup>37</sup>.

It is required to accelerate the carriage mechanics and the yarn to the full speed  $v_e$  in addition to the transportation and placement system. With each stroke from the carriage, 24 yarns are placed inside the transportation chain.

Machine width ( $W_M$ ) in cm	351
Waste at fabric edges ( $W_W$ ) in cm	10
rpm main machine shaft in rpm/rps	1500/25
Number of yarn ends	24
Mass of the carriage unit in kg	30

Table 2.25: Technical details MIS system

Based on the values from Table 2.25 the cycle time to place the inlay-yarn ( $t_e$ ) is 0.04 s and the resulting average yarn speed  $v_e$  is 92.5 m/s.

To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M+W_W = 0.5$  m ( $W_M= 0.3$  m plus double  $W_W$ ) and  $W_M+W_W = 3.7$  m ( $W_M= 3.5$  m inlay width plus double  $W_W$ ) with a standardized speed of 1.000 rpm.

24 yarn ends are placed inside the transportation chain for each carriage movement, to insert 1.000 inlay-yarns/m the speed is set to rpm=42. Therefore the standardized values reported in Table 2.26 are taken for evaluation

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_e =$ insertion time (s)	1.43	1.43
$v_e = \frac{(M_w+M_w)}{t_e}$ (m/s)	0.35	2.59

Table 2.26: Insertion time and insertion speed MIS

The approximate energy consumption ( $E_{te}$ ) and the corresponding energy consumption per single weft insertion ( $E_{ye}$ ) can be calculated (Table 2.26) according to Equation 6 and the values in Table 2.25 and Table 2.25.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{te}$ in J	1.84	100.6
$E_{ye}$ in J	0.08	4.2

Table 2.27: Energy consumption  $E_{te}$  and  $E_{ye}$  MIS

The energy to compensate the counteracting yarn tensile force  $E_{yte}$  and the corresponding energy consumption per individual yarn end  $E_{yie}$  (Table 2.28) can be calculated according to Equation 5. As displayed in Figure 1.27 and Figure 1.28 the elongated inlay yarn is transported over the complete width from the fabric. During the inlay procedure, the yarn transporting carriage has to work against the yarn tensile force from the processed yarn ends. According to yarn tensile force measurements, the average tensile force per yarn end is on average 40 cN (Figure 4.15- and Figure 4.16).

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{yte}$ (J)	4.8	35.5
$E_{yie}$ (J)	0.2	1.48

Table 2.28: Energy consumption against tensile force  $E_{yte}$  and  $E_{yie}$  MIS

An estimated additional 40% of the energy will be needed for:

- Friction compensation unwinding yarn,
- Yarn/ fixed part friction,
- Yarn/air friction,



- Mechanical friction transportation chain system,
- Mechanical friction waste yarn cutter,
- Mechanical friction carriage system.

Based on the values in Table 2.27 and Table 2.28 the total estimated energy consumption ( $E_e$ ) and the corresponding energy consumption per individual weft insertion ( $E_{ie}$ ) can be calculated according to Equation 10 (Table 2.29).

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_e$ (J)	9,3	191
$E_{ie}$ (J)	0.4	11.5

Table 2.29: Energy consumption  $E_e$  and  $E_{ie}$  MIS System

#### f. Two belt drives system

The two belt insertion system (TBS) is inserting one weft yarn with one belt at a time. However, the two belts are used alternately. The yarn end is drawn from the yarn cone via a grappling hook which is attached to a permanent rotating belt. The hook from the drawing belt is then handed over the yarn end into the hook from the transportation chain. Two belts are attached symmetrically on each edge from a transportation chain that is transporting the stretched-out inlay yarns to the knitting zone<sup>33</sup>. The technology developed is based on the use of an arrangement of belt drives, with which the currently maximum achievable production speed<sup>34</sup> from rpm= 1.400 1/min can be increased

Machine width ( $W_M$ ) in cm	351	
Waste at fabric edges ( $W_w$ ) in cm	10	
rpm main machine shaft in rpm/rps	1000/66.67	
Number of yarn ends	4	
Mass of the two transporting belts in kg	10	

Table 2.30: Technical details TBS System

With each transport sequence from a belt, 4 yarn ends are placed inside the transportation chain. Always one transportation belt is involved in transporting on weft yarn from the cone in the hooks from the transportation chain<sup>33</sup> (Figure 1.29-Figure 1.31).

Based on the values from Table 2.30 the cycle time to place the inlay-yarn ( $t_d$ ) is 0.04 s and the resulting average yarn speed  $v_d$  is 92.5 m/s.

To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M+W_W = 0.5$  m ( $W_M= 0.3$  m plus double  $W_W$ ) and  $W_M+W_W = 3.7$ m ( $W_M= 3.5$  m inlay width plus double  $W_W$ ) with a standardized speed of 1.000 rpm.

4 yarn ends are placed inside the transportation chain for each movement of the belt, to insert 1.000 inlay-yarns/m the speed is set to rpm=250. Therefore the standardized values reported in Table 2.31 are taken for evaluation.

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_f =$ insertion time (s)	0.24	0.24
$v_f = \frac{(M_w+M_w)}{t_f}$ (m/s)	2.1	15.42

Table 2.31: Insertion time  $t_f$  and insertion speed  $v_f$  TBS

The approximate energy consumption ( $E_{tf}$ ) and the corresponding energy consumption per individual weft insertion ( $E_{ytf}$ ) can be calculated according to Equation 6 and the values in Table 2.30 and Table 2.31 documented in Table 2.32.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{tf}$ (J)	22	594.4
$E_{ytf}$ (J)	5.5	148.6

Table 2.32: Energy consumption  $E_{tf}$  and  $E_{ytf}$  TBS system

The energy to compensate the counter-acting yarn tensile force  $E_{ytf}$  and the corresponding energy consumption per individual yarn end  $E_{yif}$  can be calculated according to Equation 5. As displayed in Figure 1.29-Figure 1.31 the elongated inlay yarn is transported over the complete width from the fabric. During the inlay procedure, the yarn transporting carriage has to work against the yarn tensile force from the processed yarn ends (Table 2.33). The yarn path from the cone to the knitting zone is comparable to the yarn path from the MIS system. Therefore; it can be also estimated at the inlay point at the transportation chain with an average of 40 cN per yarn end. To the actual width from the machine approximately 10 cm can be added to ensure the proper positioning inside the hooks from the transportation chain.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{yte}$ in J	0.8	6
$E_{yie}$ in J	0.2	1.5

Table 2.33: Energy consumption against tensile force  $E_{ybf}$  and  $E_{yif}$  TBS

The efficiency of a synchronized belt drive system is composed of the efficiency of its subsystems, such as the motor, bearing, and belt drive. The overall efficiency results in the ratio of output to input power. Due to the positive power transmission efficiency losses which occur due to bending stress and friction between belt and pulley are minimized with toothed belts. These losses  $E_{lbf}$  can be estimated at approximately 2% for each belt<sup>45</sup>.

The positive power transmission efficiency losses  $E_{lbf}$  need to be added to Equation 10 to calculate the complete energy consumption  $E_i$  per individual yarn end, therefore, Equation 15 consists of the following components:

$$E_{tf} = E_{lt} + E_{kinf} + E_{yf} + E_{lbf} \quad (15)$$

With:

- $E_{kinf}$  : energy used to accelerate or deaccelerate mechanical components,
- $E_{ltf}$ : energy lost during the process,
- $E_{yf}$ : energy lost due to counter-acting yarn tensile force,
- $E_{lbf}$  :positive energy transmission efficiency losses.

In addition to the 2% energy loss ( $E_{lbf}$ ) for each belt caused by the synchronous belt system, estimated further additional 50% of the energy will be needed for:

- Friction compensation unwinding yarn,
- Yarn/ fixed part friction,
- Yarn/air friction,
- Mechanical Friction transportation chain system,
- Mechanical friction carriage system.

Based on the values in Table 2.32 and Table 2.33 the complete energy consumption ( $E_i$ ) and the corresponding energy consumption per individual weft insertion ( $E_{if}$ ) can be calculated according to Equation 14. (Table 2.34):

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_i$ (J)	8.7	228.1
$E_{if}$ (J)	34.7	918.6

Table 2.34: Energy consumption  $E_i$  and  $E_{if}$  TBS

#### **g. String bar system**

The string bar system (SBS) is inserting one weft yarn at a time. An estimated machine like a Raschel-machine for lace Karl Mayer OJ 91/1 B with a knitting width of 132" (3.35 m) results in 850 machine cycles/min<sup>46</sup>.The mass of the moving components of the string

bar system is estimated at total 8 kg. The weight of the yarn (estimated yarn with 167 dtex with the length of 4x 3,71 m) is 0.0025 kg and therefore compared to the mass of the system negligible. For a single yarn in a mechanical driven unit the energy to compensate the yarn tensile force will also be neglected in this system.

Machine width ( $W_M$ ) in cm	335
Waste at fabric edges ( $W_W$ ) in cm	10
rpm main machine shaft in rpm/rps	850/14.2
Number of yarn ends	1
Mass of the transporting belts in kg	8

Table 2.35: Technical details SBS

Based on the values from Table 2.35 the cycle time to place the inlay-yarn ( $t_g$ ) is 0.07 s and the resulting average yarn speed  $v_g$  is 52.9 m/s.

To make the values comparable, the further calculation will refer to a warp-knitting machine size of  $W_M+W_W = 0.5$  m ( $W_M= 0.3$  m plus double  $W_W$ ) and  $W_M+W_W = 3.7$ m ( $W_M= 3.5$  m inlay width plus double  $W_W$ ) with a standardized speed of 1000 rpm.

One yarn end is placed inside the transportation chain for each revolution of the rod, to insert 1.000 inlay-yarns/m the speed is set to rpm=1000. Therefore the standardized values reported in Table 2.36 are taken for evaluation:

Machine width (m)	Small (0.5m)	Large (3.7m)
$t_g =$ insertion time (s)	0.06	0.06
$v_g = \frac{(M_w+M_w)}{t_g}$ in m/s	8.33	61.67

Table 2.36: Insertion time and insertion speed SBS

This represents the time used for a single inlay-insertion cycle  $t_g$  in a string bar machine. The approximate energy consumption ( $E_g$ ) and the corresponding energy consumption per individual weft insertion ( $E_{yg}$ ) can be calculated according to Equation 6 and the values in Table 2.35 and Table 2.36 documented in Table 2.37.

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{t_g}$ (J)	277.5	15228
$E_g$ (J)	277.5	15228

Table 2.37: Energy consumption  $E_{t_g}$  and  $E_g$  SBS

The string bar method cycle requires for each inlay- insertion to accelerate the bar and the insertion yarn guide and the yarn to the average speed  $v_g$ .

The string bar is positioning the inlay yarn directly to the knitting zone, therefore additional transportation and placement systems are not required and are also not to be taken into consideration in respect of energy consumption. The yarn path from the cone to the knitting zone is comparable to the yarn path in the inlay-yarn magazine insertion system. The energy to compensate the counter-acting yarn tensile force  $E_{ytg}$  and the corresponding energy consumption per individual yarn end  $E_{yig}$  can be calculated according to Equation 5 (Table 2.38). According to yarn tensile force measurements in the MIS System, the average tensile force per yarn end is on average 40 cN. The yarn tensile force situation in the SBS system is estimated comparable to the MIS system. (Figure 4.15 and Figure 4.16)).

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_{ytg}$ (J)	0.2	0.6
$E_{yig}$ (J)	0.2	0.6

Table 2.38: Energy consumption against tensile force  $E_{ybg}$  and  $E_{yg}$  SBS

The linear motor only effectively performs work during the acceleration time. This means that effective power consumption does not occur over the entire positioning time. During a standstill and when moving at a constant speed, the motor does not consume any power except to compensate for friction. The kinetic energy that occurs during braking is converted into electrical energy in the motor (generator effect) and stored in the servo controller's DC link capacitors, where it can be used for the next cycle. A continuous power consumption  $E_{dg}$  of approximately 200 W can be estimated for the string bar technology application.

The maximum speed of the linear motor technology is about 15 m/s<sup>47</sup>. Thus, this technology does not appear to be suitable for weft insertion over large machine widths. The rest of the calculation is therefore for comparison purposes only.

Further additional 30% of the energy is needed for:

- Friction compensation unwinding yarn,
- Yarn/ fixed part friction,
- Yarn/air friction,
- Mechanical friction step-motors,
- Friction compensation unwinding/winding string wire,
- Counteracting springs.

Based on the values from Table 2.37 and Table 2.38, the total estimated energy consumption ( $E_g$ ) and the corresponding energy consumption per individual weft insertion ( $E_{if}$ ) can be calculated according to Equation 14 (Table 2.39)

Machine width (m)	Small (0.5m)	Large (3.7m)
$E_e$ (J)	477.7	20057
$E_{ie}$ (J)	477.7	20057

Table 2.39: Energy consumption  $E_g$  and  $E_{ig}$  SBS

## Results energy consumption

The summary over the various systems in respect of energy consumption per individual inlay-yarn is given in Table 2.40. Some of the values are marked with an \* mark as they are only of theoretical value as either the technology is not suitable for the estimated fabric with or the technical components are not available.

Machine width (m)	Small (0.5 m)	Large (3.7 m)	Comments
Gripper method	280 J	15000 J	
TYPE	7 J	390 J	
RYGR	7 J	390* J	*) only theoretical value, technically impossible
RYC	<1* J	40 J	*) only theoretical value, technically impossible
MIS	<0.5 J	12 J	
TBS	9 J	230 J	
SBS	480 J	20000* J	*) only theoretical value, technically impossible

Table 2.40: Energy consumption per inlay-yarn for the different inlay systems considered (approximated values for a better visibility).<sup>2</sup>

### 2.1.5 Process capability

A process capability index is a numerical summary that compares the behaviour of a product or process characteristic to engineering specifications. Those values are called capability or performance indices or ratios.

They relate the “voice of the customer”, as specification requirements limit to the “voice of the process”. The index indicates if the process is capable of fulfilling the requirements in respect of productivity, customer satisfaction, or quality. A capability index reduces complex information about the process to a single number<sup>48</sup>. A capability index relates the engineering specification determined by the customer to the observed behaviour of the process. The capability of a process is defined as the ratio of the distance from the

processing centre to the nearest specification limit divided by a measure of the process variability<sup>48</sup>.

The capability index can be assessed using control charts or statistical process data.

Either case requires running the process to obtain enough measurable output data to gain a proper inside view and process status confidence. Process capability indices are only meaningful for stable processes.

Yarn breaking ratios in knitting machines follow the same principle. As long as the process is stable the breaking ratio remains below a tolerable level if any parameter in the process changes negatively the yarn breaking ratio increases and the capability index rises.

Besides yarn quality factors (max breaking load, friction values, and surface structure), general machine conditions (maintenance, machine speed, yarn tensile force level), environmental factors in the production hall (temperature, humidity, direct sunlight exposure, dust, and dirt) and labour or operator related factors (knowledge, experience, and payment schemes), the yarn breakage is influenced by:

- The number of yarn ends used simultaneously (Table 2.1),
- The estimated distance of yarn between the cone (bobbin) and the knitting zone (for the individual yarn end and as total),
- The estimated deviation angle along the yarn path (for the individual yarn end and as total),
- The number of deviation points along the yarn path.

According to the yarn length involved the deviation angle and the deviation points along the yarn path from the bobbin to the knitting zone can be calculated based on the individual deviation angle and the individual number of deviation points from an individual inlay yarn and the number yarn ends used simultaneously (Table 2.41).

The comparing rating from the different systems is made based on the individual rankings of the amount of deviation points, the complete yarn length and the complete deviation angle. The three ratings were ranked and the values were added. The estimation is that the lower the sum from the ratings is, the less critical the operation from the system will be.

The capability of the different systems is reported in Table 2.41.

	Gripper method	TYPE	RYGR	RYC	MIS	TBS	SBS
Number of yarn ends used simultaneously	1	4	1	10	24	1	1
Individual yarn length between cone knitting zone (m)	3	6	3	6	10	10	10
Deviation angle along the yarn path (°)	270	270	360	180	540	270	270
Number of deviation points along the yarn path	2	5	3	1	6	5	3
<b>Summary</b>							
Yarn length between cone and knitting zone	3	24	3	60	240	40	10
Ranking yarn length	1	3	1	5	6	4	2
Deviation angle along the yarn path	270	1080	360	1800	12960	1080	270
Ranking deviation angle	1	3	2	4	5	3	1
Number of deviation points along the yarn path	2	20	3	10	144	20	3
Ranking deviation points	1	4	2	3	5	4	2
Addition from the rankings	3	7	6	12	16	11	7
Evaluation	1	3	2	4	6	5	2

Table 2.41: Process capability various inlay-systems

### 2.1.6 Complexity

Systems consist of clearly defined individual components, which together form a functional unit. Simple systems consist of a few components; their behaviour can be fully understood and predicted<sup>48</sup>.

Complex systems contain a large number of components that interact with each other to form a functional unit<sup>49</sup>. Therefore, the complexity of the existing inlay insertion systems is determined under consideration of the number of fixed mechanical components, the number of moving mechanical components, the number of electrical motors installed, and the number of moving yarns. The failure rate is a term that has four possible variants: observed, assessed, extrapolated, and predicted. The failure rate is the proportion of failures in a particular period under stated conditions<sup>50</sup>.



In order to compare the complexity from the various inlay-insertion systems the “failure rate” or “trouble factor” form selected highlighted components is estimated from professional experience and set for a comparable evaluation (Table 2.42).

	Failure rate
Fixed components	1
Moving components	2
Motors	1
Moving individual yarn ends	5

Table 2.42: Estimated component failure rates

The amount from components in the different inlay systems described in the four first column of Table 2.43 is estimated and multiplied with the corresponding failure rate (Table 2.42). The results are expressed in the two last columns of Table 2.43. The estimation is that the lower this evaluation is the lower the overall failure rate. The rank is the classification.

	Fixed parts	Moving parts	Motors	Moving yarns	Evaluation	Ranking
Gripper method	100	50	2	1	207	1
TYPE	200	50	2	4	322	4
RYGR	200	50	1	1	306	3
RYC*	300	300	2	20	1002	6
MIS	500	200	2	24	1022	7
TBS	200	100	2	1	407	5
SBS	150	50	2	1	257	2

Table 2.43: Evaluation failure rates

## 2.2 Summary

### 2.2.1 Comparison from inlay-insertion systems in the time-line of development

The previously determined factors present a technical assessment and allow a rating from the existing inlay techniques or ideas therefore in the warp-knitting technology, from the time when it was actually up to the state-of-the-art. The comparison of the different

systems is reported in Table 2.44. This allows also in conclusion a basis to compare innovative concepts to the timeline of development.

	Gripper Method	TYPE	RYGR	RYC	MIS	TBS	SBS
Yarn speed (m/s)	400	100	70	70	20	400	400
Moved masses/inertia	--	-	-	---	---	-	
Number of yarns	1	4	2	6	24	1	1
Energy consumption (J)	549	4970	498	542,3	334,7	3,78	201,4
Process stability	++	-	+	-	-	-	+
Complexity (failure rate)	207	322	306	1002	1022	407	257

Table 2.44: Comparison of known inlay- insertion systems.

The current state-of-the-art system is the magazine inlay system with up to 24 yarn ends supplied simultaneously. The energy consumption in combination with the yarn speed for the gripper method makes the process too expensive and it is slowing down the speed of the warp-knitting process.

The rotation yarn guide shows similar negative factors and additionally the mechanical set-up with a long rotating rod makes the machine big and not easy and safe to handle. To control the rotating yarn cones and still facing a relatively high yarn speed make the system with rotation yarn cones difficult in production. In addition, the machine is to be stopped when one of the cones is empty. Then all the cones should be changed against new ones which lead to a significant amount of waste.

The reason for the success of the magazine inlay- insertion system is the low yarn speed, which makes it possible to control the bigger quantity of moving yarns. The number of yarn breakages is low as the low yarn speed also results in lower yarn tensile forces. Secondly, the energy consumption per yarn end is significantly lower than the gripper method and the yarn guide rod.

## 2.2.2 Global summary

Figure 2.5 illustrates the global conclusion from the state-of-the-art (Chapter 1) and the analysis made in this chapter on inlay yarn insertion warp-knitting technologies.

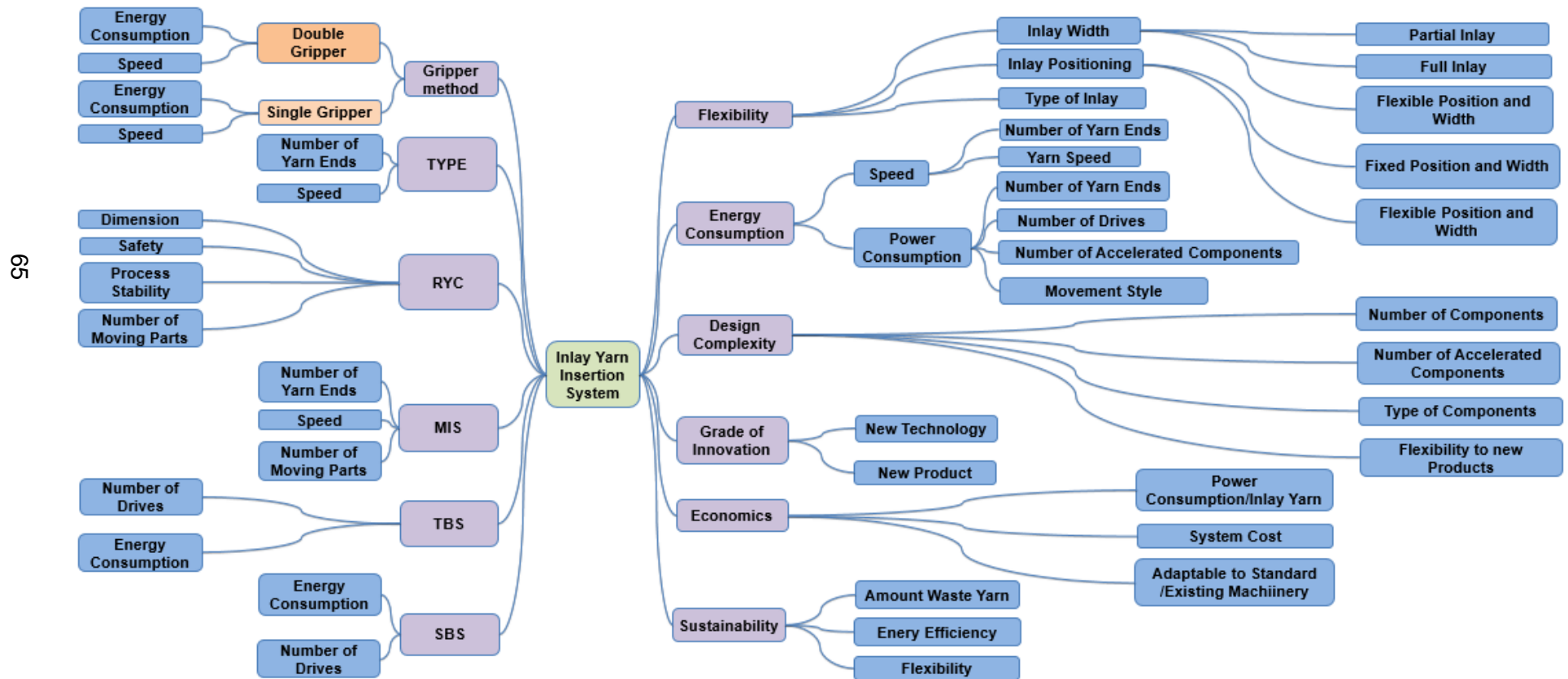


Figure 2.5: Summary on inlay yarn insertion warp-knitting technologies

## **3 Innovative inlay-insertion technologies: approach and potential solutions**

### **3.1 General approach for innovation**

#### **3.1.1 Definition of innovation**

Innovation is a process that renews and brings up to date a product or a service by applying new processes, introducing new techniques, or establishing successful ideas. According to Koltze/Souchkov<sup>51</sup>, innovation happens based on an invention. More than 99% of creative problem solving involves the use of previously known solution principles and the patterns found in the creative problem-solving process are cross-functional<sup>51</sup>.

#### **3.1.2 Holistic and systematic product or process development**

A process is the entirety of successive procedures in a system by which matter, energy, or information is transformed, transported or stored.

Only when the process is defined in its process steps and the conditions and functions of the process steps are understood, can the development for the realization of the individual functions and the function of the overall system be started. The further development of the process also means the further development and modification of components of the product or vice versa.

The innovation of inlay-insertion in warp-knitting machines has been divided into individual steps:

- Yarn storage in bobbin form on a suitable storage device, e.g. a creel;
- Pulling the yarn from the bobbin and feeding it to the knitting machine under as constant as possible yarn tensile force and elongation,
- Presentation of the inlay yarn in front of the loop-forming elements of the knitting machine in the following condition:
  - Extended and straightened out,
  - Without pretension and motionless,
  - Direction independent,
  - According to requirements in the loop formation cycle of the knitting machine,
  - Inlay-yarn is tied in through the loops formed in the cycle (knitting process),
  - Removal of the cutting waste.

### **3.1.3 The process of systematic innovation**

In principle, systematic innovation is divided into four, partly overlapping, phases<sup>51</sup>:

1. Description of objectives
2. Problem definition
3. Search and describe solutions
4. Select and describe a suitable solution

### **3.1.4 Target description**

Following the idea of ideality<sup>51</sup>, the following questions are to answer:

- What is my ideal result?
- Which path to this goal corresponds to my ideal conception?
- Where do I have to go in the long term?

The result is a clear, long-term, time and market independent target definition, as well as a concept for resource and, if necessary, damage minimization on the way to finding a solution.

## **3.2 Approach for inlay insertion**

### **3.2.1 Ideal inlay-insertion**

The objective description of an innovative inlay yarn insertion system for warp-knitting machines can be described by the following functions and properties:

It must be able to insert inlay yarns individually or in a group in the correct length, properly elongated, parallel to the machine axis, cut or uncut depending on the product, without longitudinal and transverse vibration and at the maximum possible machine speed without inlay insertion. No additional process costs should be incurred in the process sequence or additional mechanical equipment.

The new inlay-insertion process must be technologically superior to the previous systems in respect of:

- Be simpler in set-up than the well-known magazine inlay-insertion,
- Cheaper,
- More resource-saving (lower energy consumption, no cutting waste),
- Faster (the knitting machine is currently limited by the inlay-insertion system),
- A lesser twist applied to the inlay yarn,

- More flexible (different yarns),
- Patentable/Innovative,
- Sustainable.

The first important aspect is to provide the technological proof of concept in a function prototype. For this, the design and technological challenges have to be solved. Only then, in a further evolutionary step, is the system installed and adapted in a warp-knitting machine. Then, the problem areas of adapting the technology to real production machines arises. It is also important to limit the first step to the functionality itself.

In a second step, the machine speed is increased and the technical and technological developments for adaptation to large machine widths are tackled.

### 3.2.2 Problem definition alternative inlay-insertion system

In a knitting machine, one loop is formed per machine revolution (360° revolution of the machine's main shaft). When processing inlay yarns in all formed loop courses, one inlay yarn must be inserted in each loop course.

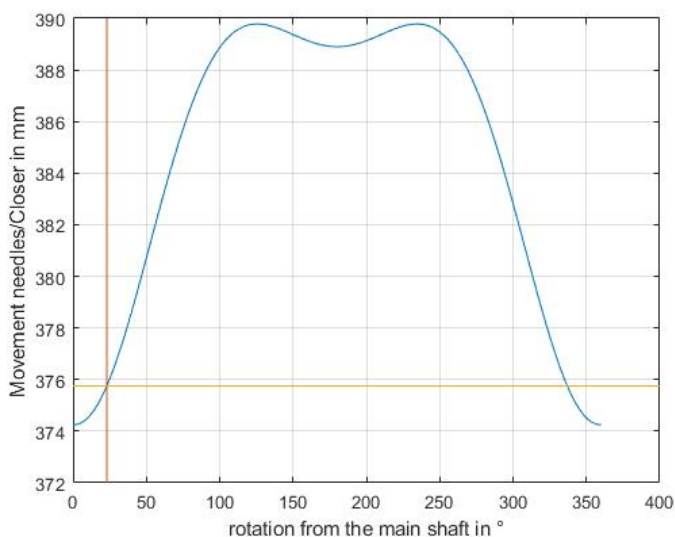


Figure 3.1: Movement diagram needle Weftronic II HKS<sup>52</sup>

The curve in Figure 3.1. is showing the movement of the compound needle body tip and the needle slider tip in the coordinate system of the machine. The compound needle tip moves 15.2 mm in the vertical direction, going 1.4 mm below the knock-over edge of the knitting sinker shown as a horizontal black parallel to the X-axis. The illustration shows that the slide needle emerges from the knock-over at a 23° machine angle and disappears again at 336°. This results in approximately 47° degrees machine angle (13% of the

machine revolution) time for the insertion of the inlay yarn. The thread must be stretched out, calm, and presented directly to the needles.

Assuming a fictitious knitting machine with standardized machine data:

Machine width ( $W_M$ ) in cm	350
Waste at fabric edges ( $W_W$ ) in cm	10
rpm main machine shaft in rpm/rps	1000/16.7
Number of yarn ends	1
Mass of the transporting belts in kg	8

Table 3.1: Technical details standardized warp knitting machine

Based on the values from Table 3.1 the cycle time to place the inlay-yarn ( $t_i$ ) is 0.06 s and the resulting average yarn speed  $v_i$  is calculated to 61.7 m/s (documented in Table 3.2).

Machine width (m)	Small (0.5m)	Large (3.7m)
$T_i =$ insertion time (s)	0.06	0.06
$v_i = \frac{(M_w + M_w)}{t_i}$ (m/s)	8.3	61.67

Table 3.2: Insertion time and insertion speed gripper method

Based on Equations 1 and 2 the time  $t_i$  to perform one inlay-yarn insertion based on the machine speed of rpm=1.000 and the available time frame from 47° degrees machine angle and a machine with  $W_M + W_W = 3.7$  m can be calculated to  $t_i = 0,008$ s and the average insertion speed based on the values from table 4.1 to  $v_i = 463$  m/s.

Traversing mechanical insertion systems must be accelerated and stopped twice for each inlay insertion. This, in conjunction with the high yarn speed, leads to extreme mechanical stresses on the drive and the insertion system itself, and this in combination with high-energy consumption.

This is circumvented by a magazine inlay system. A group of inlay yarns is inserted simultaneously in preparation for the knitting cycle. The yarns are inserted into a storage system that then feeds the stretched yarn to the knitting system. This feeding system is mechanically complex with many moving parts. It is therefore cost-intensive both in operation and as an assembly itself. The individual yarn ends of the fed group of yarns are many times deflected on their way into the knitting zone. This can lead to yarn breakage and damage to the inlay yarn.

### 3.2.3 Innovative inlay yarn insertion system

The new innovative inlay-insertion system must therefore solve the following problem areas or should be at minimum beneficiary:

- Eliminate the high accelerations of mechanical systems,
- Reduction of energy consumption,
- Realization of high yarn infeed speeds,
- Safe stretched yarn insertion,
- Simple structure,
- A free yarn path can be realized and no extreme yarn deflections take place,
- The yarn is not twisted in itself by the feed,
- Highly dynamic performance - optimum start and stop behaviour,
- High torque/power ratio,
- High positional accuracy,
- Few mechanical components have to be installed in the machines,
- Adaptable insertion can be integrated into a process chain,
- Different courses of rolls allow different widths of inlay-insertion,
- Several courses of rollers allow simultaneous insertion side by side or overlapping,
- Flexible positioning in the machine,
- No trim waste in the inlay,
- No trim waste at the fabric edges,
- A fixed fabric selvage can be produced.



### 3.3 Innovation process – brainstorming process

#### 3.3.1 Evaluation procedure

To more accurately assess solutions to be pursued after a selection process, an evaluation procedure is used to determine the value of a solution concerning to stated objectives. Technical and economic aspects must be taken into account<sup>39</sup>. The relevant functional values and features need to be compiled for every aspect (Table 3.3).

Assigning values therefore is easier if quantitative characteristics can be defined for features or groups of features, but this is not always possible. Therefore, qualitative verbal statements should be formulated when necessary.<sup>39</sup>

Function	Properties of required function carriers that inevitably result from the selected solution principle or the concept variant
Operating principle	Properties of the selected principle(s) in terms of simple and unambiguous fulfilment of function, sufficient effect, low disturbance variables
Design	A low number of composites, low complexity, low space requirement, no special material, and design problems.
Usage	Simple operation, long service life, low wear, easy and convenient operation.
Ergonomics	Man-machine relationship, no strain or interference, good shape design

Table 3.3: Examples for qualitative verbal statements in the evaluation process<sup>39</sup>

The requirements detailed in Table 3.3 lay the ground for a brainstorming process. From those brainstorming sessions, various approaches for the realization of inlay-insertion in warp-knitting machines emerged. The evaluation was carried out by assigning subjective plus or minus ratings. All categories were given equal levels without any weighting.

All the different approaches had been evaluated and assessed. There are rates given from “--” as very negative up to “++” as very positive. The rates had been added in the way that a “minus” is equalizing a “plus”. The ranking was based on summation.

### 3.3.2 Listing of the different approaches with a short description

The technical task of inserting the inlay yarn in warp-knitting machines can be achieved in various technical approaches. The approaches resembling the technical task of weaving machines which are described below:

- Projectile weaving machines use a projectile equipped with a gripper to insert the filling yarn across the machine. The principle of projectile inlay insertion allows the insertion of practically any yarn because it's securely gripped and inserted by the projectile. The gripper projectile draws the yarn into the shed. The energy required for picking is built up by twisting a torsion rod. On release, the pretension rod or another energy storing system shoots a projectile with a small hook-like device that grips the end of the yarn. The thread is then pulled from the cone along the machine axis and then presented to the knitting zone<sup>53</sup>. The projectile glides through the shed in a rake-shaped guide. Braked in the receiving unit, the projectile is then conveyed to its original position by a transport device installed under the shed.<sup>54</sup>
- In a waterjet weaving machine: The end of the yarn is weighted with a drop of liquid and transported across the width of the machine by utilizing a high-pressure lift with air nozzles arranged in a staggered pattern. A water-jet machine inserts the inlay yarn by highly pressurized water. The tractive force is provided with the relative velocity between the filling yarn and the water jet. If there is no velocity difference between the water and yarn, then there would be no tension on the yarn which would result in curling and snarling of the yarn.<sup>54</sup>
- Shaft shed machine: Several sheds are opened simultaneously and cyclically one after the other by a rotational movement<sup>51</sup>. This allows various inlay threads to be inserted simultaneously in preparation. The simultaneous insertion of four fillings in a rotor necessitates a yarn feeder sub unit that is concentrically fitted to the rotor and takes on the function of yarn distribution for the constantly fed inlay yarns. The yarns being transported with air leave the guiding channels in a synchronized sequence to enter the inlay channel. The filling yarn controller also serves as the main nozzle. The yarn clamp and the cutter are located between the filling processing and the filling channels. The clamp stops the yarn and the rotating main cutter cuts every inserted yarn. During filling insertion, each yarn tip performs a screw motion as a result of the longitudinal movement of the yarn and the constant rotation of the weaving rotor. On the receiving side, the arrival of the filling yarn is detected by an electronically controlled filling yarn detector<sup>50</sup>.
- Gripper machine: with this system, the inlay thread is transported across the machine width by two grippers that meet in the middle for thread transfer. The system is already used in gripper weaving machines. The grippers perform either a handover from the inlay

yarn in the middle from the fabric area or the use of a “long single gripper” to transport the inlay yarn over the whole width of the fabric.

- Compressed air injection (air jet): Air-jet insertion, the filling yarn is inserted into the warp shed with compressed air. The inlay yarn is drawn from a supply package by the filling feeder and each pick is measured for the inlay insertion using a stopper. Upon release of the yarn by the stopper, the inlay is fed via tandem and main nozzles. The tandem and main nozzle combination provide the initial acceleration, whereas the relay nozzles provide the high air velocity across the inlay area.<sup>54</sup>. A cutter is used to cut the yarn when the insertion is completed. The inlay yarn is shot through open guide elements similar to reed blanks via an arrangement of compressed air nozzles. This system is identical to the air-jet weaving machine. The inlay yarn is brought into contact with flowing hot air during insertion. For this purpose, the pneumatic inlay insertion device has, for example, an inlay insertion nozzle that is arranged at the side of the shed and is operated by hot air. Alternatively or additionally, there can be several hot air-driven carrying and accelerating nozzles, arranged along with the shed and pneumatically carrying, and/or pneumatically advancing the inlay yarn. The thread must be cut on one side<sup>55</sup>.

Other innovative approaches to insert inlay yarns into a warp knitting machines are described below:

- Machine gun with breaker gear: this system was originally used to shoot with a machine gun through the rotating wings of the propeller. With a high-velocity projectile, the inlay yarn can be transported along the machine axis to be presented into the knitting zone. Based on this, the inlay yarn entry could be "pre-fired" if necessary and brought into a presentation position from an intermediate storage and transportation system.

- Screw conveyor: with such a system, the inlay yarn could be transported over the machine by a mechanical screw rotating at high speed, with or without a "projectile". If necessary, the simultaneous insertion of several inlay yarns ones after the other is also possible. The use of the computer, in conjunction with the stored data of the law of motion, allows adapted velocity curves. Thus, in the initial phase, i.e. after the reversal of motion of the firing carriage, an accelerated or delayed start-up can be provided concerning a sinusoidal function<sup>56</sup>.

- Grooved drum winding machine: Machines with grooved drums are widely common for the rewinding of yarns to apply wax or paraffin. The grooved roller is generally directly driven. The yarn is moved alternately by the grooves on the circumference of the driven drum. The cylinder rotates permanently at a constant speed. The traversing is realized by the crossing grooves<sup>53</sup>.

- Crossed belt drives: Two or more permanently driven belts are equipped with yarn guiding elements or hooks. These elements interact at half distance and transfer the inlay yarn from one transportation element to the other. These belts are driven by two or more independent motors. The inlay yarn is spread out to be inserted. This eliminates the need for starting and stopping processes<sup>57</sup>.
- Rotating eyelet: The yarn is moved along a circular path by a yarn eyelet attached to the inner ring of a torque motor. The yarn path is then transferred via a guide into a traversing movement. With this type of feed, the inlay yarn is only deflected at the respective edges of the knitted fabric. This traversing movement then guides the yarn into the loop-forming area<sup>58</sup>.
- Contrary rotating wings: The yarn is traversed over the inlay area by means of synchronized contrary rotating rotors with blades. The rotating rotors are placed in two closely adjacent planes of rotation and are mounted in offset axes so that the arms sweep across the guide bar in opposite directions to define the traverse stroke.<sup>59</sup>
- Table tennis: The basic element is a yarn guiding element that is brought along a guide (rail or similar) by two beaters over the width of the machine. Those beaters can be based on rotation or linear driven, however, a rotation-based beater unit will be the preferred solution. The inlay yarn is fed in from the centre behind the machine.
- Permanent will: A yarn guide moving on a defined guide reel is continuously accelerated at every POR by energy-storing elements. These energy storing elements can be either electromagnetically empowered, spring-loaded, or a combination thereof.
- Traveller with drawstring and whip: A whip is tensioned by a drive moving along to the machine axis and strikes the yarn guide across the machine width. An individual acceleration system needs to be placed on each side of the yarn inlay zone.
- Thread guide with induction drive on a rail: In this case, the drive can be located on the upper or lower side of the drive on each side.

### **3.3.3 Evaluation and discussion of the brainstorming results**

Based on the requirements for the ideal weft insertion (section 3.2.1) the following parameters had been chosen to evaluate the basic innovative technical approaches which are the result from the brainstorming sessions.

The assessment of the different technical approaches is made according to the criteria in Table 3.4. The actual evaluation is done by assigning dimensionless values (points) for every selected criterion. The utility value analysis rate uses a spectrum of grades in order to evaluate the performance or values from the different technologies based on parameters like in Table 3.4. The grades are reaching from 0=unusable to 10=ideal.

Yarn speed	The higher the possible yarn speed the higher the ranking
Inertia	The lower the moved masses the better the ranking
Number of yarn ends	To determine the capability of the system
Energy consumption	The lower the consumption the better the ranking
Sensibility	The stable the process is judged the better the ranking
Design	The simpler the system the better the ranking

Table 3.4: Selected qualitative and quantitative criteria in the evaluation process

The ranking from the criteria in Table 3.4 is made based on grades from the utility value analysis with technical unweighted valence<sup>39</sup> according to Equation 16. The individual values and the results are reported in Table 3.5

$$W_j = \frac{\sum_{i=1}^n W_{ij}}{W_{\max} \cdot n_{es}} \quad (16)$$

With

$n_{es}$  : Number of evaluated solutions,

$W_{\max}$  : Technical value of the ideal solution,

$W_{ij}$  : Evaluations of the individual solutions.

	Yarn Speed	Inertia	Numer of yarn ends	Energy consumption	Sensibility	Design	Sum	Ranking
Rotary eyelet	8	9	1	10	10	10	48	8.00
Rotating blades	10	9	1	10	5	10	45	7.50
Grooved drum traversing	5	10	1	10	8	10	44	7.33
Crossed belt drive	7	7	5	8	8	5	40	6.67
Taversing Carriage	10	1	10	7	10	1	39	6.50
Linear drive	6	5	1	7	8	8	35	5.83
Waterjet Insertion	10	9	1	4	5	3	32	5.33
Shed shaft loom	10	2	8	3	8	1	32	5.33
Projectile Insertion	8	7	1	1	8	3	28	4.67
Screw Conveyor	2	5	1	5	3	8	24	4.00
Rotating Rod	3	7	1	5	3	3	22	3.67
Gripper Insertion	4	1	1	1	6	5	18	3.00
Permanent Will	3	4	1	3	4	1	16	2.67
Table Tennis	3	4	1	3	3	1	15	2.50
Draw sling and whip	3	3	1	3	4	1	15	2.50
Machine gun with breaker	2	1	1	2	5	1	12	2.00
Rotating Yarn cone	1	3	5	1	1	1	12	2.00
Compressed air	2	1	1	1	1	1	7	1.17

Table 3.5: Evaluation and discussion from the brain storming results

Based on the parameters in Table 3.4 the weighted results (green colour as good, yellow colour as average and red as not feasible) shown in Table 3.5 indicate the following technologies as most promising technical approaches (highlighted in green colour) for an innovative inlay insertion system for warp knitting machines:

- Rotary eyelet,
- Rotating blades,
- Grooved drum.

### **3.4 Potential solutions for an innovative inlay system for warp-knitting machines**

Further three different approaches for an innovative inlay yarn system for warp-knitting machines will be discussed in detail and prototype units will be made for the system with rotating blades and the rotating eyelet which are representing the most promising technical solutions.

#### **3.4.1 Rotating blades**

So-called traversing devices with rotors that are driven in opposite directions are known for winding yarns into cross-wound packages. A winding machine for winding yarns onto bobbin tubes, with a traversing device through which the yarn is laid back and forth, substantially transverse to the direction of travel over a traverse stroke that corresponds substantially to the bobbin length, is already state-of-the-art<sup>60</sup>.

The rotary blade yarn traversing system comprises two rotors with two or three blades each which are turning in opposite directions (Figure 3.2).

The yarn guide device has at least two rotating elements arranged as a pair, wherein the rotating elements of a pair are arranged one above the other in the axial direction and can be driven in opposite directions of rotation. Each rotating element comprises at least one yarn guide designed as a driver element for laying the inlay yarn in one individual direction. One rotor is traversing the yarn from the left direction turning point to the right side. At the direction turning point on the right side, the hand over to the blade from the rotor which is turning in the opposite direction, is made. Based on this cycle the yarn can traverse alternating over the coil under constant rotation from both rotors involved.

The use of rotary blades for yarn inlay into the warp-knitting process will allow a highly productive and energy-saving process that can be used for newly developed as well as for existing products. Also in the highly competitive international environment, this technology will create an opportunity for new machinery and products in the field of technical textiles as well as in the fashion industry.

The patent application of the Niederrhein University of Applied Sciences “Vorrichtung und Verfahren zum Vorlegen von Fäden, Textilmaschine” (apparatus and procedure for preparing yarns, textile machine) <sup>61</sup> gives the basis for a new application/process which increases productivity and reduces energy consumption (Figure 3.2).

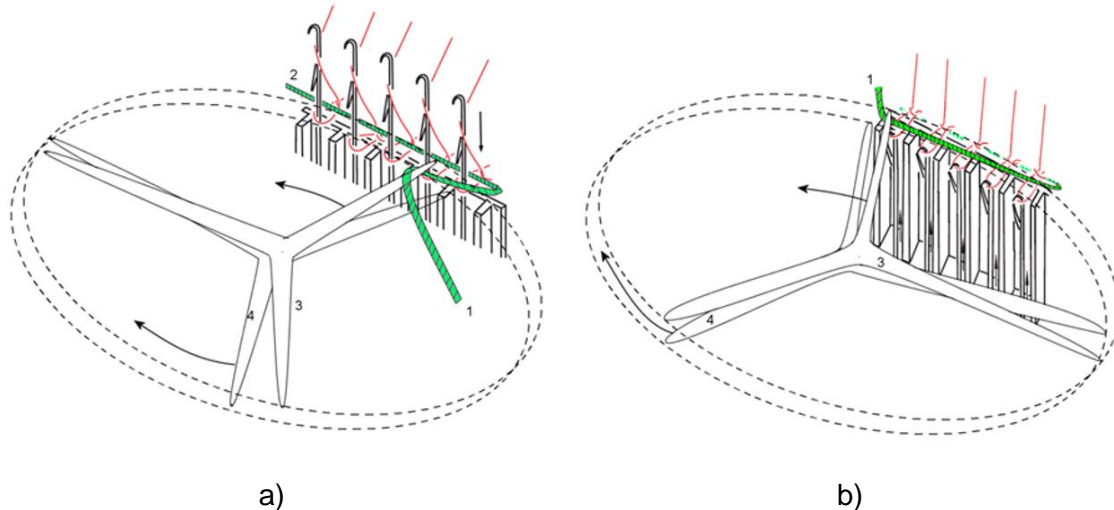
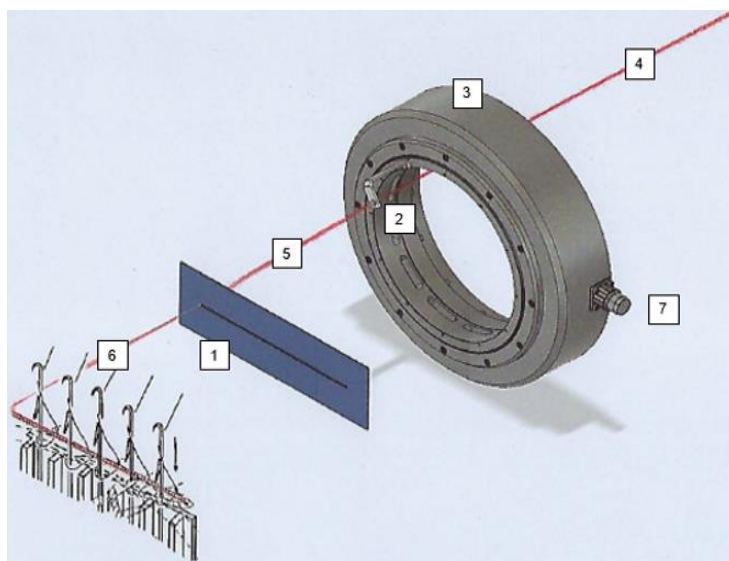


Figure 3.2: Upper rotary blade inserts yarn a) from right to left and b) at of traversing from right to left. 1: Inlay yarn coming from the cone, 2: End from inlay yarn in the fabric, 3: Upper rotary blade turning anti clock wise, catching the inlay yarn, 4: Lower rotary blade turning clockwise to traverse the inlay yarn<sup>61</sup>

### 3.4.2 Rotating thread eyelet

As described in the patent application DE102018120364.0 (2018) The inlay yarn is moved in by a threaded eyelet driven to a circular movement while attached to the inner ring of a torque motor (number 2 in Figure 2.8)<sup>58</sup>. From this circular movement, the yarn is guided through a traversing element which is transforming the circular movement into a traversing movement (number 1 Figure 3.3 and Figure 3.4 b).



- 1: Traversing element
- 2: Rotating thread guide eyelet
- 3: Static motor outer ring
- 4: Thread coming from the bobbin
- 5: Rotating thread piece
- 6: Traversing thread piece
- 7: Motor power supply

Figure 3.3: Idealistic Inlay thread positioning through a rotating eyelet<sup>62</sup>

With this type of feed, the inlay yarn is only seriously deflected on its way from the bobbin to the knitting zone at the respective edges of the knitted fabric (Figure 3.4 a). This traversing movement then guides the yarn into the loop-forming area.

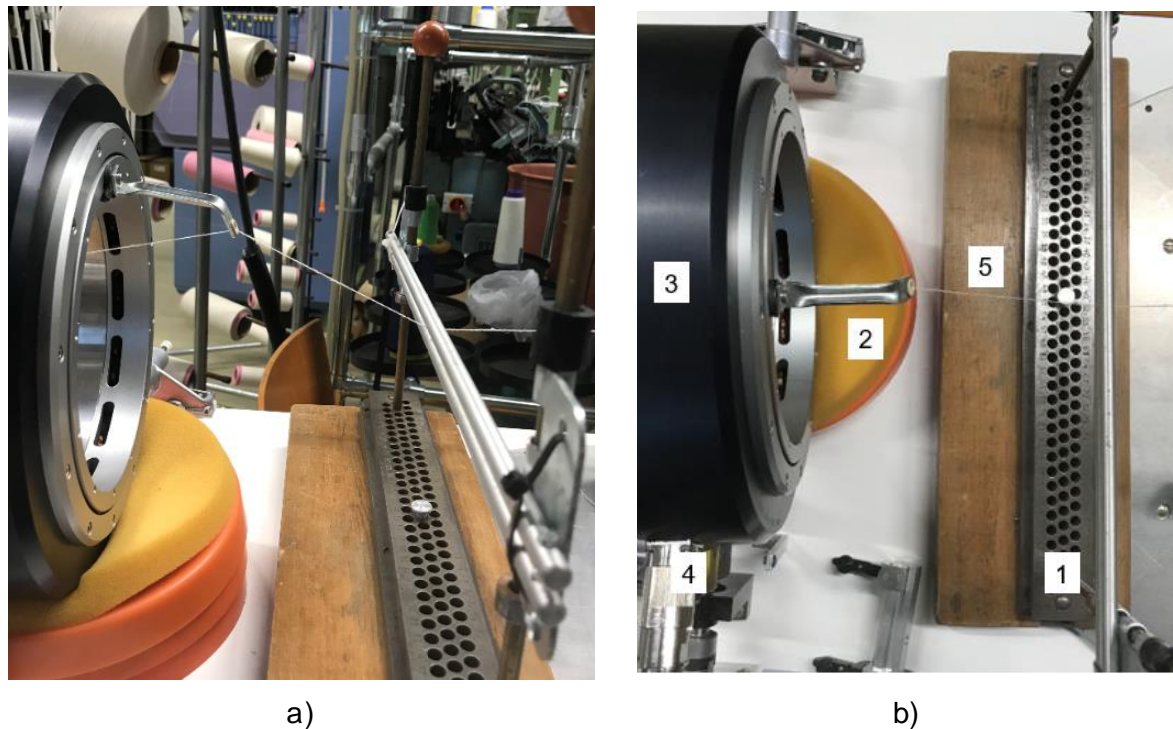


Figure 3.4: Rotating inlay eyelet a) side view and b) top view rotating. 1 = Yarn traversing guide slot, 2 = Rotating eyelet, 3 = Fixed outer-ring torque-motor, 4 = Electrical motor connection, 5 = Yarn between eyelet and guide slot<sup>62</sup>

This principle has already been confirmed in its function by basic experiments in the laboratory from the Niederrhein University of Applied Science.

### 3.4.3 Rotating grooved drum

The grooved or placing roller is directly driven by a laterally arranged motor. The yarn is oscillating, guided back and forth through the grooves driven in the roller (Figure 3.5 a-f). In the process, the load on the yarn is reduced as much as possible by the groove design.

According to the patent application DE102018127736 (2018), the rotating grooved drum (number 3 in Figure 3.6) guides the inlay yarn and directs it to the mesh-forming area via the traversing element<sup>63</sup> (number 1 in Figure 3.6).





Figure 3.5: Yarn traversing in the grooved roller of a winding machine: a) to c) from the right point of return (POR) to the left side and d) to f) from the left point of return (POR) to the right side of the machine.

This placing or traversing principle is known from the winding technique (Figure 3.5). The axis of rotation of the roller is arranged parallel to the needle bar, relative to them in such a way that a yarn running off the roller is presented to the knitting tools in a required position and has to cover the shortest possible distance to the knitting tools<sup>63</sup>. The groove system is designed in such a way that it feeds an unwinding yarn parallel to the knitting tools with a back-and-forth movement. The course of the groove system – straight and/or curved – can create differences in the effective traversing speed<sup>63</sup>. The yarn is fed directly through the groove of the laying roller. When delivering, the inlay thread is fed into the warp-knitting machine, the yarn is only minimally deflected in the groove of the laying roller and only at the laying edges.

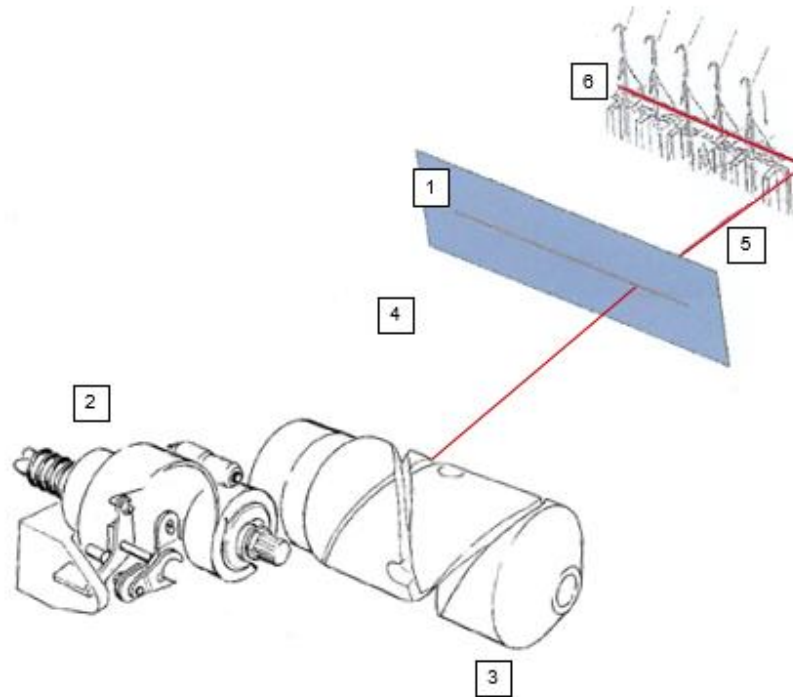


Figure 3.6: Traversing system with grooved drum. 1 = Traversing element, 2 = Driving motor, 3 = Rotating grooved drum, 4 = Yarn coming from the grooved drum, 5 = Traversing yarn piece, 6 = Knitted courses with inlay yarn<sup>64</sup>

## **4 Preliminary study: Yarn tensile force and speed measurements during industrial process**

During the loop forming process, the size of the loop is defined by the length of yarn which is incorporated in each individual loop. The parameters for the final (relaxed) loop are influenced by the yarn tensile force and the elastic elongation from the yarn during the loop forming process.

### **4.1 Basics related the yarn speed and tensile force during the knitting process**

During the loop formation the length of yarn, which is incorporated in each individual loop, defines forming process the size of the loop. This process is strongly influenced by the yarn tensile force and the fabric take-up during the loop forming process. Also affecting is the elastic elongation from the yarn during the loop forming and, in addition, about 15 percent of the yarn drawn into a newly-formed loop is robbed from already-formed neighbouring loops (robbing back)<sup>15</sup>. Altering conditions during the knitting process, like temperature, humidity, and machine speed may influence yarn or machine-related parameters and affect friction between yarn and machine pieces, i.e. eyelet, and as consequence, yarn tensile force. This ultimately influences the yarn tensile force at the knitting point during the loop formation. This causes variations in the size of the knitted loops<sup>15,31</sup>. Variations in loop length of +/-10% due to changes in yarn friction may be experienced at given cam settings and input tensile forces and these variations can be explained by the phenomenon of "robbing-back"<sup>65</sup> and balanced between inter-yarn friction and yarn bending rigidity which make the relaxation is more or less easy to obtained depending on the stress subjected to the knitted fabric during the process<sup>66</sup>. The ratio of 'robbing back' yarn to yarn, taken from the cones, varies depending on the factors described and can reach values up to 68% of the complete loop length<sup>67</sup>.

Two different kinds of yarn feeding systems are existing: positive and negative systems. The positive yarn feeding system gives better control of the yarn length delivered, but it is not usable when a variation of yarn consumption like in jacquard patterns or lace, made by a multi-guide bar machine, is needed. With a positive feeding system, a constant and correct length of yarn under low tensile force is delivered to the knitting point from the yarn cones. These cones are separated from the yarn-consuming needles by positive yarn feeders like the MPF feeder system for circular knitting machines from MEMMINGER-IRO in Dornstetten, Germany, which are directly driven from the main machine drive shaft and therefore synchronized to the machine drive from the circular knitting machine.

With the negative yarn feeding system there is no “fixed” relation between the yarn consuming knitting zone and the yarn package. The descending needles are pulling yarn directly from the yarn cone or package. As the needles descend the stitch cam, the tensile force required to pull yarn from the package increases rapidly and it becomes easier to rob back yarn in the opposite direction from the already-formed loops of needles further back that are then beginning to rise from their lowest (knock-over) position<sup>31</sup>. The ratio of ‘robbed back’ yarn, to yarn taken from the cones is fixed for a particular fabric quality produced. The negative yarn feeding system is allowing the needles to draw loops whose length is influenced by the yarn condition<sup>31</sup>. The loop-forming needles pull the yarn directly from the yarn supply (Figure 4.1). The yarn tensile force and the yarn elongation are resulting from the yarn tensile properties but also from the yarn friction against machine parts, the yarn speed, and the fabric take-up.

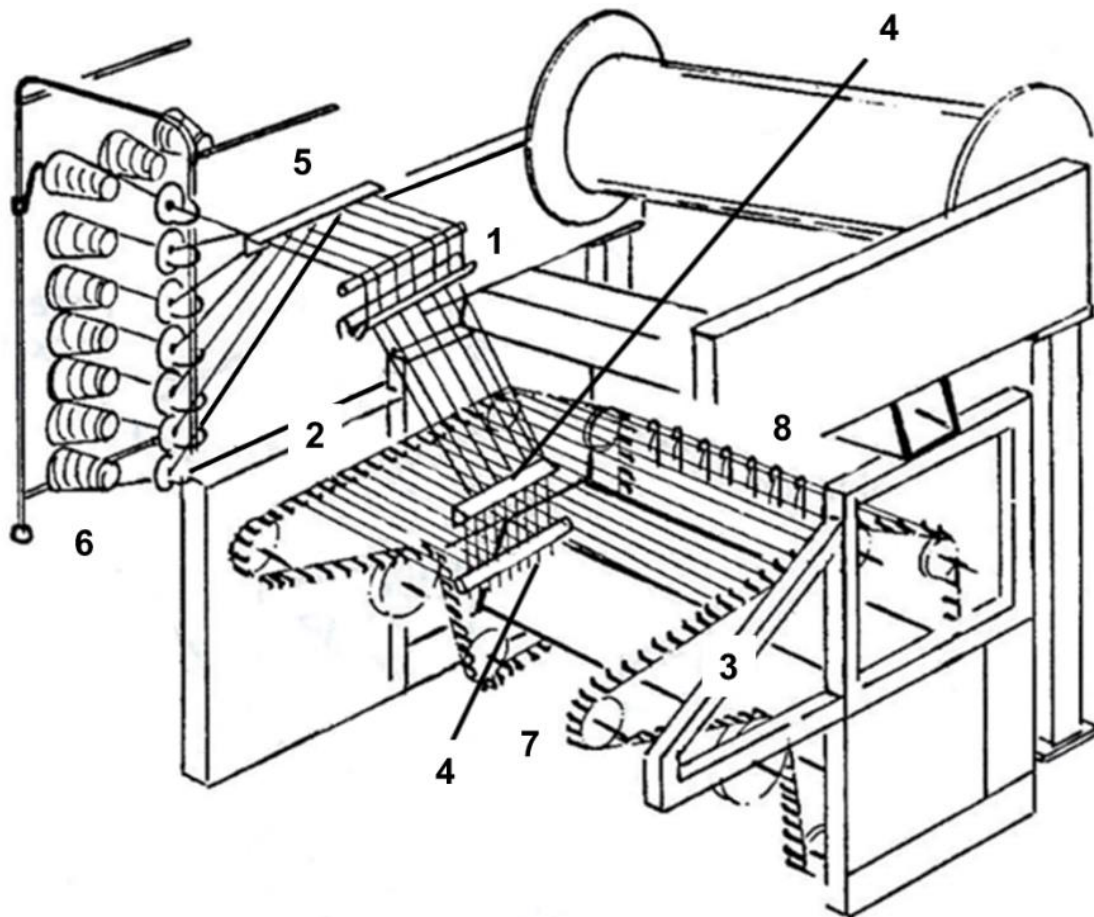


Figure 4.1: Loop formation showing the 'robbing-back' and yarn tensile forces on the needles for the warp knitting process from left to right<sup>15</sup>

Because of the back and forth movement of the inlay carriage, the yarn speed of the inlay yarn during the warp knitting process is not constant during the inlay cycle or course. Consequently, the yarn elongation and the yarn tensile force are not constant over the stroke from the inlay carriage. Therefore, yarn tensile force and yarn speed measurements are important, to understand the process of inlay yarn processing.

## 4.2 Measurements at the MIS System

For the present study, the MIS machine in the laboratory from the University of Applied Science Niederrhein, a machine (RS4-MSU-N in 18GG from Karl Mayer, Obertshausen, Germany) has been used. The principle of the machine set-up is illustrated in Figure 2.13. The creel with the bobbins and the storage feeding systems (MSF3 CAN from Memminger-IRO, Dornstetten, Germany) are placed on the side of the machine. For the measurements, a cotton two-ply yarn (2x25 tex) has been used. The inlay carriage at the backside of the machine is moving 18 yarn ends simultaneously.



P1: Pendulum eyelet  
P2: Left Point of return  
P3: Right point of return  
P4: Yarn carriage (moving)

P5: Fixed eyelet  
6: Creel with inlay yarns  
7: Transportation chain  
8: Knitting zone

Figure 4.2: Principle of an inlay warp knitting machine with measuring positions<sup>32</sup>

One complete cycle (double stroke) from the carriage over the transportation chain area, including the cross-movement to place the yarns into the transportation hooks, lasts 5.1 seconds. Therefore, 423 inlay yarn ends are inserted each minute.

On this machine for proceeding to measurements, high-frequency yarn tensile force measurements are carried out at P1 and P4 (Figure 2.13 and Figure 4.5) with yarn tensile force sensors (125.12 from Honigmann, Gevelsberg, Germany) with an acquisition frequency respecting the Shannon theorem to have a signal maximum frequency of 1 kHz. The very compact design of the 125.12 Honigmann sensors with short transducers makes it possible to record and display even the very steep and rapid increases in yarn tensile force. This sensor is fixed to have minimum interaction with the measured yarn, as recommended<sup>68</sup>, therefore the wrap angle is quite small, i.e. approximately 15°. For additional analysis, the yarn tensile force and the yarn speed are measured simultaneously at the measuring P1 (in Figure 4.2). A TMS multi-sensor (BT SR S.p.a., Varese, Italy) is

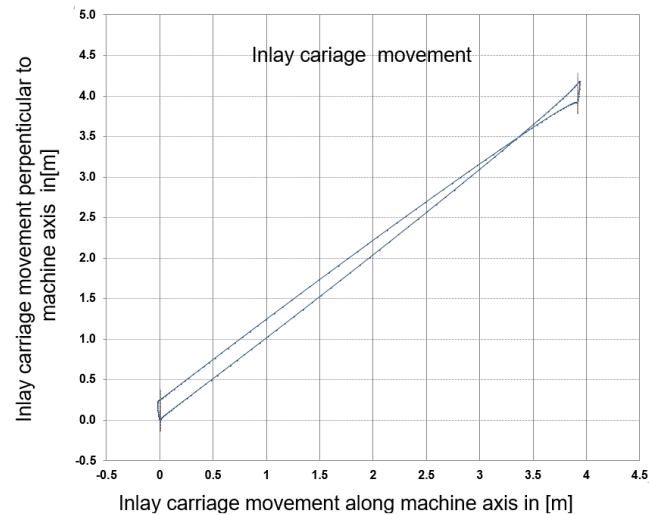
set up for this measurement. This sensor is detecting and monitors the yarn tensile force and the yarn speed, with a signal maximum frequency respectively of 200 Hz and 20 Hz. They are equipped with rollers to limit yarn abrasion and to reduce the influence of the measuring system on the textile process itself. To resume, the yarn tensile force meters had been placed in positions P1 and P4 , the yarn speed sensor at measuring P1 (Figure 4.2). To synchronize the yarn speed and yarn tensile force measurements with the carriage movement, a capacitive positioning sensor is installed on P2 measuring instantaneously the position of P4 (Figure 4.2). The traversing yarn carriage P4 (Figure 4.2) is moving along the machine axis to transport the inlay yarn over the fabric and perpendicular to the machine axis to compensate for the movement of the transport chain and to place the inlay yarn inside the hooks from the transportation chain (number 7 in Figure 4.2 and Figure 4.3).



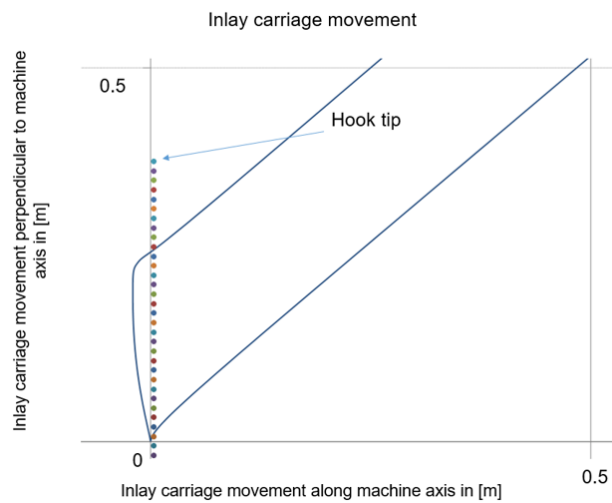
Figure 4.3: Inlay-yarns placed inside the hooks from the transportation chain

The pendulum eyelet on top of the traversing inlay carrier P1 is not in the centre of the transportation chain. The transportation chain is constantly moving the spread inlay yarns towards the knitting zone (number 8 Figure 4.2). The horizontal movement diagram from the inlay carriage from a Pinkert LZU 27 inlay warp knitting machine with a machine width of 3.85 m is visible in Figure 4.4a and b.





a)



b)

Figure 4.4: Inlay carriage movement pattern from a Pinkert machine with 3.9 m: a) over the whole machine width, b) detail view from the yarn carrier movement pattern through the hook at the left side from the machine (with courtesy from Pinkert machines)

To place the inlay yarn inside the hooks from the transportation chain the yarn feeders have to swing around the hooks from the transportation chain (Figure 4.4 a and Figure 4.4b). They have to swing through the constantly moving line of hooks and place the thread by over swinging and therefore moving around the hooks as displayed in Figure 4.3 and Figure 4.4 a and b. The speed of the carriage, the speed of the transportation chain, the number of yarn carriers mounted on the carriage, the positioning and distance from the hooks to each other on the transportation, and the defined movement pattern from the carriage along both axes are evenly important.

The x-axis in Figure 4.5 and 2.17 indicates the position relative to the left point of return (POR) P2 (Figure 2.16) from the carriage system and y-axis the height above the chain

level. P1 (Figure 4.5) is the position from the last fixed eyelet over the traversing yarn carriage from one side to the other side alternatively, i.e. from the two points of return P2 and P3 (Figure 4.5). The geometrical situation from the WIWK process with an inlay yarn carriage is described in Figure 4.5 and Figure 4.6.

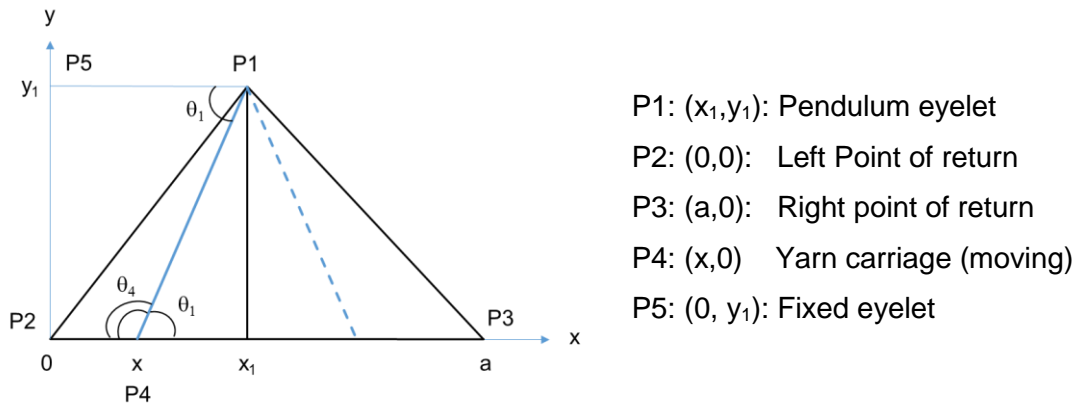


Figure 4.5: Geometrical situation of the yarn inlay process

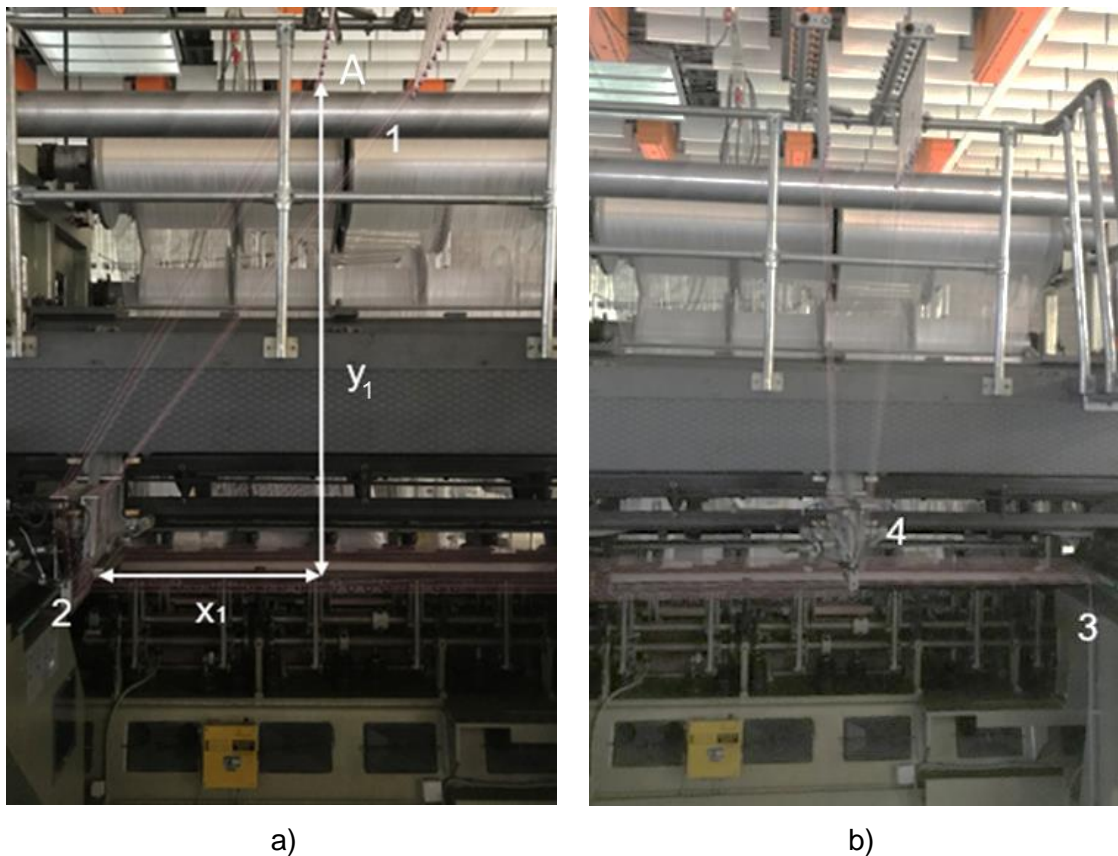


Figure 4.6: WIWK machine with a) yarn carriage in the close side and b) on the centre and with the yarn carriage in the centre. P1 is the pendulum eyelet P2 is the POR on the left side (side of the creel) P3 is the right POR and P4 is the yarn carriage.



### 4.3 Analysis from the MIS machine cycle: yarn speed

Based on the machine set-up described in section 1.6.5, the yarn speed is calculated and experimentally measured. Both approaches are compared<sup>69</sup>.

The carriage cycle is starting at the left POR P2 (Figure 4.5) and then it is moving along the machine axis passing under the pendulum eyelet to the right POR P3 (Figure 4.5) and is there returning to the starting point.

From Figure 4.5 the following equations expressing the yarn length between the pendulum eyelet and the traversing yarn carriage can be obtained. Based on the geometrical situation, the total theoretical yarn length from P1 to P4 the complete yarn carriage movement cycle can be calculated. The perpendicular movement to compensate for the movement from the chain is not considered.

- With a yarn carriage movement from P2 to P3 (Figure 4.5), i.e. left to right, the yarn path is from P2 to P4, then the yarn length  $L$  relative to yarn carriage position  $x$  is:

$$L(x) = P_2P_4 = x \quad (17)$$

- With a yarn carriage movement from P3 to P2 (Figure 4.5), i.e. right to left, the yarn path is from P3 and P4, then the yarn length  $L(x)$  relative to yarn carriage position  $x$  is:

$$L(x) = P_3P_4 = a - x \quad (18)$$

The results obtained from the carriage positioning sensor, it can be observed the yarn carriage movement is sinusoidal and can be expressed as and illustrated in Figure 4.7 a.

$$x(t) = \frac{a}{2} \cdot \left( 1 - \cos\left(\frac{2 \cdot \pi}{T} \cdot t\right) \right) \quad (19)$$

Where:

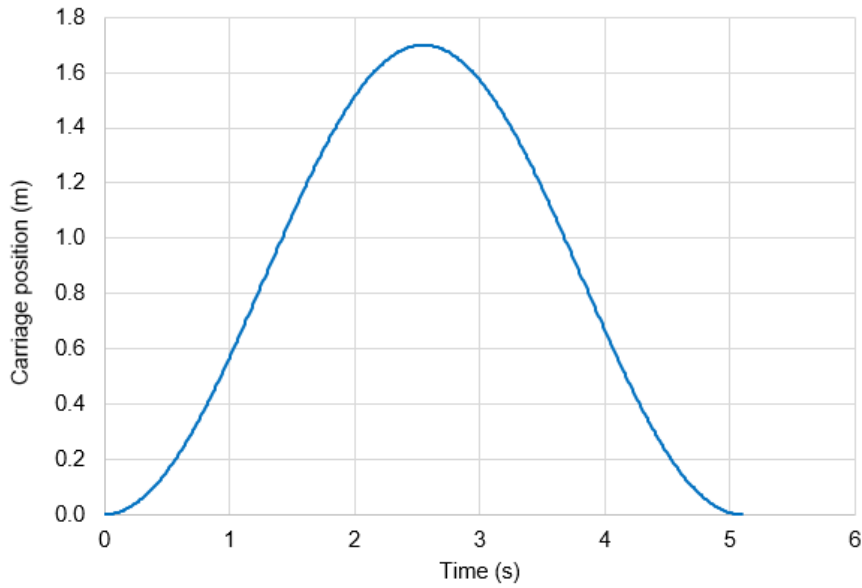
T: period of a complete yarn carriage cycle back and forth in s,

t: time (s),

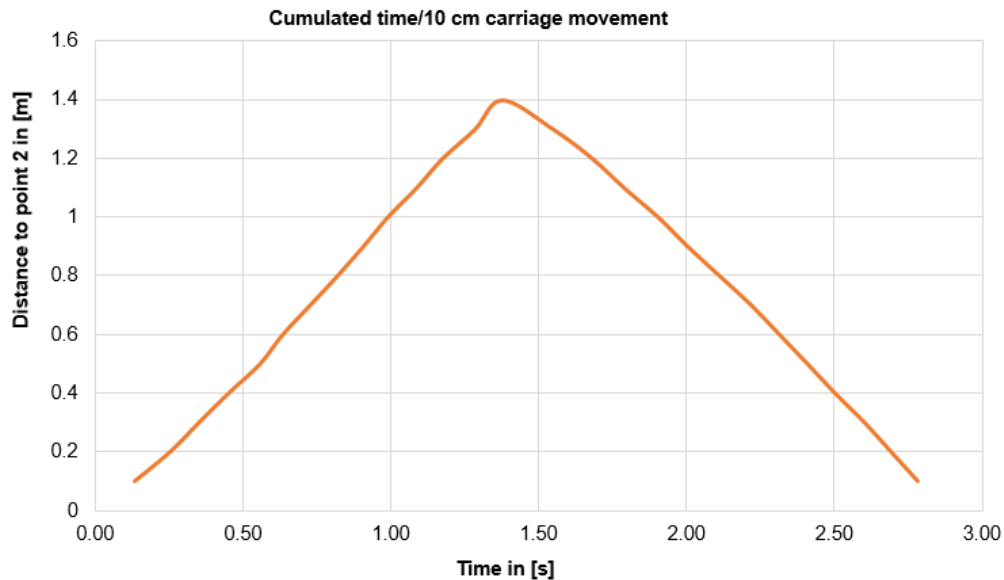
a: the distance between P2 and P3 (m).

The position of the carriage relative to time  $x(t)$  is obtained from images obtained from high-speed films taken with a camera. The pictures show the carriage position together with a scale with marks every 10cm. The traverse time from the carriage is recorded in segments with a length of 10 cm along the machine axis. The carriage movement over the 10cm length separations is documented with a high-speed video camera.

Figure 4.7 b, based on the values obtained from the high-speed recordings, shows the linear carriage movement relative to time for one complete machine cycle starting from P2 and to P3 (Figure 4.5) and return. It shows a constant speed in both directions during the inlay preparation process. The perpendicular movement to compensate for the movement from the chain is not considered.



a)



b)

Figure 4.7: Carriage relative to time for one carriage cycle in both carriage directions: a) theoretical (Equation. 19) and b) experimental (at adjusted speed to high speed video).

Both experimental and calculated carriage position relative to time are in good agreement. Based on the geometrical situation described in Figure 4.2, Figure 4.5 and Figure 4.6 and the noted Equations 17 to 19, the theoretical yarn length from the point of return (POR) to the yarn carriage, P2 or P3 depending on the carriage direction can be calculated during the complete yarn carriage movement cycle and plotted (Figure 4.8). The perpendicular movement to compensate for the movement from the chain is not considered.

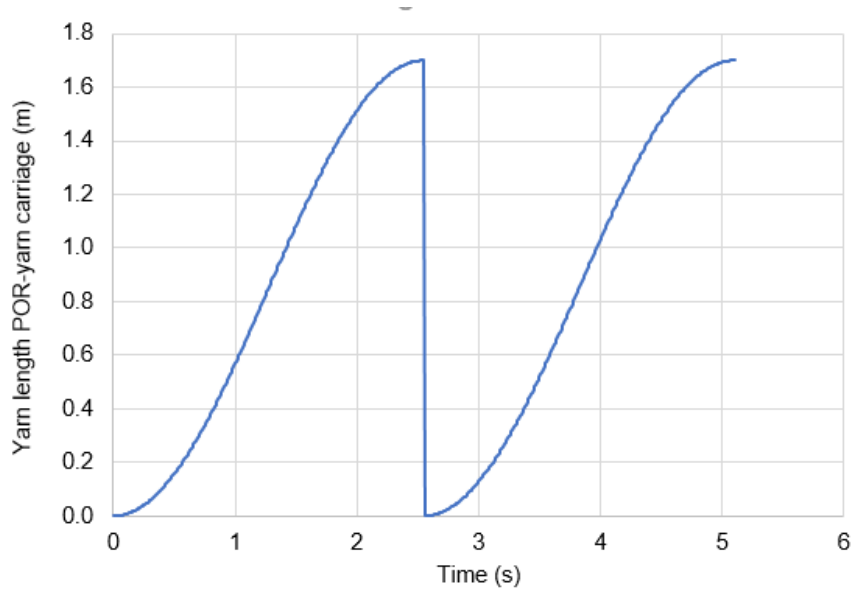


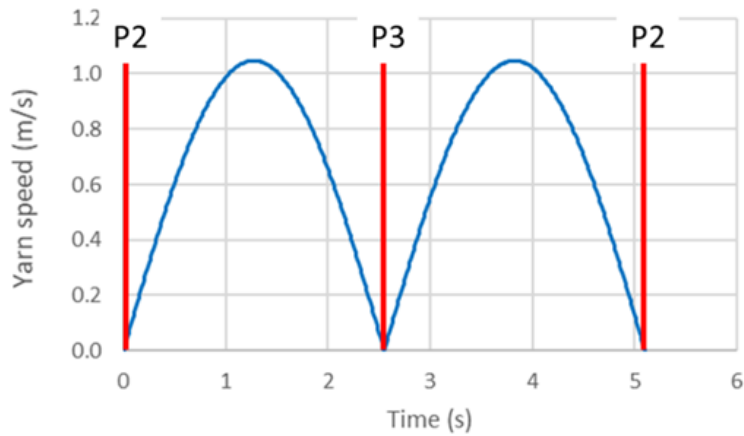
Figure 4.8: Calculated yarn length in the WIWK system studied from the POR (P2 or P3) and the yarn carriage.

Therefore, from Equations 17 to 19, the yarn carriage position can be expressed relative to time. Moreover, the yarn speed between the relevant points can be expressed<sup>69</sup>:

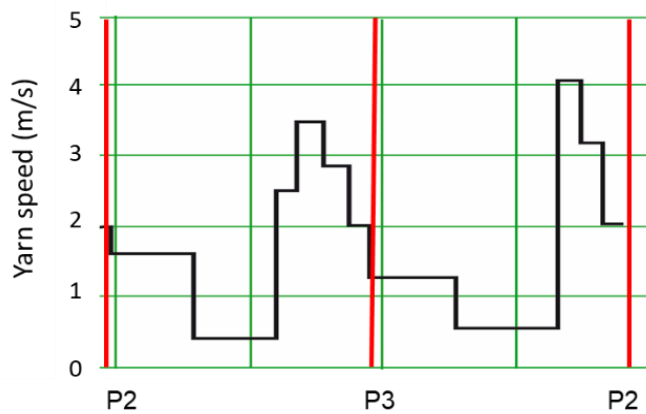
$$\text{from P2 to P3} \quad v(t) = \frac{\pi \cdot a}{T} \cdot \sin\left(\frac{2 \cdot \pi}{T} \cdot t\right) \quad (20)$$

$$\text{from P3 to P2} \quad v(t) = \frac{\pi \cdot a}{T} \cdot \sin\left(\frac{2 \cdot \pi}{T} \cdot (T-t)\right) \quad (21)$$

In the present machine,  $x_1 = 0.85$  m,  $y_1 = 1.33$  m,  $a = 1.7$  m and  $T = 5.1$  s. Figure 4.9 a illustrates the yarn speed between the POR and the yarn carriage, calculated from Equations 20 and 21 during a whole yarn carriage cycle.



a)



b)

Figure 4.9: Calculated yarn speed between POR and the yarn carriage: a) calculated and b) experimentally measured.

For an additional analysis the yarn speed is measured at the measuring POR (P1 in Figure 4.5). A TMS multi sensor (BTSR S.p.a., Varese, Italy) is set-up for this measurement (Figure 4.9 b). This sensor is detecting and monitoring the yarn speed, with a signal maximum frequency of 20 Hz which represents approximately 100 data on a whole cycle, i.e. 5.1s, and is therefore sufficiently representative. They are equipped with rollers to limit yarn abrasion and to reduce the influence from the measuring system to the textile process itself.

From Figure 4.9, it can be observed, calculated and measured yarn speed with the sensor at P2 are different. From these results, it can be concluded the real evolution of the yarn speed (Figure 4.9) is not as smooth as the speed evolution of the yarn carriage, i.e. with a sinusoidal evolution (Figure 4.9 a). In fact, the speed change is very impulsive, from the starting point to the endpoint whatever the yarn carriage direction. The maximum speed is during the final phase of the stroke.

## 4.4 Analysis from the MIS machine cycle: yarn tensile force

### 4.4.1 Theoretical approach

However, the experimental evolution shows a delay which can be due to yarn friction in the different eyelets and yarn inertia unwinding are not taken into account. A consideration of the yarn tension modification due to friction between eyelets is proposed below.

The tensile force variation during the yarn carriage cycle due to yarn friction between the different eyelets can be evaluated by using capstan theory (Figure 4.10):

$$T_1 = T_0 \cdot \exp(\mu \cdot \alpha) \quad (22)$$

With:

$T_0$ : yarn tensile force before the eyelet in N

$T_i$ : yarn tensile force after the eyelet in N

$\mu$ : coefficient of friction between the yarn and the eyelet

$\alpha$ : wrapping angle.

Two different angles – the wrapping angle  $\alpha$  and the deflection angle  $\theta$  – are involved in the analysis from the yarn path and the evolving applied like displayed in Figure 4.10:

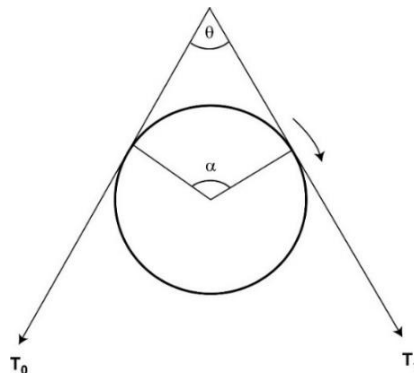


Figure 4.10: Relation between wrapping angle  $\alpha$  and the deflection angle  $\theta$ .

The relation between the wrapping angles  $\alpha$  and the deflection angle  $\theta$  can be determined based on Figure 4.10 to:

$$\alpha = \pi - \theta \quad (23)$$

Where  $\theta$  is the deflection angle.

When considering more than one capstan, the evolution of the tensile force is:

$$T_{\text{final}} = T_{\text{init}} \cdot \exp\left(\mu \sum_{1}^n \alpha_i\right) \quad (24)$$

With:

$T_{\text{init}}$ : starting point yarn tensile force,

$T_{\text{final}}$ : ending point yarn tensile force,

$\alpha_i$ : wrapping angle at the eyelet number  $i$ .

Then for several capstans, i.e. eyelets<sup>70</sup>:

$$\alpha = \sum_1^n \alpha_i = \sum_1^n (\pi - \theta_i) = n \cdot \pi - \sum_1^n \theta_i \quad (25)$$

The wrapping angle expression depends on the yarn carriage direction (Figure 4.5):

$$\text{from P2 to P3} \quad \alpha = 2\pi - (\theta_1 + \theta_4) = 2\pi - (\theta_1 + \pi - \theta_1) = \pi \quad (26)$$

$$\text{from P3 to P2} \quad \alpha = 2\pi - (\theta_1 + \theta_1) = 2 \cdot (\pi - \theta_1) \quad (27)$$

where

$\theta_1$ : angle  $\widehat{P5 P1 P4}$  and  $\widehat{P1 P4 P3}$ ,

$\theta_4$ : angle  $\widehat{P1 P4 P2}$ .

The evolution of the wrapping angle relative to time is illustrated in Figure 4.11.

The evolution of  $\theta_1$  relative to yarn carriage position is:

$$\theta_1 = \arccos(x_1 - x(t)) \quad (28)$$

The tensile force between P1 and P4 relative to yarn carriage position/time is expressed from Equation 24:

$$T_{P1P4} = T_{P1} \cdot \exp(\mu\alpha) \quad (29)$$

Where

$T_{P1}$ : Initial yarn tensile force at P1.

By considering Equations 24, 25 and 28:

$$T_{P1P4} = T_{P1} \cdot \exp\left(\mu\left(n \cdot \pi - \sum_1^n \theta_1\right)\right) \quad (30)$$

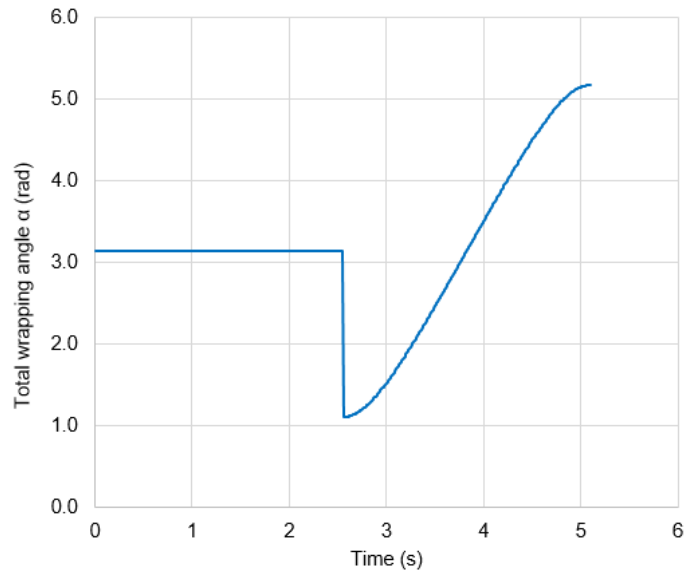


Figure 4.11: Total wrapping angle during inlay carriage movement.

The yarn tensile force is depending on the adding-up of friction at all deflection points from the yarn on its path from the yarn cone on the creel up to the knitting zone. The friction is effecting the yarn condition from the inlay yarn (Figure 4.12).

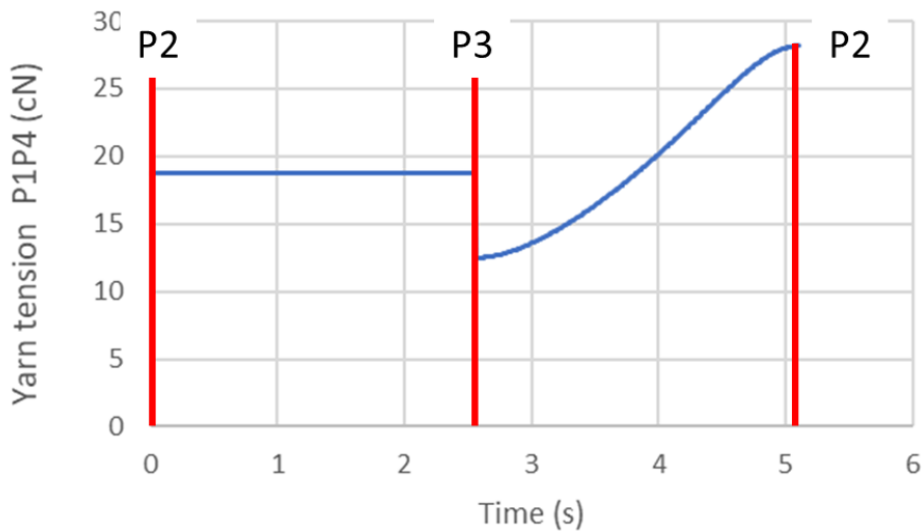


Figure 4.12: Calculated yarn tensile force evolution between P2 to P3 due to yarn friction in the eyelets

Figure 4.12 illustrates the calculated yarn tensile force during a complete yarn carriage cycle from the Equation 30 with Equation 19. The coefficient of friction  $\mu$  between the yarn and the ceramic of the eyelet has been arbitrary fixed to 0.2.

#### 4.4.2 Experimental investigation of the inlay process

To measure the yarn tensile force evolution relative to the yarn carriage position a magnetic positioning sensor is installed on the traversing carriage of the machine

(Figure 4.13 a and b) to synchronize the tensile force readings from the installed sensors at P1 and P4 (Figure 4.14) with the carriage movement. The information given by the two force sensors at P1 are similar, therefore in the following of the manuscript, two signals will be used indifferentially and will be considered to give the tensile force at P1. It reads out a concrete peak (voltage left POR P2 in Figure 4.15 and Figure 4.16) when the carriage is at the tuning position on the left side from the machine. Therefore, Figure 4.15 and Figure 4.16, between the peaks from the magnetic position sensor, is always a complete cycle from the carriage including the inlay from two weft yarns.

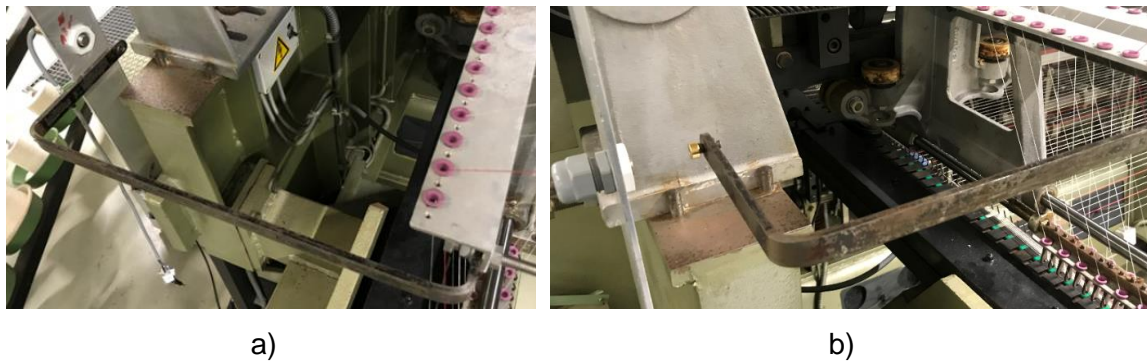


Figure 4.13: Position magnetic positioning sensor at P2 (left POR) in order to measure de position of the RS4-MSU carriage P4 a) top view, b) frontal view

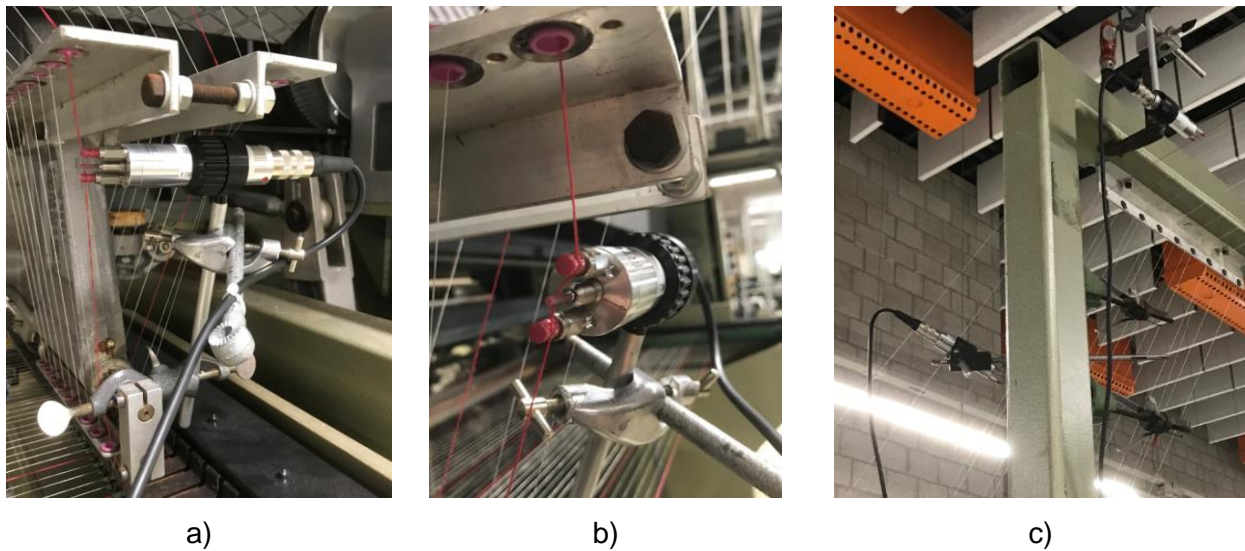


Figure 4.14: a) and b) One tensile force sensor at P4 (traversing on the carriage), c) two tensile sensor force at P1, i.e. fixed after the feeder and fixed before the last eyelet).



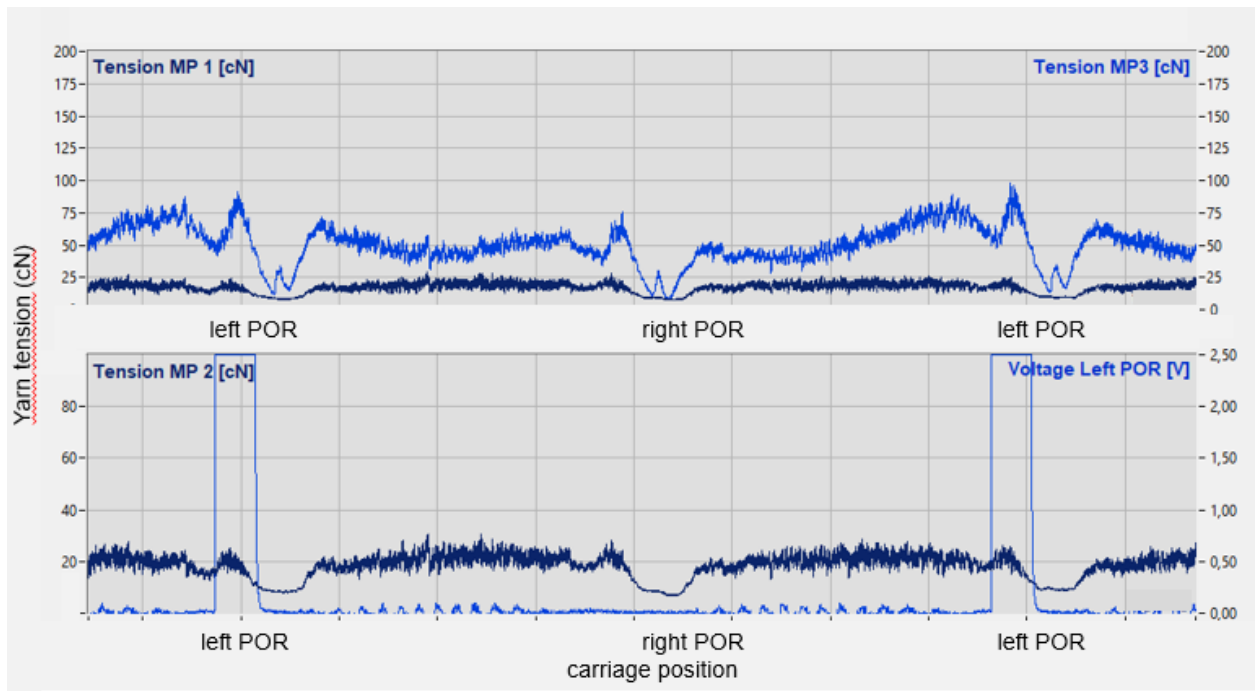


Figure 4.15: Synchronized yarn tensile force reading over one inlay carriage cycle. MP1 is the yarn tensile force measuring at P1, MP3 at P4, MP2 at P1 and the positioning sensor signal indicating when the yarn carriage is at P2.

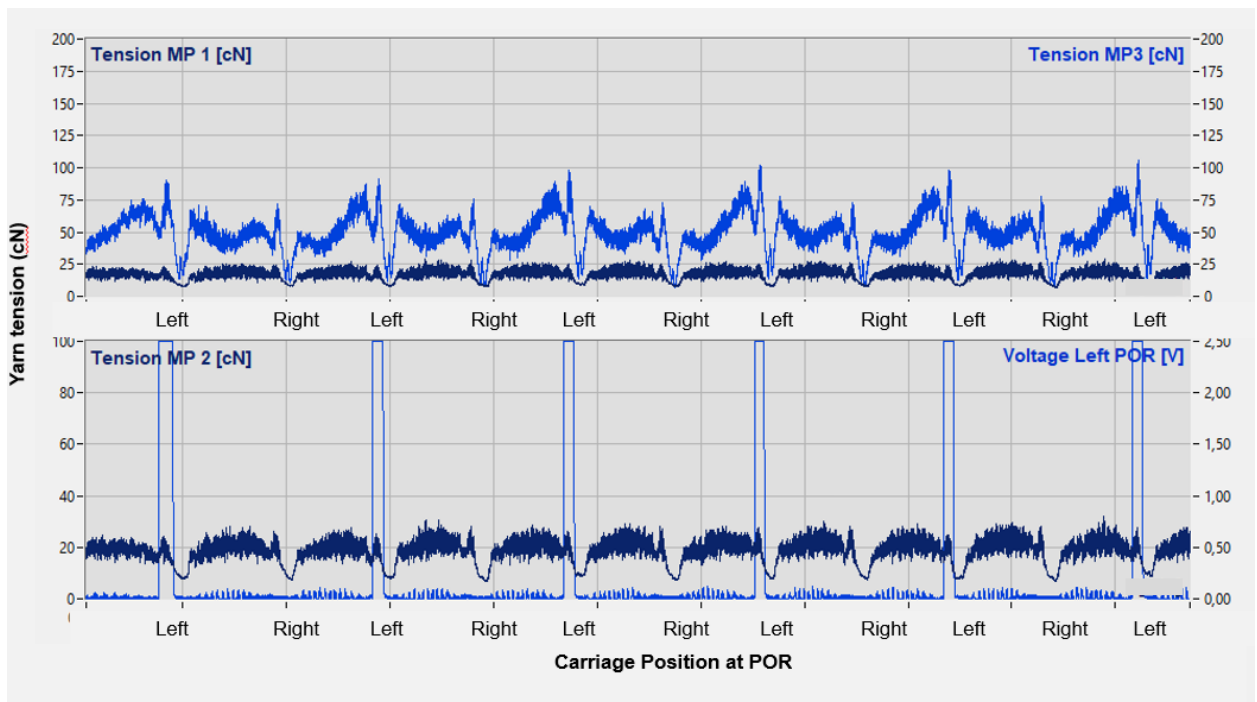


Figure 4.16: Synchronized yarn tensile force readings over several inlay carriage cycles. MP1 is the yarn tensile force measuring at P1, MP3 at P4, MP2 at P1 and the positioning sensor signal indicating when the yarn carriage is at P2.

It can be observed that the calculated yarn tensile force (Figure 4.12) and the measured yarn tensile force (Figure 4.15 and Figure 4.16) follow a similar basic cycle.

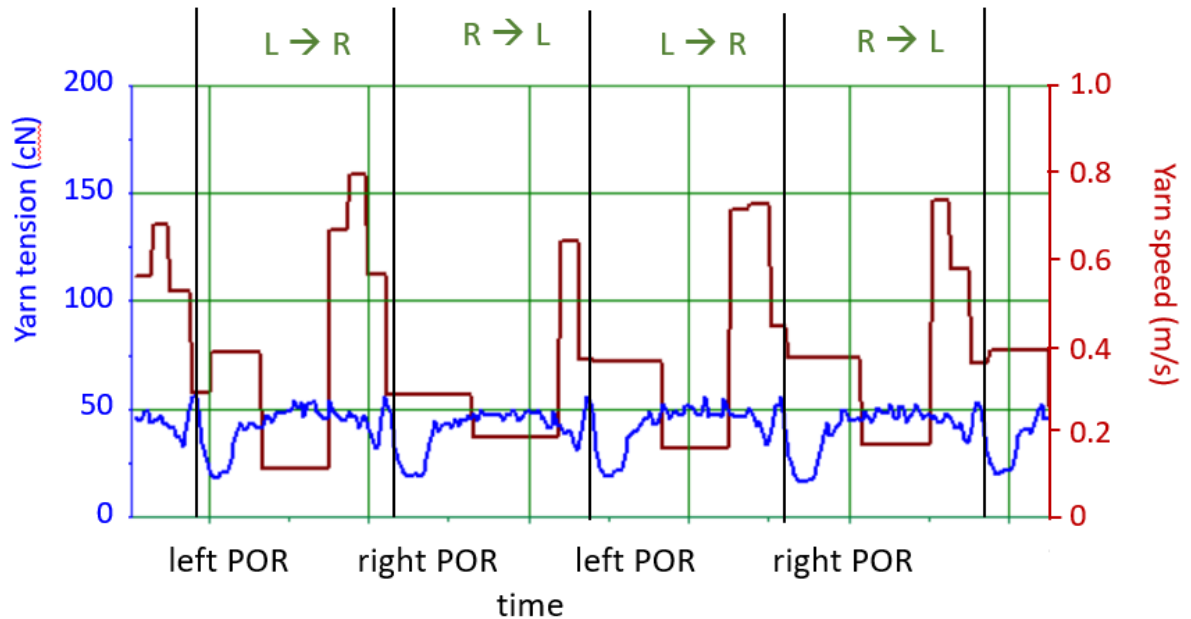
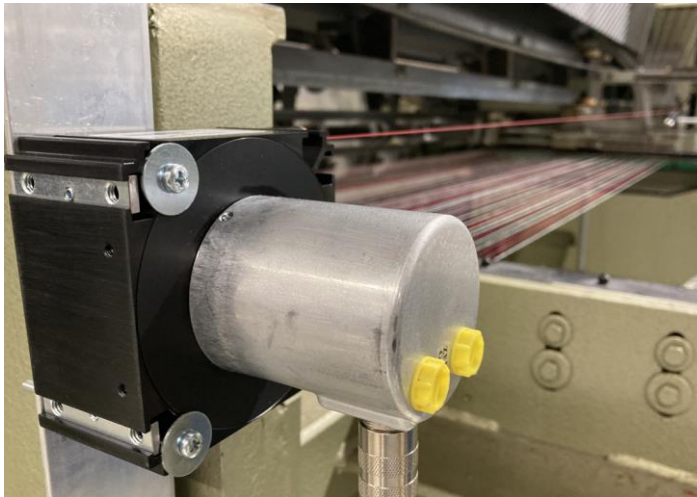


Figure 4.17: Simultaneous yarn speed (brown) and tensile force (blue) measurements at P1 in Figure 4.5

The simultaneous yarn speed and tensile force measurements at P1 (Figure 4.5) displayed in Figure 4.17 show the yarn speed is at its maximum during the second half from the carriage movement before the POR from the carriage dropping with the perpendicular movement from the carriage. The yarn speed level is higher at P2 compared to the opposite direction. The yarn speed seems not directly corresponding to the yarn tensile force. However, the evolution of the yarn tensile force between P2 and P3 can present similarities with the yarn speed evolution in Figure 4.17 but with a delay less than 1s.

In order to have a more accurate synchronization between the yarn tensile force signals with the instantaneous carriage position, a draw-wire displacement sensor (WDS-2500-P96-SR-I from Micro-Epsilon in Ortenburg, Germany) is placed according to the assembly instructions from Micro-Epsilon GmbH<sup>71</sup> at the measuring position P2 (Figure 4.18) with the signal generator attached to the moving carriage (P2 in Figure 4.5).

Figure 4.19 illustrates the yarn tensile force in different measuring points (P1 and P4 in Figure 4.5). The sinusoidal curve represents the carriage positions from the left POR, i.e. P2. The maximum from the curve indicates the maximum distance, and the minimum distance from the carriage to the left POR. Therefore, a period of the sine curve represents a complete carriage cycle with two inserted weft threads.



a)



b)

Figure 4.18: a) Positioning from the draw wire displacement sensor at P2 in Figure 4.5, b) seen from the carriage

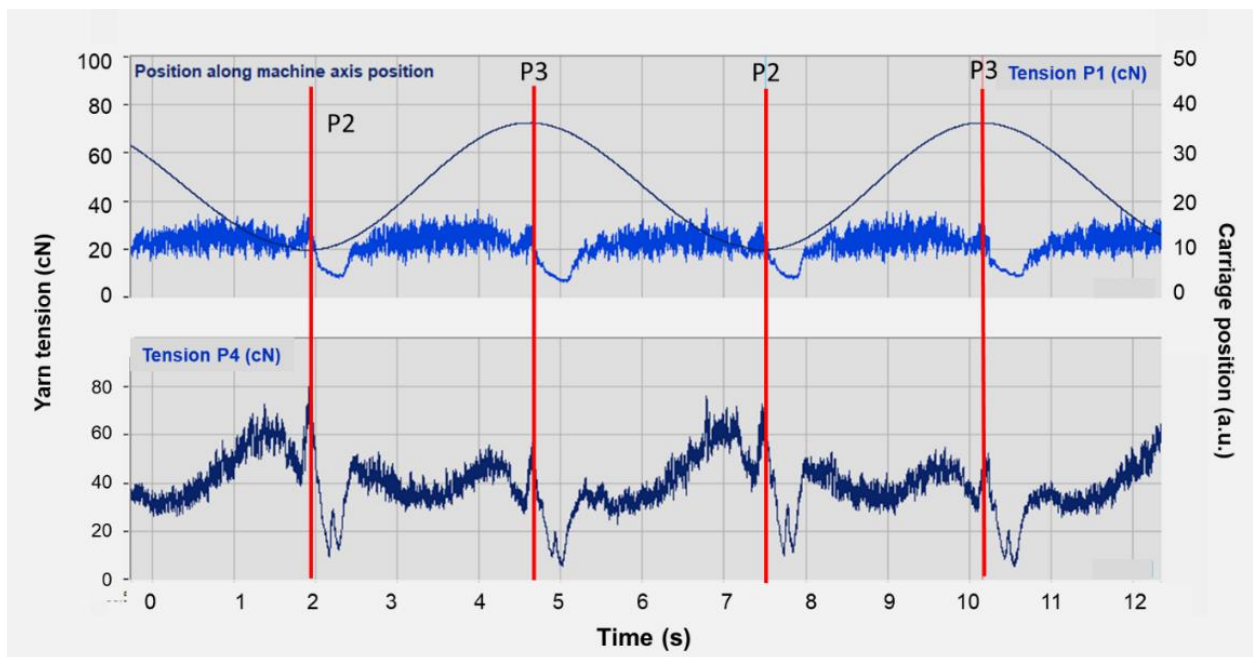


Figure 4.19: Yarn tensile forces for points P1, P4 and yarn carriage position relative to time during several knitting cycles.

Several observations can be directly done from Figure 4.19:

- The yarn tensile force drops to lower values directly before the cross-movement from the carriage system;
- The peak at the end of the half-cycle indicates the deceleration during the cross-movement from the carriage;

- The yarn tensile force level for the carriage movements towards the creel (P3 to P2) are higher than for the carriage movements going away from the creel (P2 to P3);
- The highest yarn tensile force is during the cross movement of the carriage, the lowest speed is in the middle of the carriage stroke.

#### **4.5 Conclusion from the analysis**

From experimental and calculated yarn tension, a difference between the yarn tensile force levels relative to the carriage direction is highlighted. From P3 to P2, yarn tension is lower at the beginning of the movement and higher at the end than in the opposite direction (Figure 4.19). The calculated yarn tension (Figure 4.12) shows the same evolution due to the evolution of the total wrapping angle from P3 to P2 as illustrated by Figure 4.11.

In another way, some requirements can be extracted from a qualitative point of view from the preliminary study. During the insertion of the weft yarn, the yarn tensile force and the yarn speed fluctuate greatly. This is probably causing longitudinal and transversal oscillations in the weft inlay yarn<sup>72</sup>. These oscillations get more intense with increasing machine speed and therefore increasing yarn speed. This mechanism results in limitations in the processing speed for the inlay yarn process and the warp knitting machine.

For a further increase in machine speed and to achieve greater process reliability, a more even and constant feeding of the yarn must be achieved. To improve the weft yarn feeding condition during the inlay process in warp knitting machines continuously moving transportation and placing elements are a solution, i.e. no alternating movement introducing yarn tensile force variation. An ideal solution would allow to combine the continuous movement of the components with the reciprocating placement of the inlay yarn into the knitting zone of the warp knitting machine. These continuously moving components without cyclical stopping and acceleration will also reduce the power consumption of the warp knitting machine. Further it is better to not have intermediate yarn storage that is reducing the complexity of the inlay warp knitting machine, reduces machine cost and increases the process reliability by lesser components involved in the inlay process.

#### **4.6 Targets and goals for the innovative inlay-yarn process**

The following technological targets should be processed and achieved:

- Continuously moving transportation and placing elements,
- No yarn storage,
- Individual yarns, no groups,
- No cutting waste,

- Process with high flexibility for narrow fabrics,
- Continuous inlay thread/no cutting,
- Reducing transversal and longitudinal yarn vibrations.

The loop forming process in warp knitting machines can achieve speeds of up to 4.300 rpm (tricot machine) or 2.400 rpm (Raschel machine). The limiting factor is the weft laying over the width of the warp knitting machine. This is reducing the possible machine speed drastically to a maximum of 1.500 rpm.

Based on the research made on the state-of-the-art technology the following main topics need to be achieved from an innovative inlay system for warp knitting machines to improve the efficiency and speed:

- Constant yarn tensile force during the yarn inlay to not induce distortion of the ground structure,
- Reduced twisting from the inlay yarn on its way from the bobbin to the knitting zone,
- Precise yarn guidance during the inlay procedure,
- Continuous inlay yarn/no cutting waste.

In warp knitting, weft threads are for many applications very important. The weft threads are used to create reinforcements or other mechanical/physical properties such as conductivity in certain areas of the knitted fabric. The weft insertion often represents the process limitation concerning speed, as it requires yarn guidance with high masses and accelerations. An increase in the production speed of the warp-knitting machine also brings with it a higher yarn speed. As a result, longitudinal and transverse vibrations occur in the weft yarn during the insertion phase. That factor has influence to the yarn selection.

## 5 Prototype with rotating blades

Based on the research made on the state-of-the-art technology, the patent situation in the field of winding machines and inlay warp knitting machines, and valid technical rules and standards the development of the inlay system with rotating blades is concluded. The main topics previously described in section 3.1 and 3.2 need to be achieved from an innovative inlay system for warp knitting machines to improve the efficiency and speed:

These parameters relate to the geometrical requirements, the yarn positioning requirements, machine speed, machine handling, and process reliability. In combination with the actual task definition for the rotor-based yarn inlay process in warp-knitting machines result ultimately in the prototype definition of the prototype unit.

In practical two preliminary design prototypes for the mechanical and geometrical parameters from the inlay process in warp knitting machines using rotary blades and the technical task using the rotary blades in the bobbin winding technology have been made, manually tested and evaluated. Both models are manually driven and are meant to display the proof of principle.

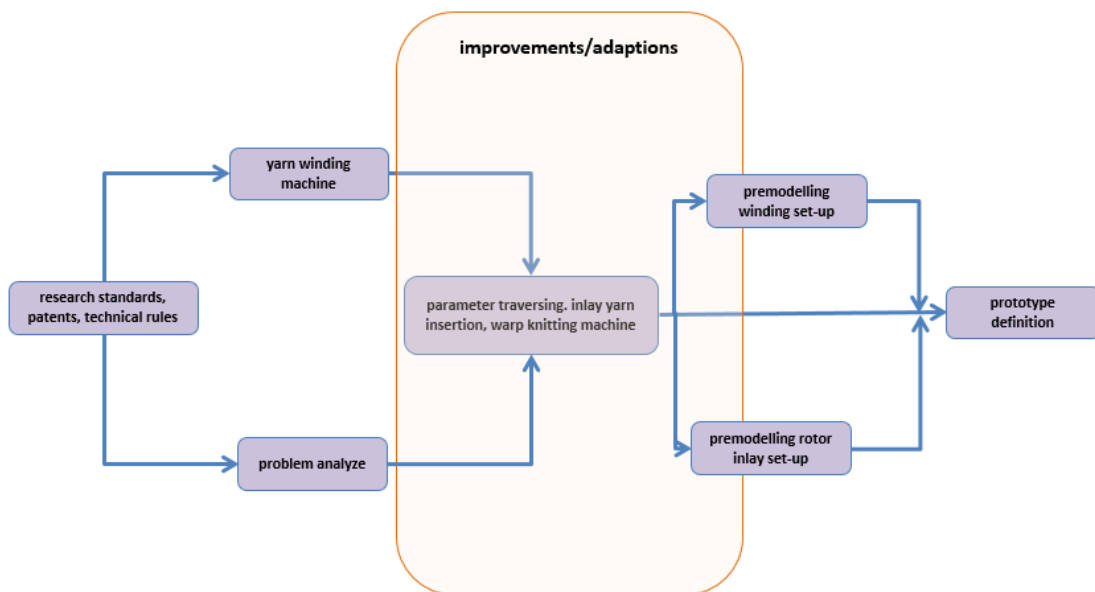


Figure 5.1: Workflow prototype definition

The result of this first step is the technical prototype definition catalogue. Based on this prototype definition the different development steps for the design of the prototype are determined. Improvements and possible adaptations are already tested in this first phase and evaluated. The complete foreseeable development process is visualized in the workflow prototype definition in Figure 5.1.

Therefore, the proposed solution is to adapt a technology that is used in the bobbin winding process.

## 5.1 General definition prototype

In the previous section, the specifications for a new and innovative traversing system for the inlay yarn insertion in warp knitting machines have been identified. Therefore, the proposed solution is to adapt a technology that is used in the bobbin winding process.

A prototype is the first or original example of something that has been or will be copied or developed; it is a model or preliminary version<sup>73</sup>.

The general definition of the prototype contains three aspects of interests<sup>73</sup>:

- The implementation of the prototype; from the entire product (or system) itself to its subassemblies and components;
- The form of the prototype; from a virtual prototype to a physical prototype;
- The degree of the approximation of the prototype; from very rough representation to exact replication of the product. Some rough prototypes may not even look like the final product.

The complete prototype models most have, if not all, the characteristics of the product. It is usually implemented full-scale as well as being fully functional. The purposes of the prototype can be:

- Functional, working, or performant,
- Form or design study,
- Proof-of-Principle,
- Visual.

The prototypes are given to a group of selected people with special interests, a focus group, to examine and identify outstanding problems before the product is finalised.

The task from the thesis is to set up demonstration units from the following two technical set-ups:

- Inlay process with rotors,
- Inlay process based on a torque motor.

From those two demonstrating units technical conclusions can be drawn and the necessary further development process can be determined and defined.



## 5.1.1 Prototype unit Inlay process with rotors

### 5.1.1.1 Analysis rotary blade process

In the historical line of development up to the current state-of-the-art, the insertion processes are characterized by machine elements, which have to perform an acceleration and braking movement for each insertion in the shortest possible time. Wing traversing systems from winding technology like the Barmag Wings<sup>®</sup> system (Figure 5.2)<sup>74,75</sup> can wind threads on cross-wound bobbins with variation within a few millimetres at speeds of up to 8,000 m/min with a traversing width of 20-30 cm.

In the case of the wing-traversing device, the thread traverses on the surface of the bobbin by several rotating wings moving in opposite directions. The two in opposite direction driving wings with blades are located at a defined angle to the rotating bobbin.

To even out the guiding speed, a shaped guide rail is guiding the yarn positioned to the carrier wings<sup>75</sup>.



Figure 5.2: Barmag Wings<sup>®</sup> rotary winding units (picture taken at Barmag AG, Remscheid)

### 5.1.1.2 Rotating blades in winding machines

A yarn winding apparatus is characterized by the ability to wind a plurality of running yarns onto a corresponding number of bobbins mounted on a common support spindle. The complete apparatus comprises a plurality of traversing assemblies, which are mounted side by side extending along the length of the support spindle, with each traversing assembly comprising a yarn guide bar and a pair of oppositely rotating rotors (Figure 5.2).



The rotors include arms which define two closely adjacent planes of rotation, and the two rotors of each assembly are mounted for rotation about offset axes and so that the arms sweep across the guide bar in opposite directions to define the traverse stroke<sup>69</sup>.

Different layout versions are discussed in patent applications.

A pair of rotors with three blades<sup>75,76</sup> or a pair of rotors of which one shows two blades and the other three blades<sup>77</sup>. The two rotors are synchronised in their speed and are turning in opposite directions. To enable traversing yarn movement the rotation centres were placed with an offset to each other. There are also systems introduced to the market in which two pairs of rotors perform a handover from the traversing yarn in the middle of the traversing path.

### 5.1.1.3 Traversing unit with different rotors

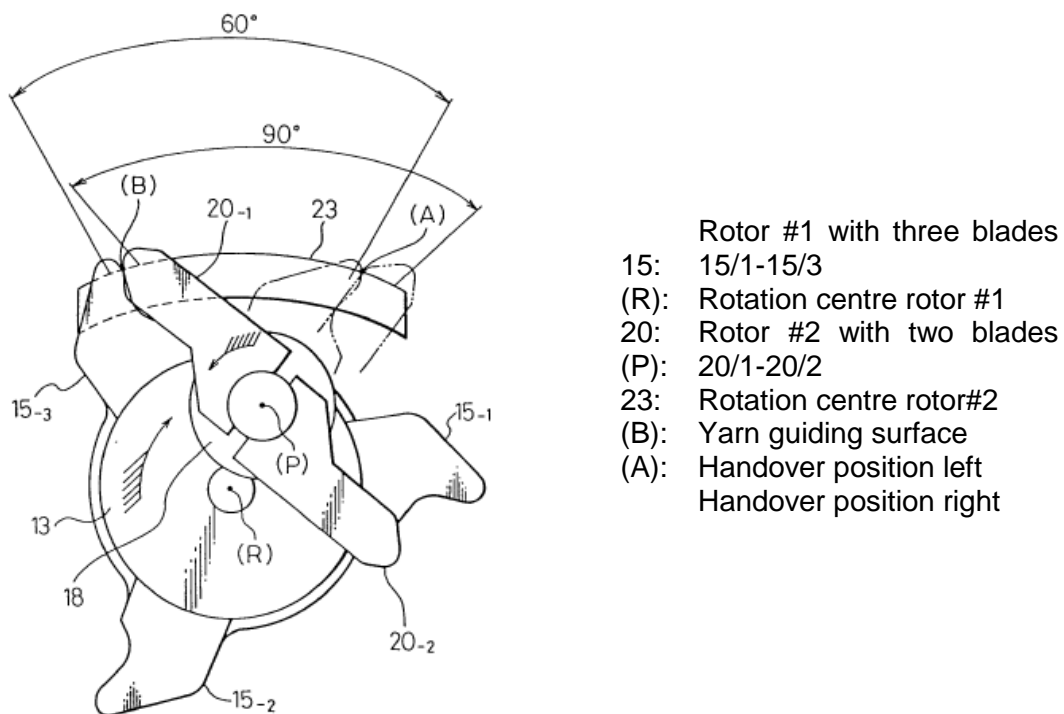


Figure 5.3: Apparatus for winding a multitude of yarns<sup>77</sup>

A traversing unit for a running yarn is mounted on a frame. The first and second rotors (numbers 13 and 18 in Figure 5.3) each rotatable mounted on the frame body. Blades fixed on the rotor (number 15 in Figure 5.3) and blades fixed on the second rotor with two blades define a distal end having a yarn guiding edge formed thereon. A yarn guiding surface (number 23 in Figure 5.3) is constructed and arranged to guide the running yarn along a yarn traversal path, wherein both rotors rotate in opposite directions. The running yarn is conveyed along the yarn traversal path by one of the blades of the first rotor

(number 13 in Figure 5.3) and traversed in the opposite direction from the blades from the rotor (number 20 in Figure 5.3)

To ensure the handover from the traversing yarn on both sides of the traversing, the rotor with three blades has to turn  $60^\circ$  and the rotor with two blades has to turn  $90^\circ$ <sup>77</sup>.

#### 5.1.1.4 Traversing unit with identical rotors

It is a winding unit from a bobbin winding machine (Figure 5.4 a). A winding cone is attached to a turning spindle on which the thread is constantly wound up. A traversing device (visible in Figure 5.4 b), which is guiding the thread back and forth over the traversing stroke transversely to its direction of travel places the tread on the winding package. It is also equipped with a guide rail extending along the traversing stroke. The guiding rail enables the winding from the thread under constant yarn tensile force and speed (Figure 5.4 a).

Two rotors rotating in opposite directions and synchronously with parallel axes achieve the traversing movement from the yarn. Blades are attached to the rotors at the same angular pitch and are arranged in two closely adjacent planes of rotation (Positions 2 and 3 Figure 5.5). The yarn path is penetrating the plane of rotation from both rotors.

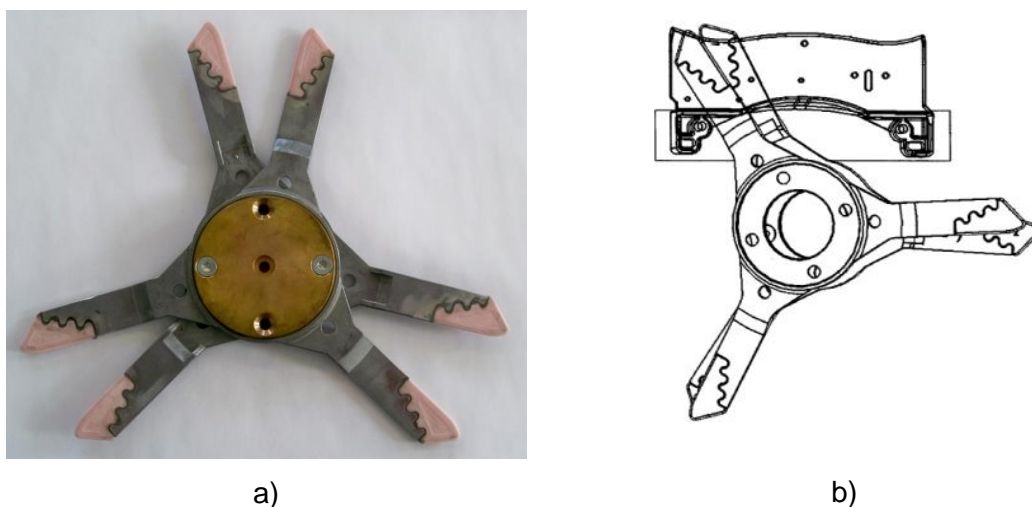


Figure 5.4: a) Pair of rotors with three blades/rotor (Barmag Wings<sup>®</sup>), b) Top view on a rotor yarn traversing unit for winding machine<sup>78</sup>

The two rotors alternately guide the yarn along the guide rail employing one of their blades during rotation (conveying phase) and thereby imparting a traversing speed to the yarn. This speed is determined by the guiding speed and the design of rotors as well as the shape of the guide rail and is transferred to a blade edge of the other rotor at the end of the traversing stroke for the return movement.<sup>76</sup>

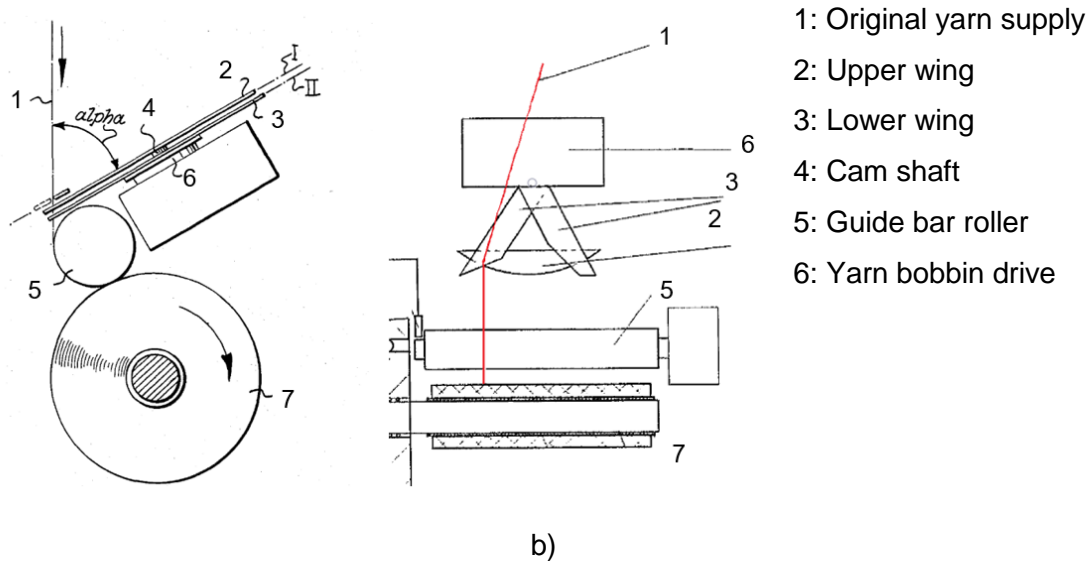


Figure 5.5: a) Side view<sup>76</sup>, b) Schematic top view<sup>74</sup> from a Barmag Birotor winding unit

### 5.1.2 Requirements for an innovative system in warp knitting machines

Based on the research made on the state-of-the-art technology the following main aspects of an innovative inlay system for warp knitting machines, to improve the efficiency and speed must be taken into account:

- Constant yarn tensile force and speed during the yarn inlay to not induce distortion of the ground structure,
- Precise yarn guidance during the inlay procedure,
- Precise yarn position control during the complete traversing,
- Maintain and control high yarn speed,
- No or just a little twist added to the yarn during the winding process,
- Individual single yarn end, no groups or batches,
- Continuously moving transportation and placing elements without regular acceleration and stopping from components,
- No intermediate yarn storage,
- Programmable inlay possible (yes/no decision for every course),
- Possibly an inlay insertion device that can be allocable in a broad machine,
- Flexible length from the inlay yarn (flexible inlay width in the fabric),
- A process with high flexibility for narrow fabrics,
- No cutting waste from the inlay yarn,
- Continuous inlay thread/no cutting.

Therefore, the proposed solution is to adopt a technology, which is successfully used in the bobbin winding process to the warp-knitting technology.

### 5.1.3 Traversing inlay systems in cone winding machines

To ensure a good bobbin build-up, the yarn is repeatedly moved back and forth across the width of the bobbin while the bobbin is rotating. This is achieved with moving or rotating thread eyelets or guides. The disadvantage of reciprocating yarn guides is that their direction of movement has to be reversed at the edge of the bobbin, this leads to considerable acceleration forces which can contribute to very rapid wear. Rotating systems can move the yarns back and forth much faster, i.e. oscillate, but at the yarn reversal point, a shock-like load can occur on the yarn<sup>79</sup>.

Besides in previously already described rotating blades technology further different technologies are used in winding machines.

#### 5.1.3.1 Grooved drum

Machines with grooved drums are widely common for the rewinding of yarns to apply wax or paraffin.

In the cone winding technology, the grooved roller is generally directly driven. The yarn is moved alternately by the grooves on the circumference of the driven drum. A laterally arranged motor drives directly the grooved or placing roller. The yarn is oscillating guided back and forth through the grooves in the roller. In the process, the load on the yarn is reduced as much as possible by applying an adapted groove design (Figure 5.6).

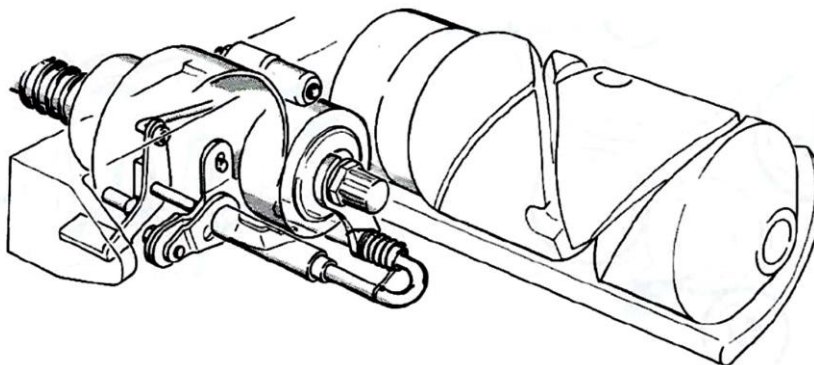


Figure 5.6: Grooved drum winder application<sup>13</sup>

The roller is feeding the yarn directly through the groove of the laying roller on the rotating package. When delivering the inlay yarn, the yarn is only minimally deflected in the groove of the laying roller and only at the edges of the needle area of the warp-knitting machine (Figure 5.7 a-c). The advantage of this system is the permanent rotating drum with no acceleration or stopping from moving masses.

The only traversing mass is the thread itself. The disadvantage of this system is the friction between the yarn and the edges from the grooves in the rotating drum and the open

structure while traversing the yarn. The only guidance from the traversing yarn, at the left and the right POR from the yarn, is the groove itself without any holding down device, or a cover.

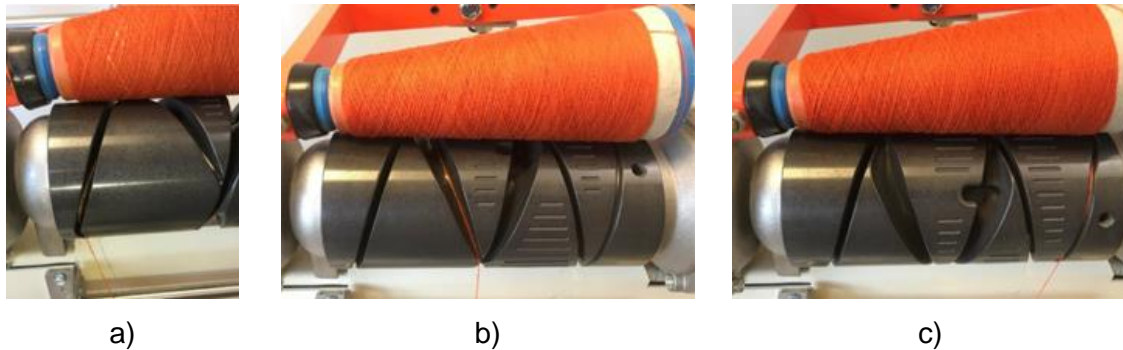


Figure 5.7: Cone winding with grooved drum: Yarn a) at the left side, b) traversing from left to right side, c) at the POR.

### 5.1.3.2 Traversing eyelet method

With this method, an eyelet moves to traverse in front of a surface-driven yarn-winding package (Figure 5.8).

The simplest winding machines have two axes of motion, the mandrel rotation and the carriage travel (usually horizontal). Two-axis machines are best suited to the manufacture of pipes only<sup>80</sup>. A piston or a linear motor can drive the eyelet.

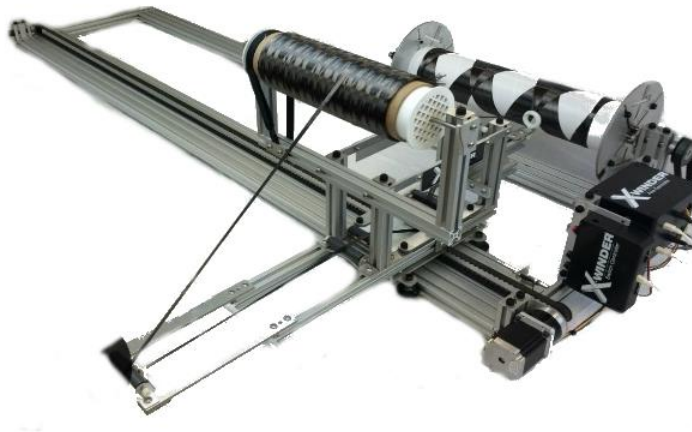


Figure 5.8: Reciprocation winding machine <sup>81</sup>

The advantage of this system is the permanent safe guidance from the yarn from the moving eyelet. The major disadvantage is the traversing mass from the complete yarn guide with permanent acceleration and stopping at every POR (direction change), which is leading to higher energy consumption.

## 5.2 Preliminary modelling

To apply rotary blades as a traversing feature in the cone winding industry is current state-of-the-art. The preliminary modelling studies are made, to understand the technical tasks from the rotary blades used in the cone winding technology on one side, and on the other side to clarify the technical requirements from the yarn inlay procedure based on rotary blades in warp knitting machines. The expertise and information gained out of these pre-modelling scenarios will be added to the list of specifications from the prototype unit.

Two preliminary models are set up:

- A small-scale model from a warp knitting unit with rotary blades. It is used to understand the principal mechanical process and the geometrical basics using the rotor blades in a warp-knitting machine model scenario,
- A model from a winding unit with rotary blades is used to understand the geometrical situation and the process in a yarn winding machine. For this model existing standard rotors of the Barmag Wings® system from the company Barmag AG in Remscheid, Germany are used. These rotary blades are identical to the planned traversing unit in the future prototype unit.

### 5.2.1 Pre-modelling rotor inlay set-up

The first prototype design is setting up the blades vertically in front of a vertically arranged and manually movable needle bar (Figure 5.9-Figure 5.11). The rotors have been cut out of hard paper following the geometry from the Barmag Wings® rotors.

This prototype showed the following aspects:

- The handover from one blade to the contrary rotating blade is possible,
- Standard latch needles are working,
- The edge needles are the most critical for the inlay process (Figure 5.10),
- The inlay yarn needs to be placed behind the plane of the needle bar (Figure 5.11 b),
- A “push or pull forward device” can be necessary for the edge needles (Figure 5.9 a),
- The centrally positioned yarn supply is possible (Figure 5.9 b),
- The traversing process leads to big contact angles from the yarn on the blades,
- The yarn will move along the blade edges during the traversing process,
- A guide bar will be needed after the traversing unit and in front of the needle bar,
- The inlay timing to the cycle from the machine is critical,
- The yarn will move on the blade during the traversing movement (Figure 5.9 b and c),
- The yarn path shows a horizontal and vertical drag angle (Figure 5.11 a and b),



- The inlay yarn tensile force needs to be controlled,
- The inlay yarn speed needs to be controlled.

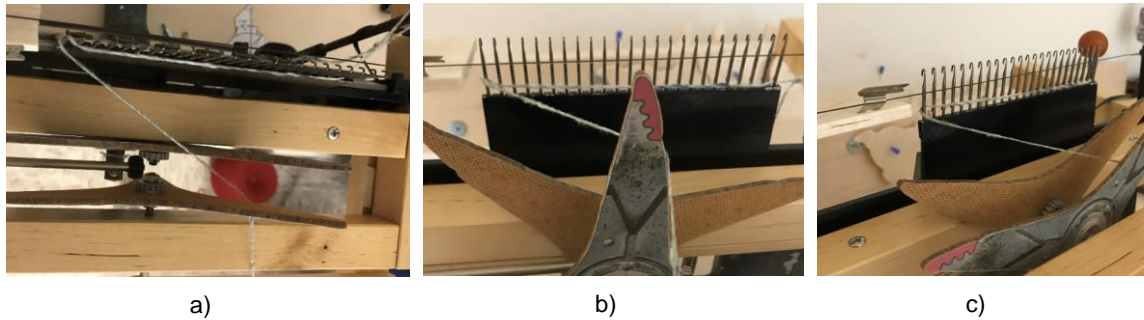


Figure 5.9: Model rotor inlay process: a) top view, b) front view, c) side view



Figure 5.10: Model rotor inlay process edge needle situation



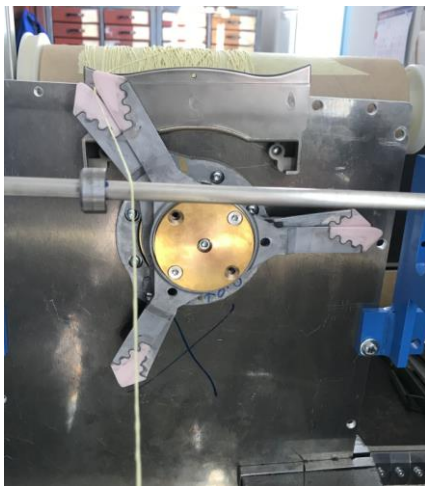
Figure 5.11: Drag angles in the wooden model: a) horizontal and b) vertical.

The frame is housing one pair of rotors. The rotors were manually driven but a model scale gearbox enables a synchronized contrary rotation.

## 5.2.2 Pre-modelling rotor winding machine set-up

Functional and proof of principle prototype from the bobbin making in winding machines using rotary blades:

The second build prototype is a mechanical model from a cone-winding machine with a pair of original Barmag Wings® winding rotor blades, the original gear box and the guide blade. The thread is guided directly through the surface covered by the rotating blades (Figure 5.12 a and b). The pair of rotors is placed vertically in front of the rotating paper board (Figure 5.12 c) winding body from the cone (Figure 5.12 a). The traversing yarn is guided over the original Barmag yarn guide plate to place it on the drum. The yarn does not have to be inserted, the back and forth movement starts directly. The transfer of the yarn from one rotor to the counter-rotating one – given by the geometry of the setup – is also given automatically (Figure 5.12d).



a)



b)



c)



d)

Figure 5.12: Model cone winding with Barmag Wings®: a) front view, b) left handover, c) top view d) right handover

The yarn speed and the correlating yarn tensile force is determined by the speed of the winding body. Differences in yarn speed and tensile force during the traversing movement from the yarn are equalized from the guide plate. The positions from the guide plate and



the assembly from blades and gearbox are based on the original Barmag geometry. This prototype showed the following aspects:

- The handover from one blade to the contrary rotating blade is possible (Figure 5.12b),
- The handover process is symmetrical – the left and the right side of the cone are technically identical,
- The traversing process in a winding machine needs small contact angles on the rotating blades (Figure 5.12d,;
- The traversing movement and the handover between the rotating blades is not related to the yarn speed,
- An additional yarn guide blade is needed to have a proper cone set-up and to equalize the yarn speed and tensile force over the complete yarn traverse in both directions (Figure 5.12 c),
- The centrally positioned inlay yarn supply is possible,
- The inlay yarn needs to be constantly stretched,
- The timing from the traversing blades to the rotating drum position is not relevant,
- The friction between the yarn and the guide blade is not relevant,
- The yarn speed is defined by the rpm of the winding cone, the traversing speed from the rpm from the rotary blades. The parameters from the cone winding structure are resulting from their combination,
- The initial yarn tensile force is primarily not critical, it just needs to be kept constant over the traversing movement,
- The yarn will not move on the blade during the traversing movement, besides being forced from the geometry of the guide blade (Figure 5.12 a and c).

These studies show the technical challenges of the rotor blade unit for the inlay yarn process in warp knitting machines and its differences from the cone winding process. This needs to be considered before entering the design and layout phase from the prototype unit. The knowledge created and the requirements had been included in the list of specifications.

### **5.3 Requirements**

Based on the preliminary trials and analysis the principal design features and technical components from the prototype with the rotating blades unit are:

- The prototype unit is made as a stand-alone machine,
- The working width is 200mm,

- The needle bar is equipped with 8 Karl Mayer 18GG needle module Z18/60-54 with Groz-Beckert needles Raschel-Spec 51.75 G01; therefore, the machine is using standard latch needles,
- The guide bars are equipped with Karl-Mayer needle modules KH-20-3-3,
- The drive and the relative timing during the knitting cycle, from all involved knitting elements, are made mechanically via the main drive shaft,
- The warp beam is located on the top,
- The warp beam is braked to avoid over-shooting from the warp yarn,
- The warp yarns are individually guided through droppers as yarn breakage detectors,
- The warp yarn is negatively fed,
- The warp yarns need to be kept individual and distant from each other through their way from the beam to the knitting zone via individual eyelets fixed on plates,
- The rim warp yarns are individually guided via spring-loaded yarn tensioners,
- The yarn supply from the inlay yarn is made directly from the cone,
- The yarn supply from the inlay yarn is guided via a spring-loaded yarn tensioner,
- Yarn breakage detector, for inlay, needs to be applied,
- The controller unit synchronizes the traversing elements with the machine drive,
- The take-up device is integrated inside the machine,
- Flexible position in respect of distance between the rotor unit and the needle bar,
- The guide bar for the inlay yarn needs to be as close as possible to the needle bar,
- Initially the guide will be an open guide plate, if necessary a closed (slot) bar is applied,
- The inlay positioning elements are set at the fabric edges and at an equal distance over the fabric width,
- The trial stitch setup is to knit pillar stitch with inlay yarn.

### **5.3.1 Yarn path difference between cone winding and inlay-yarn insertion in warp-knitting machines**

In principle, the processes of bobbin winding and weft insertion in warp knitting machines differ. The winding process in bobbin production is a continuous process that is only interrupted at the end of the bobbin. The weft insertion in a warp knitting machine is a cyclical process with several process sections, which are constantly repeated, whereby the weft insertion is only a partial step. In addition, the yarn path from the bobbin to the yarn end differs on the one hand in its geometrical design and course and on the other hand in its temporal cycle.

### 5.3.1.1 Yarn path cone-winding

In the cone-winding scenario, the yarn path is going straight from the spinning machine through the pair of rotors to be wound on the rotating yarn cone (Figure 5.13). No significant deviation angle from the yarn on the blade edge occurs during the transversal movement as the yarn is constantly wound up on the cone. During the direction change at the left or the right edge from the winding areas, the following blade in the opposite direction reaches directly into the stretched yarn. The handover from the yarn is made without an increasing deviation angle from the yarn.

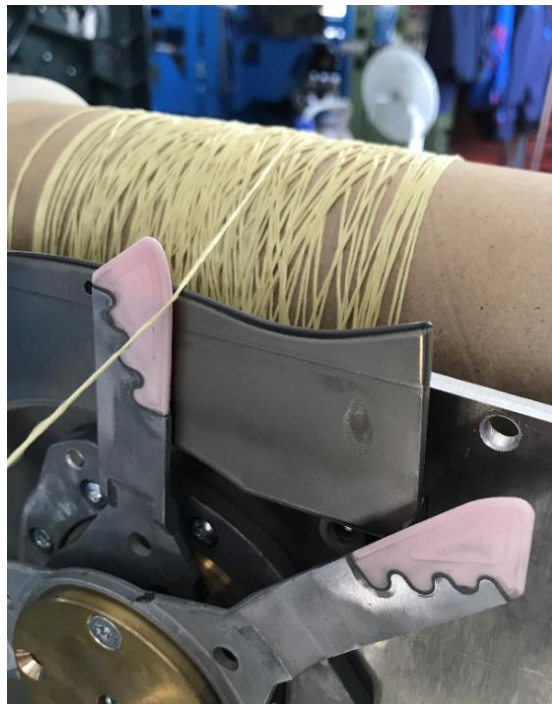
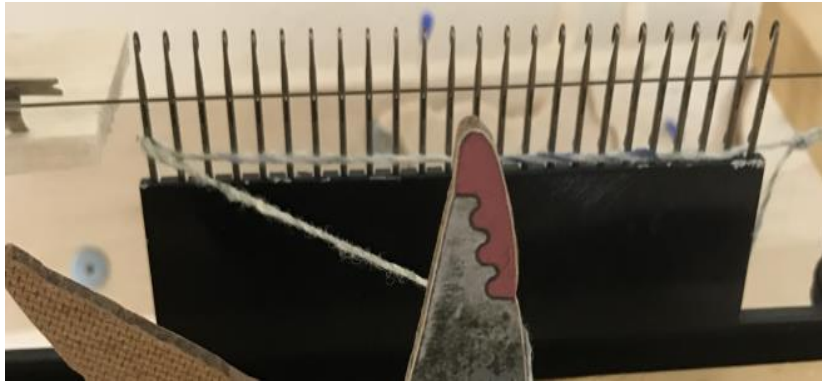


Figure 5.13: Yarn path in a cone-winding model

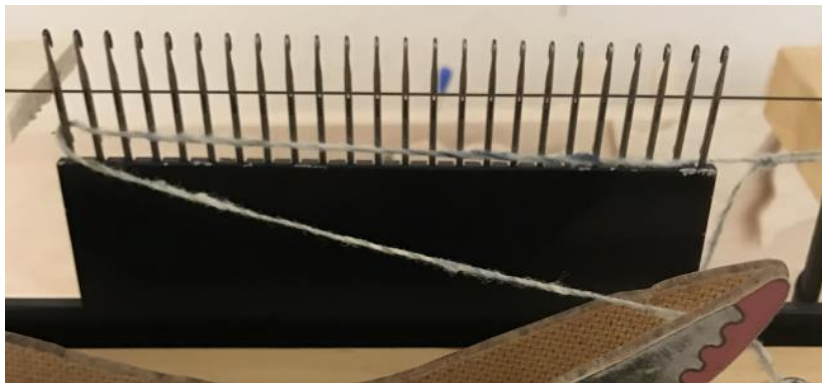
### 5.3.1.2 Yarn path inlay process in warp-knitting machines

The cycle from the process is determined by the movement of the evolved knitting elements which are directly driven from the main shaft of the machine. The insertion thread is bound into the loops. At the start of a new loop formation cycle, the insertion thread is guided by the traversing wing over the insertion area of the textile.

Therefore, as visible in Figure 5.14, the yarn path from the yarn cone through the pair of rotor blades and into the knitting area contains various deflection angles. These deflection angles are varying over the traversing movement (Figure 5.14). During initial trials while setting up the wooden demonstrating warp-knitting unit, varying deflection angle from the inlay yarn, become visible.



a)



b)

Figure 5.14: Deflection angle: a) rotor blade in the middle from the traverse movement, b) rotor blade at the right edge.

### 5.3.2 Functional and proof of principle prototype using rotary blades

Two rotors with three blades are rotating in opposite directions. These two rotors perform the direction change on each side of the warp knitting area. To ensure the proper handover from the first rotor blade to the rotor blade turning in the opposite direction, the two centres of rotation show a vertical offset.

For every full rotation of the pair of blades, 6 (=n) inlay yarns can be supplied to a warp knitting machine. The Barmag Wings<sup>®</sup> system is designed for high yarn speeds. The 250 mm stroke system enables yarn speeds of 2.500 to 4.000 m/min. Moreover, as an example, a delivery angle of 7° and a speed of 3.000 m/min results in a Barmag Wings<sup>®</sup> Birotor in a yarn speed of 365.6 m/min (6,9 m/s)<sup>82</sup>.

Based on 1.000 inlay yarn placements per minute the number of revolutions will be rpm=166.67 or rps=2.78 and 2.9 inlay yarns can be placed inside the warp knitting machine per second.

Equation 31 characterizes the rotating rotor blade idealistically as a thin aluminium plate in the shape of an isosceles triangle (Figure 5.15) rotating around its centroid axis.

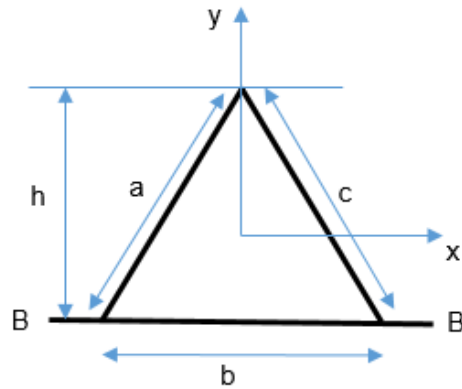


Figure 5.15: The moment of inertia of a uniform triangular plate<sup>83</sup>

The moment of inertia of a uniform triangular plate (Figure 5.15) about the vertical axis passing through its centre of mass is proportional to the sum of the squares of the sides and the mass<sup>83</sup>.

$$J = \frac{1}{36} \cdot m \cdot (a^2 + b^2 + c^2) \text{ in kg} \cdot \text{m}^2 \quad (31)$$

With:

J: moment of inertia ( $\text{kg} \cdot \text{m}^2$ )

m: mass from the blade (kg)

The complete Barmag Wings<sup>®</sup> blade system consists of two rotors, they rotate contrary, but with identical speeds and are simultaneously driven from the same belt drive and the same gearbox. Therefore, they are calculated identically.

For an isosceles triangle the length from all sides are identical.

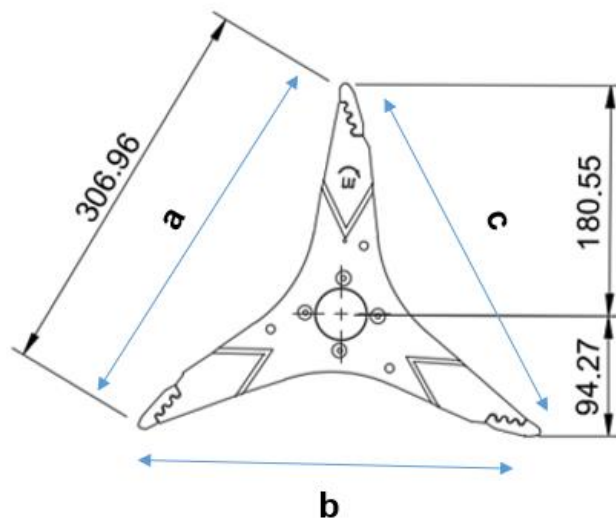


Figure 5.16: Geometry (mm) from the Barmag Wings<sup>®</sup> ACW2 blade system<sup>84</sup>

The measured values from the individual blade (Figure 5.16) from the Barmag Wings® blade system are: The mass  $m= 0.149\text{kg}$  and the length from the side from the blade corresponding to Figure 5.16 is measured with  $a=b=c= 0.37\text{m}$ .

Based on these values and Equation 31 the Moment of inertia  $I_z$  from the rotating blade can be estimated can be calculated to  $I_z= 1.7 \cdot 10^{-3} \text{ kg} \cdot \text{m}^2$

The approximate theoretical rotary energy ( $E_{bl}$ ) (Table 5.1: The theoretical rotary energy  $E_{bl}$  rotary blade system) can be calculated according to Equation 7 and the values in measured with the rotary blade:

Theoretical rotary energy	Single blade	Two blades simultaneously
$E_{bl}$ : (J)	0.04	0.08

Table 5.1: The theoretical rotary energy  $E_{bl}$  rotary blade system

An estimated additional 10% of the energy will be needed for:

- Friction compensation unwinding yarn and other mechanical interactions,
- Yarn/ blade friction,
- Yarn/air friction,
- Blade/air interaction,
- Friction in the gearbox and the belt drive.

Ideally, the system rotates at a constant speed without starting and stopping. To estimate the described losses stated from the system, the energy consumption in the start and stop scenario is estimated and the losses are estimated from this and considered to be the energy consumption for the permanent running system.

Therefore, the estimated energy consumption is set with 10% from the theoretical rotary energy consumption. This results in  $E_{blr} = 0.1 E_{bl}$ . Based on the estimated values the complete energy consumption from the blade system per inlay yarn can be calculated as reported in Table 5.2.

Rotary energy	Single blade	Two blades simultaneously
$E_{blr}$ in (J)	0.044	0.088

Table 5.2: Energy consumption  $E_{blr}$  rotary blade system

### 5.3.3 Background from the blade traversing principle

To understand the technical principle of the rotor process in respect of inlay yarn insertion in warp knitting machines, the geometrical parameters are analysed and the actual state-of-the-art process is analysed in respect of yarn tensile force and yarn speed over the stroke of the traversing carriage.

The upper part of Figure 5.17: Schematic view to the inlay yarn path shows a simplified structure of the inlay yarn path. As the yarn moves stretched and straight in the individual areas, it is possible to calculate and display the yarn length projected in a two-dimensional plane. The yarn path begins at the thread origin (bobbin at point A in Figure 5.17) leading over the guiding rail, the rotor plane to the needle bar where it is inserted into the knitted structure. A1, A2, and A3 in Figure 5.17 define the respective vertical distances between the thread origin and the guiding rail (A3), the guiding rail and the rotor plane (A2), and the rotor plane and the needle bar (A1). S1, S2 and, S3 in Figure 5.17 are the sections of the yarn to be calculated, which added together give the total theoretical yarn length.

The weft yarn is traversed and presented to the needles from the rotor blades. The yarn length is depending on the position of the rotor blades, which can be described by the angle  $\alpha$  (Figure 5.17). The two rotors, each with three blades at a distance angle of  $120^\circ$  rotate evenly in opposite directions in the simplified rotor plane. The yarn is traversed through one rotor and when the transporting rotor is overlapping with the opposite direction moving rotor, the yarn is transferred to the second rotor and transported in the opposite direction. The position of the rotor blade can be indicated by the angle  $\alpha$  at the rotor blade origin. The yarn is transferred from one blade to the contrary revolving rotor blade after each  $60^\circ$  rotor movement, therefore it results that the maximum angle  $\alpha$  is  $60^\circ$ .

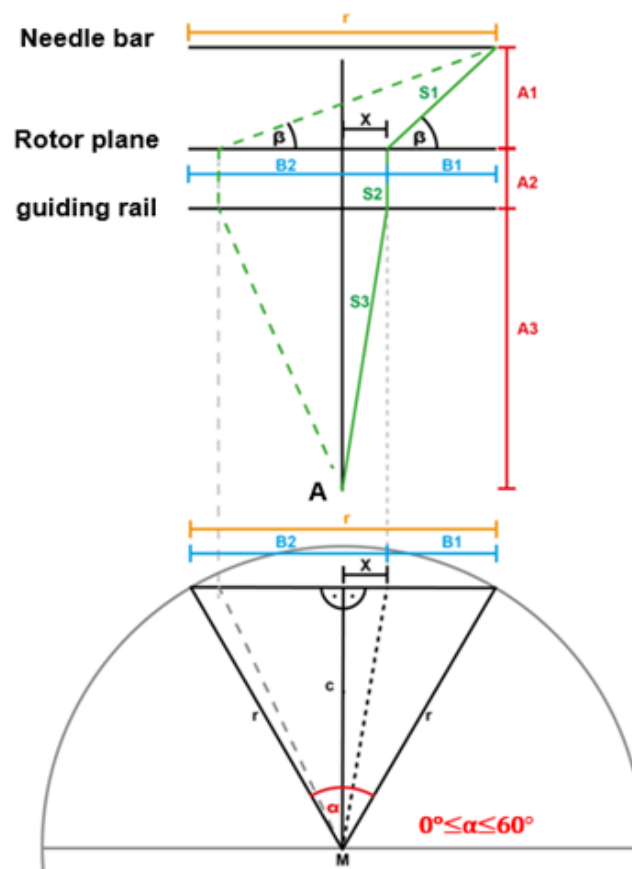


Figure 5.17: Schematic view to the inlay yarn path

A guiding rail with a guide slot is mounted between the rotors and the needle bar. Therefore, the yarn does not move in a circular movement but on a defined line between the hand-over positions from the rotor blades. An isosceles triangle is formed by the rotor blades, with an angle alpha of 60° and three sides and with a length corresponding to the radius of the rotor blades. From there it can be deduced that the inserted weft length corresponds to the radius of the rotors. To represent the movement of the weft on the guide rail, the auxiliary variables B1 and x (Figure 5.17) are needed. B1 describes the path, which the yarn has already covered on the guide rail. B2 indicates the remaining inlay yarn path.

In order to study the system, the yarn length relative to time has to be determined.

The yarn position x relative to time can be considered to have a sinusoidal movement then from Figure 5.17:

$$x(t) = \frac{r}{2} \cdot \sin\left(\frac{2 \cdot \pi}{T} \cdot t\right) \quad (32)$$

The length S<sub>3</sub> relative to time is:

$$S_3 = \sqrt{x(t)^2 + A_3^2} \quad (33)$$

with

S<sub>3</sub>: thread section between thread origin and guiding rail (m),

A<sub>3</sub>: distance between thread origin and needle bar (m).

The distance S<sub>2</sub> is equal to A<sub>2</sub>, the distance between guiding rail and needle bar and is constant.

The distance S<sub>1</sub> can be expressed as:

$$S_1 = \sqrt{\left(\frac{r}{2} - x(t)\right)^2 + A_1^2} \quad (34)$$

A<sub>1</sub>: distance between the rotor blade and needle bar (m)

From Equations 32 to 34 it comes the yarn length L<sub>(t)</sub> relative to time:

$$L(t) = \sqrt{\left(\frac{r}{2} \cdot \left(1 - \sin\left(\frac{2 \cdot \pi}{T} \cdot t\right)\right)\right)^2 + A_1^2 + A_2^2} + \sqrt{\left(\frac{r}{2} \cdot \sin\left(\frac{2 \cdot \pi}{T} \cdot t\right)\right)^2 + A_3^2} \quad (35)$$

### 5.3.4 Development steps

The prototype development is split into different development steps. Each individual work package has its own problem and task description. The development steps are independent of each other and have been processed simultaneously.



The development steps are split into two general development packages (Figure 5.18). One main package is the machine frame from the model warp knitting machine (prototype unit) including the mechanical and electrical components. This part of the design is following the state-of-the-art design from inlay warp knitting machines (machine frame in Figure 5.18). In this development step all mechanical functions, positioning from components, stability, handling, and safety features from the prototype unit were defined. The size and description of the mechanical drive components as well as the definition of the electrical motors are also included in this step. The second main package is the yarn inlay unit (yarn inlay unit in Figure 5.18) with the technical task of incorporating the rotor unit inside the prototype unit. The contained development steps (DS) “inlay yarn positioning” (to traverse the inlay yarn over the knitting area), “inlay yarn preparation” (to present it in proper and suitable condition and time inside the knitting zone), and “inlay yarn supply” (to feed the yarn from the stationary yarn cones to the traversing unit), have been the major technical challenges from the technological development.

The different development steps are listed below:

#### **DS1: Machine frame**

The machine frame accommodates, besides the main drive shaft, the traversing unit for the inlay yarn (Barmag Wings<sup>®</sup> system), the drive for the shogging from the guide bar, and the inlay-yarn placement system, the warp beam support including yarn separation and yarn detectors, and the fabric take-up. It must fulfil the requirements of stability as well as dumping vibration which may occur due to the operation.

The positions from the main drive motor and the drives for the shogging movement of the guide bar are defined. The necessary belt or direct drives has been specified. A possible attachment from a transportation chain system for the inlay yarn is technically prepared.

#### **DS2: Power chain**

The movements from all parts involved in the knitting cycle are driven from the machine’s main shaft, they have to be mechanically synchronized. The synchronisation from the individual components is controlled via cam discs. Those discs have been individually defined.

#### **DS3: Main drive/bar drive**

The required motors and their control units are electrically defined. Cables, connectors, and sensors are positioned accordingly.

**DS4: Fabric take-up**

The fabric take-down has a very important role in the process of warp knitting. It is directly connected with the central machine drive or electronically controlled. It is set up with a fixed relation to the machine's main drive.

**DS5: Warp yarn supply**

The warp beam is placed on top of the machine with yarn guidance via eyelet plates into the guide needle bar. The warp beam will be tension-loaded and with a braked shaft to avoid warp yarn overshooting. Between the warp yarn beam and the knitting zone, it was necessary to put a yarn breakage detecting unit in place to stop the machine when a warp yarn breakage occurs. During the trials, it was determined that a positive warp yarn supply is required.

**DS6: Positioning rotor traversing unit**

The positioning from the rotor blade unit and the guide plate needs to be flexible in respect of distance and positioning angle to the needle bar and the inlay yarn supply unit. The positioning must be made solid and accurate. To ensure maximum flexibility in positioning, a lateral movement with precision positioning is applied.

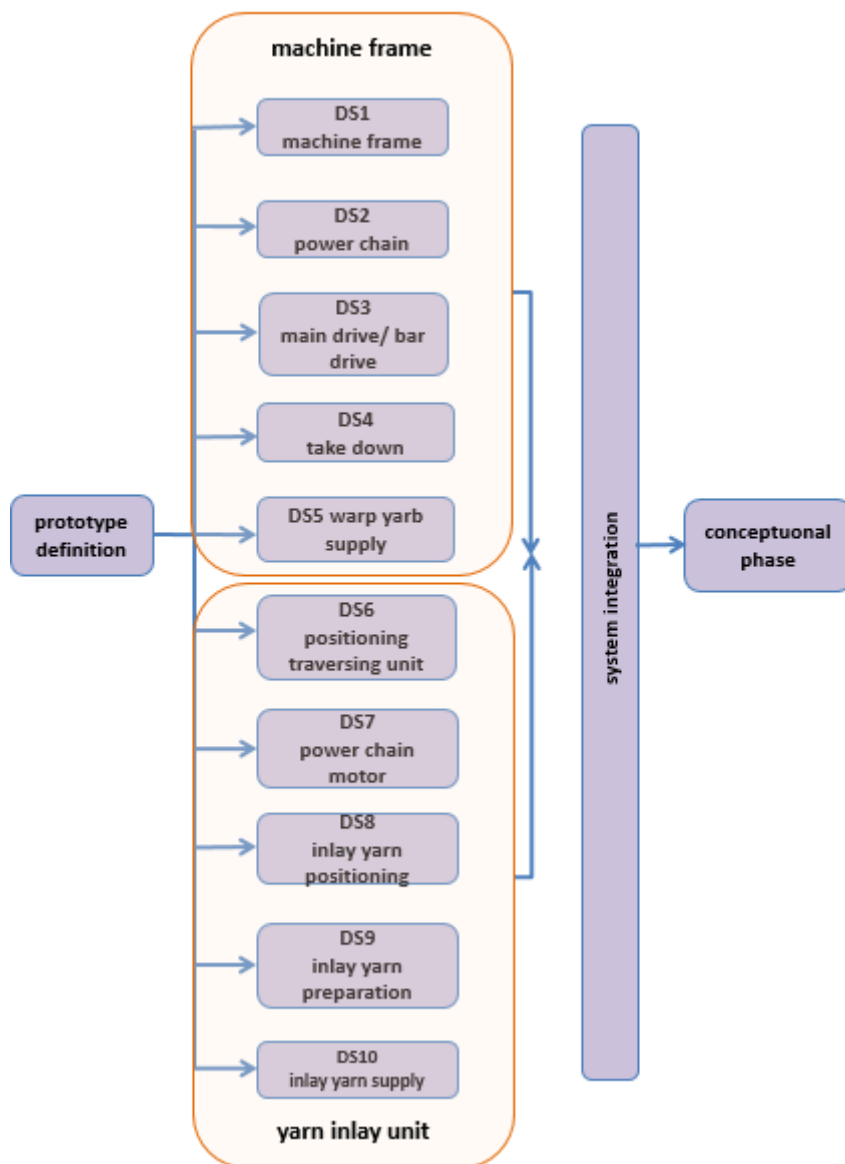


Figure 5.18: Definition of development steps prototype unit rotary blade unit

### DS7: Power chain rotor traversing unit

The drive from the rotor traversing unit is independent of the main drive from the motor. The gearbox from the synchronized contrary rotation from the blades is included in the preassembly from the rotor blade unit. Motor size and power is determined and the mounting position in the frame is fixed. The tests will show that the installation angle of the rotor unit to the needle bar changes when the distance of the rotor unit to the needle bar changes. Therefore, the power chain must be designed flexibly to allow a variable positioning of the rotor unit along the machine axis as well as a flexible distance and angle between the rotor unit and the needle bar.

### **DS8: Inlay yarn positioning**

The available time window to place the inlay yarn into the knitting zone is limited. The placement process needs to be very fast and the remaining time to conclude the machine cycle needs to be covered. The inlay yarn needs to be presented in the knitting zone in a stretched-out and vibration free. Means of an intermediate storage system the inlay yarn can be presented in the required suitable period to the knitting zone from the warp-knitting machine. This is made with yarn pushing elements that are mounted on a bar, which is driven and synchronized, from the main shaft from the prototype.

### **DS9: Inlay yarn preparation**

The traversing movement from the inlay yarn is made using the two, in opposite directions rotating, wings with three blades each. During the traversing movement, the inlay yarn is to be kept in its position on the blade to achieve process stability. A guide rod or a pair of guiding rods will be placed in front of the pair of rotors, they ensure that the inlay yarn is not “climbing” along the edge of the blade during the traversing. The technical task is to ensure that the inlay yarn is safely processed by the edge needles at the left and right POR of the traversing movement. A bar with inlay pushing elements will be installed which will be also driven from the main drive shaft. The inlay pushing elements move the inlay yarn from the transportation chain inside the knitting zone.

### **DS10: Inlay yarn supply**

In the initial setup, the yarn is drawn directly from a cone. The cone is placed in line with the centre of the fabric. If necessary, the yarn supply can be made with a yarn storage feeder like the Memminger-IRO MSF-3. The yarn feeder is mounted in line with the centre of the fabric. After the positive yarn feeder, an additional yarn breakage sensor is installed to stop the machine when the yarn is broken or the yarn traversing process is failing.

The individual development steps are integrated into the design of the complete prototype unit. A conceptual phase and further pre-studies have been made when several packages are combined, for example the rotor inlay yarn traversing unit with the inlay yarn supply (Figure 5.18). The initial design concept is made. The detailed design of the complete prototype unit is made as an integration of the designs from the development steps. All individual parts and components are designed and made. During the assembly, the assessment of the design and the functionality is directly beginning step-by-step. The loops of improvement and adaptation during this process are cycled various times until a validated final design is reached. The technical limitations, the capability, and the

improvement potential of the prototype unit are determined in the evaluation and testing phase. This process enters into analysis in the improvement loop back to the phase of design and pre-studies. This loop is repeated multiple times based on “trial and error” to finalize the development process (Figure 5.19).

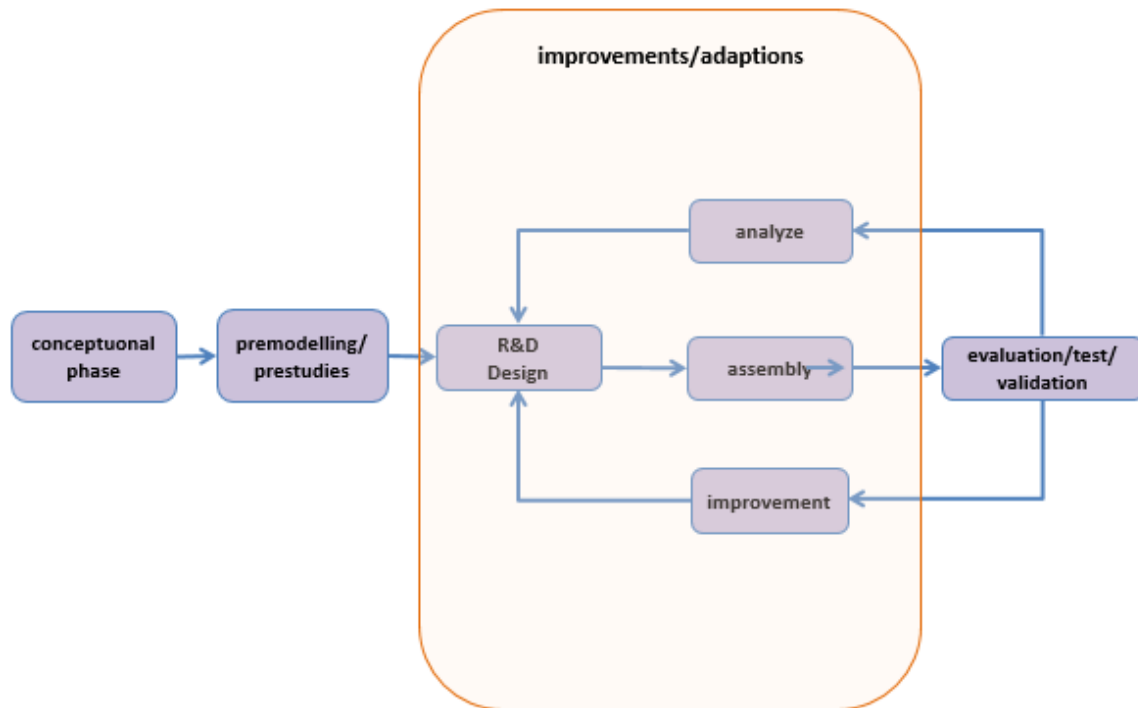


Figure 5.19: R&D process prototype unit

The complete development overview is visible in Figure 5.20. It combines the R&D process prototype unit (Figure 5.19), the previous definition of development steps prototype unit rotary blade, and the workflow prototype definition (Figure 5.18). All additional requirements for work safety need to be followed.

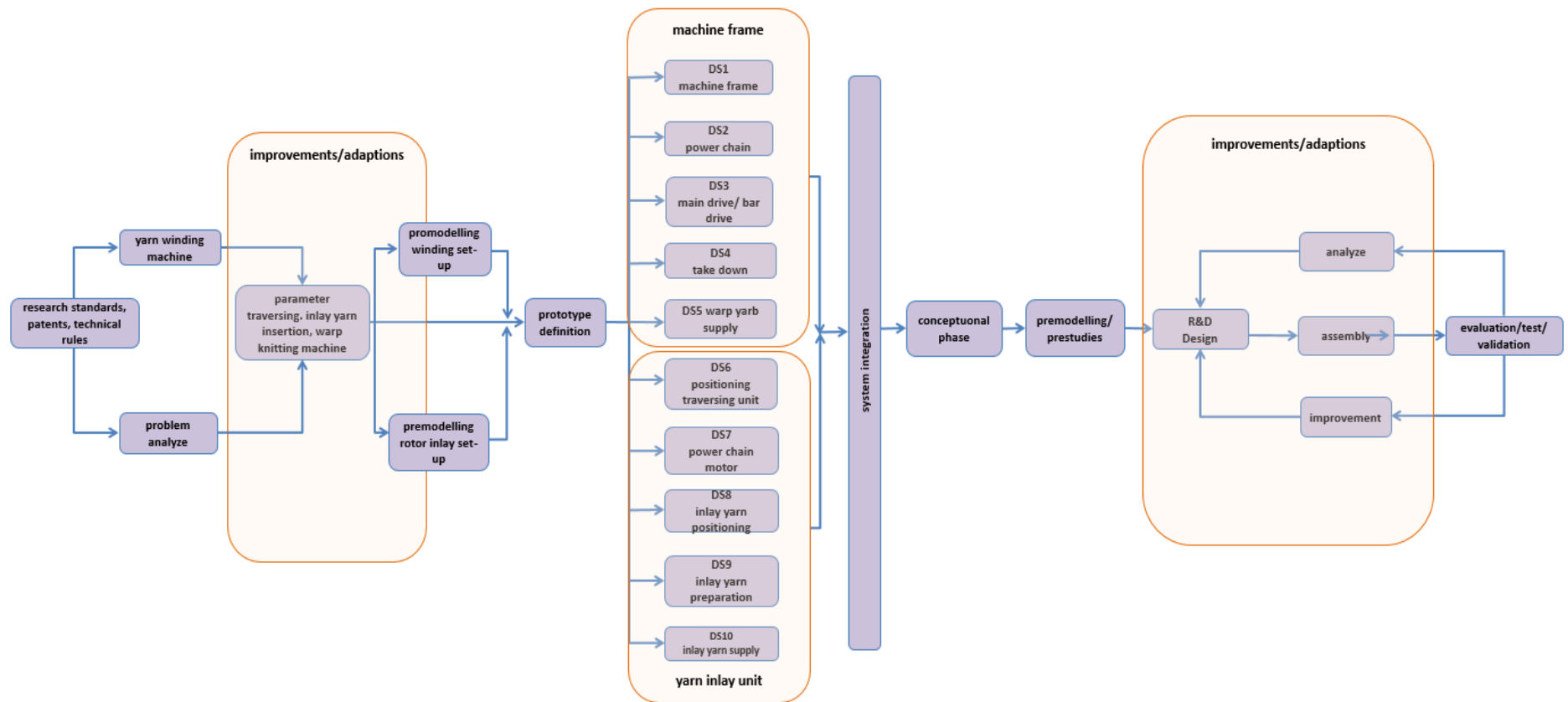


Figure 5.20: Development steps rotor based inlay system

## 5.4 Prototype design

### 5.4.1 Horizontal and vertical drag angle

The inlay yarn is fixed or locked in from the last course of loops made. After that course of loops is formed the yarn has to be transported over the width of the needle array. The inlay yarn is fixed from the last needle at the edge of the fabric.

Consequently, the transported yarn is describing an angle horizontally and vertically between the contact point on the transporting blade edge and the last needle (Figure 5.21). This deviation angle is changing during the movement from the blade over the knitting zone.



Figure 5.21: Wrap angle of the thread on the edge of the blade from the rotor

The rotating wing guides the open end of the insertion thread from the edge needle to the opposite edge of the fabric. This creates a drag angle between the plane of the needle bar and the edge of the traversing wing. The drag angle reaches its smallest value, as demonstrated in Figure 5.22 and Figure 5.23, when the wing reaches the opposite fabric edge. Partly the drag angle scenario can be reduced by placing the rotor unit at a  $72^\circ$  angle to the vertical needle bar.

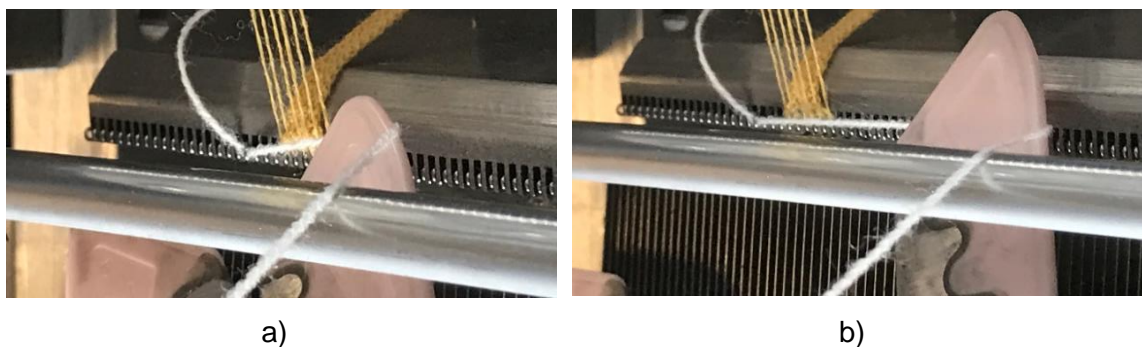


Figure 5.22: Drag angle rotor position: a) close to the fabric edge, distant to the fabric edge.

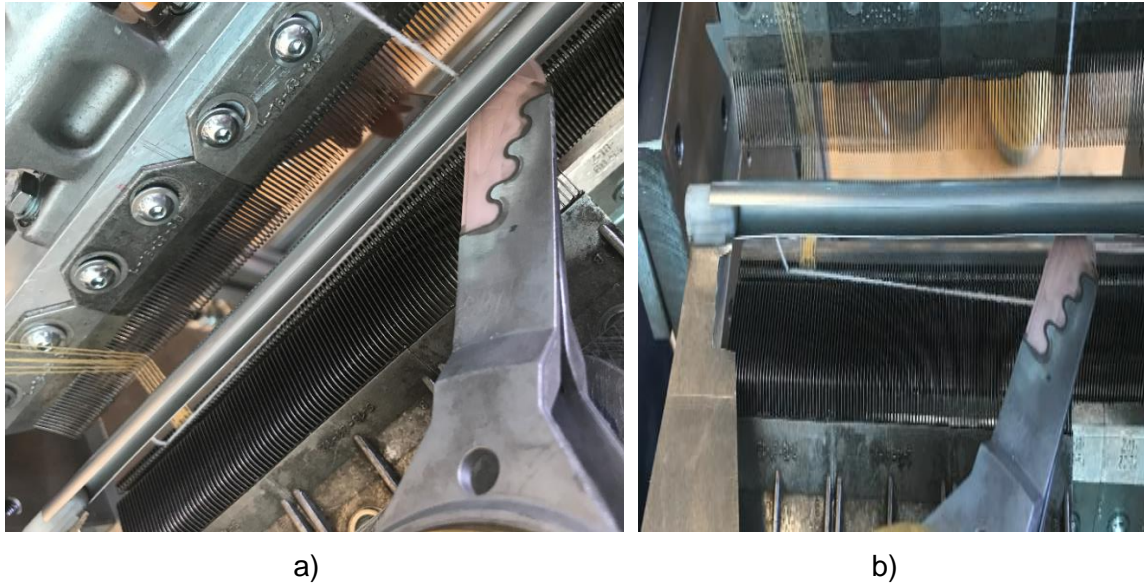


Figure 5.23: Drag angle: a) Vertical drag angle, b) Horizontal drag angle

#### 5.4.2 Timing from the process

During the making of the bobbin, the cone winding process is a constant process with a constant winding speed. With mechanical adaptations, the differences in yarn tensile force and yarn speed at the turning points can be equalized. At the end of the winding process, the process is interrupted when the bobbin is full and the winding body needs to be changed. The yarn end needs to be securely clamped and at the beginning from the new bobbin, the initial winding from the new cone will be started. In contrary, the warp knitting process is a cyclical process that is described by the movements of the involved knitting components. As already described previously, the inlay yarn can only be placed inside the knitting area during  $47^\circ$  of the knitting cycle resulting in approximately  $13^\circ$  revolution of the main drive shaft from the machine. Therefore, the constant moving rotors need to adapt to that scenario, and a yarn fixing or holding device will be necessary on both sides of the knitting area to cope with the non-cyclical process of inserting the inlay yarn into the machine cycle.

#### 5.4.3 Flexible transportation point from the yarn on the blade edge

The yarn is transported from the rotating blades across the width of the inlay area. The yarn is pulled from the yarn supplying storage feeder in a negative feeding scenario. Due to the changing wrap angle from the yarn on the transporting rotor blade and the changing yarn tensile force during the transversal movement the yarn is moving (climbing) along the rotor edge (Figure 5.24).



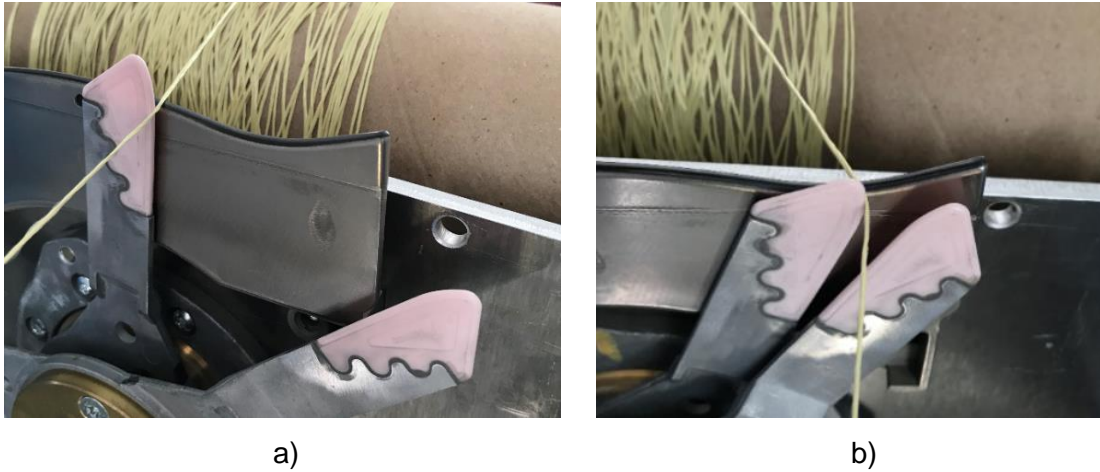


Figure 5.24: Inlay yarn on the rotor: a) in the middle from the insertion, b) at an edge from the insertion

#### 5.4.4 Rotary blade unit integration

For the initial prototype, the following topics are important to control:

- The handover from one blade to the opposite rotating blade,
- The presence of the inlay yarn on the blade during the traverse;
- The deviation angle on the blade edge to reduce stress for the inlay yarn.

Initially, the blade unit (Figure 5.25 a) was designed independently from the Barmag Wings® system.

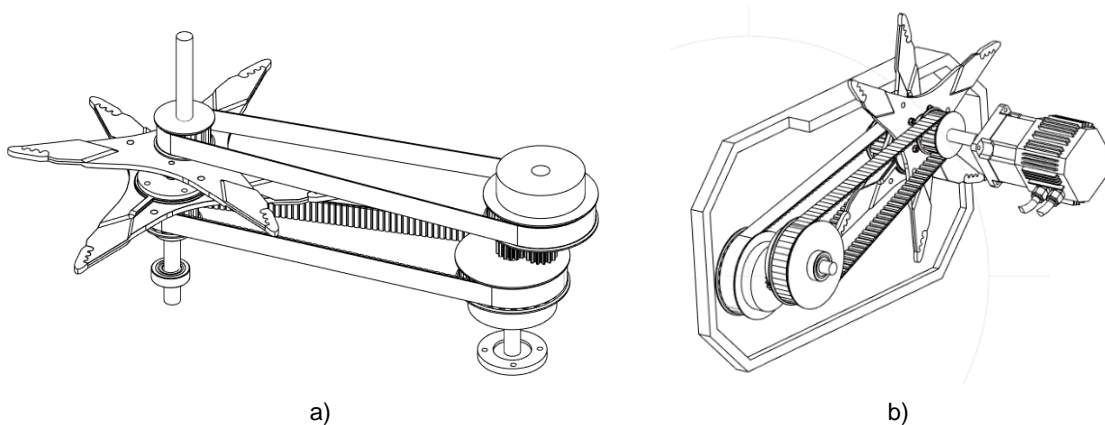


Figure 5.25: a) design study with belt drive, b) Design study with belt drive in preliminary housing using BARMAG wing ACW2 components<sup>84</sup>

The design principle had been to achieve the synchronized counter-rotating movement (number 1 and 2 in Figure 5.27) from the two rotors (Figure 5.26 a) using toothed belts (Figure 5.25 a). These belt drives could be accommodated in a housing which is allowing the yarn to pass through the rotors to be traversed and provide proper housing for the rotating blades (Figure 5.25 b).

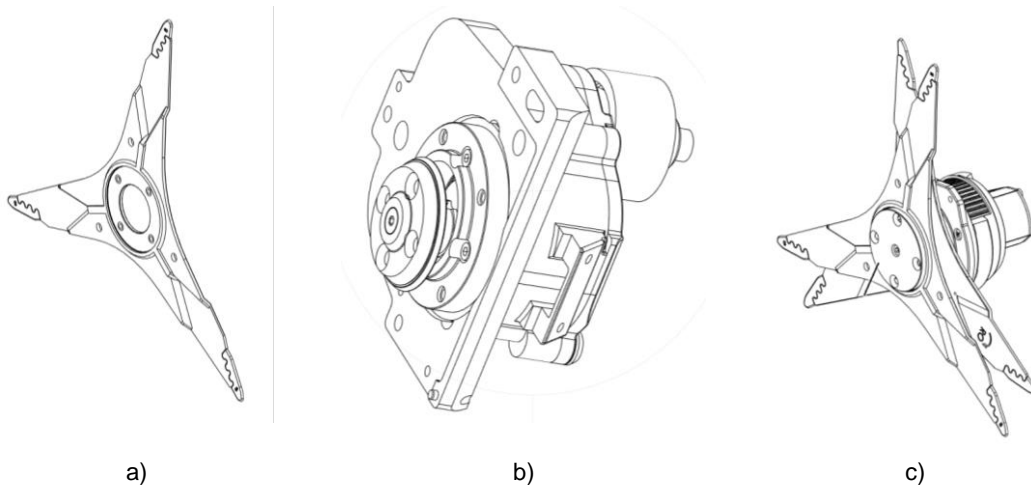


Figure 5.26: Single Barmag Wings®: a) individual winding blade, b) gear box, c) assembly blade and gearbox<sup>84</sup>.

The compact design of the Barmag Wings® mechanical gearbox (Figure 5.26 b) without belts and the possible problems with asynchronicity between the blades, due to elongation of the belt have given preference to the Barmag gearbox. The assembly from the gearbox and the pair of rotors is displayed in Figure 5.26 c. The complete twin-rotor system used in the Barmag Wings® winder system is selected.

The positioning from the rotating centres from both rotors as well as the offset positioning relative to each other (number 4 in Figure 5.27) is designed to ensure a working handover at the edges of the traversing zone.

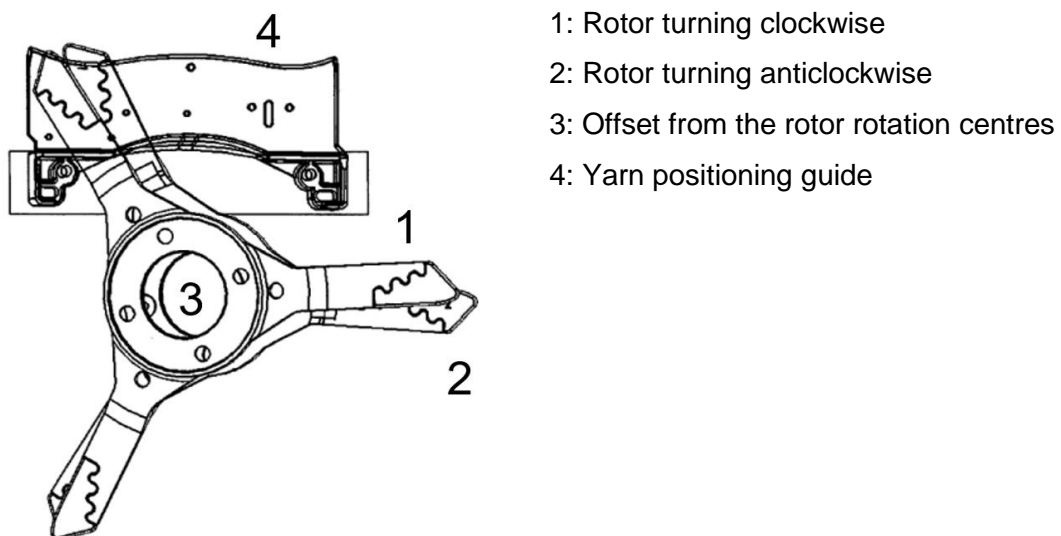


Figure 5.27: Barmag Wings® rotor system with rotor off-set <sup>75</sup>

The Barmag Wings® blade unit is placed at a relative 75° angle to the knitting needle bar (angle  $\eta$  in Figure 5.28). Therefore, the deviation angle between the needle bar and the rotor plane can be reduced. The inlay yarn is placed from the top, inside the knitting zone.

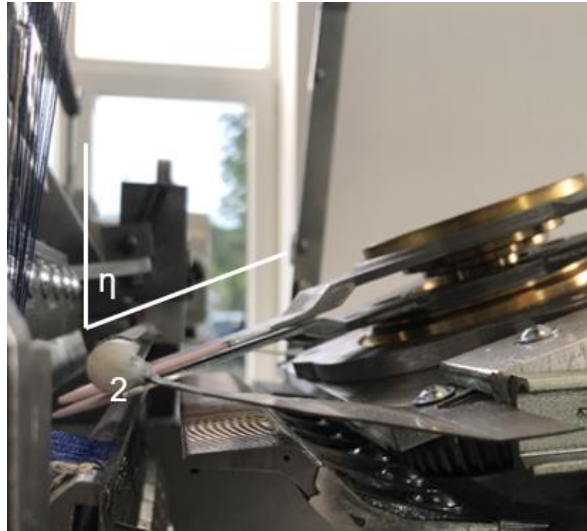
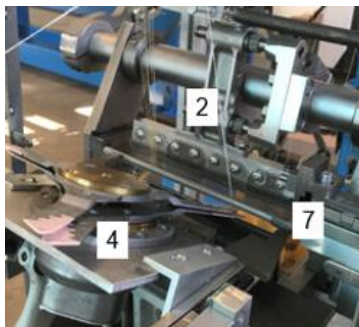


Figure 5.28: Positioning rotary device and inlay yarn guide bar

#### 5.4.5 Structure of the prototype unit rotary blade system

Figure 5.29 shows the set-up from the prototype unit. On the machine frame (number 3 in Figure 5.29 b) the traversing rotary device (number 4 in Figure 5.29 a) is mounted in front of the knitting zone (number 7 in Figure 5.29 a).



a)



d)



b)



c)

Figure 5.29: Prototype set-up rotary blade system with 1: Warp beam, 2: Inlay yarn, 3: Machine Frame, 4: Rotary blade system, 5: Inlay yarn guide, 6: Guide bar positioning, 7: Knitting zone.

The warp yarns are drawn from the warp beam (number 1 in Figure 5.29 b) which is mounted on the top of the machine while the inlay yarn is supplied from the front of the

machine (number 2 in Figure 5.29 a). The inlay yarn is guided over a guiding and positioning element (number 5 in Figure 5.29 d). The machine drive and the lateral movements are assembled at the side of the machine (number 6 in Figure 5.29 c).

## 5.5 Results

### 5.5.1 Trials

During initial trials while setting up the prototype unit the horizontal and vertical drag angle from the inlay yarn become clearly visible. The drag angle scenario can be maximally reduced by placing the rotor unit at an  $\eta$  angle of  $72^\circ$  (Figure 5.28) to the needle bar and feeding the inlay yarn from the top.

Using the rotary-based inlay unit, only one yarn end the yarn is used, therefore the yarn speed is getting high. In addition to that fact, it is considered the time frame of only 13% from a centre shaft revolution is available for the weft yarn insertion. The remaining 87% of the insertion unit has virtually to stop or wait. This would eliminate the biggest advantage of the system: the high speed-feeding potential from the constantly rotating system. To use this potential, the high-speed feeding and traversing system must place the yarn in a magazine and transportation system. From that storage unit, the inlay yarn must be presented to the knitting zone similar to the MIS-system. Still, the high-speed capabilities and the very compact and robust system, from the rotor unit with the directly attached gearbox, have their advantages to the carriage system from a magazine insertion system. These advantages become obvious when working on smaller fabric widths.

The weft insertion process is slowing down the speed of a warp-knitting machine from rpm 4.300 to approximately rpm 1.500. The state-of-the-art magazine weft insertion technology is working with 30-yarn ends simultaneously. Based on a fictive sample machine a fabric width from  $W_{ML} + W_W = 320 + 20 = 340$  cm (including cutting waste) at a speed of rpm 1.500 (rps=25) with 30 yarn ends simultaneously, the individual running yarn speed will be 2.92 m/s. This would require frequent yarn package changes or bigger packages to reduce machine downtime.

For every main drive rotation from the machine, one course of fabric with one insertion yarn is knitted. Therefore, a machine running with 1.500 rpm requires 1.500 yarn ends per minute.

## 5.5.2 Suggested Improvements

### a. Combined sinker/inlay placement part

In this process of inlay-yarn insertion, one mechanical drive component is required for the comb plate and the inlay-yarn placing element. The aim is to combine these two components into one common component (Figure 5.30) - or, depending on the design, a split component - and to execute the movement with one drive system.



Figure 5.30: Sample design combination of sinker unit and weft yarn inserting element<sup>85</sup>

Advantages of a combined part geometry:

- One group of parts including the necessary bar and the drive unit is not required anymore,
- Fewer mechanical components have to be installed in the machines,
- Cost reduction of the machine while maintaining process reliability,
- Inlay yarn remains securely guided during the entire machine cycle,
- Vibrations of the weft thread, both in the longitudinal axis of the thread and in the thread itself, are damped and the thread is safely calmed,
- Flexible weft insertion width,
- High positioning accuracy of the weft yarn.

Such combination elements on a moving bar unit have not been used in the warp knitting technology yet. The idea from the University of Applied Science Niederrhein „Vorschubelemente für eine Wirkmaschine und Wirkmaschine“) Feed elements for a warp knitting machine and warp knitting machine") was filed on behalf of the Niederrhein University of Applied Science on 23.10.2019 with the German patent application number 10 2019 128 607.7, patent-pending.

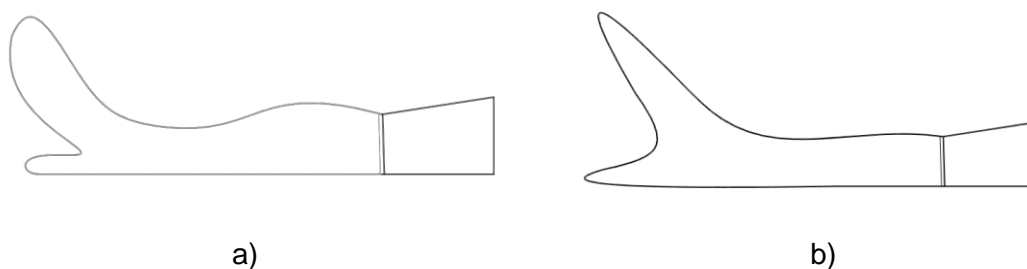


Figure 5.31: Sample geometry from a combined part: a) with a round notch, b) with a sharp notch.

Based on the initial ideas published in the patent application (Figure 5.30) different geometrical approaches have been developed and made. These innovative parts had been installed in the prototype unit and test runs have been made in order to determine if they are corresponding of the geometrical situation inside the machine and if there design is matching with the timing from the machine cycle. The best results have been achieved with the design geometries (visible in Figure 5.31 a and b) and inside the prototype unit (Figure 5.32 a and b). Due to its simple construction and compact design, it allows flexible positioning on the warp-knitting machine. It can be applied on the knitting machine for all the needles or possible only at regular distances like for example every 5-10 cm.

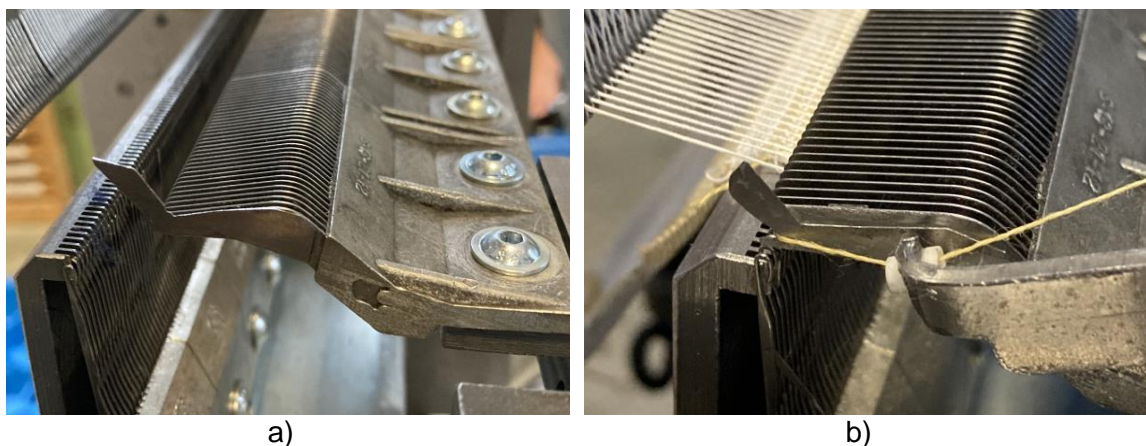


Figure 5.32: Sample geometry from a combined part: a) with a round notch, b) with a sharp notch

#### **b. Intermediate storage system**

Further to use this potential the high-speed feeding and traversing system an intermediate transport and storage system for spread yarns is applicable like in the wooden model shown in Figure 5.33. From that system, the inlay yarn must be presented individually and parallel to the machine axis and each other to the knitting zone.

The high-speed capabilities and the very compact design of the rotor unit will have an impact on the production speed of the warp knitting machine and have advantages to the carriage system from a magazine insertion system. These advantages become obvious when working on smaller fabric widths.





Figure 5.33: Wooden model placing the rotary blades unit to a transport chain system

In a preliminary wooden requirement model (Figure 5.33), it is visualized that:

- The yarns need to be transported parallel and stretched out to the knitting zone,
- The yarns need to be in equal condition to each other (elongation, tensile force, etc.),
- All vibrations inside the yarns need to be eliminated,
- The transportation needs to be synchronized to the machine cycle,
- The inlay yarn is not cut at the fabric edges.

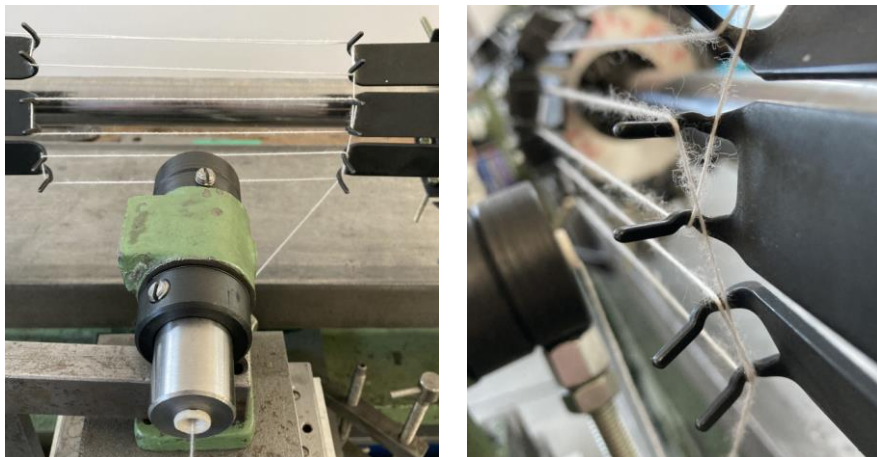


Figure 5.34: a) Inlay yarn is delivered through the centre from the drive shaft, b) inlay hooks with curved hooks/pins.

To simulate the requirements which are displayed in the wooden model a functional and real scale model has been set up (Figure 5.34).

The Figure 5.35 shows the movement during the inlay cycle. The inlay finger is below the chain on the left side of the inlay area (Figure 5.35 a). The inlay finger is moving upwards and is placing the inlay yarn over two pins of the transportation chain (Figure 5.35 b). The chain is moving further around the deflection radius of the chain, while the inlay finger is traversing on the other side from the transportation chain (Figure 5.35 c).

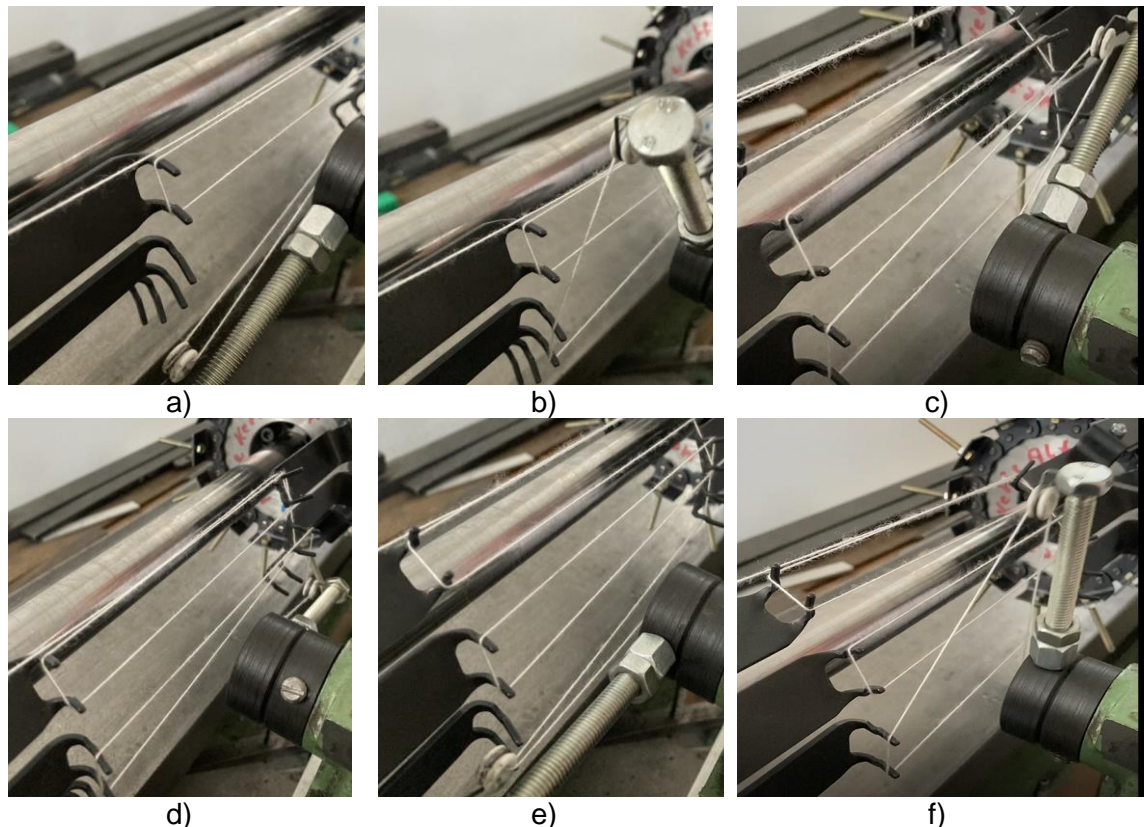


Figure 5.35 : Functional model transportation chain: a) before left POR, b) after left POR, c) during traversing, d) before right POR, e) before left POR, f) during traversing

The chain is moving further around the deflection radius of the chain while the inlay finger is traversing on the other side from the transportation chain (Figure 5.35 d). The inlay finger is moving downwards and placing the inlay yarn over two pins from the chain. The traversing movement from the inlay finger from the right side to the left side is visible in Figure 5.35 e and in Figure 5.35 f the cycle is repeating.

Further results of the study:

- The inlay yarn is from the cone delivered directly through the centre from the drive shaft (Figure 5.34 a);
- The inlay yarn need to be parallel to the machine axis, therefore straight pins without bending must be used (Figure 5.34);



- The inlay motion cycle is ideally placed at the deflection radius from the transportation chain because then it is not necessary to perform a biaxial movement with the inlay finger (Figure 5.35);
- The number of revolutions from the inlay finger must be synchronized with the chain speed (machine speed) in order to be able to place the inlay yarn parallel to the machine axis in the corresponding transportation hooks from the chain;
- If running with one end only the weft yarn package would run empty much quicker than the 24 packages in use simultaneously in the magazine insertion. Either bigger yarn packages need to be used or frequent changes in the yarn supply – which leads to more maintenance of the running machine-, are required.

The purpose of this model is to simulate that it is possible to place the inlay thread in a transportation chain under the following requirements:

- Constantly rotating movement from the inlay placement system without any start and stop,
- Positioning from the inlay yarn parallel to the machine axis in the transportation hooks,
- Positioning the inlay yarn into hooks that are distant enough from each other to make a safe handover and placement in the knitting zone possible,
- No cutting from the inlay yarn at the fabric edges,
- Feeding with less twist and deviation to the yarn as possible.

### c. Warp yarn separation

To make the warp knitting process itself productive it is recommended to separate the individual warp yarns from each other. As visible in Figure 5.36 the individual yarns can get randomly tangled together and cause, as a consequence, yarn breakage (Figure 5.37).

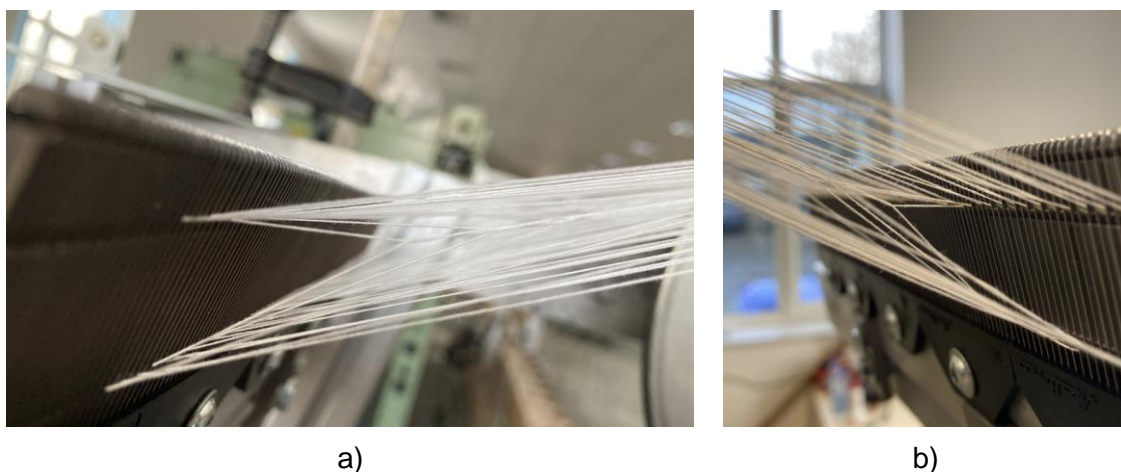


Figure 5.36: Yarns tangled together: a) between the beam and the first eyelet plate, b) after the first eyelet plate.

This is either possible while guiding the yarns through individual guide tubes or to attach eyelet blades at bigger distances to each other.



Figure 5.37: Yarn breakage due to entangled yarns

## 5.6 Conclusions

To establish a new and alternative weft insertion system several main obstacles remain. Major technical challenges will be to cope with the given machine cycle and to use the given time window as effectively as possible. Therefore, an intermediate storage unit, like a feeding chain, is needed. Further, the parallel presentation from the inlay yarn into the knitting zone needs to be done by overcoming the technological hurdles, like drag angle and blade/yarn interaction. Special yarn forwarding elements need to be developed. These yarn forwarding elements help by dumping all lateral and longitudinal yarn vibrations and movements from the inlay yarn. However, the potential of increasing speed, reduced energy consumption, and a reduction of moving parts required for the inlay technique, can be achieved working at a smaller width. The improvements and suggestions for the innovative inlay system described in context with the rotary blade system apply to the further alternative versions of inlay-yarn supplying systems.

## 6 Prototype with a rotating eyelet

The patent of the Niederrhein University of Applied Sciences "Device and Method for Feeding a Thread" (WO 2020/038816 A1 ) provides the basis for a new process based on a direct drive motor, which is more energy-saving, resource-conserving, and thus more productive and economical.

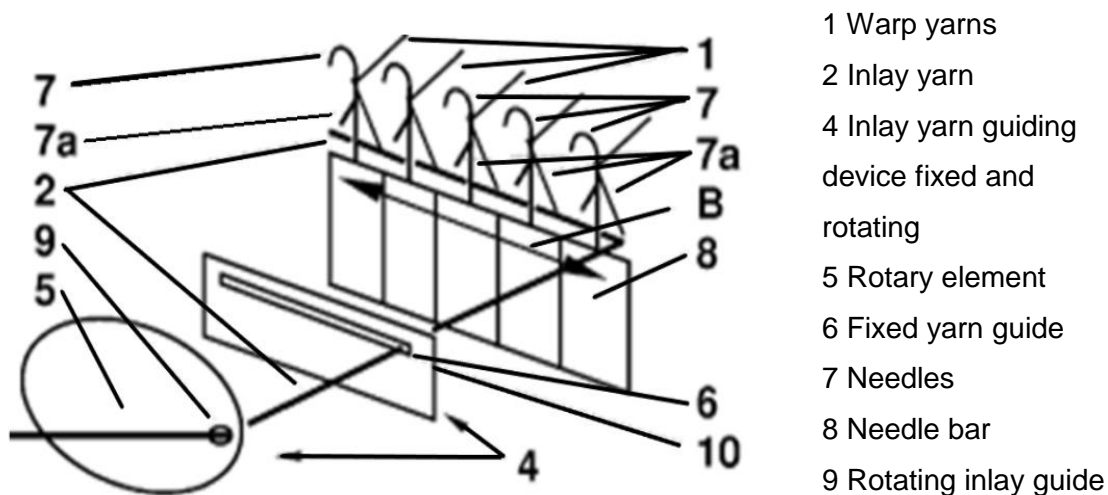


Figure 6.1: Patent visualisation WO 2020/038816 A1<sup>58</sup>

The invention relates to a device for feeding a yarn for loop-forming tools, arranged in at least one course, of the textile machine. It shows a inlay yarn guiding device (number 4 in Figure 6.1) comprising a rotary element (number 5 in Figure 6.1) and a fixed yarn guide (number 6 in Figure 6.1). The inlay yarn guiding device (number 4 in Figure 6.1) is configured to guide the path of the inlay yarn (number 2 in Figure 6.1) in a stroke range (B) in each case in front of the course of needles (number 7 in Figure 6.1) placed inside the needle bar (number 8 in Figure 6.1).<sup>58</sup>

If a conductor loop is moved in a magnetic field, a voltage is induced in this conductor loop. A current-carrying coil generates a time-varying electric field that interacts with the constant magnetic field of the rotor. The resulting force is used to generate the rotary motion. A torque motor consists of two components, the stator with coils and the rotor with permanent magnets<sup>86</sup>.

This drive unit is characterised by its self-contained concept as a complete system consisting of a torque motor and wire-race bearing unit. With the wire bearings, the rolling process does not take place directly between the rolling element and the enclosing structure, but instead on the integrated races with low friction. This makes it possible to design this drive specifically for requirements by installing it in a warp-knitting machine. The torque motors are integrated directly into the rotators. This makes it possible not only

to generate a rotary movement but also to position or execute definable cycle steps. This technical possibility is essential to ensure the positioning of the weft yarn repeatedly and precisely<sup>29,87</sup>.

In the textile environment of a warp-knitting machine, dust and fibre lint is generated. Drive systems in this environment must therefore be designed to be wear- and maintenance-free for long service life. The used torque motor has a very high nominal torque of 26.4 N·m with a maximum peak torque of 105 N·m at a defined speed span. The motor (rated current of 3.1 A with a peak current of 12.8 A) can be dimensioned smaller through this principle, resulting in energy savings of up to 30%<sup>87</sup>.

Based on the preliminary trials and analysis, the principal design features and technical components from the prototype with the rotating eyelet unit are:

- The prototype unit is made as a stand-alone machine,
- The working width is 200 mm,
- The needle bar is equipped with 8 Karl Mayer 18GG needle module Z18/60-54 with Groz-Beckert needles Raschel-Spec 51.75 G01. Therefore, the machine is using standard latch needles,
- The guide bars are equipped with Karl-Mayer guide modules KH-20-3-3,
- The drive and the relative timing during the knitting cycle from all involved knitting elements are made mechanically over the main drive shaft,
- The warp beam is located on the top,
- The warp beam is braked to avoid over-shooting from the warp yarn, i.e is negatively fed,
- The warp yarns are individually guided through droppers as yarn breakage detectors,
- The warp yarns need to be kept individual and distant from each other on their way from the beam to the knitting zone via individual eyelets fixed on plates,
- The rim warp yarns are individually guided via spring-loaded yarn tensioners,
- Yarn breakage detector for inlay, needs to be applied,
- The controller unit synchronizes the traversing elements with the machine drive,
- The take-up device is integrated inside the machine,
- Flexible position in respect of distance between the rotor unit and the needle bar,
- The guide bar for the inlay yarn needs to be as close as possible to the needle bar,
- Initially, the guide will be an open guide plate, if necessary an open (slot) bar is applied,
- The inlay positioning elements are set up at the fabric edges and equally distant over the fabric width,
- The trial loop setup is to knit pillar stitch with inlay yarn.

The distance between stator and rotor (air gap) is decisive for the size of the torque. The pre-tensioned adjustment guarantees a constant air gap. A measuring system is to be applied to determine the motor position.

Wire-race bearings with integrated direct drive are characterised by maximum energy efficiency. The integration of the drive motor into the bearing makes it possible to dispense with components such as gears and drive pinions and thus with complex lubrication circuits. The moving masses are therefore significantly lower and the loss of power due to factors such as friction and backlash is minimised<sup>87</sup>.

The patent application DE102018120364.0 (2018) "Apparatus and method for presenting threads" Applicant Niederrhein University of Applied Sciences. This principle has the following advantages compared to the state-of-the-art:

- The wrap angle of the strand from the bobbin to the mesh-forming area is eliminated,
- The surfaces of the strands are protected, especially when starting up the system,
- Reduction of the energy consumption,
- A compact and simple delivery and traversing unit,
- Existing machines can possibly be retrofitted with these units,
- The inlay process can be programmed if the inlay will be made every knitted course or only for a defined number of courses, therefore patterns are possible.

The technological basics are described in chapter 3.4.2. The thread is moved along a circular path by a threaded eyelet attached to the inner ring of a torque motor (number 2 in Figure 3.3). The yarn path is then transferred via a guide into a traversing movement (number 1 in Figure 3.3). This traversing movement then guides the yarn into the loop-forming area.

## **6.1 Preliminary modelling**

This principle has already been confirmed in its function by basic experiments at Niederrhein University of Applied Sciences. With preliminary trials, a model from a torque motor was set up in a horizontal position on a test bench. The yarn is guided through the centre hole from the motor through a linear guide slot (number 1 Figure 3.3). With these preliminary trials, the proof of principle was made that is possible to convert a rotating movement from the yarn into a horizontal traversing movement. With this movement, it is possible to perform an inlay yarn insertion into the moving needle bar from a warp-knitting machine.

The prototype development from the prototype unit with the rotary eyelet inlay insertion follows the same basic development process as the rotary blade prototype. The prototype

development is also split into different development steps. Each individual work package has its own problem and task description. The development steps are independent of each other and can be processed simultaneously but are independent to be worked on. The development steps are split into two general development packages (Figure 6.2). One main package to be worked on is the machine frame from the model warp knitting machine (prototype unit) including the mechanical and electrical components. In this work package all mechanical functions, positioning from components, stability, handling, and safety features from the prototype unit are defined. The size and description of the mechanical drive components as well as the definition of the electrical motors, connectors, and wiring are included in this package.

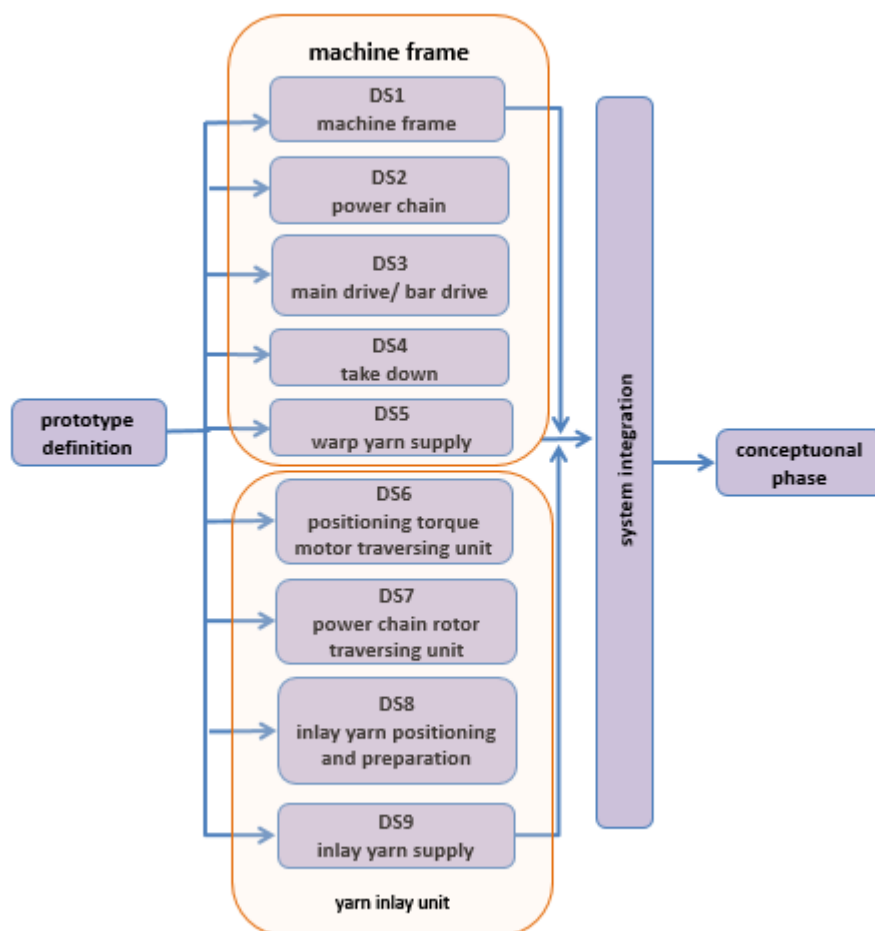


Figure 6.2: Definition of development steps prototype unit rotary eyelet unit

The second main package is the yarn inlay unit (yarn inlay unit in Figure 6.2) with the technical task of incorporating the rotary eyelet unit inside the prototype. The contained development steps “inlay yarn positioning and preparation” (to traverse the inlay yarn over the knitting area), “inlay yarn preparation” (to present it in proper and suitable condition

and time inside the knitting zone), and “inlay yarn supply” (to feed the yarn from the stationary yarn cones to the traversing unit) will be the major technical challenges.

The complete project structure overview is visible in Figure 6.3. It combines the R&D process prototype unit (Figure 5.19), the definition of development steps prototype unit rotary blade unit Figure 5.18, and the workflow prototype definition (Figure 5.1). All additional requirements for work safety need to be followed.

## 6.2 Requirements

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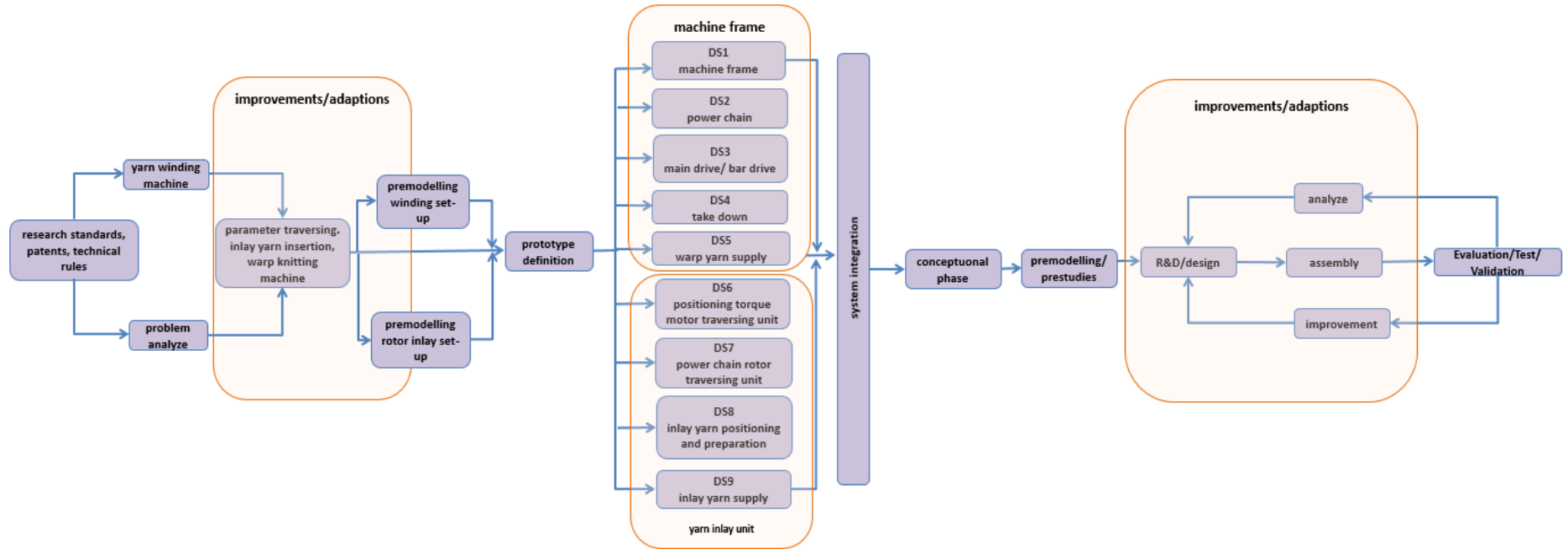


Figure 6.3: Project structure based on the rotary eyelet



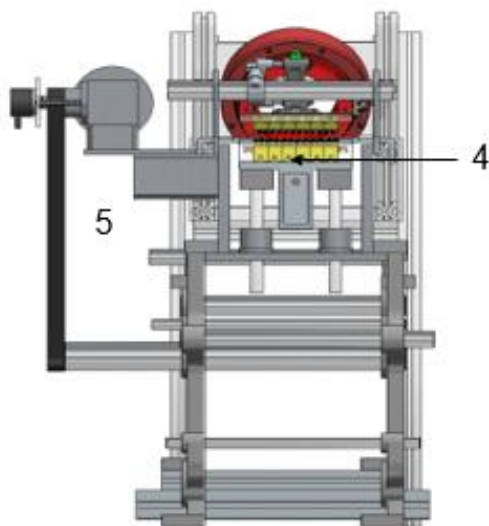
Listing from the development steps for this project:

### DS1: Machine frame

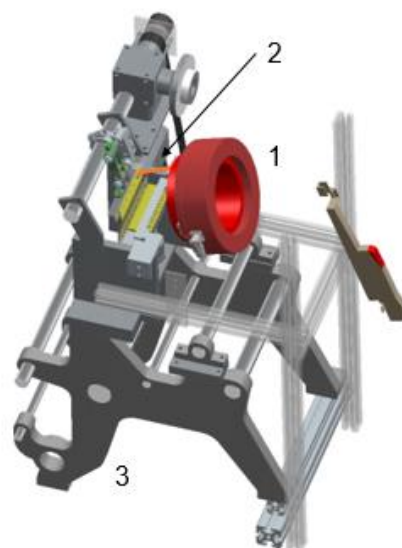
The drive system is implemented into a laboratory-scale warp-knitting machine. The prototype scale warp-knitting machine is set up newly. Therefore, a frame (Figure °6.4 c and d) is set up to fix or attach the following components or functional groups as flexibly as possible.

On this frame is installed or attached:

- The central driveshaft,
- The main drive motor,
- The guide needle bar (number 4 in Figure °6.4 a),
- The needle bar,
- The lateral drive for the guide bar,
- The rotary unit (torque motor number 1 in Figure °6.4 b),
- Eyelet bars to separate the warp yarns,
- Tensioners for the edge warp yarns,
- The warp beam,
- The guides for the inlay yarn (number 2 in Figure °6.4 b),
- The mechanical synchronization between the different movements (belts).



a)



b)

1 = Drive rotating eyelet  
2 = Rotating eyelet  
3 = Machine frame

4 = Needle bar  
5 = Main drive

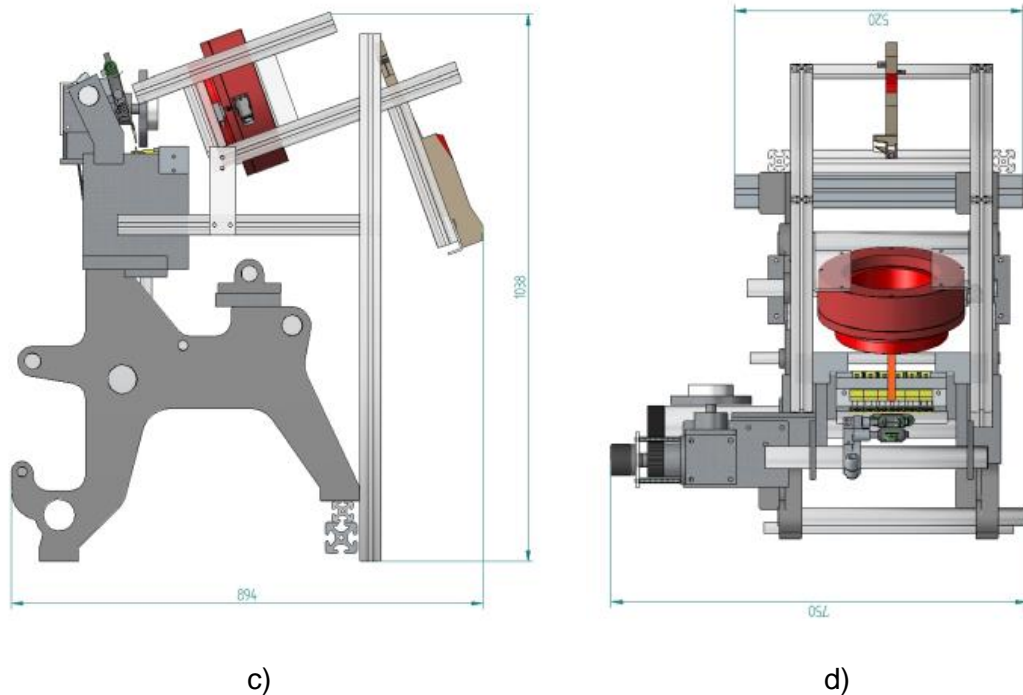
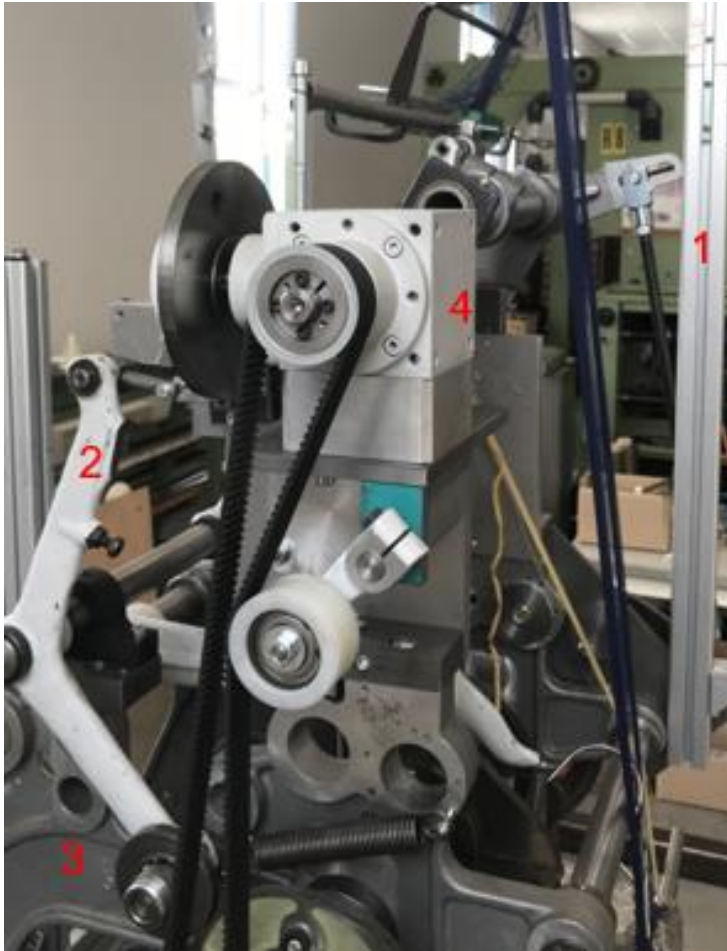


Figure °6.4: Machine frame prototype unit rotary eyelet unit: a) rear view, b) side view, c) rear view, d) top view.

The central drive shaft unit is installed and all the rotating movements from the knitting cycle are directly connected to this shaft and therefore mechanically synchronized. On the top of the machine is the warp yarn beam attached on the support (number 1 in Figure °6.5). The needle bar is moved via mechanical guides and moves freely in the Y-axis direction up and down. The individual warp yarn is guided through eyelet bars to the guide needle bar (number 4 in Figure °6.5). Besides the needle bar, the edge yarns are guided via differently positioned eyelets to separate spring-loaded tensioners. The warp beam is mounted on top of the prototype unit and driven from the warp yarns and is passively braked to avoid overshooting yarn. The inlay yarn is guided via eyelets and a yarn tensioner through the hole from the rotary motor directly through the rotating eyelet to the knitting zone.

The machine frame (number 3 in Figure °6.5a) has to absorb starting and stopping from the motor as well as possible natural frequencies during the permanent rotation of motor parts. All additional requirements for work safety need to be followed. The positions of the main drive motor, the torque motor, and the step motor for the lateral movement of the guide bar need to be defined. If necessary, the assembly from a transportation chain system for the inlay yarn needs to be prepared and synchronized with the rotating torque motor eyelet.



- 1: Warp yarn beam support
- 2: Lacing element drive
- 3: Machine frame
- 4: Guide needle bar drive

Figure °6.5: Assembly machine frame and basic structure

## DS2: Power chain

The movements from all parts in the knitting cycle are set up to the main shaft and synchronized from the machine's main shaft. The mechanical drive curves for the lateral movement of the yarn guide bars need to be evaluated and synchronized with the controller from the torque-motor.

All components need to be designed, made and then assembled into the prototype unit.

It is necessary to synchronize the following movements mechanically:

- The movement from the needle bar,
- The movement from the guide bar,
- The shogging from the guide bar,
- The movement from the inlay yarn positioners/sinker bar,
- The fabric takes down system,
- The warp yarn supply.

It is necessary to synchronize the following movements via the controller unit from the rotary device:

- The timing from the rotating inlay eyelet relative to the mechanical movements,
- The positioning from the eyelet at the fabric edges,
- The speed during the inlay procedure,
- The Yes/No inlay decision for every machine cycle.

### **DS3: Main drive/bar drive**

The required motors and their control units are electrically defined. Cables, connectors and sensors need to be selected and positioned.

### **DS4: Fabric take down system**

It is directly connected with the central machine drive or electronically controlled. Initially, there is a set up with a fixed relation to the machine's main drive.

### **DS5: Warp yarn supply**

The positioning from the warp beam is identical to the rotary blade system. It is to be placed on top of the machine, tension loaded with yarn breakage detectors for all yarns. The eyelet blades, with the individual warp yarn eyelet, are positioned to achieve a minimum deflection from the warp yarns and are still allowing a proper swing movement from the guide needle bar.

The rim yarns are fed through additional spring-loaded yarn tensioners like lateral yarn tensioners from flat knitting machines. During the trials, it will be determined if a positive warp yarn is required or not.

### **DS6: Positioning torque motor traversing unit**

The positioning from the torque motor unit needs to be flexible in respect to distance and positioning angle to the needle bar and the inlay yarn supply unit. The mechanical position is made solid and accurate. Also, a lateral movement with a precision positioning will, if possible, be applied.

### **DS7: Power chain rotor traversing unit**

The drive from the torque motor unit is independent of the main drive from the motor. The power chain allows a variable positioning of the torque motor unit along the machine axis as well as a flexible distance to the needle bar.

### **DS8: Inlay yarn positioning and preparation**

The inlay yarn is presented in the knitting zone through the eyelet, which is fixed on the turning outer ring from the torque motor unit. This eyelet must place the inlay yarn dynamically accurately so that the rim needles will be able to fix the inlay yarn during the loop formation process. This is supported with yarn pushing elements which are mounted on a bar that is driven and synchronized from the main shaft from the prototype. During the trials, it will be determined if an additional moving storage unit like a transportation chain is required or not.

### **DS9: Inlay yarn supply**

In the initial set up the yarn will be drawn directly from a bobbin (cone) through the centre hole from the torque motor unit. The inlay yarn is also guided through a spring-loaded yarn tensioner attached before the inlay yarn is led through the rotary device. This tensioner will ensure that the inlay yarn is stretched during the whole inlay cycle.

If necessary, the yarn supply can be made with a yarn storage feeder like the Memminger-IRO MSF-3.

Comparable to the rotary blade project the individual development steps will be integrated into the design of the complete prototype unit. The conceptual phase and the further development process will follow Figure 6.2 and Figure 6.3.

## **6.3 Prototype Design**

### **6.3.1 Torque motor drive unit**

The development of a possible speed profile throughout a complete 360° revolution of the torque motor and its possible implementation, in the production sequence of a warp-knitting machine was investigated and a motor design was defined. As the driving motor, the Franke direct drive torque motor unit with internal absolute measuring system type LTD-0215-Z is selected (Figure 6.6 and Figure 6.7).

The design of the motor and its controller unit is made. Mechanical dimensions, electrical definitions, wiring details, and performance are defined and adapted to the application of inlay yarn insertion in warp-knitting machines<sup>29</sup>.

The motor was, at first, put into operation as a stand-alone unit in conjunction with the control system. The set-up of this test bench (Figure °6.7) essentially corresponded to the set up during the preliminary tests.

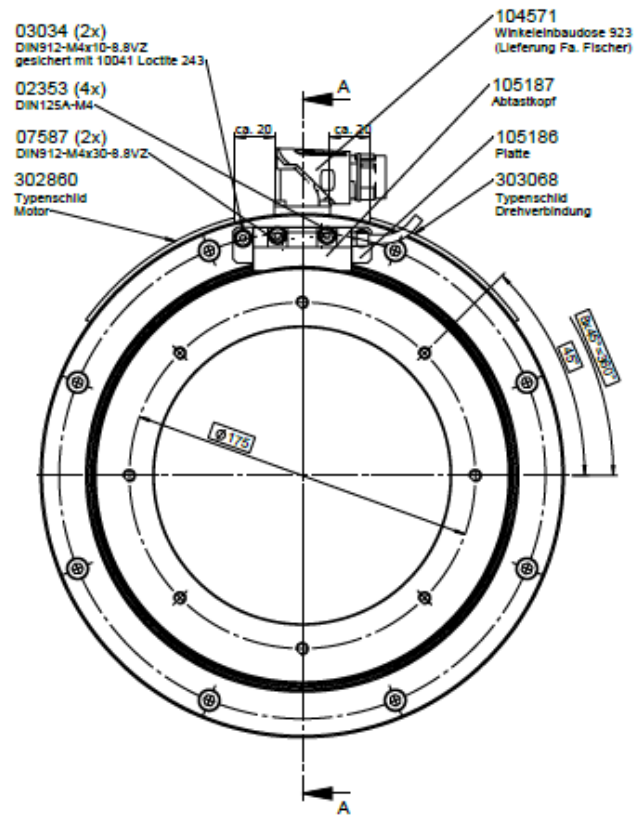


Figure °6.6: Drawing with mechanical definitions Franke LTD-215-Z Torque motor<sup>29</sup>



a)



b)

Figure °6.7: (left) Franke direct dive torque motor unit type LTD-0215-Z: a) front view, b) rear view

The controller system was connected to the motor and programmed. Test trials were carried out on a test bench before assembly to the prototype unit. Both a rotating and a traversing movement with start/stop were tested.

The mechanical and electrical components from:

- The machine frame,
- The machine frame including the motor housing,
- The electric drive and control unit,
- The needle and traversing bars,
- The bar for the inlay positioning elements,
- The lateral displacement of the needle bars,
- The warp yarn infeed incl. yarn detector and stop motion,
- The weft feeding unit,
- The take-up unit,

were developed and built.

The prototype unit was built and the torque motor is mounted relative to the knitting unit. The sensors are attached to the moving elements of the prototype unit and connected to the controller system. When fixing the motor, the positions, the distance of the motor to the active unit and the relative angle of the motor to the active unit were first freely selected. The motor was tested in this mounting position in various movement scenarios and the stability of the prototype assembly and its vibration behaviour were examined.

This drive from the LTD-0215-Z unit is characterized by its self-contained concept as a complete system consisting of a torque motor and wire-race bearing unit (Figure °6.8).

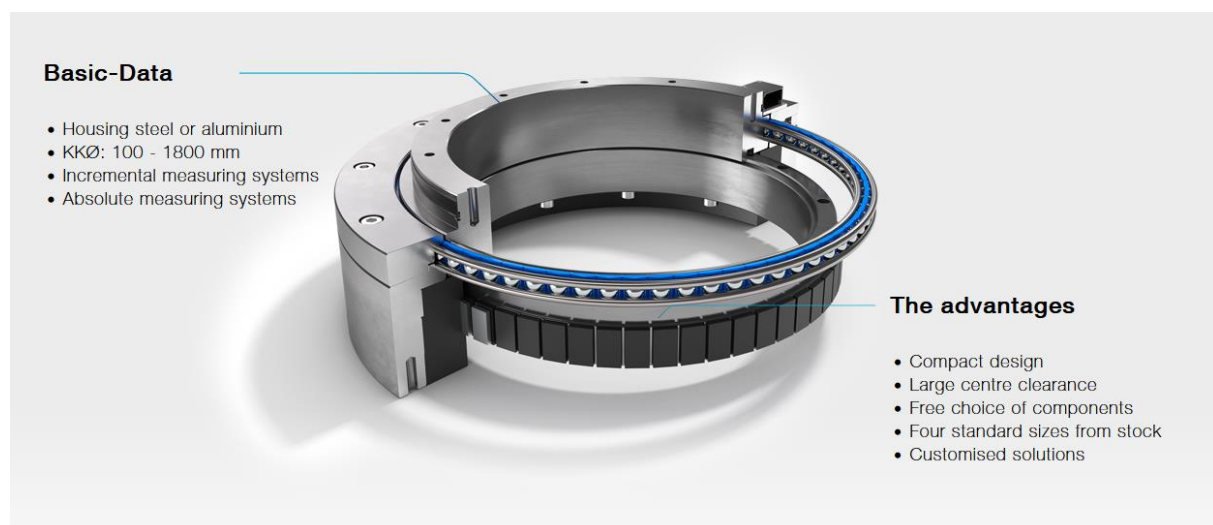


Figure °6.8: Franke direct drive with torque motor LTD<sup>47</sup>



This makes it possible to design this drive specifically for the requirements when installing it in a warp knitting machine. Its special, very compact design is ideally suited for this purpose.

In the Franke system, the torque motors are integrated directly into the slewing rings. This makes it possible not only to generate a rotary motion but also to position or execute definable cycle steps. This technical possibility is essential to ensure the positioning of the weft yarn repeatedly and precisely. In the textile environment of a warp knitting machine, a lot of dust and fiber fly is generated. Drive systems in this environment must be designed to be wear- and maintenance-free for long service life.

The torque motor has a very high nominal torque of 26.4 N·m with a maximum peak torque of 105 N·m at a defined speed span. The distance between stator and rotor (air gap) is decisive for the size of the torque. The pre-tensioned slewing ring guarantees a constant air gap.

The motor with the dimensions Da·Di·H: 265·150·105 mm<sup>3</sup> and a rated torque of 26.4N·m and a peak torque of 105 N·m (rated current of 3.1 A with a peak current of 12.8 A) is selected for the inlay insertion.

When operating this drive unit, only very low loads occur, however, it is imperative that the system reacts highly dynamically during the start and stop processes of the warp-knitting machine and neither breaks nor over-delivers the weft yarn to be inserted. This motor is designed for these dynamics. For this, a backlash-free running of the motor is indispensable. The used drive is made backlash-free and adjusted, employing an inserted pretension<sup>29</sup>.

The total losses from 179 W at a nominal speed of rpm=640 are made up of:

- Winding Losses,
- Stator Iron Losses,
- Rotor Losses.

Calculation of total losses in W at nominal speed rpm=640<sup>88</sup>:

$$P_{It} = (P_{Iw} + P_{Isi} + P_{Ir}) \tag{36}$$

With:

$P_{Iw}$ : winding losses<sup>88</sup> in N

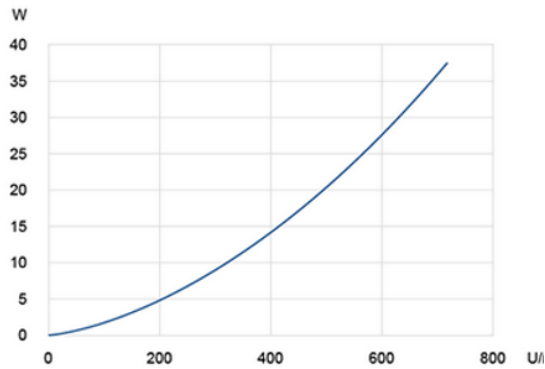
$P_{si}$ : stator iron losses in (Figure °6.9 a)

$P_r$ : rotor losses in N (Figure °6.9 b)

The winding losses are not depending on the actual rpm from the motor<sup>88</sup>. The value for  $P_{LE}$  is set to 131 N. The value for  $P_{si} = 31$  is taken from the graph “Stator iron loss” in Figure °6.9a, the value for  $P_R = 17$  J are taken from the graph “Rotor losses” in Figure °4.9b.

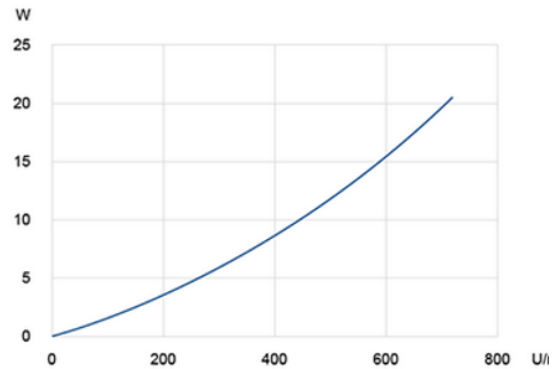


**Stator Iron Losses**



a)

**Rotor Losses**



b)

Figure 6.9: Losses  $P_{si}$  and  $P_r$  in relation to rpm<sup>88</sup>

In continuous operation with one full rotation, two inlay yarns can be placed with one complete 360° rotation. At rpm=500 therefore 4.2 inlay yarns/s can be placed. Calculation of total losses in W per yarn at speed rpm=500<sup>47</sup> with the following values:

$$P_{lW} = 131 \text{ N}$$

$$P_{si} = 20 \text{ N (Figure 4.9a)}$$

$$P_r = 12 \text{ N (Figure 4.9b)}$$

With these values and Equation 36 the winding losses can be calculated to  $P_{LT} = 163 \text{ J}$ .

In addition to these losses, a further 10% are needed for:

- Friction compensation unwinding yarn etc,
- Yarn/ fixed part friction,
- Yarn/air friction.

Based on the value  $P_{LT} = 163 \text{ J}$  and the estimations made the energy consumption ( $E_M$ ) = 179J and the corresponding energy consumption per individual weft insertion ( $E_{Mi}$ ) = 89.5J can be calculated according to Equation 36

The drive motor must be firmly anchored in the machine housing to secure the static deadweight (15 kg) of the motor and to be able to dissipate any moments that occur during a sudden stop or speed change (Figure 6.10). The positioning of the motor needs to be designed to give flexibility to adjust the position, the distance and the angle of the motor plane to the needle bar plane. The maximum width from the needle bar is determined, of the inner diameter, r from the motor and the shape from the eyelet holder bracket.

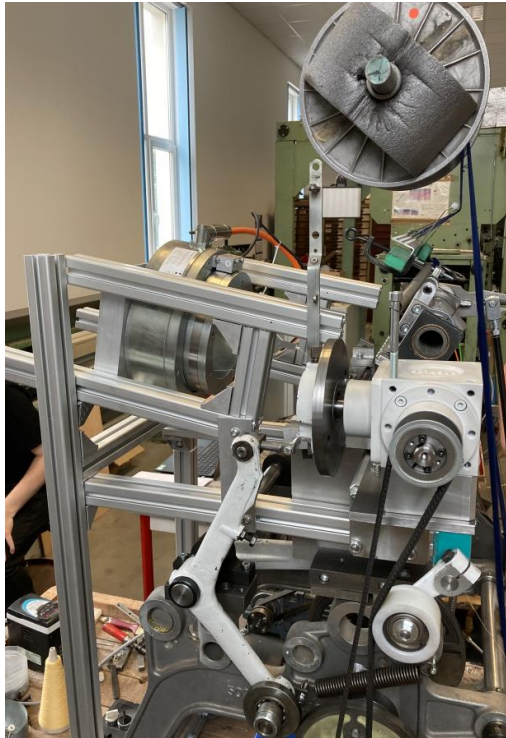


Figure °6.10: Basic set-up demonstration unit with torque motor

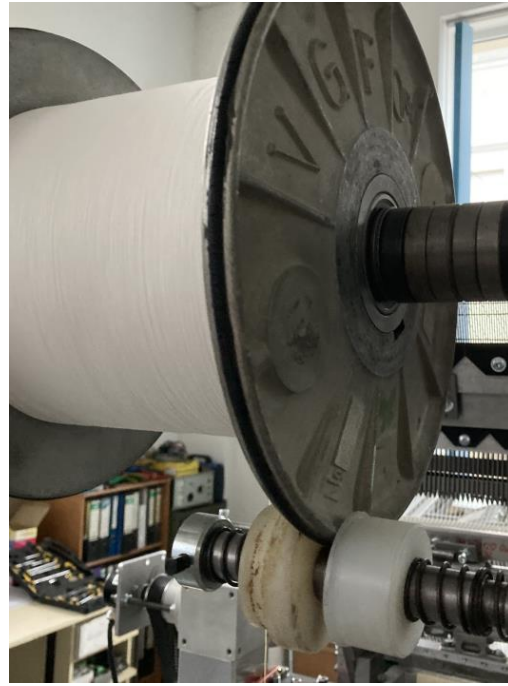
### **6.3.2 Positioning and installation of the warp beam in the prototype unit**

The warp beam locates above the knitting unit (Figure °6.11 a). The unwinding movement of the warp beam is mechanically braked (Figure °6.11 b) at the flange from the beam to prevent the warp beam from over-feeding.

The individual warp yarns (Figure °6.12 a and Figure °6.13 b) are guided to the knitting area via eyelet blades (Figure °6.12 b) in which individual eyelets for each warp yarn are fixed. All warp yarn ends are monitored via drop wires for yarn breakage (Figure °6.13 a). The edge threads of the warp beam are additionally guided through spring-loaded yarn guides similar to lateral yarn tensioners used in flat knitting machines (Figure °6.12 a). This ensures a safe and smooth warp thread run at the fabric edges.



a)



b)

Figure °6.11: a) Location from the warp beam, b) break for the warp beam at the flange.



a)



b)

Figure °6.12: Warp yarn guidance: a) including edge threads with tensioners b) after the beam





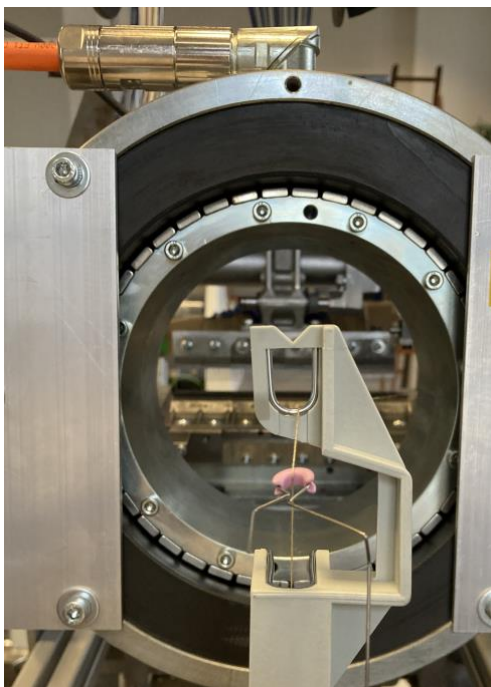
a)



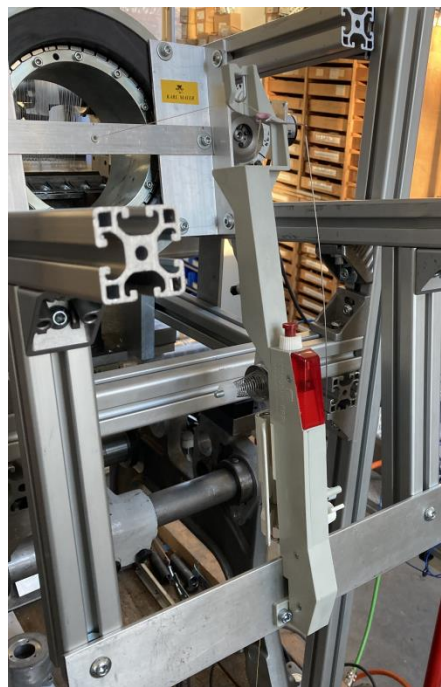
b)

Figure °6.13: Warp yarn package: a) control (droppers), b) warp yarn set-up relative to the needle bar.

The inlay yarn is pulled off the bobbin "overhead". Then it is lead to the knitting zone through the centre from the rotary device (Figure °6.14 a).



a)



b)

Figure °6.14: a) View in direction yarn path through the motor to the knitting zone, b) inlay yarn feeding into the unit.

It is guided additionally through a pre-tensioned spring-loaded yarn tensioner (Figure °6.14 b) to keep the yarn end always straight during the whole inlay cycle.

In the next step, the motor movement was synchronized with the main drive from the knitting machine, the knitting process of the prototype unit. In the process, the rotary eyelet movement and the eyelet position at the reversal points were experimentally determined and defined. The yarn must be dynamically positioned and held at the edge of the fabric. The eyelet position must secure the inlay yarn behind the edge needle and under the enclosing elements to prevent the possibility of the inlay yarn from being laid out from the needles during the reverse movement. The best position for the eyelet is slightly behind the needle plane and slightly below the knock-over edge from the needles.

The controller unit is connected to the motor. Synchronization with the machine cycle is made using positioning sensors from the needle bar. The eyelet position timing, speed, and acceleration can be programmed. Preparing trial runs with the control unit and the motor was carried out on the test bench.

A constantly rotating movement and a traversing movement with start/stop after every 180° revolution were alternatively tested.

### **6.3.3 Inlay insertion at the edge needles**

For an optimal thread insertion behind the needles in the loop-forming area, especially in the area of the two last edge needles, a backing or under laying of the thread relative to the needle position is necessary. This dynamically accurate positioning is vital for process stability, especially at higher machine speeds.

Therefore, the following points must be considered:

- The correct positioning from the inlay yarn eyelet along the machine axis,
- The correct positioning from the inlay yarn eyelet along the needle movement axis,
- Timing to the machine cycle especially to the needle and sinker movements,
- The geometry from the inlay placing elements,
- The shape from the inlay placing elements,
- The yarn tensile force,
- The control/dumping from yarn vibrations.

The inlay yarn (number 3 in Figure °6.15) is placed from the rotating eyelet from the rotary motor (number 4 in Figure °6.15) on the side of the fabric below the knock-over edge from the needle bar. The needles (number 1 in Figure °6.15) are driven out to the maximum. The positioning element (number 2 in Figure °6.15) is also driven out to the maximum, the inlay yarn is pushed safely behind the needles from the positioning element. Figure °6.15 b shows the inlay yarn, which is placed behind the needles and, starting of the red arrow to the right side below the sinkers. The part from the rotating eyelet up to the arrow (left

from the red arrow) is falsely placed on top of the sinker. This happened in this particular case due to the high position of the rotating eyelet at the edge of the knitting area.

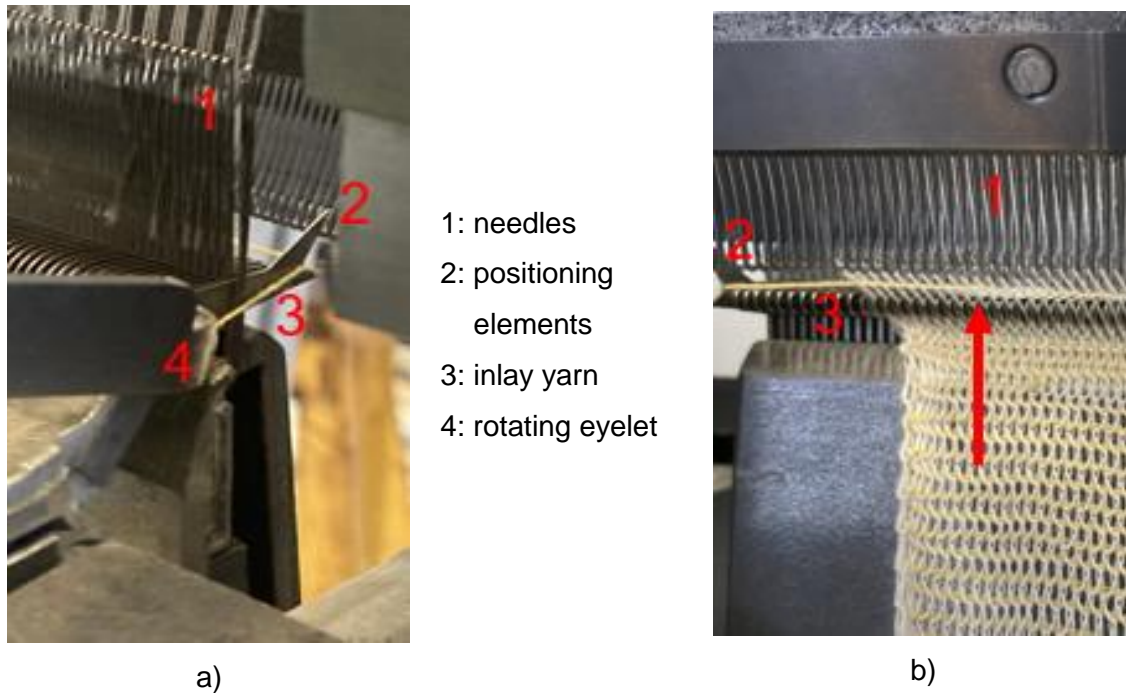


Figure °6.15: Positioning from the inlay yarn relative to the fabric: a) rear side, b) front side

This can be ideally achieved by a pendulum movement of the motor.

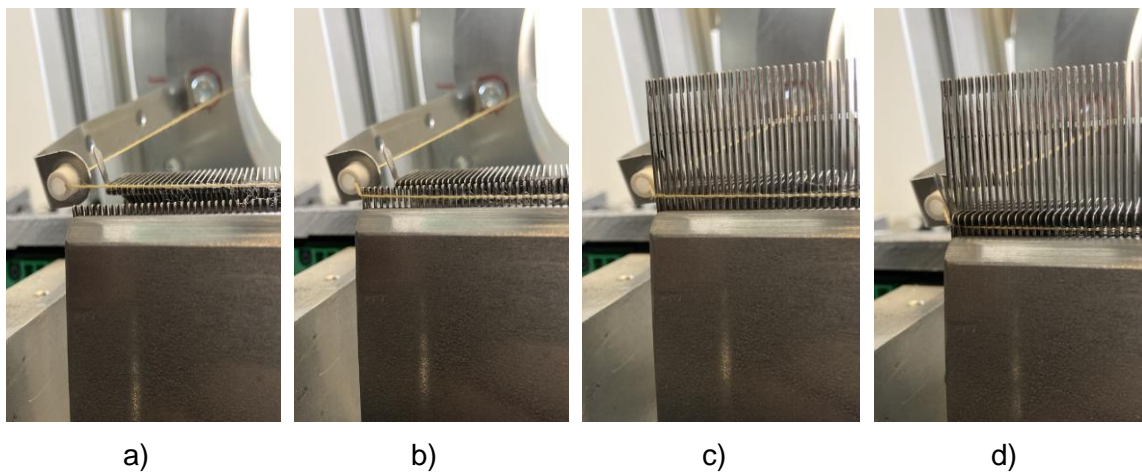


Figure °6.16: a) Inlay yarn at the edge needle, b) needles move upwards, c) needles reach maximum height, positioning elements move forward, d) the yarn is placed under the inlay elements and behind the needles. The position from the eyelet for the inlay yarn at the edge needles is visible in Figure °6.16.

In addition to this for position the inlay yarn, the yarn needs to be placed relative to the needles from the yarn placing elements.

The development of the inlay yarn placing elements is made based on the patent from the University of Applied Science Niederrhein DE 102919128607.7<sup>77</sup> and is visible in the Figure 5.30 with variants in Figure 5.31 and Figure 5.32.

## **6.4 Results**

### **6.4.1 Trials**

Using the rotary eyelet inlay only one yarn end can be inserted, therefore the yarn speed is getting high. Similar to the inlay process with rotating blades is to consider that the period of only 13% from a centre shaft revolution is available for the weft yarn insertion. The remaining 87% of the insertion unit has virtually to stop. In a difference to the blade, the system is the controller unit from the motor allowing a pendulum traversing movement, which can stop at the fabric edges. The positioning of the inlay yarn and the control from the yarn during the actual inlay movement as well as during the stop period at the edges is possible. These advantages become obvious when working on smaller fabric widths.

### **6.4.2 Suggested improvements**

The prototype set-up is working with an alternating movement from the eyelet. Therefore, the motor has to stop and restart after every inlay yarn cycle. This is caused by the available period for the inlay procedure during one revolution from the main machine drive shaft. This is creating higher energy consumption due to accelerating and stopping masses. However, this setup is allowing every machine revolution to place an inlay yarn inside the knitted course or not. The programmable controller from the motor unit is also allowing to insert or skip the inlay yarn insertion for every inlay movement. This is making the development of new innovative textile products possible with localized mechanical, optically, physical, or haptic properties.

To use the rotating eyelet as a permanent rotating feeding device intermediate storage like described need to be attached. Using this intermediate storage (transportation chain) the programming will be not possible anymore. This would be possible only when an automatic yarn knotting or splicing device would be added.

Identical to the rotating blade technology, the rotating eyelet is running with one yarn end only this is increasing the yarn consumption at the weft yarn package. It will run empty much quicker than in a system with more yarns supplied simultaneously like in the magazine insertion. Either bigger yarn packages need to be used or frequent changes in the yarn supply, which leads to more maintenance of the running machine, are required.

### **6.4.3 Comments about inlay insertion solution via a grooved drum**

The patent application WO 2020/094497A1 "Device and method for feeding a thread", applicant Niederrhein University of Applied Science provides the basis for a new process based on a grooved drum.

The invention relates to a device for feeding a thread for loop-forming needles, which are arranged in at least one course, of the textile machine. The machine is comprising a thread guiding device (number 4 in Figure 6.17) having a rotary element (number 5 in Figure 6.17), wherein the thread guiding device (number 4 in Figure 6.17) is designed to move a weft thread (number 2 in Figure 6.17) to and from in two opposite directions in a feeding region (B) in each case in front of the course of needles.

The load on the yarn is reduced as much as possible by the groove design

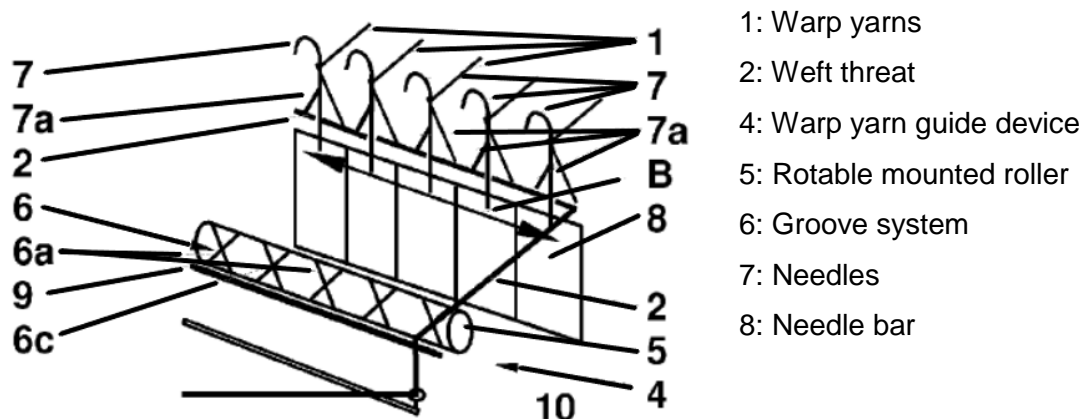


Figure 6.17: Patent visualisation WO 2020/094497 A1

This laying or traversing principle is known for the winding technique. The yarn is fed directly through the groove of the laying roller. When feeding the heating strand into the warp knitting machine, the strand is only minimally deflected in the groove of the laying roller and only at the laying edges.

Based on the experiences made during the set-up from the demonstrating units for the blade traversing technology and the rotating eyelet the control from the inlay thread during the traversing process is most important. In the rotating eyelet technology, the inlay thread position is controlled and defined from the placing eyelet. This ensures the possibility to run the system at high speed. The biggest hurdle from the system with the blade traversing technology is the lack of process stability due to the missing direct control from the inlay thread.

As visible in Figure 6.17 the system using the rotating drum is also not defining the position of the inlay yarn and the following difficulties will also appear:

- Horizontal and vertical drag angle,
- Timing from the process,
- Positioning from the inlay yarn at the edge needles,
- Open yarn supply without eyelets.

The set-up from a prototype unit based on this technology is therefore not considered.



## 6.5 Conclusions

In order to establish with the rotating eyelet a new and alternative weft insertion system further detailed developments are necessary. The rotating eyelet can be implemented as:

- Constantly rotating solution with an intermediate inlay yarn storage, without patterning possibility,
- Alternating yarn movement with start and stop, with patterning possibility.

This shows the potential of the rotating eyelet system to establish as a yarn inlay technique, especially for narrow fabrics.

Further steps of development will be to made:

- A flexible width from the inlay yarn possible (narrow or wider inlay area),
- To make the position from the inlay yarn flexible (movable unit along the machine axis).

These technologies allow either the development of new textile products with new features and properties, or the flexible positioning will allow the technology to be applied in wider machines as a flexible and solid inlay positioning device.

## Conclusion and outlook

### Final conclusions

The research study has been completed in four stages and resulted in the following conclusions:

- Analysis of the historical timeline of technical developments in respect of inlay yarn insertion technologies in warp knitting machines, including an evaluation of the different technologies according to selected aspects,
- Defining the requirements for an innovative process and formulating the necessary textile and technological properties. Comparison with the development process to date and the current state-of-the-art. Investigation of the state-of-the-art inlay process regarding the underlying basic parameters such as yarn tensile forces and yarn speed,
- Planning, designing, and building to small scale, prototype units: one for the process using rotating blades and one for the rotating eyelet attached to a torque motor.
- Analysing the innovative processes and evaluation.

In warp knitting, inlay yarns are inserted, which often represent the process limitation in terms of speed. Yarns are also laid in the weft insertion process, which in turn requires yarn guidance with high masses and accelerations. Within the scope of this Ph.D. study, innovative inlay insertion technologies are designed, developed and tested. All warp knitting technologies can benefit from the new inlay insertion technologies. The special challenge will lie in the technical interaction of the individual processes. Initially, the knitting process can take place separately from the inlay-yarn preparation process. Only when both process steps are independently optimised for the joint process should they be combined. The development of a prototype that implements the innovative principle of inlay yarn insertion into warp knitting machines can illustrate the mode of operation and provides the basis for convincing future users of the technology. The emphasis is not yet on process optimisation and the development of the speed potential, but rather on testing the interaction of the new components and leading them to a functioning process.

The first technology analysed is the blade traversing principle. The principle of the rotary blade yarn traversing is known from state-of-the-art bobbin winding machines. An important point of analysis is to work out the technological differences when using a yarn traversing unit in a winding machine and when using it in a warp knitting machine. The aim was also to examine the functions of the various components of the traverse unit and to determine possible design and process-related influence parameters. The main challenges from the development are:

- Yarn friction on the leading edges of the traversing blades,
- Yarn positioning on the transport blades during the traversing process,
- Yarn positioning and timing at the reversal points and its secure positioning during the loop formation process
- Yarn insertion at the edge needles,
- Yarn angle differences to the needle bar when transferring the yarn from one rotor wing to the opposite wing,
- "Drag angle problem" - the yarn is stretched from the edge needle over the blade. This creates an angle between the yarn path and the needle base. This drag angle occurs both horizontally and vertically.
- Only a small portion of the complete machine cycle is available for inlay insertion. These two technology groups must be synchronised with each other.

To establish a new and alternative inlay insertion system based on rotating wings, several main obstacles remain. Major technical challenges will be to cope with the given machine cycle and to use the given time window as effectively as possible. Therefore, an intermediate storage unit like a feeding chain is needed. Further, the parallel presentation from the inlay yarn into the knitting zone needs to be done to overcome the technological hurdles like drag angle and blade/yarn interaction. Special yarn forwarding elements need to be developed. These yarn forwarding elements will also help by dumping all lateral and longitudinal yarn vibrations and movements from the inlay yarn.

To cope with the limitations of the rotary blade technology, the technology with a rotating eyelet was developed and built. First of all, the traversing movement of a yarn achieved in basic experiments, starting from a rotating yarn movement, was checked and confirmed in an experimental set up. The prototype unit was assembled and the motor was mounted relative to the active unit. When attaching the motor, the positions, the distance of the motor to the knitting plane and the relative angle of the motor to the knitting bar were first freely selected. The motor was tested in this position in various movement scenarios like a pendulum movement or constant rotation. The motor movement was synchronised with the knitting process of the prototype unit. In the process, the eyelet movement and the eyelet position at the reversal points were experimentally determined and fixed. For an optimal inlay insertion behind the needles in the loop-forming area, especially in the area of the two edge needles, a backing or underlying of the yarn relative to the needle position is necessary. A pendulum movement of the motor can ideally achieve this.

The rotating eyelet can be implemented as:

- Constantly rotating solution with an intermediate inlay yarn storage without patterning possibility,
- Alternating yarn movement with start and stop with patterning possibility.

This shows that the potential of increasing supply speed, reduced energy consumption and a reduction of moving parts required for the inlay technique can be achieved working at a smaller width.

### **Limitations from the studies**

In this research study, two selected innovative inlay yarn technologies had been developed to a prototype stage. Based on the limited resources two out of three technologies had been selected and the technology using a grooved drum was not further discussed in the research study. This prototype stage can only show the capabilities and the major technical hurdles of innovative technology. These applications are new to warp knitting and are associated with challenges and risks. As the next step, a real pilot machine needs to be developed. With this real pilot machine, production parameters like maximum machine speed, maximum width and limits concerning the inlay yarns used can be determined. Neither the Niederrhein University of Applied Science nor the University of Haute Alsace do have not the necessary technical resources like tooling machines or assembly capabilities to design, manufacture and build these machines. Based on the results gained with the prototype units, machines using the innovative technology for market-ready products can be developed and introduced to the market. Also for this aspect, the Niederrhein University of Applied Science or the University of Haute Alsace have no marketing access to the international textile machinery market. The development of new, highly productive products can also follow from the project.

The realisation of the prototype serves to demonstrate the feasibility and potential to potential licensees or buyers. In doing so, the practicality and advantages of the system should be demonstrated.

### **Outlook**

The results from this research study indicate the potential for innovative technologies to increase the machine speed as well as the flexibility of warp knitting machines with inlay yarns. This concerns not only the development of new machine technology but also the development of textile products with either new features or also products that can be produced more economically is possible. Further tasks and hurdles remain, but they don't seem too complex and critical, especially when considering narrow fabric applications. To develop further, the following general paths of development are foreseeable:

- **A flexible width from the inlay yarn possible** (narrow or wider inlay area). With this approach, the innovative application can be attached to wide frame warp knitting machines. Besides technical applications, also applications for example in lace technology are possible.

- **A flexible position from the inlay yarn** (movable unit along the machine axis). With this approach, the innovative application can be attached to wide frame warp knitting machines. Technical applications with localized features like local reinforcements and local electrical connectivity are possible. In addition, applications for textile and clothing like trims, bandages or elastic applications are possible.

The completed work shows clear potential for a very flexible and movable weft insertion system that can be positioned on a knitting machine. These flexible weft insertion systems:

- are more cost-effective, more variable and suitable for all yarns and weft materials such as wire, etc,
- allow either the development of new textile products with new features and properties or the flexible positioning will allow the technology to be applied in wider machines as a flexible and solid inlay-positioning device.

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## Résumé en Français

### Introduction

La technologie du tricotage à maille jetée a été développée plus récemment que les autres méthodes de production d'étoffes. Le tricotage est un procédé de fabrication de mailles. En plus des fils formant les mailles, des fils de trame peuvent être insérés de façon rectiligne dans le tricot.

Les fils de trame insérés par tricotage chaîne représentent souvent la limite du procédé de fabrication en termes de vitesse de la machine car l'alimentation des fils de trame nécessite leur guidage réalisé par des éléments mécanique en mouvement donc représentant par des masses dont l'accélération est élevée. De plus la fenêtre de temps disponible dans le cycle de tricotage pour former les mailles à partir du métier à tricoter chaîne est court. Les processus d'insertion de trame sont caractérisés par des éléments de machine qui doivent effectuer un mouvement d'accélération et de freinage pour chaque insertion dans le temps le plus court possible. Les systèmes d'insertion de trame les plus modernes tentent d'augmenter la vitesse utilisent un magasin de préparation des fils de trame avant leur arrivée dans la tête de tricotage et donc leur insertion. Ils augmentent ainsi le rendement du métier à tricoter chaîne en insérant simultanément plusieurs fils de trame. Le deuxième objectif est de préparer le fil d'insertion dans un système de stockage intermédiaire afin d'élargir la fenêtre de temps pour l'insertion de la trame. Par ailleurs, les fils subissent moins de contrainte qu'en tissage par exemple où le fil de trame est préparé pendant le cycle de tissage. De plus, les lignes de production sont alors très encombrantes.

Les développements innovants des dernières décennies ont considérablement fait progresser les domaines d'application tels que la production de dentelle, de filets, des agrotextiles, des géotextiles, des spacer fabrics pour les sièges automobiles, etc. De plus, comme il est possible d'insérer des fils droits dans la structure textile, on peut l'utiliser pour fabriquer des structures présentant un allongement très faible voire nul, ce qui les rend compétitifs par rapport aux étoffes tissées. Ces étoffes sont alors particulièrement utiles comme renforts de matériaux composites pour les pièces mécaniques structurelles, ou pour insérer des fils qui ne supportent pas la courbure parce qu'ils sont très délicats, comme les fibres de carbone ou des fibres optiques, ou rigides, comme les fils métalliques. Dans ce cas, le fil inséré améliore les propriétés mécaniques/physiques du tissu. Le fil d'insertion peut être inséré sur toute la largeur de la surface textile (insertion totale) ou seulement sur une zone spécifique du textile (insertion partielle).

La base d'un nouveau système d'insertion de trame innovant est d'insérer le fil de trame à vitesse élevée, en utilisant des éléments de guidage du fil en mouvement constant afin d'éviter les phases d'accélération et de décélération. En plus d'une augmentation de la productivité du métier à tricoter Chaîne ou Rachel, l'objectif recherché est également de réduire la consommation d'énergie et de réduire l'encombrement de la machine.

Les buts et objectifs spécifiques de ce projet de recherche étaient les suivants :

(1) Faire une revue technologique des méthodes de production de tricots à maille jetée en se concentrant sur le processus de formation des mailles dans différentes technologies de tricotage.

- Bases de la conception des tissus,
- Possibilités de fabrication des structures textiles,
- Technologies de production des tricots,
- Construction technique des tissus tricotés.

Ce travail est présenté au chapitre 1.

(2) Passer en revue les technologies d'insertion de fils de trame en suivant la chronologie de leur développement afin de déterminer et d'évaluer les aspects positifs et négatifs de ces différentes approches :

- Insertion du fil de trame dans les machines textiles,
- Insertion du fil de trame dans les machines à tricoter
- Insertion du fil de trame dans les machines à tricoter Chaîne ou Rachel

Cet examen analytique est présenté dans les chapitres 2.

(3) Évaluer et déterminer les exigences technologiques d'un nouveau système innovant d'insertion de fil de trame.

- Développement systématique du produit ou du processus,
- Définition des problèmes d'un système alternatif d'insertion de fil de trame,
- Processus d'innovation,
- Solution technique innovante pour un système d'insertion de fil de trame pour machines à tricoter Chaîne et Rachel.

Cette revue analytique est présentée au chapitre 3.

(4) Évaluer les paramètres technologiques qui influencent le fil de trame et la structure obtenue pendant le processus dynamique lui-même :

- Les bases relatives à la vitesse et à la tension du fil pendant le processus de tricotage,

- Mesures au niveau du système MIS (magazine insertion system),
- Analyse du cycle de la machine MIS,
- Conclusion des mesures.

Cette analyse est décrite et présentée au chapitre 4.

(5) Construire une approche de développement basée sur la méthode d'innovation systématique et en déduire les approches de développement les plus bénéfiques. En outre, concevoir et mettre en place deux prototypes de systèmes innovants d'insertion de la trame dans les machines à tricoter la chaîne de plus petite largeur.

- Définition générale de l'unité prototype,
- Analyse du processus des pales rotatives,
- Analyse du processus de tramage par barres à passettes dans les métiers à tricoter chaîne,
- Exigences importantes pour un système innovant dans les machines à tricoter chaîne,
- Systèmes de pose du fil dans les bobinoirs à cône,
- Modélisation préliminaire du système à pales rotatives, observations et définition du prototype,
- Structure du projet, étapes de développement du prototype de système à pales rotatives,
- Conception et mise en place du système prototype à pales rotatives,
- Suggestions d'améliorations du système à pales rotatives,
- Prototype avec œillet rotatif,
- Modélisation préliminaire du système à œillet rotatif, observations et définition du prototype,
- Structure du projet, étapes de développement du prototype du système à œillet rotatif,
- Unité d'entraînement du moteur entraînant l'œillet,
- Conception et mise en place de l'unité prototype du système à œillet rotatif,
- Améliorations suggérées pour le système à œillet rotatif,
- Conclusions et améliorations suggérées.

Cette analyse est décrite et présentée dans les chapitres 5 et 6.

(6) Conclure sur les résultats obtenus dans ce projet de recherche, sur la conception des deux prototypes et énoncer les perspectives techniques.

## **Chapitres 1 et 2 : Etat de l'art et analyse comparative des systèmes d'insertion de trame existants**

Des critères fondamentaux ont été identifiés dans la revue bibliographique et les techniques d'insertion de trame existantes sont évaluées ; il s'agit de :

- la vitesse du fil,
- les masses en mouvement, leur inertie,
- le nombre de fils de trame concernés par un cycle de préparation,
- la consommation d'énergie,
- la stabilité du procédé,
- la complexité du procédé.

La comparaison des différentes solutions technologiques est synthétisée (Tab. 2.44). Ainsi les bases permettant d'évaluer les différents concepts potentiellement innovants sont discutés :

- Le système actuel le plus moderne est le magasin de préparation des trames avec jusqu'à 24 fils préparés simultanément. La consommation d'énergie associée à la vitesse du fil rend le processus trop coûteux et ralentit la vitesse du processus de tricotage chaîne.
- Le guide-fil rotatif présente des facteurs négatifs similaires et, de plus, l'installation mécanique avec une longue tige rotative rend la machine encombrante et difficile à manipuler en toute sécurité.
- Le contrôle des cônes de fil rotatifs tout en faisant face à une vitesse de fil relativement élevée rend le système avec cônes de fil rotatifs difficile à produire. De plus, la machine doit être arrêtée lorsque l'un des cônes est vide. Tous les cônes doivent alors être remplacés par de nouveaux, ce qui entraîne une quantité importante de déchets.

La raison du succès du magasin de préparation des trames est la faible accélération et décélération subies par les fils, ce qui permet de contrôler une grande quantité de fils en mouvement. Le nombre de casse de fil est faible, car la faible vitesse du fil entraîne également une réduction des forces de tension exercées sur le fil. Ensuite, la consommation d'énergie par fil est nettement inférieure à celle de la méthode de préhension et de la tige de guidage du fil.

## **Chapitre 3 : Technologies innovantes d'insertion d'inlays : approche et solutions potentielles**

### **Analyse systématique**

Afin de développer un système innovant, le principe de l'innovation systématique est appliqué. Il se divise en quatre phases, qui se chevauchent en partie :

- Description des objectifs
- Définition du problème
- Recherche et description des solutions
- Sélectionner et décrire une solution appropriée

La description de l'objectif visé nécessite d'identifier les réponses aux questions suivantes :

- Quel est mon résultat idéal ?
- Quel chemin vers cet objectif correspond à ma conception idéale ?
- Où dois-je aller à long terme ?

Le résultat de cette analyse systématique est une définition claire de l'objectif, à long terme, indépendante du temps et du marché, ainsi qu'un concept pour la minimisation des ressources et, si nécessaire, des dommages sur le chemin de la recherche d'une solution.

### **Définition d'un système d'insertion de trame innovant**

#### 3.2 Approche pour l'insertion d'un inlay

##### 3.2.1 Insertion idéale de l'inlay

La description objective d'un système innovant d'insertion de fils inlay pour les machines à tricoter chaîne peut être décrite par les fonctions et propriétés suivantes :

Il doit être capable d'insérer des fils d'inlay individuellement ou en groupe à la bonne longueur, correctement allongés, parallèlement à l'axe de la machine, coupés ou non selon le produit, sans vibrations longitudinales et transversales et à la vitesse maximale possible de la machine sans insertion d'inlay. La séquence du processus et les équipements mécaniques supplémentaires ne doivent pas entraîner de coûts supplémentaires.

Le nouveau procédé d'insertion d'inlays doit être technologiquement supérieur aux systèmes précédents en ce qui concerne :

- être plus simple à mettre en place que l'insertion d'inlays dans les magazines bien connus,
- Moins cher,
- Plus économe en ressources (consommation d'énergie réduite, pas de déchets de coupe),
- Plus rapide (le métier à tricoter est actuellement limité par le système d'insertion des inlays),
- Une moindre torsion appliquée au fil d'inlay,
- Plus flexible (différents fils),
- Brevetable/Innovant,
- Durable.

Le premier aspect important est de fournir la preuve technologique du concept dans un prototype fonctionnel. Pour cela, les défis de conception et de technologie doivent être résolus. Ce n'est qu'ensuite, dans une étape évolutive ultérieure, que le système est installé et adapté dans une machine à tricoter chaîne. C'est alors que se pose le problème de l'adaptation de la technologie aux machines de production réelles. Il est également important de limiter la première étape à la fonctionnalité elle-même.

Dans une deuxième étape, la vitesse de la machine est augmentée et les développements techniques et technologiques pour l'adaptation aux grandes largeurs de machine sont abordés.

### 3.2.3 Système innovant d'insertion de fil d'inlay

Le nouveau système innovant d'insertion de fils d'incrustation doit donc résoudre les problèmes suivants ou en être au minimum bénéficiaire :

- Élimination des fortes accélérations des systèmes mécaniques,
- Réduction de la consommation d'énergie,
- Réalisation de vitesses élevées d'introduction du fil,
- Insertion sûre du fil étiré,
- Structure simple,



- Un parcours libre du fil peut être réalisé et aucune déviation extrême du fil n'a lieu,
- Le fil n'est pas tordu en lui-même par l'alimentation,
- Performance hautement dynamique - comportement optimal au démarrage et à l'arrêt,
- Rapport couple/puissance élevé,
- Haute précision de positionnement,
- Peu de composants mécaniques doivent être installés dans les machines,
- L'insertion adaptable peut être intégrée dans une chaîne de processus,
- Différentes courses de rouleaux permettent différentes largeurs d'insertion d'inlays,
- Plusieurs rangées de rouleaux permettent une insertion simultanée côte à côte ou en chevauchement,
- Positionnement flexible dans la machine,
- Pas de déchets de coupe dans l'inlay,
- Pas de déchets de coupe sur les bords du tissu,
- Une lisière de tissu fixe peut être produite.

## **Chapitre 4 : Etude préliminaire : Mesures de la force et de la vitesse de traction du fil pendant le processus industriel**

### **Résultats de l'étude préliminaire**

Pendant le processus de formation de la maille, la taille de la maille est définie par la longueur de fil qui est incorporée dans chaque boucle individuelle. Les paramètres de la boucle finale (après formation) sont influencés par la force de traction du fil et l'allongement élastique du fil pendant le processus de formation de la maille.

A partir de la tension du fil mesurée expérimentalement sur une machine Rachel grand trameur et calculée par un modèle analytique, une différence entre les niveaux tension du fil par rapport à la direction du chariot est mise en évidence. De droite à gauche, la tension du fil est plus faible au début du mouvement et plus élevée à la fin que dans la direction opposée. La tension du fil calculée par le modèle analytique montre la même évolution

due à l'évolution de l'angle d'enroulement total de droite à gauche et donc le frottement en découlant par la loi du cabestan.

Par ailleurs, certaines exigences peuvent être extraites d'un point de vue qualitatif de cette étude préliminaire. Pendant l'insertion du fil de trame, la tension et la vitesse du fil fluctuent fortement. Cela provoque probablement des oscillations longitudinales et transversales dans le fil de trame d'insertion. Ces oscillations s'intensifient avec l'augmentation de la vitesse de la machine et donc de la vitesse du fil. Ce mécanisme entraîne une limitation de la vitesse de préparation du fil de trame et du métier à tricoter chaîne.

Pour augmenter encore la vitesse de la machine et obtenir une plus grande fiabilité du procédé, une alimentation plus régulière et constante du fil est nécessaire. Ainsi, pour améliorer les conditions d'alimentation du fil de trame pendant le procédé d'insertion dans les métiers à tricoter Chaîne et Rachel, des éléments de transport et de positionnement du fil de trame à mouvement continu constituent une solution idéale, c'est-à-dire qu'ils permettent d'éviter tout mouvement alternatif introduisant une variation de la tension du fil. Une solution idéale consiste à combiner le mouvement continu des éléments avec le placement alternatif du fil de trame dans la zone de tricotage du métier à tricoter chaîne. Ces composants en mouvement continu, sans arrêt ni accélération cyclique, permettent de réduire également la consommation d'énergie du métier à tricoter chaîne. De plus, il est préférable de ne pas avoir de stockage intermédiaire du fil, ce qui simplifie le métier à tricoter, réduit le coût de la machine et augmente la fiabilité du processus en réduisant le nombre de composants impliqués dans le processus d'insertion de trame.

### **Objectifs du processus innovant d'insertion de fil de trame**

Les objectifs technologiques suivants doivent être étudiés et atteints :

- Des éléments de transport et de placement en mouvement continu,
- Pas de stockage de fils,
- Fils individuels, pas de groupes,
- Pas de déchets de coupe,
- Procédé à haute flexibilité pour les tissus étroits,
- Fil d'incrustation continu/aucune coupe,
- Réduction des vibrations transversales et longitudinales du fil.

Le processus de formation des mailles dans les métiers à tricoter Chaîne et Rachel peut atteindre des vitesses allant jusqu'à 4300 tr/min (métiers Chaîne) ou 2400 tr/min (métier Rachel). Le facteur limitant est l'insertion de la trame sur la largeur du métier à tricoter. Cela réduit considérablement la vitesse de la machine à un maximum de 1500 tr/min.

Les principales étapes suivantes doivent être suivies pour augmenter la productivité d'un métier Chaîne ou Rachel lors de l'insertion d'une trame :

- Tension constante du fil pendant l'insertion de la trame pour ne pas induire de déformation de la structure de base,
- Réduction de la torsion du fil de trame lors de son passage de la bobine à la zone de tricotage,
- Guidage précis du fil pendant la procédure d'insertion,
- Fil d'insertion continu ce qui entraîne l'absence de déchet de coupe.

## **Chapitre 5 : Prototype d'insertion de trame à pales rotatives**

Sur la base des recherches effectuées dans l'état de l'art de la technologie, de la situation des brevets dans le domaine des bobinoirs et des machines à tricoter chaîne avec insertion de trame, et des règles et normes techniques valides, le développement d'un système d'insertion de trame à pales rotatives, principe initialement utilisé pour le bobinage, a été réalisé.

Ce prototype doit vérifier les objectifs définis précédemment à savoir les exigences géométriques, les exigences de positionnement du fil, la vitesse de la machine, la manipulation de la machine et la fiabilité du processus.

En pratique, deux prototypes de conception préliminaire pour les paramètres mécaniques et géométriques du processus d'insertion de trame dans les métiers à tricoter Chaîne et Rachel utilisant des pales rotatives ont été réalisés, testés évalués. Les deux modèles sont actionnés manuellement et sont destinés à présenter la preuve du concept.

Le résultat de cette première étape est le catalogue de définition du prototype technique. Les différentes étapes de développement pour la conception du prototype sont déterminées. Les améliorations et les adaptations possibles sont déjà testées dans cette première phase et évaluées. Le processus complet de développement prévisible et la planification des tâches sont décrits.

Pour mettre en place un système d'insertion de trame nouveau et alternatif, plusieurs obstacles majeurs subsistent. Les principaux défis techniques seront de faire face au cycle de la machine et d'utiliser la fenêtre de temps donnée aussi efficacement que possible. Par conséquent, une unité de stockage intermédiaire, comme une chaîne d'alimentation, est nécessaire. En outre, la présentation parallèle du fil d'insertion dans la zone de tricotage doit être réalisée en surmontant les obstacles technologiques, comme l'angle de traînée et l'interaction pale/fil. Des éléments spéciaux d'acheminement du fil doivent être

développés. Ces éléments permettent d'évacuer toutes les vibrations et tous les mouvements latéraux et longitudinaux du fil de trame. Cependant, le potentiel d'augmentation de la vitesse, de réduction de la consommation d'énergie et de réduction des pièces mobiles nécessaires à la technique d'incrustation peut être atteint en travaillant sur une largeur plus petite. Les améliorations et suggestions pour le système d'incrustation innovant décrit dans le contexte du système à pales rotatives s'appliquent aux autres versions alternatives de systèmes d'insertion de trame.

## **Chapitre 6 : Prototype avec œillet rotatif**

Le prototype réalisé est un dispositif d'alimentation d'un fil pour des outils de formation de mailles, disposés dans au moins un parcours, de la machine textile. Il s'agit d'un dispositif de guidage de fil de trame comprenant un élément rotatif et un guide-fil fixe. Le dispositif de guidage du fil de trame est configuré pour guider la trajectoire du fil de trame dans une plage de course donnée devant une rangée d'aiguilles de la fonture.

Le système utilisé est pour entraîner le guide-fil ou l'œillet en rotation est une couronne a entraînement direct. Dans l'environnement textile d'un métier à tricoter chaîne, de la poussière et des peluches de fibres sont générées. Les systèmes d'entraînement dans cet environnement doivent donc être conçus pour être sans usure et sans maintenance pour une longue durée de vie. Le moteur couple utilisé a un couple nominal très élevé de 26,4 Nm avec un couple de pointe maximal de 105 Nm à une plage de vitesse définie. Grâce à ce principe, le moteur (courant nominal de 3,1 A avec un courant de pointe de 12,8 A) peut être dimensionné plus petit, ce qui permet de réaliser des économies d'énergie pouvant atteindre 30%.

D'après les essais et l'analyse préliminaires, les principales caractéristiques de conception et les composants techniques du prototype avec l'unité à œillet rotatif sont les suivants :

- L'unité prototype est fabriquée comme une machine autonome,
- La largeur de travail est de 200 mm,
- La barre à aiguilles est équipée de 8 modules d'aiguilles Karl Mayer 18GG Z18/60-54 avec des aiguilles Groz-Beckert Raschel-Spec 51.75 G01. La machine utilise donc des aiguilles à clapet standard,
- Les barres de guidage sont équipées de modules de guidage Karl-Mayer KH-20-3-3,
- L'entraînement et la synchronisation relative pendant le cycle de tricotage de tous les éléments de tricotage concernés sont effectués mécaniquement par l'arbre d'entraînement principal,

- L'ensouple est située sur le dessus,
- L'ensouple est freinée pour éviter le dépassement du fil de chaîne, c'est-à-dire qu'elle est alimentée négativement,
- Les fils de chaîne sont guidés individuellement par des droppers qui servent de détecteurs de rupture de fil,
- Les fils de chaîne doivent être maintenus individuels et éloignés les uns des autres sur leur chemin de l'ensouple à la zone de tricotage par des œillets individuels fixés sur des plaques,
- Les fils de chaîne de la jante sont guidés individuellement par des tendeurs de fil à ressort,
- Un détecteur de rupture de fil pour l'incrustation, doit être appliqué,
- L'unité de commande synchronise les éléments de déplacement avec l'entraînement de la machine,
- Le dispositif d'enroulement est intégré dans la machine,
- Position flexible en ce qui concerne la distance entre l'unité de rotor et la barre à aiguilles,
- La barre de guidage du fil d'incrustation doit être aussi proche que possible de la barre à aiguilles,
- Initialement, le guide sera une plaque de guidage ouverte, si nécessaire une barre ouverte (fente) est appliquée,
- Les éléments de positionnement de l'inlay sont placés sur les bords du tissu et à égale distance sur la largeur du tissu,
- La configuration du point d'essai consiste à tricoter un point pilier avec un fil d'inlay.

La distance entre le stator et le rotor (entrefer) est déterminante pour l'importance du couple. Le réglage précontraint garantit un entrefer constant. Un système de mesure doit être appliqué pour déterminer la position du moteur.

L'utilisation de ce système présente les avantages suivants par rapport à l'état de l'art :

- L'angle d'enroulement du brin entre la bobine et la zone de formation des mailles est éliminé,
- Les surfaces des brins sont protégées, notamment lors du démarrage du système,
- Réduction de la consommation d'énergie,
- Une unité d'alimentation et de déplacement compacte et simple,
- Les machines existantes peuvent éventuellement être équipées de ces unités,

- Le processus d'incrustation peut être programmé si l'incrustation doit être faite à chaque rang de tricot ou seulement pour un nombre défini de rangs, ce qui permet de créer des modèles.

Le fil est déplacé le long d'une trajectoire circulaire par un œillet fileté fixé à l'anneau intérieur d'un moteur couple. La fil est ensuite dévié via un guide-fil dans un mouvement de va-et-vient. Ce mouvement de va-et-vient guide ensuite le fil dans la zone de formation des mailles.

Afin d'établir avec l'œillet rotatif un nouveau système alternatif d'insertion de trame, des développements plus détaillés sont nécessaires. L'œillet rotatif peut être mis en œuvre comme suit :

- Solution à rotation constante avec stockage intermédiaire du fil de trame, sans possibilité d'exécution de motifs,
- Mouvement alternatif du fil avec démarrage et arrêt, avec possibilité de création de motifs.

Cela montre le potentiel du système d'œillet rotatif comme technique d'insertion de trame, en particulier pour les tricots étroits.

D'autres étapes de développement devront être réalisées afin :

- d'obtenir une largeur flexible du fil de trame (zone d'insertion étroite ou plus large),
- de rendre la position du fil de trame flexible (unité mobile le long de l'axe de la machine).

Ces technologies permettent soit le développement de nouveaux produits textiles avec de nouvelles caractéristiques et propriétés, soit le positionnement flexible permettra à la technologie d'être appliquée dans des machines plus larges comme dispositif de positionnement de trame flexible et solide.

## **Conclusion et perspectives**

### **Conclusions finales**

Ce projet de recherche a été réalisé selon quatre étapes et a abouti aux conclusions suivantes :

- Analyse de la chronologie historique des développements techniques concernant les technologies d'insertion de fils d'insertion dans les métiers à tricoter chaîne, y

compris une évaluation des différentes technologies en fonction de certains aspects sélectionnés,

- Définition des exigences d'un procédé innovant et formulation des propriétés textiles et technologiques nécessaires. Comparaison avec le processus de développement à ce jour et l'état actuel de la technique. Étude du processus d'insertion le plus récent en ce qui concerne les paramètres de base sous-jacents tels que la tension et la vitesse du fil,
- Planification, conception et construction à petite échelle de prototypes : un pour le processus utilisant des pales rotatives et un pour l'œillet rotatif relié à un moteur couple.
- Analyse des processus innovants et évaluation.

Dans le tricotage chaîne, des fils d'insertion sont insérés, ce qui représente souvent la limitation du procédé en termes de vitesse. Les fils sont également positionnés dans le précédé d'insertion de la trame, ce qui nécessite un guidage du fil avec des masses et des accélérations élevées. Dans le cadre de cette étude, des technologies innovantes d'insertion de trame sont conçues, développées et testées. Toutes les technologies de tricotage Chaîne peuvent bénéficier des nouvelles technologies d'insertion de trame. Le défi particulier réside dans l'interaction technique des différents procédés. Dans un premier temps, le procédé de tricotage peut se dérouler séparément du procédé de préparation du fil de trame. Ce n'est que lorsque les deux étapes du procédé seront optimisées de manière indépendante qu'elles pourront être combinées. Le développement d'un prototype qui met en œuvre le principe innovant de l'insertion du fil de trame dans les métiers à tricoter chaîne peut illustrer le mode de fonctionnement et constitue la base pour convaincre les futurs utilisateurs de la technologie. L'accent n'est pas encore mis sur l'optimisation du procédé et le développement potentiel de la vitesse de production, mais plutôt sur le test de l'interaction des nouveaux composants et sur leur conduite vers un processus fonctionnel.

La première technologie analysée est le principe utilisant des pales rotatives. Ce principe est connu sur des bobinoirs. Un point important de l'analyse a été de déterminer les différences technologiques lors de l'utilisation d'une unité de placement du fil dans un bobinoir et lors de son utilisation dans un métier à tricoter chaîne. L'objectif était également d'examiner les fonctions des différents composants de l'unité de déplacement et de déterminer les éventuels paramètres d'influence liés à la conception et au processus. Les principaux défis du développement sont les suivants :

- Frottement du fil sur les bords d'attaque des pales,

- Positionnement du fil sur les pales de transport pendant le processus de traversée,
- Positionnement et synchronisation du fil aux points d'inversion et son positionnement de façon fiable pendant le processus de formation des points,
- L'insertion du fil au niveau des aiguilles de bord,
- Différences d'angle du fil par rapport à la fonture lors du transfert du fil d'une pale du rotor à la pale opposée,
- "Problème d'angle de traînée" - le fil est tendu depuis l'aiguille de bord sur la pale. Cela crée un angle entre la trajectoire du fil et la base de l'aiguille. Cet angle de traînée se produit à la fois horizontalement et verticalement.
- Seule une petite partie du cycle complet de la machine est disponible pour l'insertion de la trame. Ces deux groupes technologiques doivent être synchronisés l'un avec l'autre.

Pour établir un nouveau système alternatif d'insertion de trame basé sur des pales rotatives, plusieurs obstacles principaux subsistent. Les principaux défis techniques seront de s'adapter au cycle donné de la machine et d'utiliser la fenêtre de temps donnée aussi efficacement que possible. Par conséquent, une unité de stockage intermédiaire comme une chaîne d'alimentation est nécessaire. En outre, la présentation parallèle du fil d'insertion dans la zone de tricotage doit être effectuée pour surmonter les obstacles technologiques tels que l'angle de traînée et l'interaction pale/fil. Des éléments spéciaux d'acheminement du fil doivent être développés. Ces éléments permettront également d'évacuer toutes les vibrations et tous les mouvements latéraux et longitudinaux du fil d'insertion.

Pour faire face aux limitations de la technologie des pales rotatives, la technologie avec un œillet rotatif a été développée et construite. Tout d'abord, le mouvement de va-et-vient d'un fil obtenu dans les expériences de base, à partir d'un mouvement rotatif du fil, a été vérifié et confirmé dans un dispositif expérimental. L'unité prototype a été assemblée et le moteur a été monté par rapport à l'unité active. Lors de la fixation du moteur, les positions, la distance du moteur par rapport au plan de tricotage et l'angle relatif du moteur par rapport à la barre de tricotage ont d'abord été choisis librement. Le moteur a été testé dans cette position dans différents scénarios de mouvement comme un mouvement de pendule ou une rotation constante. Le mouvement du moteur a été synchronisé avec le processus de tricotage de l'unité prototype. Au cours de ce processus, le mouvement de l'œillet et la position de l'œillet aux points d'inversion ont été déterminés expérimentalement et fixés. Pour une insertion optimale de la trame derrière les aiguilles dans la zone de formation de la maille, en particulier dans la zone des deux aiguilles de



bord, un soutien du fil par rapport à la position de l'aiguille est nécessaire. Un mouvement pendulaire du moteur peut idéalement y parvenir.

L'œillet rotatif peut être mis en œuvre comme :

- Solution à rotation constante avec un stockage intermédiaire du fil sans possibilité de dessin,
- Mouvement alternatif du fil avec démarrage et arrêt avec possibilité de formation de motifs.

Cela montre que le potentiel d'augmentation de la vitesse d'alimentation, de réduction de la consommation d'énergie et de réduction des pièces mobiles nécessaires à la technique d'incrustation peut être atteint en travaillant sur une largeur plus petite.

### **Limites de l'étude**

Dans ce projet de recherche, deux technologies innovantes d'insertion de fil de trame ont été développées jusqu'au stade de prototype. En raison des ressources limitées, deux des trois technologies ont été sélectionnées et la technologie utilisant un tambour rainuré n'a pas été examinée plus avant dans le projet. Ce stade de prototype ne peut que montrer les capacités et les principaux obstacles techniques d'une technologie innovante. Ces applications sont nouvelles pour le tricotage chaîne et sont associées à des défis et des risques. L'étape suivante consiste à développer une véritable machine pilote. Avec cette machine pilote réelle, les paramètres de production tels que la vitesse maximale de la machine, la largeur maximale et les limites concernant les fils de trame utilisés peuvent être déterminés. Ni l'Université des Sciences Appliquées de Niederrhein, ni l'Université de Haute Alsace ne disposent des ressources techniques nécessaires, telles que des machines-outils ou des capacités d'assemblage, pour concevoir, fabriquer et construire ces machines. Sur la base des résultats obtenus avec les unités prototypes, des machines utilisant la technologie innovante pour des produits prêts à être commercialisés peuvent être développées et introduites sur le marché. Pour cet aspect également, l'Université des Sciences Appliquées de Niederrhein ou l'Université de Haute Alsace n'ont pas d'accès marketing au marché international des machines textiles. Le développement de nouveaux produits à haute productivité peut également découler du projet.

La réalisation du prototype sert à démontrer la faisabilité et le potentiel aux licenciés ou acheteurs potentiels. Ce faisant, il s'agit de démontrer le caractère pratique et les avantages du système.

## Perspectives

Les résultats de ce projet de recherche indiquent le potentiel des technologies innovantes pour augmenter la vitesse de production, ainsi que la flexibilité des machines à tricoter chaîne dans le cas de l'insertion de fils de trame. Cela ne concerne pas seulement le développement d'une nouvelle technologie de machine mais aussi le développement de produits textiles avec de nouvelles caractéristiques ou des produits qui peuvent être obtenus de manière plus économique est possible. D'autres tâches et obstacles subsistent, mais ils ne semblent pas trop complexes et critiques, surtout si l'on considère les applications de structures étroites. Pour poursuivre le développement, les voies générales de développement suivantes sont prévisibles :

- Une largeur flexible du fil de trame insérée est possible (zone d'insertion étroite ou plus large). Grâce à cette approche, l'application innovante peut être fixée sur des machines à tricoter chaîne de grande laize. Outre les applications techniques, des applications, par exemple dans la technologie de la dentelle, sont également possibles.

- Une position flexible du fil de trame (unité mobile le long de l'axe de la machine). Avec cette approche, l'application innovante peut être attachée aux machines à tricoter chaîne de grande laize. Des applications techniques avec des caractéristiques localisées comme des renforts locaux et une connectivité électrique locale sont possibles. En outre, des applications pour le textile et l'habillement comme les garnitures, les bandages ou les applications élastiques sont possibles.

Les travaux réalisés montrent clairement le potentiel d'un système d'insertion de trame très flexible et mobile qui peut être positionné sur un métier à tricoter. Ces systèmes d'insertion de trame flexibles :

- sont plus rentables, plus variables et conviennent à tous les fils et matériaux,
- permettent soit le développement de nouveaux produits textiles avec de nouvelles caractéristiques et propriétés, soit sa flexibilité permettra à la technologie d'être appliquée dans des machines plus larges en tant que dispositif de positionnement de trame flexible et solide.