Faculty of Mechanical Science and Engineering
Institute of Textile Machinery and High Performance Material Technology

Automation of crochet technology and development of a prototype machine for the production of complex-shaped textiles

Jan Lukas Storck

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Reviewer

Univ.-Prof. Dr.-Ing. habil. Yordan Kyosev

Prof. Dr. rer. nat. Dr. n. techn. habil. Andrea Ehrmann

Univ.-Prof. Dr.-Ing. Kristin Paetzold-Byhain

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Abstract

In the future, due to the climate crisis and the need to reduce CO_2 emissions, an increasing demand for lightweight materials such as textile reinforced composites can be expected. Because of rising raw material and energy costs, the application of more near net-shaped composites is promising for reducing manufacturing costs and waste. However, conventional textile technologies are limited in their ability to produce the necessary complex-shaped textiles. In order to address this problem by using alternative technologies that have not yet been industrially established, this thesis deals extensively with the development of a crochet machine and the investigation of respective textiles.

Crochet is a stitch-forming technology in which, unlike knitting, the loops of a stitch originate both vertically and horizontally from previously formed stitches. With versatile crochet, it is especially possible to create complex three-dimensional (3D) shapes because new stitches can be formed at any point on a fabric. Previous crochet machine approaches are inadequate and severely limited in scalability to an industrially applicable machine. Industrially established machinery called crochet machines are misleading in their designation because they are knitting machines that can only roughly mimic crochet structure but cannot form true crocheted fabrics.

The Crochet Automaton (CroMat) crochet machine developed and patented here enables for the first time the automated production of chain stitches (CHs), slip stitches (SLs), single crochet stitches (SCs), half double crochet stitches (HDCs), turns (T1 and T2), increase stitches (INCs) as well as decrease stitches (DECs) and other operations according to the principle of flat crocheting based on a chain line. In addition, by manually removing and re-hanging the produced fabric, new stitches can be formed at almost any point to produce complex-shaped 3D textiles according to the capabilities of crochet. For example, it is possible to produce shapes relevant for near net-shaped composites such as double T-beams with the developed CroMat prototype. With manually suspending different stitch rows or fabrics on the machine, it is also possible to join them by simultaneously crocheting a course through them.

In addition to the mechatronic prototype with ten axes, the world's first tool for designing machine-crocheted textiles is developed. It includes error checking, generation of the G-code for machine control and a preview of the designed fabrics. Beyond a graphical user interface (GUI) with standardized crochet symbols, a higher-level programmability is added through specifying a shape by 2D polygons and automatically generating corresponding, machine-crochetable patterns.

The first topology-based modeling framework for machine-producible crochet structures was developed for the preview. A similar modeling was developed for manually crocheted fabrics, which differ from the machine-produced ones only in the fact that the fabric is turned after each row and thus the stitches are formed from different sides. Both models can be used as a basis for simulative finite element method (FEM) investigations, which were used in this work to simulate crocheted fabrics for the first time.

Furthermore, the tensile properties of manually crocheted fabrics were systematically investigated for the first time and the properties of the first crochet composites were researched. Crocheted textiles (and corresponding composites) have basically similar properties as knitted textiles but have a tendency to withstand higher forces. Together with the shaping capabilities, the CroMat crochet machine is generally highly promising for the automation of crochet and especially for the future production of near net-shaped composite reinforcements.

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Declaration of authorship

I hereby certify that I have prepared this thesis without the unauthorized assistance of third parties and without the use of other than the indicated materials; the contents taken directly or indirectly from external sources are marked as such.

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Bielefeld, 21.11.2023

Jan Lukas Storck

List of abbreviations

2D	Two-dimensional
3D	Three-dimensional
ABS	Acrylonitrile butadiene styrene
Al.	Alia (used in the Latin phrase “et al.”, meaning “and others”)
ANP	Auxiliary needle pair
Approx.	Approximately
ARM	Advanced RISC machines
ASTB	Add stitch at the beginning of a course
ASTE	Add stitch at the end of a course
ASTM	American Society for Testing and Materials
BA	Border area
BL	Back loop
BY	By (regarding CC license)
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CC	Creative commons
cf.	Confer (Latin for “compare”)
CH	Chain stitch
CI	Course indicator
CNC	Computer numerical control
CPU	Central processing unit
CroMat	Crochet Automaton (name of the developed crochet machine)
CSV	Comma-separated value
CYC	Craft Yarn Council
D	Stitch depth
DC	Direct current
DEC	Decreasing (crochet operation)
DLP	Digital light processing
Dr.	Doctor
DOF	Degrees of freedom
e.g.	Exempli gratia (Latin for “for example”)
eCAADe	Computer aided architectural design in Europe
EN	European norm
F-code	Feed rate code
FDM	Fused deposition modeling
FEM	Finite element method
FLO	First lay over
G-code	Geometry code
GUI	Graphical user interface
H	Stitch height
HDC	Half double crochet stitch
HSBI	Hochschule Bielefeld – University of Applied Sciences and Arts
i.e.	Id est (Latin for “in other words”)
INC	Increasing (crochet operation)
IP	Intellectual property
ISO	International Organization for Standardization
ITM	Institute of Textile Machinery and High Performance Material Technology
L	Stitch length
LL	Leading loop
M-code	Machine code

n.d.	No date
NASA	National Aeronautics and Space Administration
NC	Non-commercial (regarding CC license)
ND	No derivatives (regarding CC license)
NEMA	National electrical manufacturers association
NI	Needle indicator
NURBS	Non-uniform rational basis spline
PAN	Polyacrylonitrile
PC	Personal computer
PLA	Polylactic acid
PM	Permanent magnet
PID	Proportional–integral–derivative
Prof.	Professor
PWM	Pulse width modulation
RC	Radio control
RISC	Reduced instruction set computer
RSTB	Remove stitch at beginning of a course
RSTE	Remove stitch at end of a course
RTM	Resin transfer molding
SA	Stitch area
SC	Single crochet stitch
SD	Standard deviation
SL	Slip stitch
SLA	Stereolithography apparatus
STL	stereolithography
T1	Turn with one CH
T2	Turn with two CHs
TD	Test direction
TRIZ	Teoria Reshenia Izobretatelskih Zadatch (Russian for "theory of inventive problem solving")
TU	Technische Universität
UD	Unidirectional
USB	Universal serial bus
UV	Ultraviolet
VARI	Vacuum-assisted resin infusion
VR	Variable reluctance
WLAN	Wireless local area network
YTF	Yarn tension factor
ZIM	Zentrales Innovationsprogramm Mittelstand (German for "central innovation program for small and medium-sized enterprises")

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1 Introduction

1.1 Motivation

The context for the development of a crochet machine is set by the rising prices for raw materials and energy together with the resulting demand for lightweight structures made of textile-reinforced composites for automotive, aerospace or general mechanical component applications [1]. Against this background, the requirements for a more efficient production of composites and a minimization of waste are increasing [1]. Waste can be significantly reduced if near net-shaped preforms are used, i.e., the textile reinforcement is already shaped like the component to be manufactured [1-3]. Compared to the conventional approach, in which plain fabrics are draped into the shape of the component in a laborious manual process and in which about 40% to 50% of the textile material is discarded, overall costs can be saved in an amount of about 36% [1,4].

Corresponding near net-shaped composites are commonly produced with knitting machines, which enable the knitting of diverse structures and three-dimensional (3D) shapes [2,5]. However, knitting, as well as existing textile technologies in general, are limited with respect to the direct production of reinforcements for near net-shaped composites [1].

As a textile technology that is not yet been technically established, crochet is particularly suitable for the production of complex 3D structures. In principle, a new stitch can be formed at any point of the textile [6], which makes it possible to create very complex shapes such as hyperbolic planes [7-10]. In crochet, yarn is interlooped to form a fabric, and compared to knitting, the stitches are intermeshed not only vertically but also laterally [11-13]. In general, crochet offers a greater variety of stitch types than knitting [2,6,14]. Also of great advantage is that in crochet only the lastly formed stitch is open, as opposed to the entire last row in knitting [6]. This facilitates an easy re-hanging of textiles in a future crochet machine for the production of complex shapes [6].

However, no machines for automating crochet have yet become widespread. Industrially utilized machines called crochet machines are actually knitting machines that can produce structures with only superficial similarities to crocheted textiles [14-17]. Initial approaches to true crochet machines include a prototype for crocheting rectangular flat fabrics [6,18] and one for circular crocheting [14,15]. The latter is called Croche-Matic and was developed in parallel to and independently of the developments described in this work. These prototypes are not suitable for scaling up to industrial production of near net-shaped composites, because the functional scope of the first prototype is too limited and the stitch formation of the second is too error-prone. For the development of an industrially applicable machine, a new, scalable crochet machine prototype is required, which, in addition to reproducible stitch formation, also offers possibilities for shaping the fabric in complex forms.

To be able to efficiently produce near net-shaped composites in complex shapes in the future and to use the possibilities of crochet technology in this context, the development of automation by means of a suitable machine is necessary at first. Corresponding innovations in this field, which has been little worked on and researched to date [19], hold great economic potential and can open up new markets. Beyond the production of reinforcements for near net-shaped composites, an industrially applicable crochet machine would generally enable the automated production of commercial crochet products, such as clothing, home textiles or plush toys (amigurumi), which are currently produced manually, mostly under poor working conditions [14,15,20]. Furthermore, automation of crochet is necessary for a realistic application of the technical possibilities presented so far. Among others, these are crocheted textiles as sensors [21], scaffolds for tissue engineering [22] or crocheted fabrics for sound absorption [23].

1.2 Aim

At the beginning of the work, the aim was to develop a new technique for joining textile components. This was to be based on the principle of crocheting, which is known for being able to join fabrics by drawing the loops of a crocheted row through each of them [10]. In solving this task, it became evident that the crocheting technology must first be automated suitably before it can be used for joining in the next step. The necessary automation of crochet is of such complexity that in view of the limited time available, the work is restricted to the development of a crochet machine. In agreement with Prof. Dr. Kyosev, the extensive development of an innovative joining technology based on crochet is scheduled for future work. Generally, automation of crochet with an industrially scalable crochet machine, which provides the basis for manufacturing and joining of components, is in itself highly promising, as stated above.

Thus, in line with the need to develop an industrially scalable crochet machine, this work presents the innovation of the Crochet Automaton (CroMat) crochet machine. This builds on the first approach of a true crochet machine for rectangular fabrics [6,18] and is designed to enable the production of more complex stitch types. Accordingly, flat crochet based on a chain line is to be automated. Compared to the alternative approach of the circular crochet machine [14,15], a significantly higher reproducibility of stitch formation is intended with the developed CroMat prototype.

The prototype should be able to implement all desired functions for the first time and to produce small sample fabrics. Due to the early stage in the automation of crocheting, the intention is to demonstrate the possibilities of machine crocheting with the prototype. An ideal technical implementation of the crochet machine is therefore not the goal. However, scalability to an industrially applicable crochet machine is to be provided. Another fundamental goal is that the CroMat machine can use the possibilities of crochet for shaping fabrics according to near net-shaped composite reinforcements. Besides the general automation of crocheting textiles, the production of technical textiles, such near net-shaped composites, are the intended field of application.

Within the scope of this development, the motion sequences for the formation of chain stitches (CHs), turns (T1 and T2), single crochet stitches (SCs), half double crochet stitches (HDCs), increase (INC) and decrease (DEC) according to the principle of flat crochet based on a chain line are to be automated for the first time. As part of the analysis of the stitch structure, a modeling framework is to be developed that can be used as a basis for finite element method (FEM) simulations. In order to investigate the suitability for the intended application of the production of composite reinforcements and to enable the deriving of further fields of application, the basic mechanical properties of (manually) crocheted fabrics are to be researched and first composites are to be produced from them.

To digitalize the crochet process and to ensure the operability of such a novel textile machine, it is necessary to develop the first design tool for machine-crocheted textiles. This tool should be able to validate the crochetability and generate the G-code to control the mechatronic crochet machine. A preview possibility of the designed textiles is also pursued. A process to automatically generate crochet patterns that can be produced with the CroMat prototype according to the shapes of 2D polygons is to be developed as an option. This should further facilitate the operability of the machine.

The comprehensive work carried out and the construction of the CroMat prototype described in detail are intended to lay the foundation for the further advancement of crochet machines suitable for application in an industrial context. The fundamentals of crochet automation created by this work enable the future technical application of crocheted textiles, such as complex-shaped reinforcements for near net-shaped composites. Overall, the work makes a significant contribution to the exploration of crochet technology and its utilization via the invention of the CroMat crochet machine.

1.3 Work structure

The work is organized as follows. Section 2 describes the relevant technical and scientific background for the development of the CroMat. Manual crocheting is described in detail in section 2.1. Section 2.2 deals with the fundamental machines for automating knitting, which is related to crochet, while section 2.3 illustrates the existing approaches to automating crochet. Rapid prototyping (RP) and electric motor technologies relevant to the development of CroMat are addressed in sections 2.4 and 2.5. The fundamentals of composites with textile reinforcements are described in section 2.6.

In section 3, the developed principles of the patented operation of the crochet machine are first described (3.1). Then, the innovation beyond the patent is addressed (3.2). The final motion sequences of the fundamental machine elements are illustrated in section 3.3. Furthermore, the structure as well as the operation of the finalized CroMat prototype is described in section 3.4 and the application is exemplified in 3.5. Section 3.6 addresses the developed design tool for machine-crocheted fabrics with which the prototype machine can be programmed. Finally, in 3.7 the chapter on machine development concludes with a consideration of the fulfillment of the requirements for the CroMat prototype from section 3.1.3.

Section 4 is dedicated to the research carried out beyond machine development. In 4.1 the developed topology-based modeling framework of manually crocheted textiles is explained, while 4.2 deals with the mechanical properties of manually crocheted fabrics (also as composite reinforcements). The modeling of the structure of machine-crocheted fabrics, including a simulative comparison to the manually produced ones, is the content of section 4.3. Section 4.4 shows the approach to automated shaping and generation of machine-crocheted structures. As the last part before the conclusion (section 5), exemplary machine-crocheted samples are presented in 4.5.

2 Technical and scientific background

This section sets the context for the development of the CroMat, which is one of the first machines to automate crocheting. The relevant background information is briefly summarized to give an overview of the current state of science and technology. In the first part, the reader is provided with the basics of the technology of crochet and the current (technical) applications are described. As a technology related to crochet and already established in the industry, section 2.2 deals with knitting machines. In section 2.3 the few previous approaches regarding the automation of crocheting are addressed. The RP principles and technologies used for the development of the CroMat crochet machine are presented in section 2.4 with a focus on fused deposition modeling (FDM) 3D printers. In line with the need for a mechatronic rather than mechanical machine to automate crochet, section (2.5) describes the principles of using electric motors. Lastly, an overview of composites reinforced with textiles is given in section 2.6.

2.1 Crochet

The textile handicraft crochet is related to weft knitting, as a fabric can be created from a single yarn by forming loops and interlocking them with the surrounding loops, following the principle of interlooping [A1,11,13]. In the past, these techniques were not necessarily distinguished [11]. In 1966, a delimiting definition was articulated by Irene Emery, according to which in crochet "each loop is drawn through two previous loops, the corresponding one in the previous row and the previous one in the same row" [12], whereas in knitting, a loop is only drawn vertically through a loop of the previous row [12]. In contrast to knitting, the formation of a stitch must be completed in crochet before the next one can be started [17]. Besides the disadvantage of limiting the production speed, this has the advantage that only one stitch is open at a time and not the entire row [6]. For this, a single hand-held hook needle is used to manipulate loops and hold the leading loop (LL) of the open stitch [19]. Crochet stitches consist of several loops and are similar to knots [24]. Unlike knitting, automated production of crocheted fabrics is not yet established in the industry.

Crochet became popular for decorative and functional textiles in 19th century Europe [11]. The first description of crochet that corresponds to today's definition was published in the Netherlands in 1823 [11]. Techniques directly preceding crochet in the second half of the 18th century were known as shepherd's knitting and tambour embroidery [11]. The use of hook needles, the precursors of modern crochet hooks, can also be dated to this period [11].

Today, crochet is an extremely versatile technique for creating arbitrary, complex 3D textile structures, as for example the work on crocheting hyperbolic geometries or Lorenz attractors illustrates [7,8,25]. The technique's flexibility is shown by the possibility to build a new stitch at any point of the already created fabric by pulling a new loop through an arbitrary stitch and through the LL. However, in most cases a new stitch is formed at the stitch next to the last working stitch. A working stitch is a stitch of a previous row (or round) in which the crochet hook is inserted to form a new stitch.

In the following, the crochet technique for stitch formation is described in more detail in section 2.1.1, while section 2.1.2 addresses the crocheting of fabrics. In addition, the applications of crocheted textiles are considered in section 2.1.3 and an overview of the scientific research relating to the technology is given in section 2.1.4.

2.1.1 Technique and stitch formation

This work is focused on crocheting in rows based on a chain line to produce planar fabrics. Circular crocheting with crocheting in rounds after starting from a chain circle or magic circle are alternative techniques, which can create flat surfaces or 3D shapes [17]. The latter is based on seamless tubes and has similarities to circular knitting. Thus, in accordance with the machine implementation of knitting, automated crochet is also to be distinguished between flat and circular. Circular crochet requires a machine different to the one developed in this work.

The common starting techniques of crocheted textiles performed with a conventional crochet hook are illustrated in Figure 1. Crocheting in rows of planar fabrics is started based on the chain line as shown in a) and requires the turning of the fabric with a change of crochet direction after each row. Regarding circular crocheting, which is done in spirals without turns or changes in the crochet direction, the chain circle is depicted in Figure 1 b) while the magic ring is shown in c) [17].

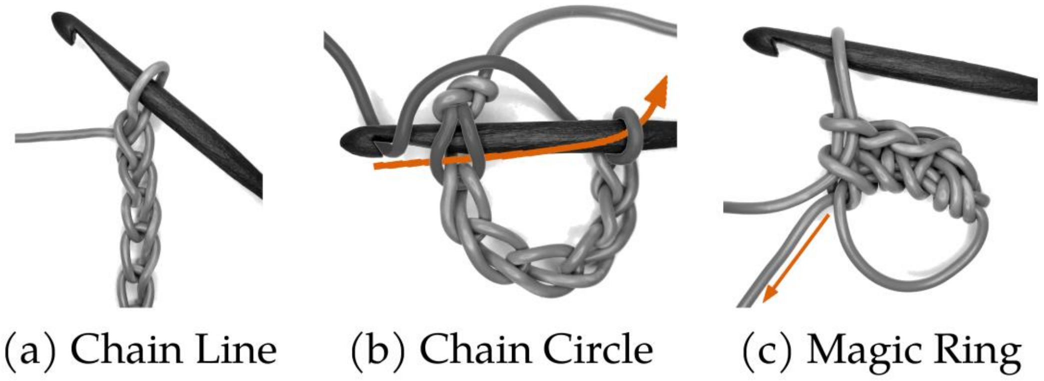

Figure 1. The three techniques of starting are crocheted textile. Reproduced from reference 17 with kind permission by the authors.

Furthermore, the work primarily considers CHs, SLs, SCs and HDCs, which are the most common crochet stitches [17]. The formation of these stitches is currently implemented in the developed CroMat crochet machine. Designations, symbols and descriptions of stitches and crochet in general are based on the crochet industry standards published by the Craft Yarn Council (CYC) [26].

The construction of any crocheted textile is based on the combination of a few simple operations and principles. A new stitch is basically formed by drawing a new loop through the LL. Thereby, the latter becomes part of the fabric while the newly drawn loop becomes the LL, which is held by the crochet hook. In this process, the new loop can be drawn additionally through an old loop or stitch (or more generally through yarn segments already processed in the fabric). This is done by inserting the crochet hook into the old stitch and yarn over. The latter is the general operation for forming a new loop by wrapping a yarn segment between the fabric and yarn supply around the crochet hook. When inserting the crochet hook, the loop or loops held by the crochet hook slide on its shaft.

In addition to a yarn over while the crochet hook is inserted into a working stitch, a yarn over can also be done before the crochet hook is inserted into a working stitch, which results in placing another loop next to the LL on the crochet hook. Generally, a loop can be drawn through all loops wrapped around the crochet hook, or only through a few. When there is only one loop left on the crochet hook, it becomes the new LL and the stitch formation is completed. Different types of crochet stitches are built from these basic operations.

The simplest stitch formed in crocheting is the CH. There, a new loop is formed in the air, which is only drawn through the LL and not through a working stitch (note the German term "Luftmasche" which translates directly as "air stitch"). By definition, a CH is not a crochet stitch because vertical anchoring is not present due to the lack of drawing the loop through a working stitch. However, CHs are crucial for crocheted fabrics since they form the first row and are part of the transitions between subsequent rows. Additionally, CHs are used in openwork crochets where the stitches of the next row are not anchored in all the stitches of the previous row, meaning that at least some of the stitches of the next row are CHs [11]. CHs are used not only in crochet but also in other textile technologies, as for instance in decorative passementerie [11].

SLs, as the simplest true crochet stitches, are made by drawing the new loop through a working stitch before it is drawn through the LL. For this, the crochet hook is inserted into the working stitch and the new loop is grabbed by the needle via a yarn over in the inserted state. The process of creating a SL is depicted in Figure 2 a). Commonly no new stitches are built based on SLs, which are predominantly used for moving across the fabric without expanding it or for connecting two stitches [16].

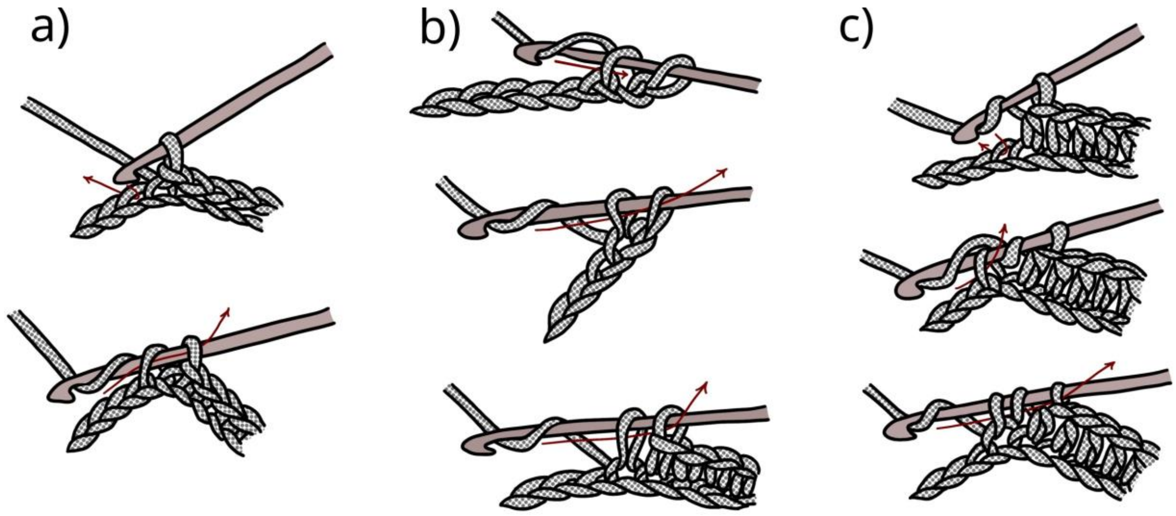

Figure 2. Principle of stitch formation with a given first row of chain stitches (CHs). **a)** Slip stitch (SL). **b)** Single crochet stitch (SC), where the third frame depicts the last step of the stitch formation at a different position. **c)** Half double crochet stitch (HDC). Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

Figure 2 b) shows the forming of a SC which requires an additional step. At first, just as in the case of SL, the crochet hook is inserted into the working stitch and a new loop is picked up by a yarn over. Then, in contrast to SL, the new loop is drawn only through the working stitch. Thus, the new loop and the LL are on the crochet hook and, as depicted in the second frame of Figure 2 b), a yarn over is performed again. This creates a new loop which is then drawn through the previously formed loop, which emerges from the working stitch, and through the LL. Note that the third frame of Figure 2 b) depicts the last step of SC formation at a position amidst the row.

By yarning over before inserting the crochet hook in a working stitch, an HDC can be distinguished from a SC. This additional yarn over is shown in the first frame of Figure 2 c) and renders HDC more complex. The following process is similar to SCs. As depicted in the second frame, a new loop is grabbed by the crochet hook and then pulled through the working stitch. Compared to a SC, three instead of two loops are on the crochet hook when the last yarn over is performed. Accordingly, this new loop is pulled through all three loops on the crochet hook in the last step for HDC (third frame).

The increasing complexity of the stitches by processing more loops for one stitch is illustrated by Figure 3. There it can be seen that for SC an additional loop is located halfway up the stitch compared to SL, and that for HDC there is a further loop.

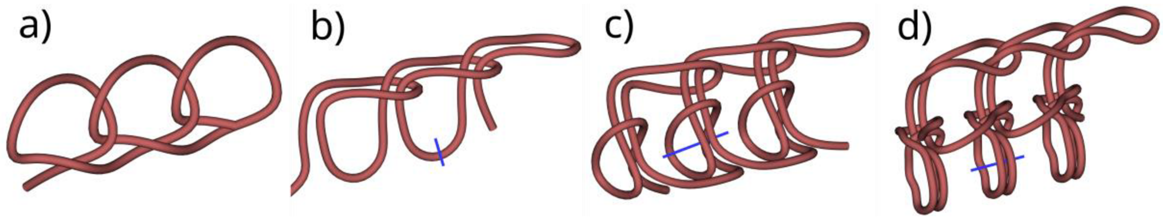

Figure 3. Structure of the basic crochet stitches. **a)** CH. **b)** SL. **c)** SC. **d)** HDC. To get a complete representation of one stitch, three stitches are modeled in a row. The blue lines indicate the region where the connection of the middle stitch with the previous row is in principle.

By adding more steps based on the described basic operations, more crochet stitch types can be created. For example, a double crochet can be created as the next more complex stitch by pulling the loop of the last HDC yarn over not through all three loops on the crochet hook, but only through the foremost one. Subsequently, a yarn over is performed again and the new loop becoming the LL is drawn through the two remaining loops on the crochet hook. Moreover, in treble crochet, the complexity is further increased by adding two loops by yarn overs on the crochet hook before inserting the crochet hook into the working stitch. With increasing complexity, the stitch height (*H*) also increases.

Furthermore, INC and DEC operations are common in crochet to shape the fabric by altering the number of stitches in a row (or round) [16]. These operations exist based on all stitch types. With INC, stitches are added in the current row by building multiple stitches based on the same working stitch of the previous row (hence pulling the loops of the new stitches through the same stitch). Theoretically, any number of stitches can be added this way.

For DEC, loops of one new stitch of the current row are drawn through several working stitches of the previous row – according to the quantity of stitches to be reduced. In this case, each time the crochet hook is inserted into a stitch of the previous row, the steps for forming the current stitch type are performed until the last yarn over in each case. Thus, several loops accumulate on the crochet hook, all of which have their origin in different stitches of the previous row. These stitches are joined by pulling the new loop of the last stitch's final yarn over through all loops on the crochet hook.

With regard to the specific insertion point of the crochet hook into a working stitch, several possibilities exist. Theoretically, the crochet hook can be inserted anywhere between two arbitrary yarn strands [16,17]. However, the most common insertion points are illustrated in Figure 4 [17]. In the following, only the variant shown in a) with an insertion point under both legs of the top loop is considered in this work. This typical variant is used in the stitch formation process of the developed crochet machine.

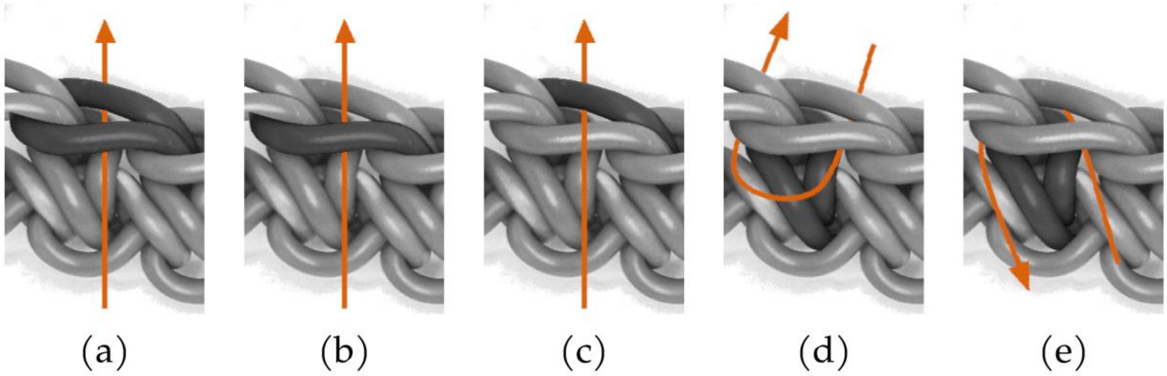

Figure 4. Overview of typical ways of inserting the crochet hook into the working stitch. **a)** Under the two legs of the top loop. **b)** Under the front leg of the top loop. **c)** Under the back leg of the top loop. **d)** From behind around the post. **e)** From the front around the post. Reproduced from reference 17 with kind permission from the authors.

2.1.2 Crocheting a fabric

To create a crocheted fabric, the stitches are formed sequentially so that only one stitch is open at a time. For the considered flat crocheting in rows, at the end of a row, a CH is formed as a turn if SLs or SCs are formed in the next row. If the next row consists of HDCs, two CHs are formed at the end of the row to correspond to the higher HDCs. Accordingly, for more complex and also taller stitch types, more CHs can be created within a turn. In accordance with the name, the fabric under construction is rotated during such a turn, so that the stitches are formed from the other side in the new row.

Figure 5 illustrates the creation of an exemplary crocheted fabric. Here, besides photos and topology-based models (cf. section 4.1), the representation is also provided by crochet chart symbols corresponding to the crochet standard published by the CYC [27]. Stitches and other crochet operations are represented by such symbols. From the visual representation of a pattern, the algorithm for crocheting the fabric emerges implicitly. Additionally, crochet patterns and the corresponding algorithms can be described by text-based instructions, using, among others, the abbreviations for the stitches already introduced here [28].

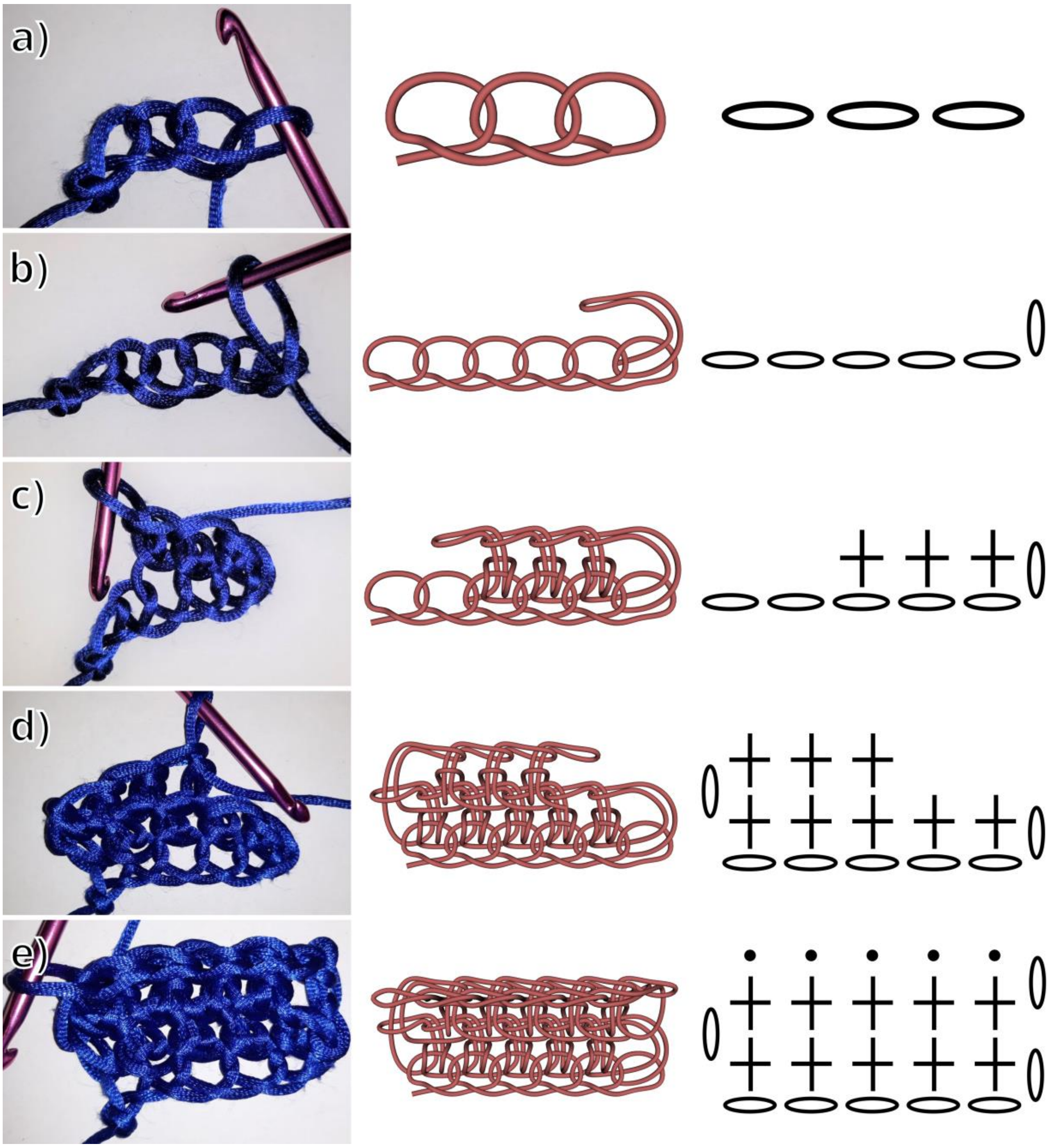

Figure 5. Illustration of the creation process of an exemplary crocheted fabric consisting of five stitches per row with CHs in the first row, SCs in second and third as well as SLs in the last row. Photos are displayed in the first column of the figure, corresponding topology-based computer models in the second column and symbols according to Craft Yarn Council (CYC) in the third one. **a)** Three CHs of the first row. **b)** Complete first row with five CHs and a turn to the second row. **c)** Additional three SCs in left direction in the second row. **d)** Another three SCs, heading to the right in the third row. **e)** Whole fabric with final SL row.

Referring to the visualized crochet process in Figure 5, the photo of a) shows a slip knot, which is necessary for the first CH. The LL of the first turn is depicted in Figure 5 b) at the right end of the first CH row. Note that the LL of the turn becomes a CH when the first stitch (a SC) of the second row is created, and that in the next row a stitch is anchored in the CH of this turn. As shown in Figure 5 c), the three SCs of the second row are oriented to the left. According to the change of direction as the fabric is turned after each row, the SCs of the third row point to the right and are visible from the other side (cf. d)). Figure 5 e) displays the SLs of the last row which are rotated by about 90° and are placed on the SCs of the third row. To finish the crocheting of the simple fabric with another knot, the free end of the yarn needs to be pulled through the loop of the last SL. In this way, a complete fabric can be created without the need for a separate method for creating a seam [29].

Crochet can also be used for joining. This is done by drawing the loops of the connecting stitches not only through the working stitch of one textile, but at the same time through another working stitch of a second fabric [10]. This is used, for example, to make fabrics from the popular granny squares.

The structures of fabrics consisting of SCs or HDCs are illustrated by microscopic images of exemplary fabrics and an alternative modeling approach (cf. section 4.3) in Figure 6. Point 1 indicates the connection of a stitch to a previous stitch of the same row. Besides, this upper connection to the previous stitch, SCs have an additional connection at the bottom as marked with 2. HDCs have this connection at the middle around point 4. The connections to the row beneath, as the second anchoring point of a stitch, are indicated by 3 for both stitch types.

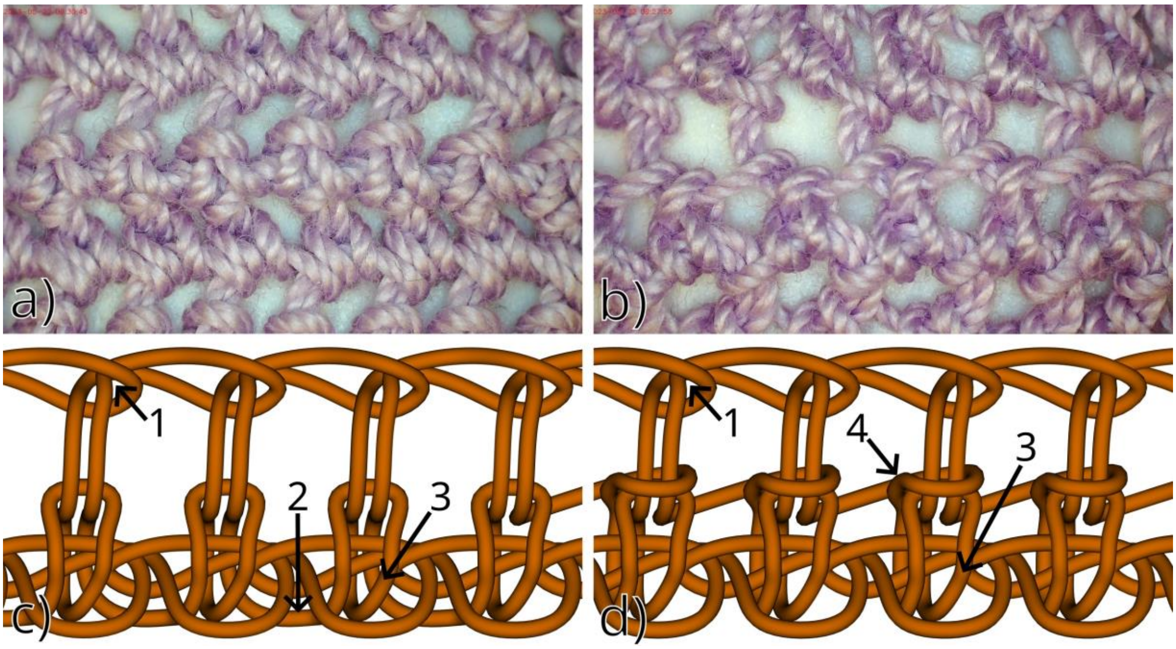

Figure 6. Structure of SCs and HDCs. **a)** Reflected light microscopic image of a fabric consisting of SCs. **b)** Image of HDCs combined to a fabric. **c)** Topology-based model of a SC row facing in right direction and built on a slightly different modeled CH row. **d)** Model of HDCs. Important points are indicated by numbers. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

As with knitted textiles, crocheted textiles are described by courses and wales. In machine knitting a course, which can be formed in one knitting cycle, denotes a horizontal row of stitches formed on adjacent needles [30]. A wale is generally characterized by interconnected stitches formed by one needle in succession and building a column [30]. As can be seen from the marked wales in Figure 7, the crocheted stitches of a wale are slightly offset with each course. In the following, the terms course and wale are used for describing the fabrics instead of row and column. Further information on the general structure and manual production of crocheted textiles can be obtained from reference 17.

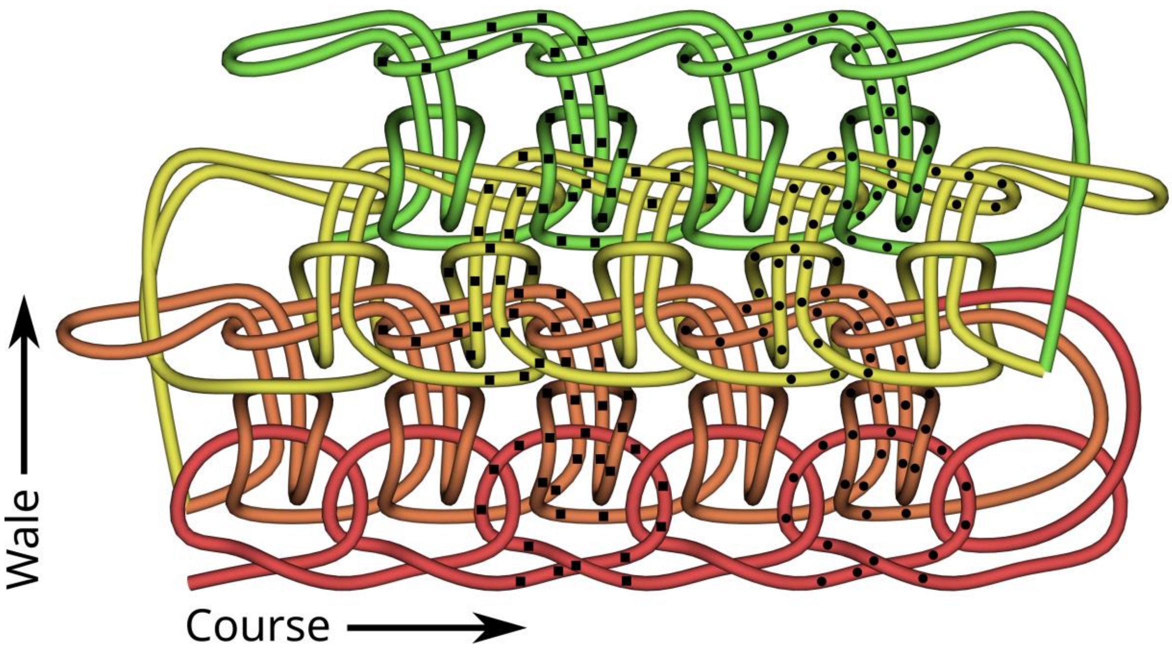

Figure 7. Illustration of course and wale in a crocheted fabric consisting of CHs and SCs. Various courses running in horizontal direction are distinguished by different colors, while two of the wales are marked additionally.

2.1.3 Applications of crochet

So far, there are no established technical applications of crocheted textiles [A2]. The scientific approaches existing in this context will be considered in the next section (2.1.4). In general, crocheted fabrics are used as clothing, home textiles and plush toys (amigurumi) [A1,20]. For example, some types of kippot (Jewish headdresses) are traditionally crocheted. Commercial crochet products are sold at similarly low prices to machine-knitted products [31]. Due to the lack of automation in crochet, these products have to be produced by hand under poor working conditions [14,15]. Furthermore, crochet's popularity is increasing as a hobby with non-commercial use [32]. However, through platforms such as Etsy, some home crocheted products are also offered for sale.

To crochet, especially in a community, is known as similar crafts for increasing the wellbeing [32-34]. Crochet can be linked to charity, such as donating crocheted chemo caps to patients [35] or crocheted items to soldiers [36]. Also, the Crochet Coral Reef Project, in which coral reefs are crocheted to draw awareness to environmental degradation [37,38], and the yarn bombing movement, where public space is decorated by knitted and crocheted textiles [32,39,40], show that crochet can be applied in the context of activism.

2.1.4 Research overview on crochet

To obtain an overview of the scientific publications on crochet, the Web of Science Core Collections is considered. In this, 2103 scientific publications were found in December 2022 by searching for the keyword "crochet". As can be derived by the bar chart of the research areas in Figure 8, many of these publications do obviously not relate to the textile technology of crocheting. For example, one of these papers deals with magnetic crochet, which is a geomagnetic disturbance related to solar flares [41].

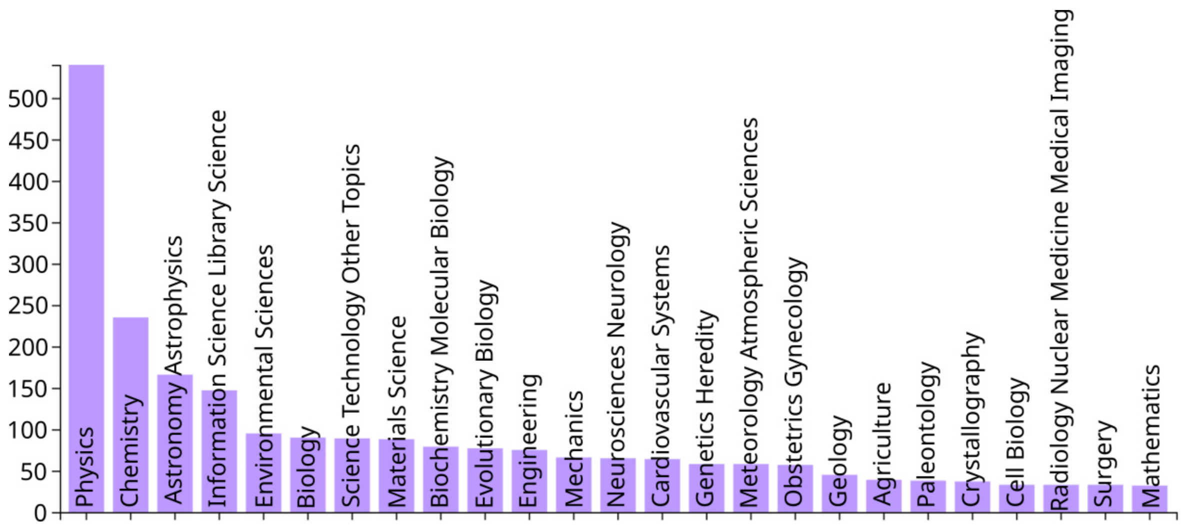

Figure 8. Counted publications per research area, which were found by searching for "crochet" in the Web of Science (December 2022). The labeling of the bar chart created by the Web of Science [42] has been slightly modified to improve readability.

Through filtering by the keyword "textile", the results were reduced to 55 publications. The corresponding research areas are given in Figure 9. Slightly less than half of these (24 publications) deal with special warp knitting machines, which are called crochet machines (in German "Häkelgalonmaschine"), or textiles created by these [43-66]. These machines (cf. section 2.2.3) are unable to produce crocheted fabrics and are thus not true crochet machines [6,17]. Others, also called crochet machines, can only produce CHs [6], which by definition are not crocheted textiles [12].

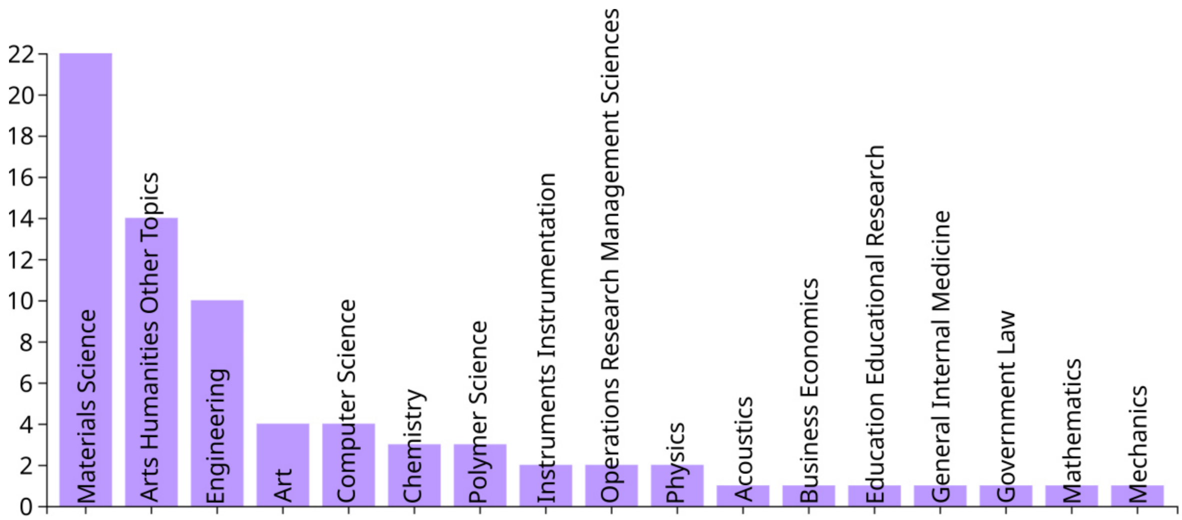

Figure 9. Counted publications per research area, which were additionally filtered by "textile". The labeling of the bar chart created by the Web of Science in December 2022 has been slightly modified to improve readability [67].

A large proportion of the other publications listed in the Web of Science Core Collection (filtered by "textile") deal with sociological, cultural or artistic aspects of crochet [68-80]. There are also publications that deal with crochet in a historical context [11,81,82]. The remaining publications relevant to this work can be categorized as technical applications of crochet.

One of these technical applications is to use a crocheted textile as a strain sensor. Hence, a manually crocheted chain of stainless steel yarn can be used as an integral component of a strain sensor for smart textiles [83]. Likewise, Zhang et al. [84] have constructed a textile strain sensor from a manually crocheted row of CH stitches. However, such chains, even if manually crocheted, are not crocheted textiles according to the definition by Irene Emery [12].

A textile sensor constructed from a truly crocheted textile was presented by Bobin et al. [21]. In this regard a crocheted fabric was used for its elasticity with dielectric and conductive threads to sense the elbow joint flexion based on a neural network. Such a promising crochet sensor would benefit from automated production.

In the context of another technical application, Shi et al. [23] have found that crocheted textiles have good sound absorption properties. However, practical application is hindered by the time-consuming and manual production of crocheted textiles. A further promising application of crochet is to mimic the human skin by a crocheted scaffold with similar physical properties and strain-stiffening behavior for tissue engineering [22]. The crocheted textile was combined with electrospun nanofiber mats commonly used for tissue engineering to form a sandwich. The cells grew well on it and the scaffold was considered highly desirable for tissue engineering applications.

Moreover, crochet swatches with conductive threads coated by thermochromic paint were developed as dynamic displays and were investigated in terms of design and fashion applications [85]. The crocheted textiles can only be considered as examples and are not necessary for developing such a display. In another application, where the textile does not necessarily have to be a crocheted one, a black crocheted fabric is used as a light absorber to evaporate contaminated water and condensate clean water as a simple method for areas with water scarcity [86].

This insight into the publications listed in the Web of Science shows that the production, properties and applications of crocheted textiles have been scarcely researched to date. This becomes particularly clear in comparison to the scientific literature on knits. Knitted textiles are related to crocheted ones and have been made with the use of machinery since 1589 [11,87]. The Web of Science Core Collection returned 12254 results when searching for the keyword "knit" and 5761 when additionally filtering for "textile" in December 2022. These are 100 times more publications than on crocheted textiles. As reasons for this discrepancy, the younger technology of crochet and the lack of automation of it can be assumed. Most knowledge about crocheted textiles is spread through blog posts on the Internet nowadays [17].

Further research

Beyond the Web of Science, there are other noteworthy publications on crocheted textiles. For instance, in one of the few studies to address the mechanical properties of crocheted textiles, the curling behavior of these was investigated in 1994 [88]. Artificial extensor hoods for anatomically correct testbed hands were identified as promising applications of crocheted textiles [89,90]. In this robotic context, the crocheted structure has shown better mechanical properties compared to plain yarn and is suitable to mimic the complex tendons and ligaments of the human hand. There are also publications in a mathematical context, where crocheted textiles are used to form complex shapes such as hyperbolic planes [7-9,25]. For example, it has been mathematically proven that any topological surface up to homeomorphism can be crocheted [10].

Furthermore, research has been carried out regarding digital representations and computing of crochet structures, which are conventionally described by text-based crochet instructions or symbolical crochet charts. A sophisticated approach was proposed by Seitz et al. [16,17] with a domain specific language based on a graph structure. For designing and visualizing 2D as well as 3D crochet patterns, conventional crochet symbols are used that can be set by a user according to the sequence and process of manual crocheting. The options at each step in the fabric creation process are constrained by the developed editor taking into account various crochet methods, to ensure the validity of the designed crochet structures. From the digital representation text-based instruction for manual crocheting can be generated automatically.

Nakjan et al. [20] presented a tool based on mapping 2D sketches to 3D primitives for designing crocheted dolls (amigurumi), which are produced via circular crocheting starting from a magic ring. The dolls are modeled with the 3D primitives and a pattern as well as instructions for crocheting are computed accordingly. Also intended for amigurumi design, Edelstein et al. [91] have developed an approach for the automatic generation of crochet patterns and instructions for manual production based on closed triangle meshes as 3D input models. From a starting point, set by the user, and a given stitch size, a crochet graph representation based on SC, IND, and DEC is generated while considering the interconnectivity of the stitches as well as the crochetability. Components of the amigurumi that are to be produced separately can also be joined into a coherent object by crochet [91].

Another approach for designing 3D circular crocheted objects was introduced by Çapunaman et al. [92]. Based on a developed computational framework, 3D objects designed by computer-aided design (CAD) tools are decomposed into stitches along a single continuous spiral yarn path. The process is based on a non-uniform rational basis spline (NURBS) UV division. For shaping this stitch path according to the input object, INC and DEC are used. The algorithm is calibrated according to the influence of the crocheter's individual style on the object to be crocheted by means of evaluated crochet swatches, from which the influencing parameters of the yarn and the crochet hook can be derived in addition to the stitch size. Instructions for manual production are generated from the calculated crochet pattern.

In a subsequent paper, the framework was extended to allow the design of complex branching geometries with the creation of corresponding crochet patterns [24]. An algorithm was developed to connect the points of a point cloud with lines and to generate branching geometries. The lines were used to create connected tubular surfaces, which are then divided into branches to automatically generate crochet patterns and instructions for the manual production of these.

Moreover, Guo et al. [19] also computed crochet patterns according to input 3D objects (as manifold 3D triangle meshes). A stitch mesh data structure and corresponding pipeline from previous related work regarding knitted textiles [93,94] is used to tile the surface with crochet stitch-faces according to the rules of crocheting. These faces are mapped to information about topology for visualizing the represented 3D shapes with computer models and to information regarding manual crocheting to generate the instructions.

Zaharieva-Stoyanova and Bozov [95] have developed unified graphic primitives for digital representation of crochet using an XML-based language. This approach is based on preliminary work on a portable knitting format [96] and is intended to allow multiple crochet patterns to be represented in a format that is interchangeable between different software tools. Another paper deals with crochet software and clustering of stitches that are often used repetitively [97]. In addition, there are numerous software tools for designing manually crocheted textiles [17].

2.2 Knitting machines

Given the similarity of crochet to knitting, this section covers the established machines for the automated production of knitted textiles. The foundation of modern knitting machines lies in the development of the stocking hand frame by Reverend William Lee of Calverton in Nottinghamshire in 1589 [98]. In this muscle-powered machine, a thread is laid over a series of bearded needles and formed by sinkers on each needle into loops, which are then drawn through the old loops on the needles by moving the sinkers and pressing the beards [98,99].

According to German classification, the stocking hand frame is a *Einfaden-Kurlier-Flachwirkmaschine* [99]. This is because *Wirkerei* (in English: warp knitting) is characterized by needles moving together and loop formation by sinkers or yarn guides [30]. In contrast, with *Stricken* (in English: weft knitting), the loops are formed by drawing of the needles moving in succession [30]. According to the slightly different classification in the English-speaking world, the stocking hand frame belongs rather to weft knitting. Weft knitting is defined by a loop formation in succession at each needle in the same knitting cycle with a weft yarn that then forms a horizontal course in the textile [100,101]. This applies to the stocking hand frame because the loops are sequentially formed from a weft yarn by the sinkers [102]. Warp knitting is characterized by simultaneous loop formation at each needle in a joint movable needle bar through overlaps by separate warp guides (and yarns) in the same knitting cycle [100,101,103]. The yarns thus form vertical paths in the textile. In the following, the English classification system is used.

The basic principle of the stocking hand frame is still used today in weft and warp knitting machines [98]. According to the long history of knitting machines, they are based on mechanically implemented movements [104]. This is characterized, for example, by the movement of needles via knitting cams (weft knitting) or the transmission of the movement of the needle and guide bars from the main cam-shaft by mechanical gears (warp knitting). Such mechanical movements as well as the mechanical control of these (e.g., with punched cards, or pattern wheels) are slow, maintenance-intensive, expensive to manufacture and difficult to adjust to new patterns [104]. Therefore, in modern machines electronic systems are increasingly used to control the machine with advantages in terms of speed, independence from a main drive and greater versatility through machine programming per software [104].

With most knitting machines, techniques are possible to influence the patterning and properties of a textile. For example, a non-knitted yarn, which usually remains relatively straight, can be incorporated in the fabric during the knitting process via laying-in or weft insertion [100]. Also, plating allows loops of two or more yarns to be formed simultaneously so that one yarn dominates the technical face of the fabric while the other dominates the technical back [100]. Furthermore, open-work structures can be created by not connecting all wales within the fabric by sinker loops or underlaps [100]. Contrary to this, in close structures all wales in a course are connected by loops. For the sake of completeness, plush and pile should be mentioned as further techniques to influence the knitted structure [100].

The basic types of knitting machines are presented below. Section 2.2.1 deals with the machinery used for weft knitting, while section 2.2.2 focuses on warp knitting machines. The crochet gallon machines are addressed separately in section 2.2.3.

2.2.1 Weft knitting

The straight bar frame (also called cotton machine) is the most similar machine to the stocking hand frame used in modern times [105]. Likewise, a yarn (course) is placed over a bearded needle bar and formed successively into loops via sinkers on each needle, so that these can be drawn through the old loops on the needles while pressing the beard (closing the needle hook) [106]. From a central rotary shaft, several needle bars on different knitting heads are moved by engineering cams to produce simultaneously identical textiles [105]. The machines are large and expensive but are recognized for their high productivity of high-quality garments [105]. Due to the single needle bar, only single-jersey fabrics with one type of weft knitted base structure can be produced [107].

In general, four types of weft knitted base structures are distinguished. Plain (in German called *rechts-links*) refers to the simplest and most economical weft knitted base structure that can be made with one needle bed and by drawing all loops in the same direction [107]. The knitting action for producing a plain fabric with latch needles is displayed in Figure 10. In contrast to plain, both face loops and reverse loops are visible on one side of a fabric with the rib structure (German term *rechts-rechts*), and therefore no curling occurs [107]. Two needle beds (double jersey) predominantly arranged in 90° angle opposite each other with a needle offset are required for the production. The interlock structure also requires two beds but with needles exactly facing each other [107]. Only face loops are seen on both sides of respective fabrics since loops of two yarn courses are confronting each other. In the purl structure (*links-links*), especially the reverse loops can be seen on both sides, although in the wales there are both face and reverse loops [107]. This requires special double-ended latch needles, which are moved back and forth between two needle beds positioned exactly opposite each other.

Alongside the basic weft knitting machine class of the straight bar frame, the class of circular knitting machines is also employed, with which all four weft knitted base structures can be produced in tubular fabrics by an appropriate machines. Predominately latch needles are arranged vertically in a rotating cylinder, while various cam systems and yarn feeders are fixed on the outside so that multiple stitches are formed on each needle during one revolution [107,108]. With circular machines, the highest productivity in weft knitting can be achieved [108]. Figure 10 shows the formation of single-jersey (one cylinder) plain fabric according to the principle of circular weft knitting.

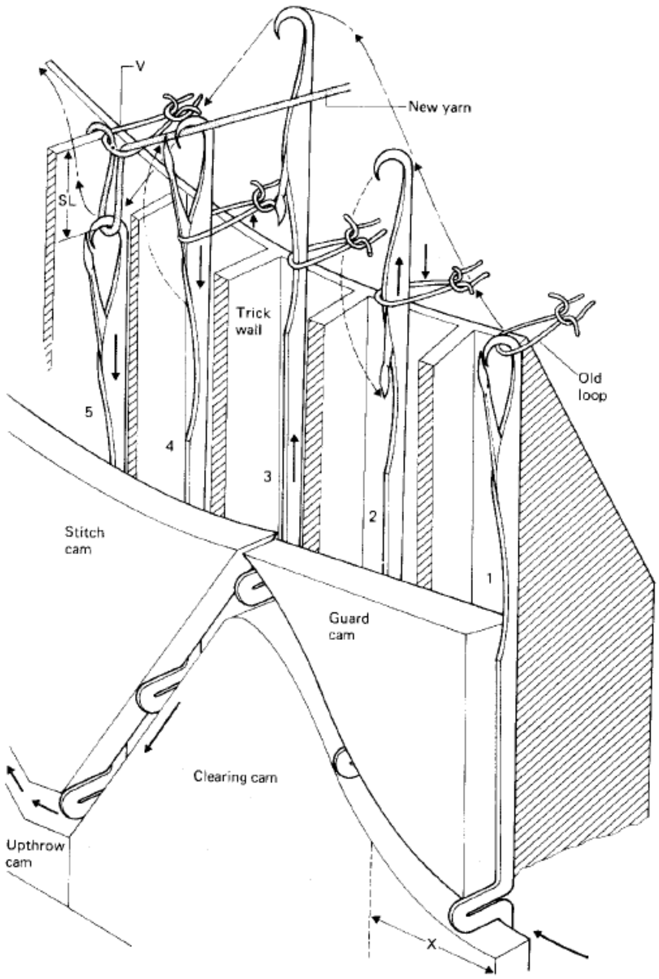

Figure 10. Knitting action of latch needles in a circular machine for the production of plain weft knitted fabric at one feeder. 1: Needle in rest position in a trick of the clockwise rotating cylinder. 2: Needle rises through contact of the butt with the clearing cam, old loop is hold in position by sinkers (not shown) and opens the latch. 3: Clearing position and beginning of yarn feeding. 4: New yarn is grabbed by the descending needle moved by the stitch cam while the old loop closes the latch. 5: The new loop is drawn through the old one which is knocked over. Length of the new loop is determined by the indicated distance, before the needle rises to the rest position. Reprinted from reference 30, Copyright (2001), with permission from Elsevier.

The third class of weft knitting machines are flat-bed machines with a bi-directional cam system (cf. Figure 11) that reciprocates across the width of the machine [105]. This cam movement over the stationary needles is the major difference to circular machines. Otherwise, the knitting action and loop formation is very similar. Flat-bed machines are slower but can produce the most diverse structures in weft knitting [108]. As with circular knitting machines, there are also different types of flat-bed machines for producing the four weft knitted base structures. There are machines for single jersey (plain) with one needle bed, purl with double-ended needles or rib with two needle beds arranged as an inverted V [105].

Especially the V-bed weft knitting machines can produce complex 3D fabrics and whole seamless garments without the necessity of subsequent cut and sew processes [101,108]. Several tubular forms can be produced simultaneously in different places on the machine by alternately knitting of needles in both beds [101]. Electronic needle selection expands the flexibility of pattern and structure options [100,101,109]. Also, by transferring loops between different needles including sideways racking of the beds, a variety of shapes can be fabricated [101,110]. The principle of a loop transfer from a needle of one bed to one of the other of a V-bed machine is depicted in Figure 11. It is to mention that special latch needles with a ledge for presenting the loop to be transferred and a spring clip for assisting the insertion of the tucking needle into the loop are required [111].

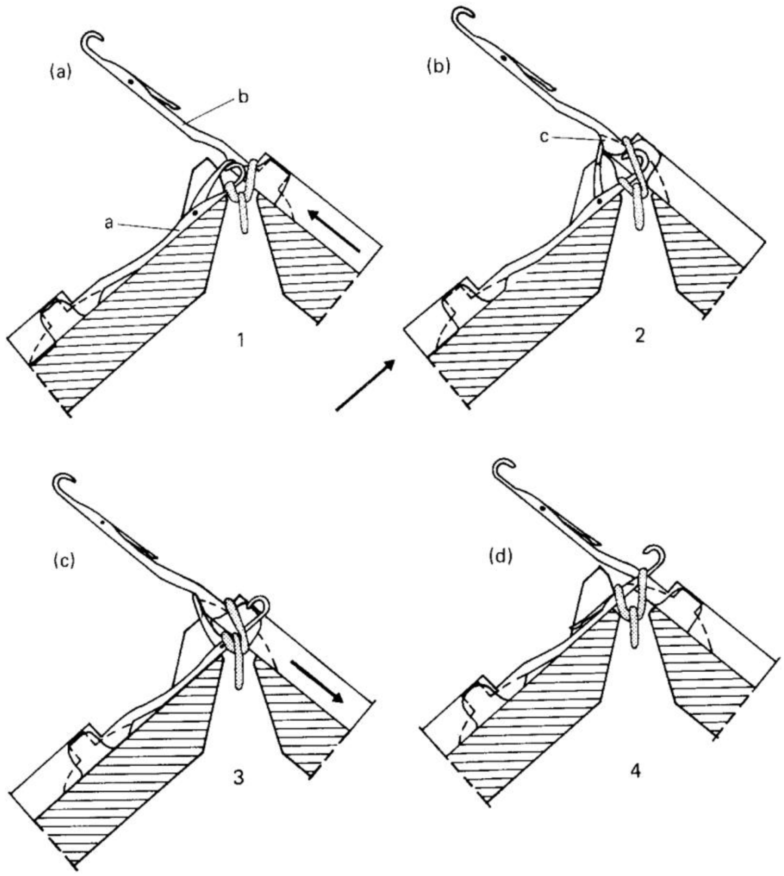

Figure 11. Loop transfer on a V-bed flat rib machine from needle *b* to needle *a*. **a)** Delivering needle *b* moves to transfer height while a slight needle bed rack is performed to place the needles closely together. **b)** With needle *b* at transfer height, needle *a* moves forward to slide its hook between the spring clip and the shaft of needle *b* and thus also into the loop, which is held in position by the ledge of *b*. In the process, the latch of *a* is opened by the stop latch *c* of needle *b*. **c)** Needle *a* is at transfer height and needle *b* retracts, causing the loop to be transferred to be placed appropriately in the hook of *a*. **d)** The loop is transferred, and needles *a* and *b* can subsequently enter their resting positions as well as the needle bed can be moved back again. Figure is taken from reference 111. Used with permission of Elsevier Science & Technology Journals, from Knitting Technology: a comprehensive handbook and practical guide, 3th ed. Woodhead Publishing Limited, 2001; permission conveyed through Copyright Clearance Center, Inc.

Loop transfer is also realizable with the straight bar frame and circular machines and is generally used in weft knitting to change the textile's width (increasing, decreasing) as well as for patterning [99,111]. To achieve patterning, incorporating different yarns into one textile is also possible. Furthermore, the structures created by weft knitting can be supplemented with tuck and float stitches. In contrast to the basic knitted loop stitch shown in Figure 10, a tuck stitch is produced in principle when a needle receives a new loop which is not drawn through the old loop but is tucked next to the still held old loop [112]. After optionally picking up more tucks, a new loop is pulled through the loops on the needle in a subsequent knitting cycle to complete the tuck stitch formation [112]. In a float stitch, no new yarn is picked up on a needle and accordingly it is not pulled through the held old loop [112].

Considering the manifold possibilities of modern V-bed machines, special machine-specific commercial CAD systems with a pixel-based programming interface became established. In the programs M1plus and KnitPaint of the market leaders Stoll and Shima Seiki, stitches and generally machine operations are represented by icons, which can be arranged graphically in a tabular form [101,113,114]. The columns of the table correspond spatially to the needles of the machine and the rows temporally to the operations performed successively with the needles. As further visualizations to facilitate the design process, a preview of the fabric and a technical view are provided [101,104,114]. KnitPaint offers also 3D simulation of the yarn and needles during the manufacturing process [114]. Debugging and automated error checking are also implemented [114]. The research pursues approaches of higher-level programming independent of the specific machine with an editing of 3D knit products instead of stitch level instructions [19,93,113,114].

2.2.2 Warp knitting

Warp knitted textiles were never made manually and are nowadays manufactured by tricot or raschel machines [98,115]. The two classes are relatively similar in stitch formation and differ in particular by the sinkers and the load on the needles. In the simple tricot machines, the needles are subjected to greater stress due to the textile being drawn off at an angle of about 90° [99,116]. The sinkers, which are connected in front and behind the needles, are responsible for holding-down, knocking-over as well as general support of the loop formation [116].

In comparison, the sinkers of raschel machines simply hold the loops in position while the needles move upwards [116]. These move away from the needles for the further stitch formation steps, as can be seen in Figure 12 where the knitting cycle of a raschel machine is displayed in principle. A knitting cycle corresponds to one revolution of the machine's main drive shaft. In Figure 12 it can also be seen that the textile is pulled off nearly parallel to the needles, which reduces the forces on the needles [99].

In the past, the warp machine classes could also be distinguished by the type of needles, as tricot machine tended to use bearded needles, while raschel tended to use latch needles [99,115]. Now, there is a trend towards compound needles for both machine types, which have a separately driven slider to open and close the needle hook [115,116]. These enable high speed due to avoiding problems of loop distortion and metal fatigue of bearded or latch needles [116].

As illustrated in Figure 12, warp knitting machines usually have at least two guide bars with correspondingly two yarn guides per needle, which may be moved individually [115]. The overlap usually goes over one needle but can also be laid over two, which, however, causes severe stress on needles and yarn due to the simultaneously knocking-over of the two yarn sharing needles [117,118]. Between two overlaps an underlap takes place, meaning that yarn segments are laid underneath the needles by the yarn guides [117]. This allows connecting the wales on different needles with each other and patterns can be created by the number of needles spanned by the underlaps, hence by the length of the guide bar swing

[115,117]. This swinging can be implemented, for example, by a mechanical tracing of a chain track with links of different heights assembled according to the desired pattern or by means of linear motors [115].

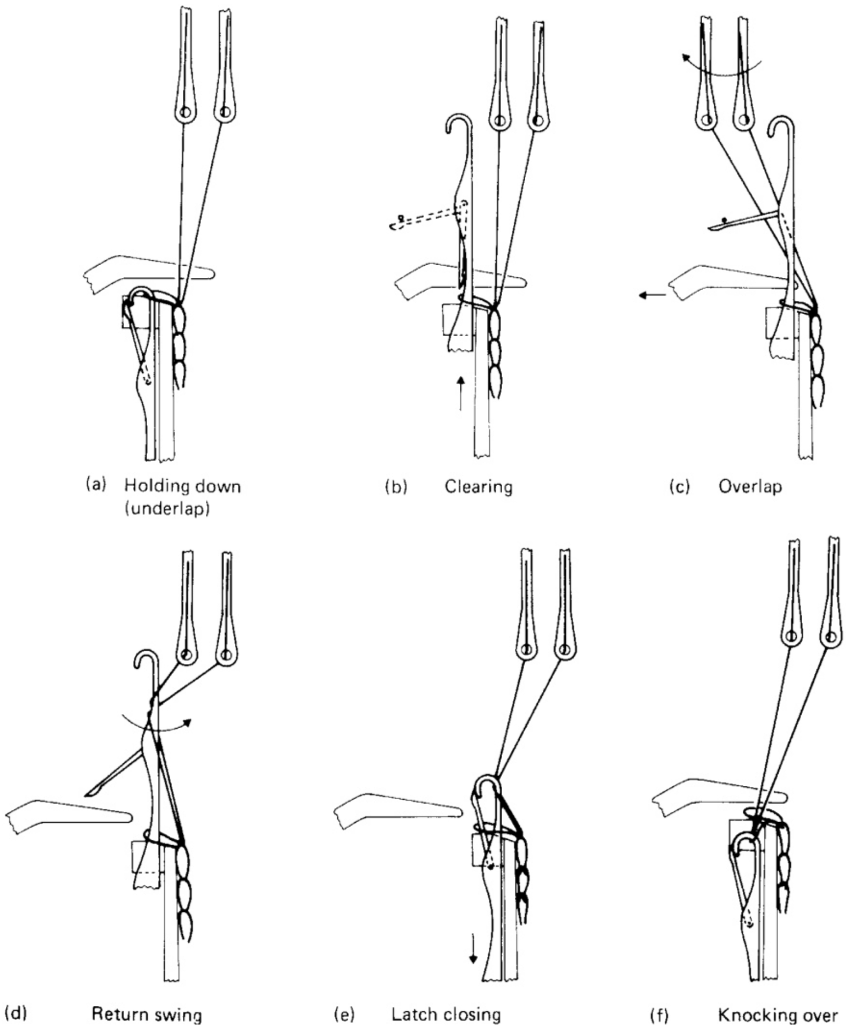

Figure 12. Principle of stitch formation on a raschel warp knitting machine with a single needle. The motion sequence occurs simultaneously on all needles of the machine. **a)** Underlap swing of the two guide bars is performed while the sinkers retain the loop positions at the trick plate. **b)** The needle bar rises for clearing the old loops and latches are kept open by latch wires. **c)** To enable the overlap swing of the yarn guides, the sinker bar is retracted. **d)** After the guide bar swing, yarns are wrapped around the needles by the return swing of the yarn guides. **e)** The latches are closed by the old loops due to the downward moving needles. **f)** The sinkers move forward while knocking-over is performed, afterwards the next cycle can start. Figure is taken without modification from reference 116. Used with permission of Elsevier Science & Technology Journals, from Knitting Technology: a comprehensive handbook and practical guide, 3th ed. Woodhead Publishing Limited, 2001; permission conveyed through Copyright Clearance Center, Inc.

Patterns can also be created by varying the direction of overlap and underlap. For an open lap, the underlap goes in the same direction as the previous overlap, and for a closed lap, it goes in the opposite direction [117]. If a needle always receives an overlap from the same yarn guide in successive courses, a pillar stitch is created. If, for example, the overlap between two wales alternates in each course, a tricot lap is generated or if the overlap direction is maintained in at least two successive courses, an atlas lap can be generated [115].

The Warp Knitting Editor 3D is an example of a common CAD tool for designing warp knitted structures based on the definition of specific lapping movements [119]. With a graphical user interface (GUI), a lapping diagram can be created according to the defined machine and yarns. Besides different output options, the developed structure is visualized by a generated topology-based 3D model of the fabric. This supports the design process and can be used as a basis for further simulations, such as FEM.

2.2.3 Crochet gallon machines

Contrary to their name, crochet gallon machines, sometimes just called crochet machines, do not produce crocheted fabrics, but warp knitted ones. These belong to the class of raschel machines and are characterized by closed lap pillar stitches produced by each needle and associated warp guide, horizontally connected with weft inlays [116]. Crochet gallon machines are equipped with a single horizontally arranged needle bar and, besides latch needles, often special carbine bearded needles are used which allow overlapping from one side only [99,116]. Another special feature is that no sinkers are used, but the fabric is retained between the knock-over verge and a hold back bar [116]. This arrangement can be seen in Figure 13 a), while the basic knitting cycle with weft inlay is depicted in Figure 13 b).

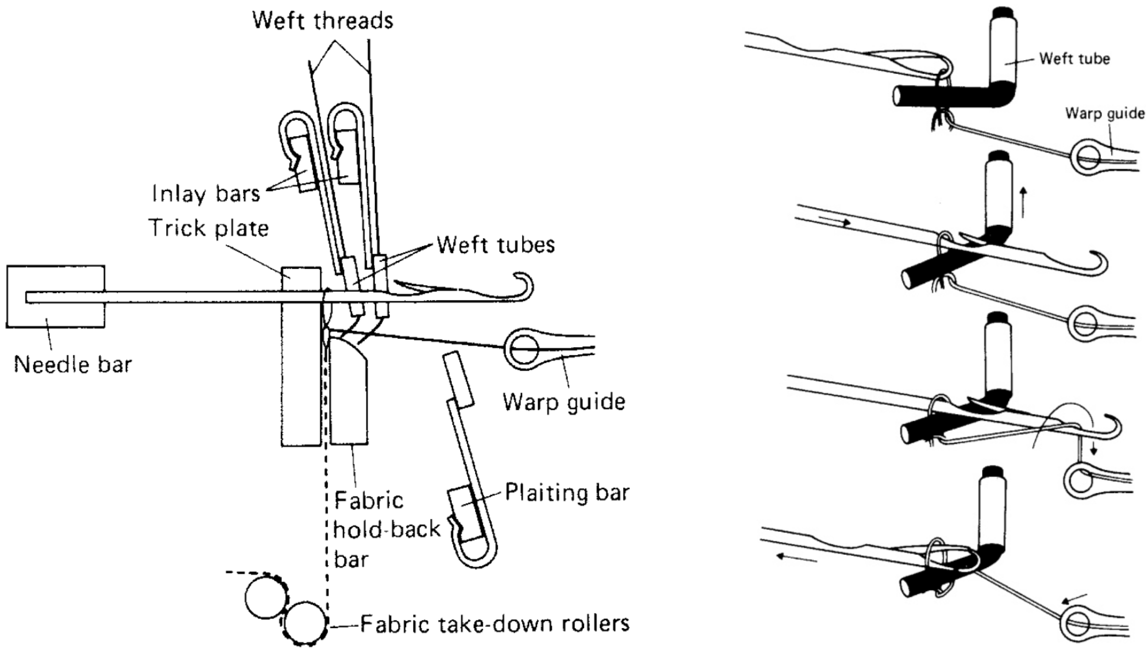

Figure 13. Left side: Basic machine elements of a crochet gallon machine. **Right side:** Principle of building a pillar stitch with weft inlay. From top to bottom, the weft yarn is laid in front of the fabric as a first step. By moving the needle forward above the weft yarn, the old loop is cleared. In this position a new loop is wrapped around the needle by the overlapping warp guide. In the last step, the needle retracts to knock-over the old loop, while an underlap is performed causing the warp guide to resume the initial position. Both sides are taken without modification from reference 116 and are used with permission of Elsevier Science & Technology Journals, from Knitting Technology: a comprehensive handbook and practical guide, 3th ed. Woodhead Publishing Limited, 2001; permission conveyed through Copyright Clearance Center, Inc.

Generally, crochet galloon machines have the advantages of simple construction with short setup time and the ability to easily process a wide variety of materials. Often these machines are used to produce narrow bands, fancy open-work structures or passementerie [99,116].

Crochet galloon machines cannot produce crocheted textiles, because for the formation of a stitch, loops are not drawn both through an old stitch in the row below and through the previously formed stitch in the same row. Vertical connection is given as usual in knitting, whereas horizontally the stitches are not connected by interlooping but only by weft inlay. No loop is drawn through an old loop of the same course. Thus, the definition of crocheted textiles by Irene Emery [12] is not fulfilled. Also, crochet galloon machines process many yarns into stitches at the same time, whereas crochet takes only one yarn at a time.

A similarity to structures common in crochet is the pillar stitch formed by the crochet galloon machine, which corresponds to crocheted CHs. But these also do not meet the definition of crochet stitches and are used only for the formation of the first row and for transitions. The modeled structure of pillar stitches with a weft inlay is shown in Figure 14. By comparing this with the model of a crocheted textile from Figures 5 or 6 (section 2.1.2), the structural differences between the two types of fabrics become evident.

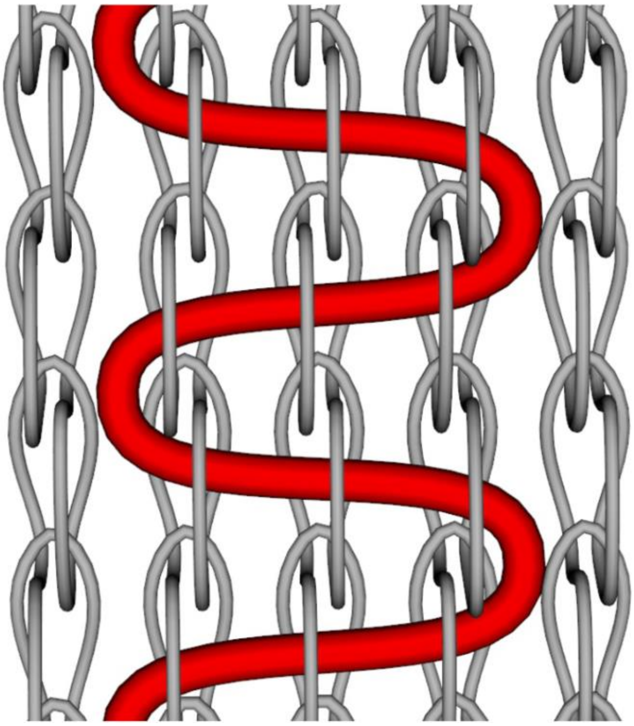

Figure 14. Model of a fabric consisting of pillar stitches with a laid-in yarn. Figure taken without modification from reference 120. Copyright © 2020, from Warp Knitted Fabrics Construction by Yordan Kyosev. Reproduced by permission of Taylor and Francis Group, LLC, a division of Informa plc.

2.3 Existing crochet machine approaches

This section presents the few previous approaches for automating crochet technology. The development of the CroMat crochet machine built on the approach from section 2.3.1, while the other presented approaches do not constitute a basis for the CroMat development. In section 2.3.2 a mechatronic prototype for the automation of the circular crochet is shown. Section 2.3.3 presents another approach developed simultaneously with the CroMat, based on a robotic arm. Finally, section 2.3.4 addresses further publications dealing with (partial) automation of crochet.

2.3.1 First approach to automate crochet

As a relevant preliminary work and the first approach to automate the crochet process, this section deals with "the largest crochet machine in the world", as it is called in an article published in Melliand International in 2019 [6]. This article presents an initial prototype developed by the working group *Textile Technologies* at Hochschule Bielefeld – University of Applied Sciences and Arts (HSBI), based on the German patent (DE 10 2016 015 204 A1 2018.06.21) from 2018 [18].

The humorously named approach depicted in Figure 15 implemented already some concepts that were improved with the CroMat crochet machine developed in the present work. However, this first crochet machine approach is only capable of producing SLs and has major problems regarding the repeatability of stitch formation.

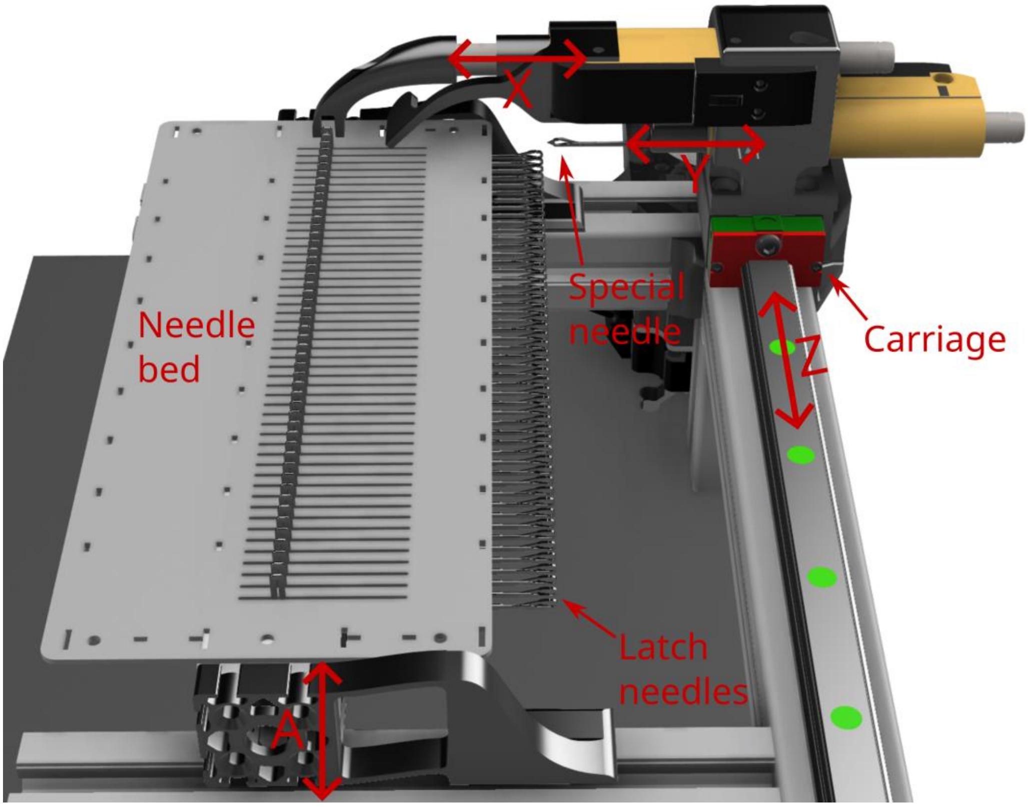

Figure 15. Computer-aided design (CAD) model of the main components and axes of the initial prototype of a crochet machine according to the approach described as "the largest crochet machine in the world". The model was created by the authors of reference 6.

The design of the initial prototype is based on single jersey flat-bed knitting machines but has an additional latch needle opposite the latch needle bed [6]. As can be seen from Figure 15, this special latch needle can be moved along axis Z on a sliding carriage parallel to the needle bed and along Y orthogonal to it via a linear motor. The special needle holds the respective LL at any time, hence fulfilling the function of the crochet hook. The latch needles of the bed can be moved along the X-axis via a linear motor. This allows a stitch suspended on the latch needle to be cast off, as it is usual with knitting machines. According to the A-axis, the height of the entire needle bed can be adjusted (motor and mechanism are not shown). Changing the height is necessary so that the special needle can be inserted into a stitch of the textile suspended on the needles of the needle bed.

The process of building the SLs with the initial prototype can ideally be comprehended with the associated YouTube video [121]. As a first step, the special needle is placed in front of an old stitch on the next needle of the needle bed, which is raised to allow for suitable insertion. The insertion along the Y-axis as a second step is favored by the tapered point at the front of the special latch needle. Nevertheless, this is frequently erroneous and the yarn or an adjacent stitch is penetrated. During insertion, the LL, previously held by the special needle, slips onto the shaft of the special needle. In the third step, the old stitch, in which the special needle is still inserted, is cast off from the latch needle of the needle bed by moving the respective latch needle forward and backward via the linear motor of X. After casting off, the needle bed is lowered to insert the yarn fed by the yarn guide (not shown in Figure 15) into the latch needle of the needle bed. During the fourth and final step, the yarn is also grabbed by the special needle (yarn over) and pulled by it through the old stitch in which it was inserted and through the loop on the shaft of the special needle (former LL). Thus, a new stitch has been formed and a new LL lies in the hook of the special needle.

The described stitch formation process of the initial prototype corresponds to the sequence of manually building SLs described in section 2.1.1. For this, the latch needles of the needle bed are used to hold the last formed stitches at each needle position, so that in a subsequent step a loop can be drawn through it with the special needle to form a new stitch. The suspension of the SLs on the latch needles of the bed is depicted in Figure 16. There it is also shown that initially a single jersey weft knitted fabric, which cannot be produced with the machine, needs to be suspended on the needles of the needle bed before SLs are built upon it. It is to mention that due to the lack of reproducibility of the stitch formation, the presented fabrics were made with machine elements moved by hand.

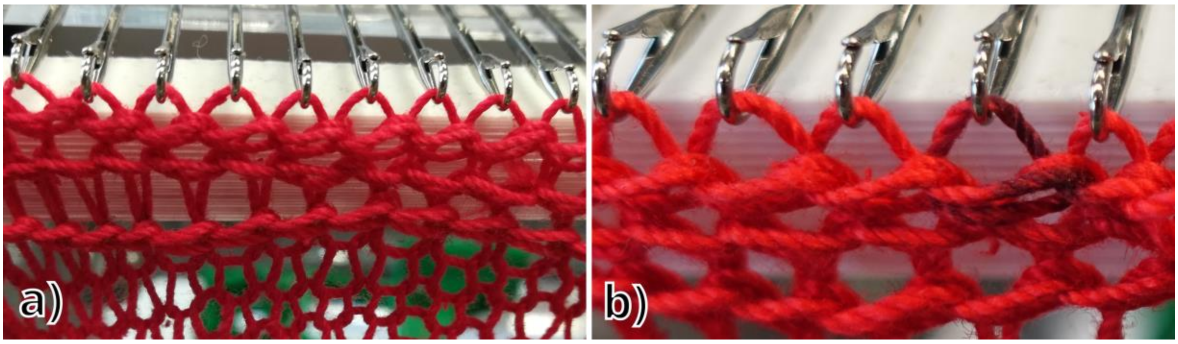

Figure 16. SLs produced according to the initial crochet machine prototype and suspended on latch needles. **a)** Photograph of the fabric with visible loops of the foundation weft knitted fabric. **b)** Close-up of the SLs suspended on the needles.

According to the suspension of SLs in the machine, stitch formation differs from manual crocheting. Because the single yarn segment of the stitch is held by the needle, which in manual crocheting actually constitutes the lower part of the stitch, the SL is built upside down. Thus, the new loop is drawn through the free space under this single yarn segment, instead of through the free space under the two yarn segments forming the loop of the stitch. These different locations of needle insertion and the correspondingly different interlooping to the courses above and below is visualized in Figure 17.

The conventional point of crochet hook insertion, where the new loop is to be drawn through the old stitch, in manually crocheting is marked by the blue circle in Figure 17 a). Regarding the first crochet machine approach, the special needle is inserted at the blue marking in Figure 17 b). Accordingly, the connection to the course beneath is developed at a different point of the stitches, as indicated by the green dashes. In general, there are various ways to insert the crochet hook in manual crocheting (cf. Figure 4 in section 2.1.1), which is why there are no incorrect locations. However, the usual location shown in Figure 17 a) is considered in this work for automation with the CroMat.

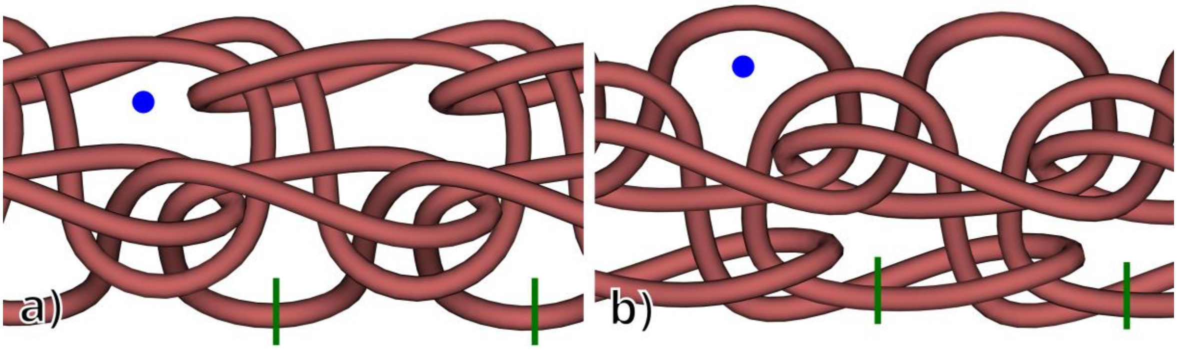

Figure 17. Models of SL courses with positions of needle insertion marked by blue circles and regions of interlooping with the courses below by green dashes. **a)** Typical case of manual crocheting. **b)** Case of the initial crochet machine prototype with upside down formed stitches.

Despite the differences from manual crocheting, the process meets Irene Emery's [12] definition of the formation of crocheted stitches. According to the capabilities of the prototype, rectangular fabrics consisting of SLs can be constructed. An example of such a fabric is shown in Figure 18. As can be seen there by the difference between a) and b), the crochet has two clearly distinguishable sides. In contrast to manual crocheting, the fabric is not turned after each course in the machine, which is why yarn is always drawn through from one side. This is analogous to plain fabrics produced by single jersey weft knitting machines, which also have a technical front and back [107].

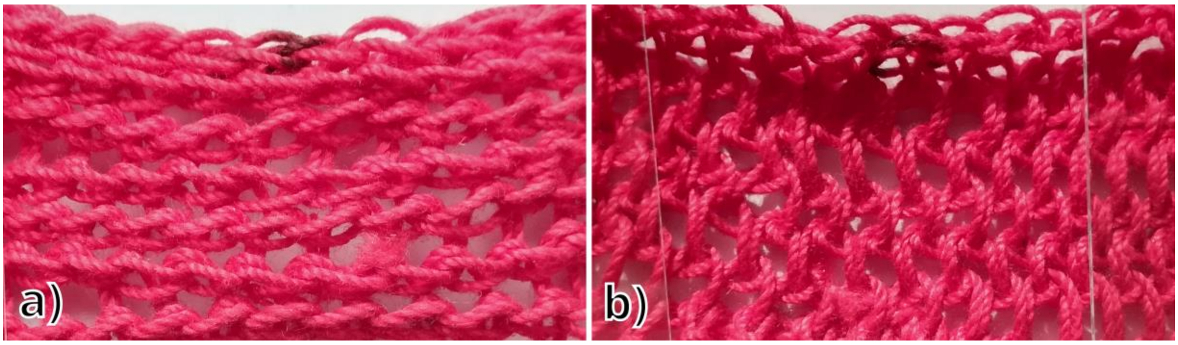

Figure 18. Photographs of fabrics consisting of SLs crocheted using the initial crochet machine prototype with manually moved machine elements. **a)** Technical face of the fabric. **b)** Technical back.

2.3.2 Circular crochet machine approach

After the patent application of the CroMat crochet machine on the 5th of April 2022, the Master Thesis of Gabriella Perry [15] was published by the Harvard University Graduate School of Design, in May 2022. Her work deals with the development of a circular crochet machine. Additionally, a corresponding paper was published in mid-2023 [14].

2.3 Existing crochet machine approaches

The circular crochet machine prototype, which is called Croche-Matic and shown in Figure 19, was designed to automatically crochet a magic ring with twelve stitches in one revolution consisting of CHs, SCs as well as INC and DEC stitches [14,15]. A magic ring is a common crochet technique where initially a ring of yarn is formed on which then stitches, like SCs, are built (cf. Figure 1 in section 2.1.1). Building on these stitches of the first revolution, further stitches can be formed in a spiral. The diameter can be changed via INC and DEC to adjust the shape of the cylindrical crochet object. This technique can be used, for example, to make amigurumi stuffed animals, which is the intended application of the Croche-Matic.

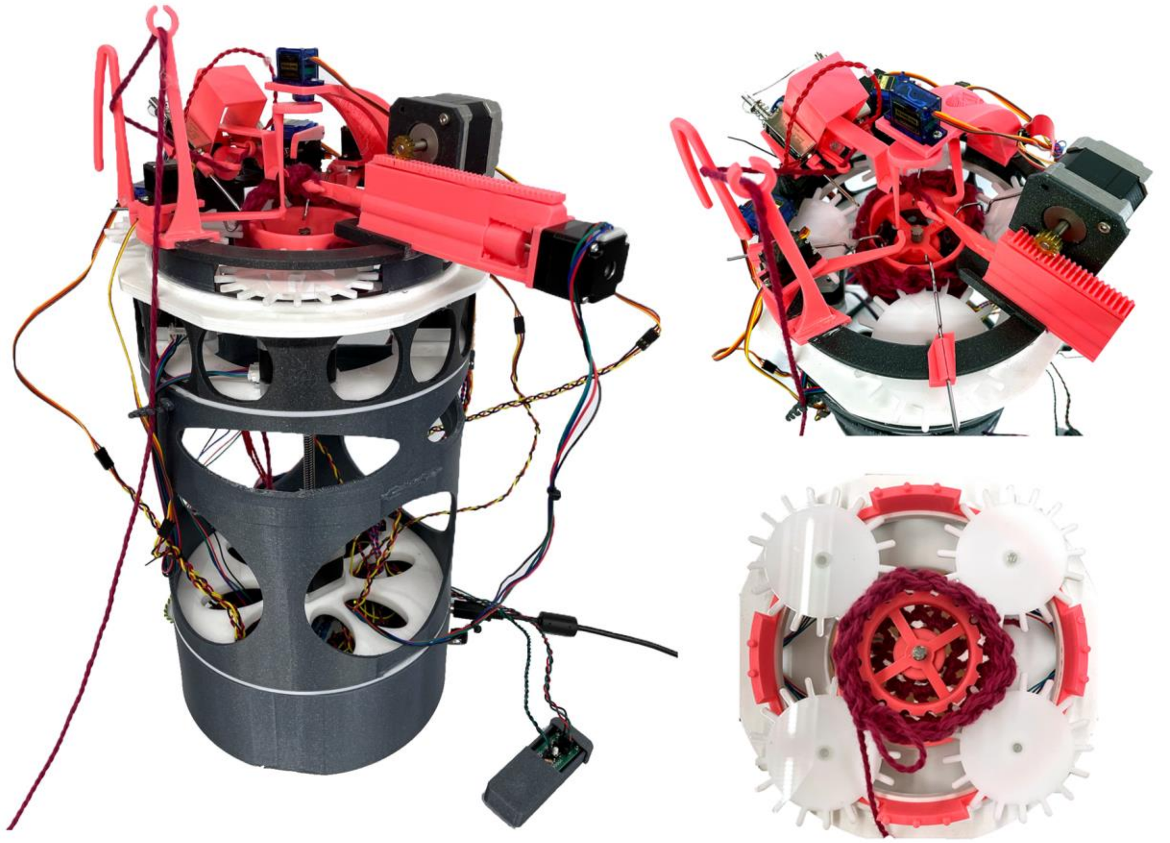

Figure 19. Croche-Matic machine [14]. Images created by Gabriella Perry and republished with permission. Copyright © 2023, IEEE.

Similar to the flat crochet prototype presented in section 2.3.1, the Croche-Matic machine is a mechatronic design with nine axes driven by stepper motors and micro servos, and many 3D printed polylactic acid (PLA) parts. The detailed motion sequences can be observed in the respective YouTube video [122]. A horizontally positioned conventional crochet hook, capable of translation and rotation, is used for the stitch formation according to the movements in manual crocheting. To assist the crochet hook insertion, the current working stitch is held by two smaller moving crochet hooks. A special axis is included to position the loops appropriately on the crochet hook so that they do not slip down when the hook is moved. After the new stitch is formed, the old stitch is released, and the fabric, which is placed between a central cylinder and four gears at the periphery (cf. Figure 19), is rotated so that the crochet hook can be positioned relatively to the next working stitch. Since the stitches are not held by needles or other machine elements, the orientation of the fabric is not precisely defined.

The initial stitches of the magic ring are manually crocheted before the fabric can be placed in the machine. 30 mechanical motions including all nine axes are executed for the formation of one SC. Basically, the motions of stitch formation do not differ between flat and circular crocheting. Thus, the motion sequences developed by Perry et al. [14,15] could also be transferred for flat crocheting. Croche-Matic is the first machine that has successfully automated INC and DEC crochet. The machine formation of SCs was previously described as part of this work by the CroMat patent application.

Major problems regarding the reproducibility of stitch formation are reported [14,15]. Thus, the rate of successfully formed stitches is 50.7% and it was only possible to form four SCs in succession. The main reason for this is the incorrect pick-up of the working stitch, so that the crochet hook is often inserted at a wrong point. Also, the movement and positioning of the crocheted textile is described as a cause of error. Both are due to the lack of a system to retain the formed stitches and secure the fabric. In this regard, the approach described in section 2.3.1, which itself also has major problems regarding the reproducibility of stitch formation, is better designed by suspending the formed stitches on latch needles. In general, the technical implementation of the first approach of a flat crochet machine is superior to the design of the Croche-Matic, because conventional and proven machine elements such as latch needles, or a belt driven sliding carriage were used there.

The developments and research accomplished in the present work are under no circumstances based on the Croche-Matic machine or the technical implementation of the motion sequences described in references 14 and 15. This is because the basic design and motion sequences of the invented CroMat were developed and filed for patent before references 14 or 15 were published. The similarities of the Croche-Matic machine to the CroMat, such as the mechatronic construction with many axes driven by stepper motors and micro servos, are due to the complex motion sequences of crocheting that require such an approach. The work of Perry et al. shows that circular crochet can also be automated with simple means and that it has fundamental similarities to flat crochet, so that the developments from the present work can be transferred to the circular crochet process in the future.

2.3.3 Crocheting with a robotic arm

Near the end of this work, the approach of automating crochet based on a robotic arm for large scale applications was presented for the first time. Nix and Sprecher [123] used a KUKA robotic arm to crochet a chain line and to form crocheted stitches based on an existing textile. The latter required 3D scanning of the existing textile to locate the openings for insertion of the crochet needle, which is designed as a latch needle, and to calculate the tool path accordingly. Interestingly, the textile and not the needle was moved for the stitch formation.

For the chain line, scanning of the textile is not required because the crochet hook does not need to be inserted into any working stitch. Furthermore, the approach to derive the tool path of the robotic arm for crochet with dynamic motion capture of the manual movements was described. In the future, the textile could be visually captured during fabrication to calculate the points for needle insertion. This fabrication technology is intended to find application in textile architecture, where robotic arms are already used to build textiles based on other technologies [123].

In another publication of the same authors [124] the approach of using a robotic arm for automated crocheting of large textile structures is continued. Instead of moving the crochet hook or the textile by the robotic arm, a device, which performs the crocheting action locally and is shown in Figure 20, is to be moved along the crochet path by a robotic arm. The feed system is intended to feed the yarn to the device, which can be wrapped around the crochet hook by the looping mechanism for a yarn over. The stitching mechanism inserts the crochet hook into a stitch, which is positioned appropriately by the product upper guides. The latter shall move the fabric one stitch position further relative to the crochet hook after each stitch formation. The system is intended for building INC and DEC, while the stitch types that are to be produced are not specified.

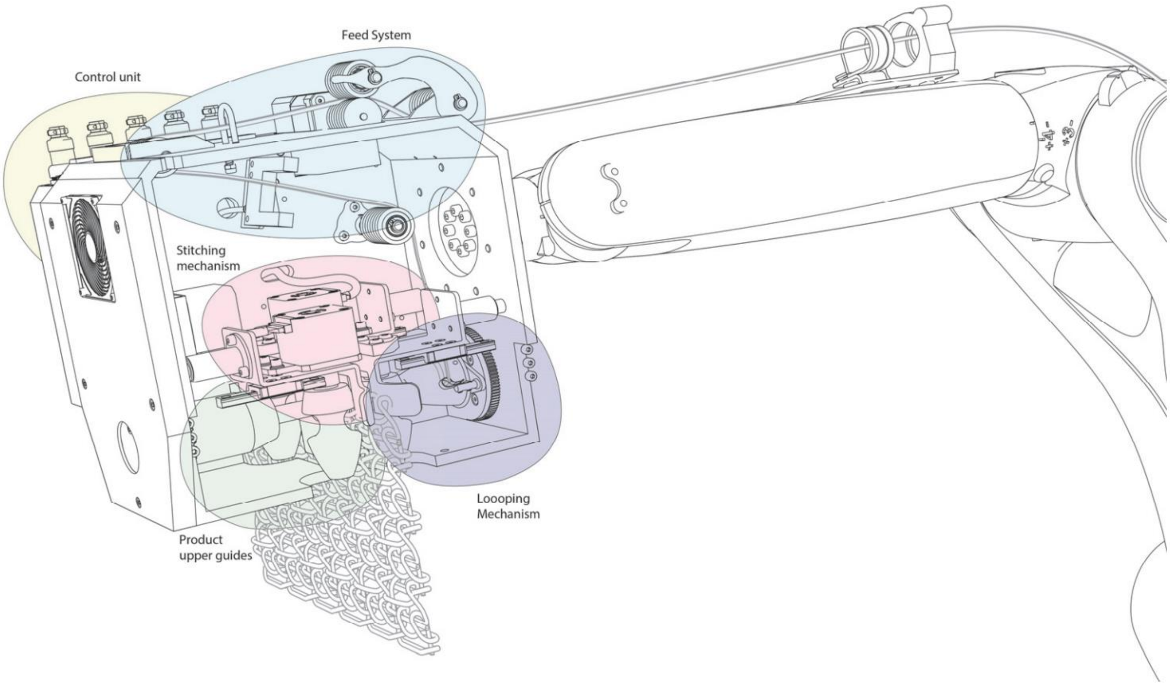

Figure 20. Diagram of the crocheting device moved by a robotic arm. Reproduced from reference 124 (originally published by Education and research in Computer aided architectural design in Europe (eCAADe) 2023) with kind permission by the authors and publisher.

A proof of concept is not given, and it remains open how a reproducible insertion of the crochet hook at the appropriate opening of the working stitch is ensured. It is also uncertain how the large textile to be produced will be supported so that the moving crocheting device can add a new row of stitches as shown in Figure 21. Without additional supporting structures, a crocheted textile has no structural stability, so layers cannot easily be stacked as in 3D printing (cf. section 2.4.2). Therefore, it is too early to make a thorough assessment of the potential of this approach in terms of a practically applicable crochet machine. The approaches from the first publication of crocheting with a robotic arm [123] is also too immature at the current stage to assess its suitability for future industrial applications.

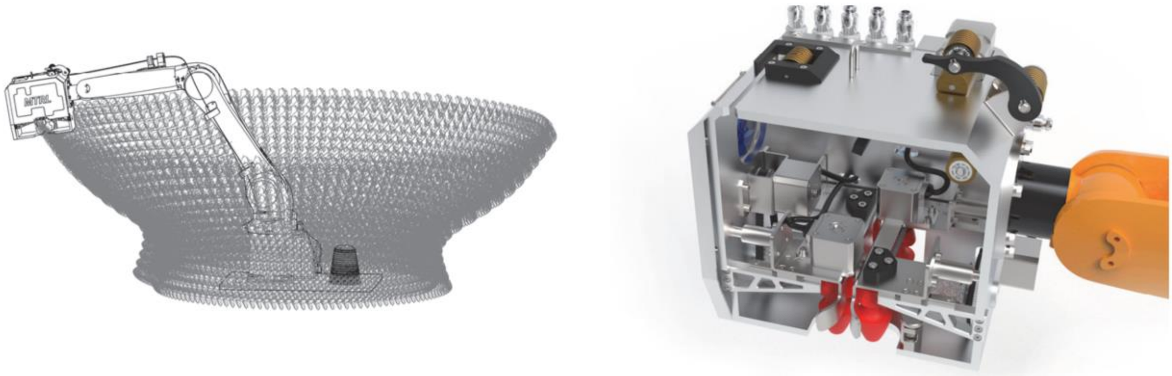

Figure 21. Concept of crocheting large scale textiles with a robotic arm (left) and rendered illustration of the crocheting device (right). Reproduced from reference 124 (originally published by eCAADe 2023) with kind permission by the authors and publisher.

2.3.4 Further attempts to automate crocheting

In addition to crochet gallon machines (see Section 2.2.3), there are other knitting machines that are called crochet machines because the fabrics they produce look similar to crocheted textiles [17]. An example of such a machine is the "Warp knitting/crochet warp knitting machine" by Richard Gangi filed as a patent in 1987, which is similar in construction to a warp knitting machine [125]. Furthermore, a flat edge crochet stitch sewing machine (18E from Merrow, Fall River, Massachusetts United States of America) has existed since 1899 and is often used to edge pillows, scarves or blankets [126]. This single needle and single thread sewing machine can be used to create a fabric border that is similar in appearance to a border created by manual crocheting [17]. However, crocheted fabrics cannot be produced with such a sewing machine.

Another approach to automating the crochet process is a machine by Johanna Riedl and Emanuel Gollob, used as an art project, that can generate an endless row of CHs [17,127]. Since only a single row can be generated, it also cannot be used to crochet whole fabrics. Strictly speaking, CHs do not meet Irene Emery's definition of crocheted stitches [12], so this "chain stitch crochet machine" cannot actually be categorized as a crochet machine. The structure of the CHs can also be created with knitting machines such as crochet gallon machines (cf. Figures 13 and 14 in section 2.2.3).

Moreover, there is an approach of a counting crochet hook that supports manual crocheting as a partial step towards automation [128]. The patent published in 2020 features a crochet hook with a display and two counters, each of which can be incremented by pressing a button. The counters are intended to aid the crocheter by tracking row and stitch counts.

In another approach to improve manual crocheting by improving the crochet hook, a crochet hook was developed that significantly reduces the wrist rotation required for crocheting [129]. The aim is in particular to enable people suffering from wrist arthritis to continue crocheting. The 3D printed device allows the rotation of the crochet hook via an internal mechanism by actuating a thumb lever.

These further approaches to automating crochet technology are not relevant with regard to the CroMat machine described here. They were not used as a template for the development of the crochet machine and are only described for the sake of completeness.

2.4 Rapid prototyping

In product development, prototyping is the process of creating a prototype. Generally, a prototype can take many forms, such as a pencil sketch, a virtual FEM model, or a physical structure similar to the product being developed [130]. The specific implementation of a prototype is determined by its purpose in the product development process. For example, a prototype can be used in an early design phase as a rough physical model for experimenting and testing solution approaches [130]. Another important aspect is communication based on the demonstration of a potential product using a corresponding prototype [130]. In a later phase of product development, a prototype can be built from several developed sub-assemblies to test the interaction of the integrated parts [130]. Finally, prototypes support the planning and execution of product development because they often represent milestones that are used to decide on the next steps [130]. Prototypes can also be used to test the developed production line of a new product.

The RP approach is presented below in section 2.4.1. 3D printing that is based on this approach is described in more detail in section 2.4.2.

2.4.1 Development approach

In view of the development pressure of the modern industry to bring new products to the market as quickly as possible, while the complexity of new products is simultaneously increasing, the system of RP has become established [130-132]. This enables faster production of physical prototypes by using different technologies compared to the former manual prototyping [130]. Thus, not only time but also costs can be saved significantly [130].

The underlying approach of RP is based on the use of CAD to create a 3D virtual model or prototype [130]. As an intermediate step before the actual production of the physical prototype, the CAD model is converted into a general format for the representation of 3D geometries [130]. Stereolithography (STL) files have become established as the de facto standard here, whereby the surfaces of the virtual object are approximated with triangles [133,134]. A slicer is used to translate such a file into the specific commands of a machine for the physical production of the model [130]. The 3D model is divided into several layers, which can then be built up by the RP machine one after the other to produce the 3D object [130].

Many different processes can be used for fabrication, most of which can be counted among the additive manufacturing process [133]. This process belongs to the fundamental fabrication processes along with subtractive and formative [133]. A well-known example of a subtractive fabrication is computerized numerical control (CNC) milling, where material is removed from a solid block until the desired shape is achieved. Examples of formative processes are sheet metal bending or plastic injection molding [133].

In additive processes, parts of a starting material are added at specific locations in order to build up a coherent body piece by piece according to the shape of the 3D object. In terms of RP, such processes are classified as liquid-based, solid-based or powder-based [130]. This distinction is related to the nature of the starting material. Accordingly, in liquid-based, the material is in the liquid state and is converted to the solid state in the shape of the 3D object by curing [130]. In solid-based RP processes, a solid material can be melted, as in the popular FDM process, for example, in order to apply it at suitable points [130]. Powder-based differs from this in that the solid is present as a powder that can be assembled by joining methods [130]. Such additive processes are also referred to as 3D printing.

2.4.2 3D printing

The additive manufacturing of 3D objects based on a computer-controlled process by applying material layer by layer can be defined as 3D printing [135].

SLS and SLA printing

As a powder-based 3D printing process, selective laser sintering (SLS) is very popular [136]. In this process, individual areas of a layer of powder particles are heated with a laser so that they fuse with the particles in the surroundings and thus with the already manufactured object parts [136,137]. This causes the particles to fuse at the contact surfaces without liquid material flowing away [137]. In addition to polymers, ceramics and metals can be used with this process [137].

SLA printing, as liquid-based process, represents another widely used 3D printing technology. There, the printed part is created in a pool of liquid resin by either moving the part further down for each layer and exposing it from above or moving the part further up to be exposed from below through a window [135]. In both cases, high resolutions can be achieved by curing thin layers according to the part's cross section via ultraviolet (UV) induced photopolymerization [138]. For this purpose, lasers are conventionally used, while digital light processing (DLP) modules can also be used to expose the entire layer at once. With DLP, an UV lamp is used to illuminate a micromirror array that serves as a configurable mask so that only the desired cross-sectional area is illuminated [139,140]. Each small mirror corresponds to a pixel and can be turned on or off depending on the pattern [139].

SLA/DLP printers were originally designed for the industrial sector but are now also accessible to the consumer sector [140,141]. This development was made possible in particular by the expiry of patents in 2009 [141,142]. Accordingly, there are nowadays a variety of low-cost printers suitable for desktop printing, and a large online "maker" community. FDM 3D printers, which are easy to operate, are even more widespread in the consumer sector [A3,142]. The availability of low-cost FDM printers and corresponding parts provides opportunities for a very cost-effective RP.

FDM printing

As the most common 3D printing technology today, FDM is based on the extrusion of thermoplastic material in the semi-molten state [135]. The material is above the glass transition or crystallization temperature but below the melting temperature [143]. A correspondingly heated nozzle is moved in the plane according to the cross-sectional area of the object to print each layer. Between the layers, the nozzle is moved vertically with respect to the layer thickness. The deposited material cools rapidly in the ambient air, connects with adjacent lines along with the layer below, and solidifies [144]. A large number of thermoplastic polymers such as PLA or acrylonitrile butadiene styrene (ABS) can be printed and are fed to the heating element near the nozzle as a filament rolled up on a spool [135]. To ensure a suitable structure of the object with, for example, overhangs, support structures can be added which can be easily removed during the post-process step of finishing the manufactured component [135].

According to this principle, a cost-effective and tool-free production of many complex objects with a wide variety of material properties and for a wide variety of applications is possible [A3,145]. In addition to its use in the consumer sector and alongside its application for RP, FDM printing also offers opportunities for industrial production [145]. Especially the production of small series or individualized products is promising here [145]. 3D printed medical devices, such as prostheses for children or hearing aids, are examples of the application of additive manufacturing in industrial production [145]. On demand 3D printing of spare parts in aerospace is another industrial application beyond RP [145]. Also, FDM printing is used for the production of lightweight parts in textile machines. Commercial FDM printers now provide a high-quality and low-cost alternative for the production of utilitarian parts [146]. Overall, 3D printing is seen as one of today's enabling technologies with an increasing market [A4,141].

The main components of an FDM printer are a heatable bed, a movable print head with heating element and nozzle, filament supply as well as a controller board with suitable firmware to control the axes of motion and other elements [141]. In consumer printers, these are often attached to a frame made of aluminum extrusion profiles. Figure 22 illustrates the structure of a respective printer. The print head can be moved along the X-axis via a belt driven carriage guided by rollers in the grooves of the aluminum rails. The entire X-axis can be moved along Z with two ball screw drives actuated by two motors. The heated print bed can be moved along the Y-axis with another belt driven carriage with rollers. The aluminum rails, in which the rollers of the belt driven carriages run, are V-shaped, which is why this system of linear guidance is also known as a V-slot pulley. Furthermore, E is a fourth, rotational axis responsible for feeding the filament. As is common with 3D printers, standardized national electrical manufacturers association (NEMA) 17 stepper motors are implemented, where the housing's front is standardized.

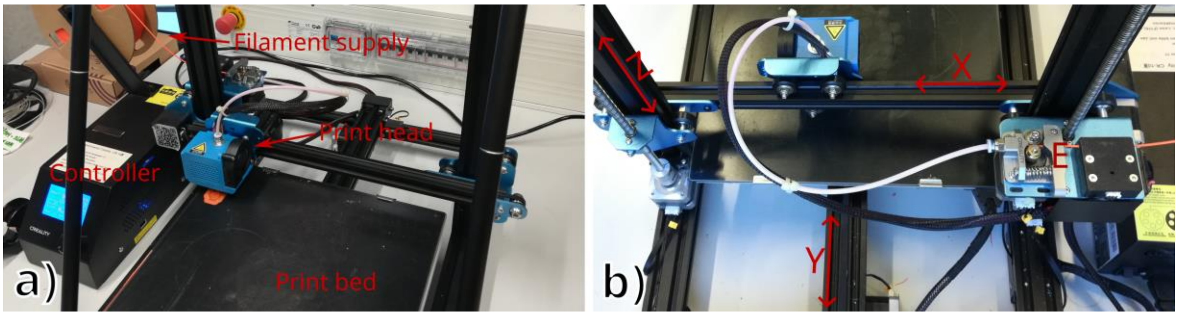

Figure 22. Structure of a commercial fused deposition modeling (FDM) 3D printer. **a)** Front view during printing of a component made of orange filament fed from a spool. **b)** Rear view of the axes of motion.

The FDM printer shown in Figure 22 is a Creality CR-10 V2 3D printer (Shenzhen Creality 3D Technology Co., Ltd, China), which was used for the RP of this work and for the production of the FDM printed PLA parts of the CroMat. For this purpose, the parts were designed using the CAD program Autodesk Fusion 360 (Autodesk, United States of America) and the exported STL files were sliced using Prusa Slicer (Prusa Research a.s, Czech Republic). A Photon Mono X (Shenzhen Anycubic Technology Co., Ltd., China) was used for the SLA printing performed as part of the RP.

2.5 Electric motors

Electric motors are machines for converting electrical energy to mechanical energy and are often the "workhorses" of a system [147]. Generally, they are divided into alternating current (AC) and direct current (DC) electric motors. DC motors, which are easy to control and more widely used, are categorized as brushed and brushless [147,148]. Brushed motors are characterized by high torque at low speeds but have low efficiency and high maintenance due to wear of the commutator brushes [148,149]. Brushless motors do not require maintenance and are often smaller and lighter but are slightly more expensive to purchase [148,149]. In these, the commutation is done by electronic controllers that switch positive and negative current to the two phases of the motor, making this type of motor popular for computer-controlled applications [149].

Stepper motors are described in more detail in the following section 2.5.1, whereas servo motors are covered in 2.5.2. Finally, section 2.5.3 describes the G-code commands for digital control of both motor types.

2.5.1 Stepper

The motion of the axes of a 3D printer as a computer-controlled, mechatronic machine is performed by stepper motors. Stepper motors are DC brushless, synchronous electric motors [150]. Such motors are widely used in industry, especially when precise positioning, for example of machine tools, is required [151]. High accuracy is also achieved with these motors in terms of speed control [151].

In stepper motors, one revolution is divided into discrete steps [151]. According to the control of the signal pulses sent to the motor, the steps are passed incrementally to take desired positions [151]. After approaching, the motor holds the position until further commands. Rotation occurs due to magnetic interaction between the poles of the energized stator winding and the poles of the rotor without windings [152]. This can be designed as an open loop and does not require position feedback as long as the motor is operated within its load limits [151].

Stepper types

Stepper motors can be categorized as variable reluctance motor (VR), permanent magnet (PM) or hybrid. In VR stepper motors, which do not use PMs, the multi toothed rotor has no windings, while the soft iron stator has toothed poles divided into three to five phases [152]. When one phase is energized, the motor moves to a position where the reluctance of the magnetic circuit becomes minimal [152]. If a next phase is energized, the motor moves to a correspondingly different position. In contrast, a PM stepper motor rotates due to magnetic attraction and repulsion between the poles of the PM in the rotor and the electromagnetically switchable poles of the soft iron stator [151].

The hybrid stepper motor is a combination in that the rotor is a PM with two staggered toothed soft iron rims on its poles, which follows the rotating electromagnetic field created when the stator is connected [151]. The teeth of the rotor help in guiding the magnetic flux [151]. The hybrid stepper motor is the most common type and has an increased torque characteristic compared to the other ones [152]. This stepper type is distinguished with regard to the design of the stator windings. The unipolar type has two coil windings and one center tap each, while the bipolar type has two coil windings without center taps [151]. In the latter, the phase polarity can be reversed by an H-bridge and the current can always flow through a whole coil (rather than just half a coil), allowing for larger torques [151]. In unipolar stepper motors, current flow is only possible in one direction, so the phases have a fixed polarity.

Stepper motor control

Hybrid stepper motors are mostly controlled by microprocessors [151]. The frequency of the pulses generated by these directly influences the speed of the stepper, while the length of the movement is proportional to the number of pulses [150,151]. A common angle of a full step is 1.8°. To achieve higher accuracy with additional positions between step angles and to enable jerk-free moves, micro stepping can be used in hybrid stepper motors with a suitable control unit [151]. Micro stepping is based on controlling the direction and magnitude of the currents applied to the two coils [151]. However, this reduces the torque slightly [151]. The overall torque depends on the voltage applied by the driver [128].

Drivers are used to supply stepper motors with suitable voltage pulses according to the desired movement [150]. As peripheral elements, they receive signals from the central processing unit (CPU) of the microcontroller about the steps to be executed. The CPU receives the information about the movements to be performed mostly in the form of G-codes, which can be programmed by the user with aid of software tools (cf. section 2.5.3). For open-loop control, an additional limit switch, often designed as a mechanical switch, is required for each stepper motor at the limit of the corresponding motion axis [150]. Before an exact positioning can be ensured, the limit switch must be actuated by an element moved by the corresponding motor in order to set a defined initial position for the control.

2.5.2 Servo motors

Servo motors are generally not characterized by a special type of motor, but by a closed-loop control system for controlling the motor's operation [153]. Thus, pneumatic or hydraulic motors can also be used. However, in mechatronic systems, such as 3D printers, CNC milling machines or robotic applications, DC electric motors are mostly used for servo systems [154-156]. In the following, a servo motor denotes an electric motor with closed-loop control.

A mechatronic servo system can be controlled either in terms of point-to-point position control with considering the time and position of the end point, or in terms of motion [156]. The latter is called contour control and always requires a strict control of the velocity in addition to the position control [156].

In robotic applications, servo motors have advantages over stepper motors in terms of fast response, relatively constant speed/torque ratio, and higher speeds [155]. Another advantage over open-loop stepper motors is that no limit switches are needed. In addition to robotic applications, servo motors are also widely used in hobby applications such as radio-controlled (RC) cars [153]. Such servos usually have a motor arm, which is moved by a DC motor via an integrated gearbox, and a unit for position detection including a control circuit [153]. These low-cost servos are often used in prototyping, e.g., in the Croche-Matic prototype of a crochet machine shown in section 2.3.2.

For position control, an encoder can sense the actual position (rotation angle) and feed it to a proportional-integral-derivative (PID) controller, which adjusts the control of the motor to achieve the commanded position [154]. Typically, a PID controller processes the input signal, consisting of a setpoint value with subtraction of the feedback actual value (or controlled variable), taking into account proportional, integral, and derivative factors [154]. The resulting output signal is then fed to the motor as the controlled system. It should be noted that servo motor control usually considers only the position of the servo and not the position of the moved object subjected to load [156].

The target position is usually sent by a microcontroller, which also provides the necessary power, to the servo motor via a digital pulse width modulated (PWM) signal on a dedicated channel [153]. In general, PWM is based on an alternating on and off switching of power and the resulting duty cycle as the ratio of the on time to the whole period (100% duty cycle corresponds to always on) [153]. When used as a signal transmission, the pulse width corresponds to a specific data value, and the leading edge of each pulse can be used as a clock. When controlling a servo motor, the pulse width corresponds to a specific angle [153]. For example, the period corresponds to 20 ms and the pulse width is divided between 1 ms and 2 ms to fixed angular positions between 0° and 180°, thus operating in a duty cycle range of 5% to 10% [153]. The control loop integrated in the motor ensures that the position is taken, which is set in each period.

2.5.3 G-code

G-code designates geometry code and is the common name for the CNC language RS-274D (cf. International Organization for Standardization (ISO) 6983 standard) [157,158]. Originally this language was developed to describe the job information for a CNC machine as output from the CAD or computer-aided manufacturing (CAM) system [157]. A corresponding part program defines how the machine must manufacture the object and describes among other aspects the tool path [157]. In addition to the programming language, G-code is also often used to describe a text file as a variant of the part program sent to the machine that can be viewed by the user [158].

G-code commands refer in particular to the movement of the axes of the machine. For example, *G21* can be used to set the unit to millimeters and *G1 X10* can be used to move the X-axis by 10 mm [158]. In addition to the name-giving G-codes, there are also machine (M) codes which control other aspects of the machine and with which, for example, servo motors can be controlled via *M280* [159]. Regarding 3D printers, where the use of G-codes is common, the extruder, for example, can also be controlled via M-codes. Furthermore, there is also a feed rate (F) code to set the speed of the axes, e.g., that of the extruder [158].

To generate the machining paths, G-code uses linear interpolation (*G1*) for linear movements and circular interpolation (*G2*/*G3*) for circular arcs [158,160]. In a G-code command, the next position is always specified, and several axes can be moved simultaneously [160]. In this case, the velocity of the axes (considering the allowed maximum velocities and accelerations) is adjusted to reach the target point simultaneously [161]. The target points of movements are specified in absolute coordinates or as relative movements from the current point. The command *G91* can be used to set the relative indication [162]. Another important command is *G28*, with which a "homing" of the specified axes is carried out by approaching the limit switches and setting the reference positions [163].

The G-code control language has been applied for several years and is now used widely among CNC machines and 3D printers [164]. It is important to note that G-code programs are machine-specific [157]. Accordingly, for 3D printers, their specifications are considered by the slicer, which automatically generates the G-code from the STL file created with a CAD program (cf. section 2.4.2) [158]. The G-code program is then often transmitted to the machine via a universal serial bus (USB) connection or USB flash drive. For CNC machines, the G-code is generated directly by the CAD/CAM system and sent to the machine controller, for example [150,164]. With the controller's firmware, the G-code is interpreted and the electronic signals are generated to implement the commands [150]. Marlin is an example of a respective open-source firmware used in many commercial 3D printers [165].

2.6 Textile composites

In the context of the climate crisis with the need to reduce CO_2 emissions, the scarcity of raw materials and the high energy prices, the use of composite-based lightweight constructions is becoming increasingly important [1]. In composites, the fibers of a textile structure consisting of e.g., aramid, carbon, glass or even basalt are embedded in a rigid matrix, often consisting of epoxy [2,166-171].

In general, textile composites have the advantages over other materials of good mechanical properties with a low weight [166-169]. In addition, they are relatively inexpensive to manufacture, easy to handle, and resistant to corrosion [168,170]. A disadvantage is that composites exhibit anisotropic and often inhomogeneous properties due to the textile reinforcement [168,172]. Nowadays, composites are a widely used material and have applications in wind energy, automotive, aerospace, marine vessels, sports, medical devices and generally as mechanical components [1,167,168,170,173].

In the following, the manufacture of composites is addressed in section 2.6.1. The near net-shaped composites, for which crochet technology is promising, are outlined in section 2.6.2.

2.6.1 Composite production

Unidirectional (UD) prepregs with parallel fibers pointing in only one direction were originally used as textile reinforcements [166]. Today, it is common to apply woven fabrics as reinforcements, while knitted or braided fabrics are also being used [168]. Woven composites, where the plain weave structure is the most common one, have good dimensional stability and out-of-plane strength, but are rather poor at resisting in-plane sheer and are worse at draping into complex shapes than the other textile reinforcement types [168].

Knitted fabrics have good formability due to their stitch structure [2,166,168]. These also have higher impact resistance than woven composites but have poorer in-plane mechanical properties [2,168,169]. Braided reinforcements are manufactured by orthogonal interlacing of one axial yarn set with one or more braided yarn sets [168]. Corresponding composites resist impact, shearing or twisting well and have high stability under tension, while they have low stability in compression [168].

The manufacture of composites from textile reinforcements involves three general aspects, impregnation with the matrix material, molding and subsequent consolidation [166]. Impregnation with a liquid thermosetting matrix material, which can also be performed after molding, is often carried out using liquid molding techniques such as resin transfer molding (RTM) or similar processes [168,173]. During consolidation, the resin is then usually cured under heat and pressure [173]. Alternatively, a thermoplastic matrix can be used, which is present as a solid at room temperature and must be melted for consolidation [166,173]. This offers the advantage that the matrix material can, for example, be also knitted directly [166].

The textile reinforcement is generally formed using a mold. In RTM, for example, the textile is placed between the two halves of the mold, after which resin is pumped in and the composite is cured in the mold [173]. To ensure uniform wetting of the fibers with the matrix material, a vacuum can be applied during molding [173]. A corresponding vacuum-assisted resin infusion (VARI) shortens the processing time and enables the production of large parts such as windmill blades in one piece [174].

For small series and prototyping, the less reproducible hand lay-up method is often used, where the textile is manually placed in the mold and impregnated with resin [168,173-

175]. This can also be improved with a vacuum by placing the impregnated preforms in a vacuum bag after molding for curing [175]. The curing can also be carried out at room temperature [175].

Generally, several textile layers (corresponding to the desired thickness) are stacked to build up a composite [1,175]. Mostly, plain textiles are used for creating 3D shapes, which require an elaborate manual draping process to be formed into the desired shape [1,173,176]. This results in limited reproducibility, high cost, and a lot of waste material [1].

2.6.2 Near net-shaped composites

A promising approach to reduce waste material and draping effort in composite manufacturing is the use of (near) net-shaped reinforcement, with 3D textiles in the direct shape of the component to be manufactured [1-3,169,173]. This can save time and cost in production [2,3,169]. It is estimated that 50% of the composite costs are due to the mostly manual cutting and draping of the textile reinforcements and that 40% to 50% of the raw material is waste [1]. If, in addition, all necessary textile layers of the reinforcements are manufactured directly as a coherent textile, further draping efforts and costs can be reduced [1,173]. Also, the mechanical out-of-plane properties can be improved due to the through-the-thickness connections [173].

For such near net-shaped composites, the flat-bed weft knitting technology is considered to be particularly suitable due to the wide range of structures and shapes that can be produced [2,3,169,176]. The lower in-plane stiffness and strength of knitted fabrics compared to woven reinforcements is due to the loop structure with strong curvature of the fibers [2,166]. However, the curved nature of the knit structure results in advantages in terms of formability and drapability to complex shapes [2].

The versatility of knitting technology can be used, for example, to directly incorporate holes for bolts of the later component into a knitted reinforcement. This results in superior mechanical properties due to the maintained fiber continuity, in comparison to drilling after completing the composite [2,3]. As another example, weft knitted reinforcements in the form of T-beams can be used to produce corresponding composites [2,177,178]. These have significantly better mechanical properties than T-beam composites made by the conventional method from draped and laminated 2D textiles [177].

Complex textile reinforcements such as those for near net-shaped composites are still relatively expensive and more suitable for a high value application of a narrow batch (for example aerospace industry) [176]. A widespread use of near net-shaped composites is limited due to the lack of efficient and cost-effective fabrication technologies for textile reinforcements in complex shapes [173,176]. In general, existing textile technologies for the direct fabrication of complex shapes, such as 3D skin-stringer structures or biaxial reinforced tubes, are not advanced enough in relation to the needs [1,173,176].

3 Crochet machine development

The developments of the CroMat crochet machine were performed within a third party funded project (*HaekelMasch*, ZIM (zentrales Innovationsprogramm Mittelstand) project KK5129701PK0, German Federal Ministry for Economic Affairs and Climate Action) with the Maschinenfabrik HARRY LUCAS GmbH & Co. KG, the kessler systems GmbH (called project partners in the remainder) and the HSBI. The project was initiated and led by the author.

In this section, the aspects of designing the CroMat crochet machine are discussed with a focus on the prototype developed by the author of the work. Accordingly, the innovation process is first described in section 3.1, which led via initial prototypes to the patenting of the CroMat. Beyond the patent, further improvements were achieved to the crochet machine as illustrated in section 3.2. The developed motion sequences of the fundamental machine elements for the automation of crocheting are the result of these conceptualization phases and the work with the initial prototypes. A description of the automated motion sequences abstracted from a specific machine is given in section 3.3. The final CroMat prototype at the end of the development phase can perform these motion sequences to crochet fabrics and is presented in section 3.4. The automated production of a crocheted fabric with the prototype is exemplarily shown in section 3.5. Section 3.6 is dedicated to the developed software for the design of machine-crocheted fabrics and the control of the machine. Finally, the functionality offered by the CroMat prototype is summarized in section 3.7.

3.1 CroMat innovation process

Given the lack of automation in crochet to date, the perspective of replacing commercial handmade crochet products, and promising new areas of technical application [21-23,85,86,89,90], the potential market value of a crochet machine is appealing. The basic idea of such a machine is given by the first crochet machine approach presented in section 2.3.1. In this context, the successful technical implementation as well as the patent filing to protect the intellectual property (IP) lead to an innovation according to the definition of Koltze and Souchkov [179]. Both these sufficient aspects of an innovation have been dealt with in this work.

In the context of the innovation process (cf. Figure 23 in section 3.1.1), this chapter deals with the definition and concept phases. Firstly, the framework of the development phases is described in section 3.1.1. According to the definition phase, the first approach for the automation of crochet presented in section 2.3.1 is analyzed in 3.1.2 to derive the necessary requirements for an effective and improved crochet machine prototype. The requirements regarding this CroMat prototype as the results of the definition phase are described in 3.1.3. Concerning the conceptual design of the improved prototype, section 3.1.4 describes the fundamental machine elements considered as the starting point for the CroMat development. Section 3.1.5 deals with the approaches to develop a reliable process of inserting the crochet needle in a working stitch. The new, developed method for suspending the formed crochet stitches is addressed in section 3.1.6. Lastly, in section, 3.1.7 the yarn guide as well as the filed patent of the novel CroMat crochet machine are described.

3.1.1 Development phases

Figure 23 contextualizes the developments regarding an effective crochet machine, called CroMat, that were accomplished as part of this work, within the typical phases of the innovation process according to Koltze and Souchkov [179]. Starting with an idea, which was initiated here by the first crochet machine approach (cf. section 2.3.1), the goal and the characteristics of the innovation are identified in the definition phase, e.g., with the help of creative techniques. In this regard, the requirements for the improved crochet machine are presented in section 3.1.3. These are mainly derived from the first crochet machine approach and are for example, a substantially more reliable stitch formation process, more stitch types that can be created or capabilities for shaping the fabric.

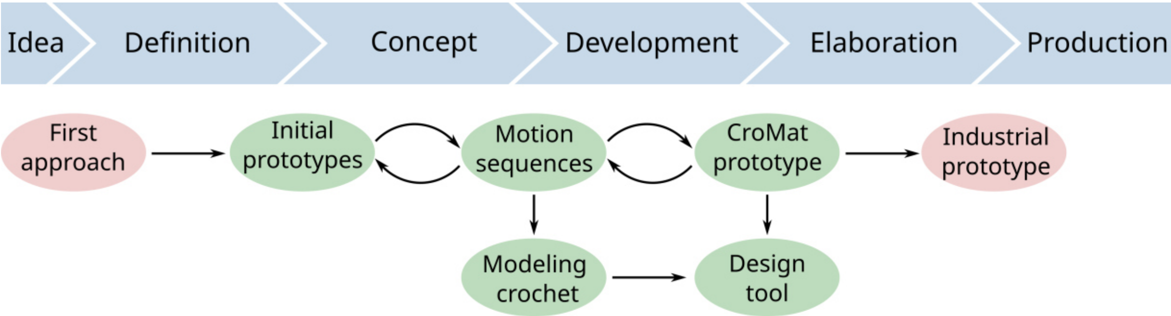

Figure 23. Phases of innovation according to Koltze and Souchkov [179] and crochet machine development process. The green bubbles mark the developments conducted in this Ph.D. thesis. The foundation, analyzed but not developed here, is the first approach of a crochet machine highlighted with red background. Also, the industrial prototype is marked by red.

In the conceptual phase, various solution approaches are developed by means of initial models and prototypes (see sections 3.1.4 to 3.1.7). The goal here is to develop efficient motion sequences of the fundamental machine elements that form the basis of the crochet machine. This is achieved in an iterative way through a mutually influencing process between the initial prototypes and the motions for stitch formation. At the end of the concept phase with the focus on the motion sequences for the stitch formation process, the joint patent by the project partners, HSBI as well as the author of the dissertation is filed (cf. section 3.1.7).

Developing a machine process of stitch formation is a fundamental and integral part of the product development of the crochet machine [179]. The elaborated stitch formation processes are illustrated in section 3.3. In the development phase, the most promising approach for realizing the respective motion sequences is implemented as the CroMat prototype. Additionally, in the development phase, the crochet structures are modeled based on the machine's stitch formation processes in contrast to also developed models of manually crocheted fabrics. Based on these models and on the capabilities of the CroMat, a tool for specifically designing machine-crocheted fabrics and controlling the respective machine is developed, too (cf. section 3.6). The modeling is explained in more detail in sections 4.1 and 4.3.

With the finished and tested CroMat prototype, the elaboration phase of the innovation process starts, in which the prototype is optimized and finished to an industrial standard. This industrial prototype is directly derived from the CroMat in a collaborative development of the project partners and the author of the dissertation. The author's development work ends with the assistance in the development of the industrial prototype. Generally, a finished industrial prototype marks the milestone for the start of a subsequent series production, which is considered as the last phase of the innovation process [179].

TRIZ framework

The innovation process according to Koltze and Souchkov [180] described in Figure 23 is accompanied by the *theory of inventive problem solving* (with the abbreviation TRIZ corresponding to the original Russian designation *Teoria Reshenia Izobretatelskih Zadatch*). TRIZ is a systematical method for enhancing the effectiveness and efficiency of product development or innovation processes by generalizing the problem and searching for solutions at an abstract level with a variety of tools [181]. The search for solutions is based on generalized concepts derived from the analysis of a multitude of inventive solutions to problems in the form of patents (more than 1.5 million) [180]. Nowadays, especially in the entrepreneurial context, the introduction of systematics into the innovation process is considered to be highly relevant [179]. Within the framework of this theory, problem solutions are classified at different levels, which are to be seen in the context of evolutionary development steps of technical systems [180]. The highest level, namely the discovery of new scientific principles or effects, is classified at level 5. With descending levels, the challenge decreases and it is possible to rely more and more on established methods and solutions.

In this classification of the level of problem solving, the development of the improved CroMat crochet machine, which is the core of the present work, can be classified in level 3. This is because it is characterized by the opening up of a new field of application and a new market through a known combination of function and principle. For this classification, the crochet machine is to be seen as a combination of the principle of crocheting and the function as implementation with a mechatronic machine, which is considered as a known approach concerning textile machines. The market innovation results from the fact that the machine allows for the first time the automated production of crocheted textiles on an industrial scale, enabling novel products in the form of technical crochet. Especially, crocheted fabrics consisting only of SLs are a novelty, because these stitches cannot be used in manual crocheting to construct whole fabrics from them [16].

However, level 3 is also characterized by the fact that the problem to be solved has already been solved elsewhere [180]. This does not apply to the development of the CroMat prototype. Since the machine formation of the crochet stitches SCs and HDCs according to flat crocheting based on a chain line has not been solved before (the CroMat solution was introduced with the patent application before the Croche-Matic solution, see section 2.3.2). Following this perspective, the CroMat can also be understood as a pioneer invention with the specific development of a product or process through a novel combination of function and principle. This would fulfill the criteria of level 4. Thus, depending on the interpretation, the development of the CroMat crochet machine is to be categorized in levels 3 and/or 4 of the classification of the level of problem solving according to Koltze and Souchkov.

Furthermore, with regard to the S-curve as a model of the evolution of technical systems, the development work can be more clearly classified at the first stage "make it work", which is characterized by a relatively low ratio between performance of the result and development effort. At the end of this stage, the system is capable of executing its primary function without errors for the first time. The next stages, with an increasing slope of the curve, are "make it work right" and several optimization stages until performance decreases again in relation to the required development effort [182].

3.1.2 Analyzing the first crochet machine approach

Based on the study of and experiments with the initial prototype of the first approach to automate the crochet process (cf. section 2.3.1), the following issues were identified in the course of the present work. The most limiting problem is the lack of reproducibility of appropriate insertion of the special needle into a working stitch. With slight warping or displacement of the suspended textile, the special needle is not inserted into the correct clearance of the old stitch. The pronounced point of the special needle slightly increases the probability of hitting the right spot, but also often leads to yarn of the suspended textile being pinned. A camera-based control of the position of the special needle including detection of the correct stitch would be necessary, or an alternative variant of suspending the textile.

The need for a pointed hook of the special latch needle is also a problem, since hardly any such commercial machine needles exist. Groz-Beckert, for example, as the world market leader for machine needles, had in 2022 only two models with a similarly pointed needle hook (Spec. 47.89 G 103 and Spec. 44.58 G 101), but both are too small for use in a crochet machine (cf. section 3.4.3). The needle used in the initial crochet machine approach is an improvised single-piece design that is not suitable for a commercial machine. Developing an appropriate professional needle would be too costly, preventing the economical sale or use of a crochet machine.

Another issue is that only SLs can be produced, which are in manual crocheting rather utility stitches and not used for creating whole fabrics out of them [16]. Also, in contrast to manual crocheting, these stitches are suspended upside down at the needles (cf. Figures 16 and 17 in section 2.3.1). Manually crocheting a fabric consisting of SLs is troublesome, because this type of stitches strongly contracts, and thus it is difficult to insert the needle in the old stitches when building the next course. With the construction of the initial prototype, it is not possible to create more complex structures such as SCs, which are more frequently used.

The fact that a knitted fabric must first be created with other means, which is then suspended in the machine, before the SLs can be created on top of it, is another disadvantage. It would be more appropriate to start with crocheted CHs, as is usual in manual crocheting.

From an engineering perspective, raising and lowering the entire needle bed in the process of stitch formation is also problematic. On the one hand, a large mass must be moved rapidly, especially in a scaled industrial machine. On the other hand, the produced fabric and a corresponding take-off system must always move along with it, which increases the error probability of the process further. A further potentially problematic high mass is caused by the two linear motors on the carriage of the belt driven linear actuator along the Z-axis (cf. Figure 15 in section 2.3.1). The corresponding movement is discontinuous and characterized by a pause for building a new stitch followed by fast motion to the next needle position.

Besides the mentioned issues of the first approach to automate crochet, the initial prototype has some useful concepts that were followed in the development of the CroMat crochet machine prototype. Hence, the structure of a single needle representing the crochet hook arranged opposite a needle bed with several latch needles carrying the textile appears to be generally suitable. Accordingly, existing technology and machine elements of conventional single bed flat knitting machines can be taken as a basis. Placing the formed stitches on needles for subsequent needle insertion in the next course together with the omission of turning the fabric after each course are also adopted concepts.

Furthermore, the construction of the initial prototype from aluminum extrusion profiles and 3D printed parts according to RP is reasonable. Also motor control with G-code known from CNC milling or 3D printers with the help of open-source software is well suited for prototyping and for the crochet machine developed in this work. This corresponds to a fundamentally mechatronic design, which is more flexible than the conventionally rather mechanical textile machines. However, the implementation of controls with a laptop sending G-codes via wireless local area network (WLAN) to a Raspberry Pi single-board computer connected to the motor drivers by an Arduino Mega microcontroller is too cumbersome for direct adaptation.

Due to the shortcomings of the first crochet machine approach of "the largest crochet machine in the world", simple improvements of it were inadequate to develop an industrially applicable crochet machine. Therefore, a new approach is needed, which in particular solves the problem of reliable insertion of the crochet hook needle into an old stitch and, in addition to SLs, also enables the formation of more complex, more commonly used stitches such as SCs and HDCs. Furthermore, with regard to a future industrially used crochet machine, it is necessary that the advantages of crochet technology with regard to the formation of complex 3D structures or with regard to joining can be exploited with a machine.

3.1.3 Definition of crochet machine prototype requirements

As described in the previous section, the CroMat prototype developed during this work is to be an improvement and extension of the first approach for the automation of flat crocheting presented in section 2.3.1. The respective requirements are mostly derived from this approach and from the analysis of the predicted use case of an industrial crochet machine. The latter is the automation of the production of conventional crochet products on the one hand, and the novel production of specialized technical textiles on the other.

According to Chua et al. [130], a prototype is defined generally as an "approximation of a product (or system) or its components in some form for a definite purpose in its implementation". In this context the CroMat prototype is the approximation of a future industrial machine for flat crocheting with the purpose of developing and testing suitable implementations of the crochet stitch building process to fulfill the crochet machine requirements. It serves as a basis for subsequent optimization concerning an industrial prototype and future machines in series production. Thus, the CroMat prototype corresponds to the tested prototype according to Koltze and Souchkov [179] between the development and elaboration phase of the innovation process. In this context, the CroMat does not yet have to be built in an ideal design from industrial standard components but should allow quick conversions through a modular structure to enable experimenting with different solutions regarding the implementation of stitch formation motion sequences. All required features have to be effectively implemented in the CroMat but not necessarily in the most efficient way.

The requirements regarding the CroMat prototype as machine for the automation of flat crocheting are listed below:

- Building at least the stitch types SC and HDC as well as the corresponding turns with one or two CHs, beyond SL;
- Securing stitches in the common orientation used in manual crocheting, and not upside down as in the first crochet machine approach;
- Using the most common stitch insertion point being under the two top loops of a stitch;
- Starting of the machine process based on an initial course of CHs (chain line);
- Usage of common machine elements from knitting or other textile machines;
- Means for shaping the fabric's width by implementing INC as well as DEC;
- Providing as much flexibility as possible regarding crochet patterns;
- Allowing for production of open work crochet;
- Robust stitch formation process;
- Motion sequences and fundamental machine structure must provide scalability to a future industrial crochet machine;

- Implementation of the smallest possible stitch size and needle gauge;
- Enabling of taking advantage of crochet's potential to create complex structures in terms of near net-shaped composites;
- Providing possibilities for joining textiles;
- Using inexpensive components;
- Utilizing the same machine elements for all stitch types and machine operation;
- The machine should be as simple as possible;
- Machine control with a single computer;
- Ease of use by people who are unfamiliar with crochet.

Different stitch types are to be implemented in the prototype to develop a preferably universal machine from which optimized implementations with fewer functions can be derived. This is partly due to the fact that it is difficult to predict which stitch type potential customers would particularly like to utilize. Creating several types of stitches with one machine corresponds to the innovation principle of universality according to TRIZ, in which several functions are generally fulfilled with one object [182].

The CroMat prototype shall demonstrate the possibilities of automated crocheting. In this context, the advantage of crocheting that new stitches can be formed at any point of the fabric already produced should be utilizable with the machine. It is also intended that it is possible to join fabrics based on the machine's stitch formation. Because crochet generally offers the possibility to join textiles by pulling the loops of the new stitches simultaneously through working stitches of two (or more) textiles [10].

With future specialized implementations, the focus can also be better put on increasing manufacturing speed. Current measures to give scalability to high speeds are, for example, a low weight of moving components or a parallelization of movements. The robust stitch formation process especially necessitates improving the insertion of the crochet hook needle into the working stitch. The production of the smallest stitch size while ensuring a safe stitch formation process is pursued, because generally scaling to larger stitches and needles is easier than scaling to smaller ones. By using inexpensive components, the development work with the prototype is facilitated and different components can be tried out more efficiently. It also ensures that the costs of a future commercial machine remain low. For an ease of use of the machine, a dedicated tool for designing the fabrics and controlling the machine is necessary. This should include a preview of the designed fabric with a presentation of the unique crochet structures.

Due to these necessary requirements for an elaborated crochet machine, a straightforward upgrading of the first crochet machine approach is not sufficient, and a completely new machine needs to be designed. Especially a new, reliable principle of inserting the crochet needle always in the right spot is required.

Fundamental machine design and first model

Essentially, the development of a crochet machine can be broken down to the ideal implementation of the necessary motion sequences for the formation of crochet stitches. In the context of systematic innovation, ideality is understood in terms of adaptation to the parent system with sufficient benefit at minimum cost or effort [182]. Here, the higher level of the parent system is the supposed use-case of a crochet machine in the industrial context. Thus, the stitch formation motion sequences must be reliable, fast and scalable to an industrial textile machine while the complexity of the machine elements is to be as low as possible to comply with the requirement of minimum expense. Also, well-established and proven types of machine elements used in the textile industry are to be preferred over completely new developments.

With regard to the ideal development of machine motion sequences for the formation of crochet stitches, the fundamental machine elements are studied in the beginning. Fundamental machine elements are specified here as those in direct contact with the yarn. These are the crochet needle, which manipulates the yarn, the auxiliary needles in the needle bed, on which the stitches are suspended, and the yarn guide, which provides the yarn to the crochet needle. Generally, to keep the complexity low and to facilitate a later machine implementation, all stitch types are to be formed with the same machine elements and with as few degrees of freedom (DOFs) as possible. From the design of these fundamental machine elements and their movements, the necessary further construction of the crochet machine results. An orientation for the design of these fundamental machine elements is provided by the first crochet machine approach (cf. section 2.3.1).

Regarding the auxiliary needles, the first crochet machine approach showed the suitability of conventional latch needles arranged in a needle bed to hold the formed stitches, similar to single jersey weft knitting machines. Such a system, proven in conventional textile machines, is adapted for the development of the CroMat. Additionally, the basic concept of a single needle, which corresponds to the crochet hook of manual crocheting and is positioned opposite the needle bed, is also taken from the first approach of a crochet machine. However, the SL forming motion sequence of the fundamental machine elements is not adopted. This is especially due to the error-prone process of inserting the special needle, which was modified by attaching a tapered tip, into the working stitch. Also, the performed vertical movement of the entire auxiliary needle bed is a cause for the necessity of substantially different movements of the fundamental machine elements for stitch formation (cf. section 3.1.2).

The formation of at least SCs, HDCs, INCs, and DECs shall be automated by the new crochet machine design. Prior to the patent application of this work, no automation of these stitch types or operations was reported. Hence, only the technique of manual crocheting was the basis for the development of their automated formation process. Consequently, the first stage of development was to analyze the steps and movements of SC and HDC in manual crocheting. Results of this analysis can be obtained from sections 2.1.1 and 2.1.2.

Based on these analyses, the development approach was to transfer the corresponding motion sequences of manual crocheting to the fundamental machine elements with movements on trajectories that are as constant as possible. Figure 24 displays these fundamental machine elements of the new crochet machine derived from the first approach in their basic arrangement with indicated principal motion axes. In this respect, the specific implementation of the machine elements and movements in an actual machine was not considered in these first steps.

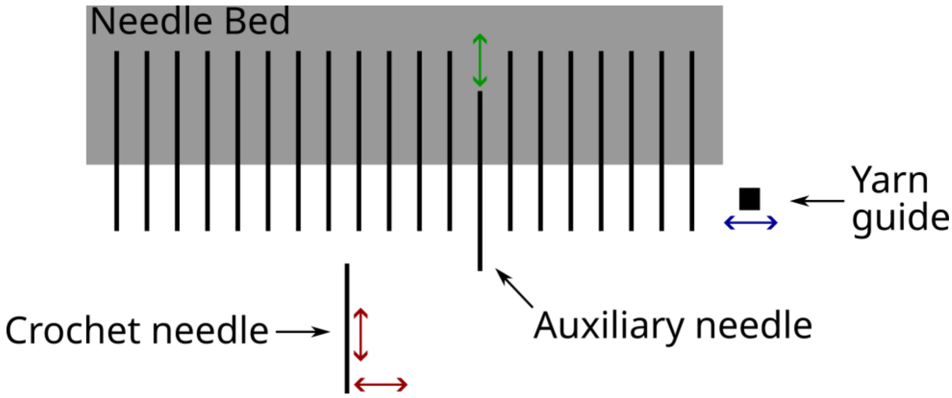

Figure 24. Schematic illustration of the crochet machine's fundamental machine elements and their basic motion axes.

For the trials in the development of suitable motion sequences for the fundamental machine elements, physical models were used in accordance with the basic structure shown in Figure 24. At this early stage of development, it was decided not to use computer models. This is because it is very difficult and time-consuming to simulate the yarn physically correctly. The use of physical models is more efficient in this case. In particular, moving the machine elements by hand has the great advantage that the handiwork of manual crocheting can be transferred directly. Also, early experimenting with physical prototypes correspond to the principles of RP [130]. In this regard, fivefold scaled latch needles were 3D printed using the SLA printing technique. These and the wooden construction for the needle bed are depicted in Figure 25.

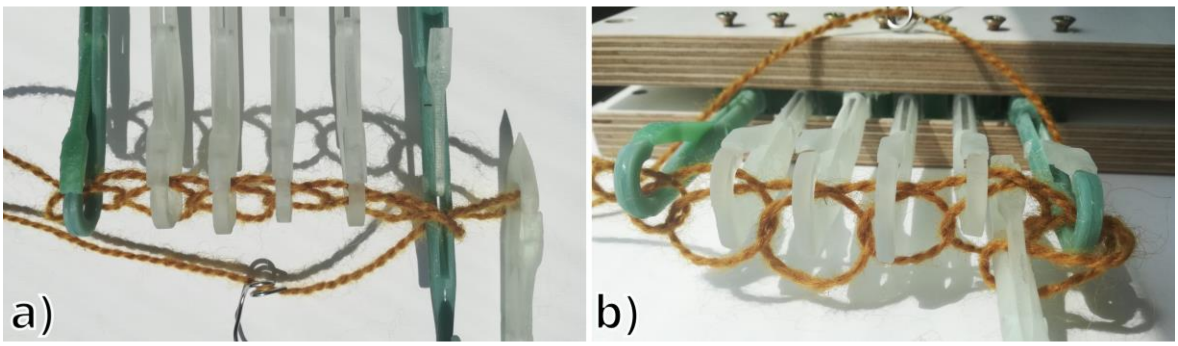

Figure 25. Photographs of the first model of the fundamental machine elements used for developing suitable motion sequences. **a)** Top view. **b)** Front view with the crochet needle inserted into one of the CHs suspended on the auxiliary needles.

Figure 25 shows the first prototype of the crochet machine with the initial CH row suspended on the auxiliary needles and the crochet needle holding the LL while the yarn is moved by hand. In the context of conventional knitting machine needles, compound needles are an alternative design variant to the depicted latch needles. The slightly outdated bearded needles are not considered in this context.

The needles are equidistantly spaced so that there is sufficient space for the crochet needle to move between them to perform the yarn overs required for SCs and HDCs while not being inserted into a working stitch. A general principle to be taken into account is that the crochet needle must be extended along its longitudinal extension direction so that the LL in the hook of the needle can slip onto the shaft in order to be able to draw another loop through it in the next step.

A horizontal insertion of the crochet needle into a working stitch corresponding to the first crochet machine approach is depicted in Figure 25 b). With the crochet needle in the same plane as the auxiliary needles it is not possible to place yarn in the hook of the crochet needle. The yarn over must be done either above or below the level of the auxiliary needles to avoid collision. This requires an additional vertical movement or variation in the angle of the crochet needle if the needle bed is not to be moved as in the first approach. However, compared to these yarn over difficulties, the difficulty of reliably and efficiently inserting the crochet needle into a working stitch is the limiting critical factor. The implementation of the latter determines the yarn over possibilities, which are to be considered in a subsequent step. Therefore, the problem of needle insertion will be addressed first.

3.1.4 Crochet needle insertion process

The error prone process of inserting the special latch needle representing the crochet hook in the working stitch, to draw yarn through it as part of the SL formation process, was identified as the most limiting problem of the first approach of a flat crochet machine (cf. section 3.1.2). Inserting the crochet hook into a working stitch is generally a fundamental part of stitch formation in manual crocheting (cf. section 2.1.1). Thus, an efficient machine implementation of this process is essential not only for SLs but also for the other stitch types such as SC or HDC.

According to the tools provided by TRIZ, the ideality concept is used to describe the goal of the improved crochet needle insertion process [182]. Ideally, the crochet needle can be inserted in the shortest possible way with minimal movements and always error-free exactly at the optimal insertion point of each working stitch, which are spaced equidistantly and as closely as possible. Also, yarn (becoming a new loop) must be able to be picked up as quickly and safely as possible in the inserted state. In this regard no additional machine elements or systems shall be needed to keep the complexity of the process low. Other conditions for an ideal process are that proven and inexpensive machine elements are used and that the stitches are suspended properly after their formation in accordance with manual crocheting.

From this description of the ideality of the crochet needle insertion process emerges the core problem of the implementation in the first crochet machine approach. Namely, due to inevitable, small movements of the fabric, the center of the clearances of a working stitch as the optimal point for insertion of the needle is not always at a fixed position. Hence, the ideal position for inserting the crochet needle is not firmly defined with respect to the needle positions and the distances between the ideal working stitch clearances are not identical. This is also the main error source of the Croche-Matic prototype (cf. section 2.3.2). The stitch formation errors result from this problem because the crochet needle is moved by the machine by identical increments to fixed positions at each needle, which holds a stitch, to be inserted there. However, the center of the working stitch's clearance is not always in this position.

According to the systematic approach of the TRIZ method, this definition of the problem is followed by the search for solutions on an abstracted, generalized level to reach the described goal. A wide variety of methods can be used for this purpose [181]. Here, the so-called *feature transfer* is selected, in which the question is pursued whether there are already better solutions for similar functions that can be transferred to the existing problem [182].

In this regard, the loop transfer of a V-bed knitting machine (cf. Figure 11 in section 2.2.1) is a promising and proven solution for inserting a transfer needle *a* into a loop suspended on a transfer needle *b*. There, *a* is relative to the loop on *b* at a defined position for the insertion and the clearance of the loop is also at a fixed position between the shaft of *b* and a spring clip attached to the side of needle *b*. Needles *a* and *b* are oriented at about a right angle to each other. During the insertion into the loop, needle *a* slides between the shaft and the spring clip of *b*, which is pushed to the side and spreads the loop. From this, the principle can be abstracted that for a safe insertion of a needle into a stitch, the opening of the loop is reliably located in space between two machine elements, which are in discrete positions. For the needle insertion, the yarn of the loop is moved out of the way by the machine elements.

The following possible solutions result from the consideration of the *feature transfer*:

1. Suspending a crochet stitch on a transfer needle and directly adopting the loop transfer process of V-bed knitting machines;
2. Suspending a stitch on a conventional knitting machine needle and an additional component functioning as external transfer spring clip;
3. Suspending a stitch on two conventional knitting machine needles;
4. Suspending a stitch on specially designed machine elements.

At this point, regardless of the solution variant, it is not specified whether the crochet needle requires a tapered tip as in the first crochet machine approach. It is also not specified whether compound or latch needles are used. Also, it is left undecided how the stitches are suspended on the needles with respect to their orientation. This can be done upside down as in the first approach or in the common orientation of manual crochet. However, the stitches are generally suspended in such a way that the carrying needle also hooks into the crochet needle insertion clearance shown in Figure 16 in section 2.3.1.

Suspending on transfer needles

According to the first possible solution, transfer needles with spring clips are used for all auxiliary needles in the needle bed and a stitch is suspended on each one. A potentially suitable transfer needle would be the Vo-Spec. 100.75 G 01 from Groz-Beckert (Needle-No. 167450). The crochet needle must be able to take discrete positions at each transfer needle to be inserted into the stitches. Relative to the auxiliary needles, the crochet needle can have a fixed angle of about 90°, as is common with V-bed machines, and the insertion of the yarn is done above the level of the auxiliary needles. This principal setup is illustrated in Figure 26.

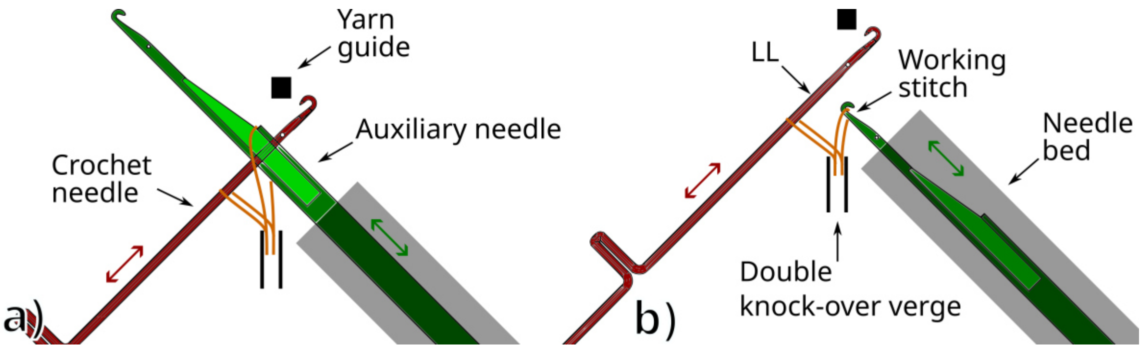

Figure 26. Setup for the possible solution of suspending the crocheted stitches on transfer needles. **a)** Insertion into the working stitch supported by the spring clip. **b)** Driving out the crochet needle above the crocheted fabric to receive a yarn over in the not inserted state.

As can be seen in Figure 26, a double knock-over verge, which is similar to the knock-over verge and a hold back bar of crochet gallon machines (cf. Figure 13 in section 2.2.3), is necessary. Without one, the crochet would be left to move excessively, and the stitches would slip down the shaft of the auxiliary needle when at resting position (cf. Figure 26 b)). It is to note, that presenting the working stitch with a transfer needle for insertion of the crochet needle results in moving the crocheted fabric.

Arranging the crochet needle at a fixed angle relative to the bed of auxiliary needles has advantages. On the one hand, no further movements are necessary to allow the yarn over regarding the inserted crochet needle. This was necessary in the first crochet machine approach, where the crochet needle is arranged parallel to the plane of the auxiliary needles, which need to be lowered before the yarn can be placed in the crochet needle (cf. section 2.3.1). On the other hand, the crochet hook can be driven above the crocheted fabric to perform a yarn over in the uninserted state, which is necessary for creating SCs and HDCs. This can be done simply when the auxiliary needle is in the standard, not extended position as depicted in Figure 26 b). A disadvantage is that the transfer needle with the working stitch must extend slightly to lift it, so that the insertion of the other needle is facilitated, as shown in Figure 26 a) or Figure 11 in section 2.2.1.

Suspending on a conventional needle and an external spring clip

By separating the spring clip from the needle and using another machine element for it, the angle required between the crochet needle and the auxiliary needles is less restricted. This allows a more obtuse angle, which favors the insertion of the crochet needle in the working without the necessity of lifting it by the transfer needle. If the yarn guide is located under the auxiliary needle bed and the crochet needle is inserted from above in an angle, the stitch can be conveniently positioned with the support of a knock-off edge. The corresponding setup is illustrated in Figure 27.

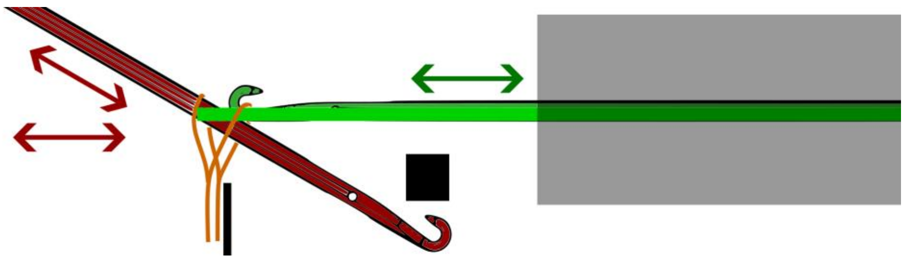

Figure 27. Schematic illustration of inserting the crochet needle diagonally from above in a working stitch suspended on a conventional knitting machine needle with an external spring clip in form of a simple elastic beam. Here a simple knock-over verge is used.

However, a disadvantage is that in addition to using a conventional knitting machine needle, a suitable machine element as an external spring clip must be developed. This could be a flexible beam which is located next to the auxiliary needle and is pushed to the side by the crochet needle in a similar way to the spring clip of the transfer needle. For developing such a motion sequence, CAD was used, which is a common innovation technology for virtual product or process development [179].

Due to the difficulties of simulating the yarn, it was omitted for the animation illustrated by Figure 28. While inserting the crochet needle, the flexible beam is pushed aside, and the clearance of the working stitch as ideal insertion point is spread. After yarn over for placing another loop in the hook of the crochet needle besides the LL, the crochet needle is retracted and positioned for the final yarn over. For this, while the auxiliary needles are extended, the crochet needle is inserted at the right side of the flexible beam belonging to the second auxiliary needle. Thus, the beam is pushed to the other side and the crochet needle is not inserted into any stitch but is behind the imaginary crochet to receive the final loop, which is going to be drawn through the two other loops on the crochet needle's shaft.

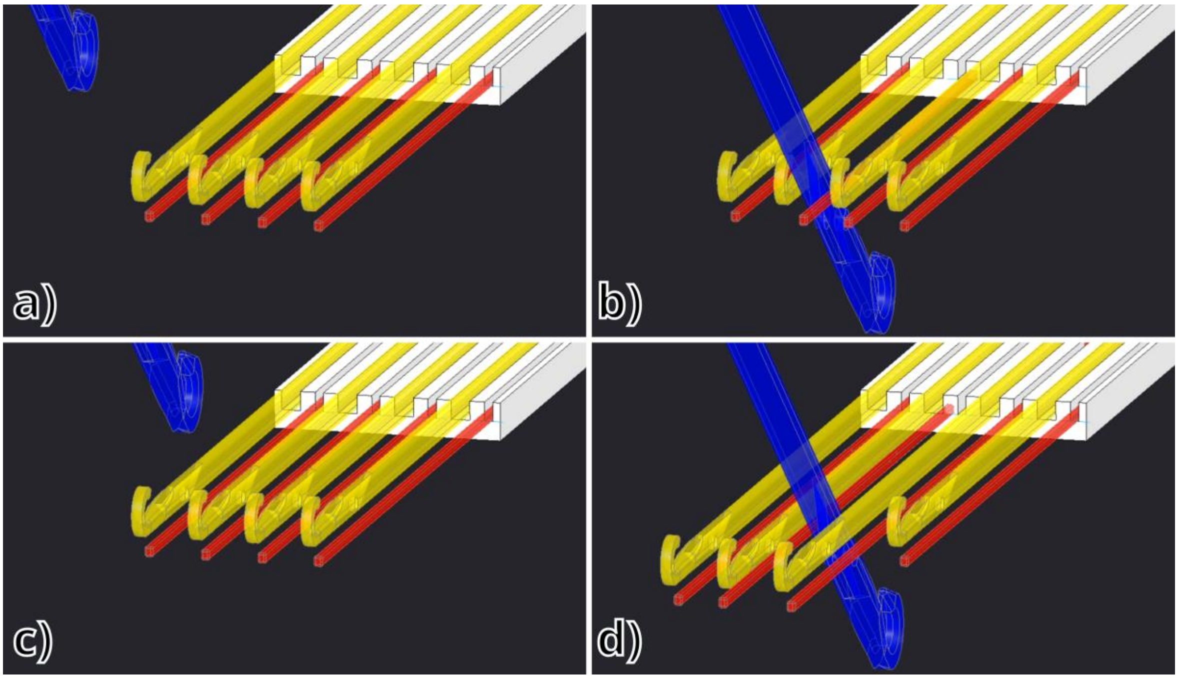

Figure 28. Snippets from an animation of building a SC with a flexible beam (red) at the right side of each conventional latch needle (yellow) as auxiliary needle. The animation was done with Creo 4.0 from PTC Inc. **a)** The crochet needle (blue) is positioned to be inserted in the imagined working stitch suspended on the second auxiliary needle and flexible beam. **b)** Inserting the crochet needle while pushing the flexible beam aside. **c)** Retraction of crochet needle after yarn over. **d)** Extending the crochet needle for the final yarn over at the flexible beam's right side.

Regarding the motion of the fundamental machine elements depicted in Figure 28, the crochet needle is inserted behind the crocheted fabric by moving the needles and beams, on which it is suspended, forward. Such a movement of the textile is unfavorable with regard to a reliable machine operation. A better alternative is the movement of the crochet needle towards the needle bed for driving it out along its longitudinal axis behind the crocheted textile.

Suspending on two conventional needles

By replacing the flexible beam with a second conventional latch needle, the third possible solution for improving the crochet needle insertion process can be implemented. This arrangement also allows to insert the crochet needle from diagonally above in stitches suspended on horizontal auxiliary needles. Compared to the second solution variant, the advantages arise that conventional textile machine elements can be used and that mechanical contact of these associated with wear is not necessary. However, crochet stitches are potentially larger because they are suspended on two elements with a fixed spacing.

As can be seen in Figure 29, the optimal insertion point is always between the two latch needles bearing the working stitch. Even if the fabric is moved, the spanning over two needles ensures that the clearance of the working stitch is in the same position between the needles. It can also be seen in Figure 29 that the CHs are suspended differently than in Figure 25 in section 3.1.4. The topology of the stitches remains the same, only different segments are placed over the needles. Here, their orientation results from crocheting the stitches directly onto the needles. The respective shape of the stitches is similar to the SLs from the first crochet machine approach (cf. Figure 16), but the stitches are inverted and therefore oriented as in manual crochet. This method of suspending the CHs fits better with the subsequent courses and is therefore kept for the further course of the work.

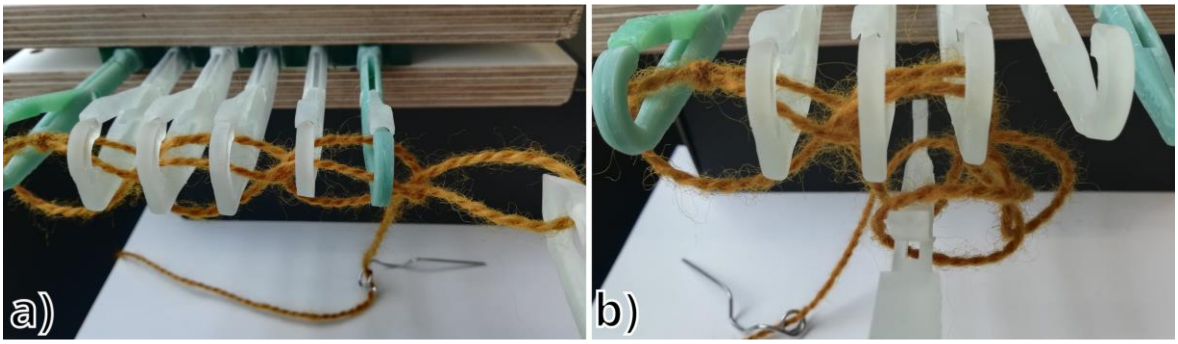

Figure 29. Principle of suspending crochet stitches on two conventional needles. **a)** The resulting structure of the first CH course. **b)** Crochet needle being inserted diagonally from above with the leading loop (LL) slipped on the shaft and a new loop placed in the hook of the crochet needle by a yarn over.

Suspending on special machine elements

Special machine elements, which resemble the minimum requirements for holding the crochet stitches and which can be FDM printed easily, were developed. These are the auxiliary bars depicted in Figure 30. The crochet stitches, which are suspended on two auxiliary bars similar to the third possible solution, are placed in the bars' recesses. The elongated tips of the bars as well as a double knock-over verge, which is used here again (cf. Figure 31), prevent undesired slipping of the stitches.

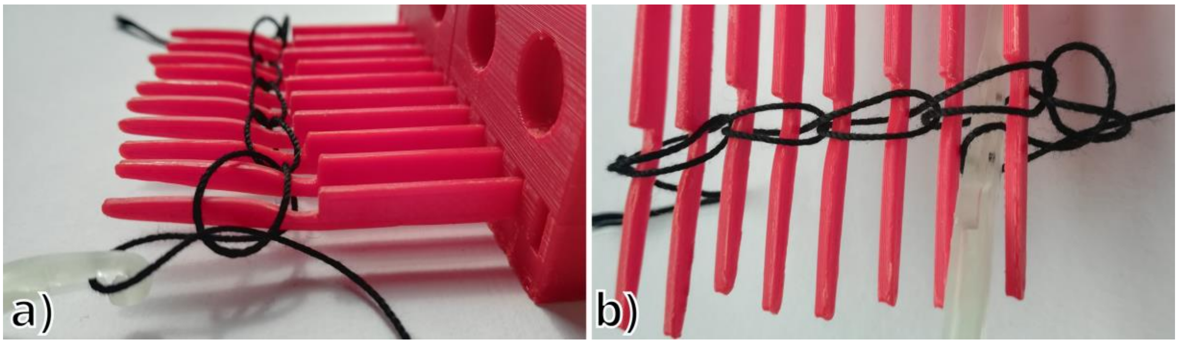

Figure 30. Possible solution of suspending crochet stitches on two auxiliary bars as special machine elements. **a)** Side view of the bars and of the hook of the downsized crochet needle. **b)** Slanted insertion of the crochet needle in a working stitch.

The auxiliary bars and crochet needles shown in Figure 30 are scaled only two times compared to the size of typical machine elements, rather than five times like the needles in Figure 29. This reduction in the size of the model is a necessary development step for the subsequent use of more refined models. Due to the simple manufacturing of the auxiliary bars, they are particularly suitable for further test runs.

As illustrated in Figure 31, moving the crochet needle nearer to the needle bed allows for yarn overs in the uninserted state, which are required for SCs and HDCs. Also, the compound needle with open and closed slider used as the crochet needle can be seen. Such a compound needle is assessed to be more suitable than a latch needle, due to the possibility of opening or closing it at any time and the elimination of the risk of a latch getting caught in the loops of the textile.

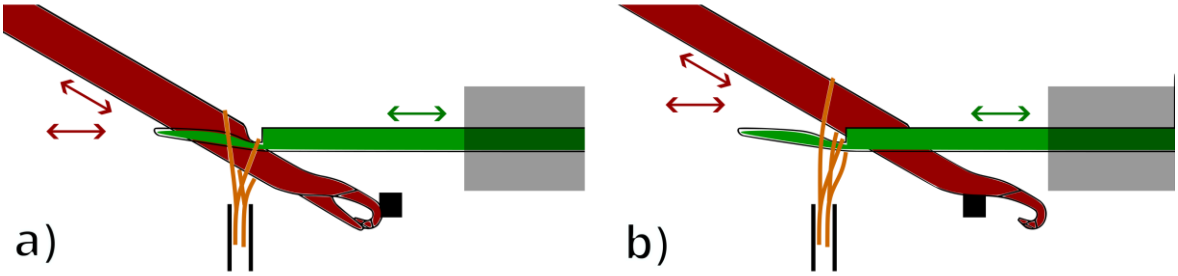

Figure 31. Schematic arrangement of fundamental machine elements with auxiliary bars to suspend the crochet stitches and with a compound needle as crochet needle. **a)** Crochet needle is inserted into the working stitch between two auxiliary bars. **b)** Crochet needle is moved further to the needle bed to be extended behind the crocheted textile for a yarn over in the uninserted state.

Further tests for selecting a solution

Regarding the selection of the ideal solution for the crochet needle insertion process, further test runs are necessary. On the one hand, this is due to the fact that all four solutions presented provide safe insertion of the crochet needle into the working stitch. On the other hand, the manual movement of the fundamental machine elements offers little reliable information about the suitability of the implementation in a machine. Therefore, the first prototypes and models are refined for further test runs before a final decision is made on the method of inserting the crochet needle into a working stitch.

Due to the mentioned advantages concerning RP, the fourth solution variant is chosen as starting point for the prototype refinement and additional trials. In this regard, the principal arrangement of the fundamental machine elements as depicted in Figure 24 in section 3.1.4 is transferred to a construction of aluminum extrusion profiles. The crochet needle is SLA printed and the auxiliary bars are FDM printed, which is known for producing functional parts with a decent quality [146]. In this specific prototype iteration, shown in Figure 32, the machine elements as well as the yarn are still moved by hand, but the linear guiding restricts especially the movement of the crochet needle. Fredric Meyer contributed to the construction of this iteration under supervision of the author as part of his employment in the *HaekelMasch* project.

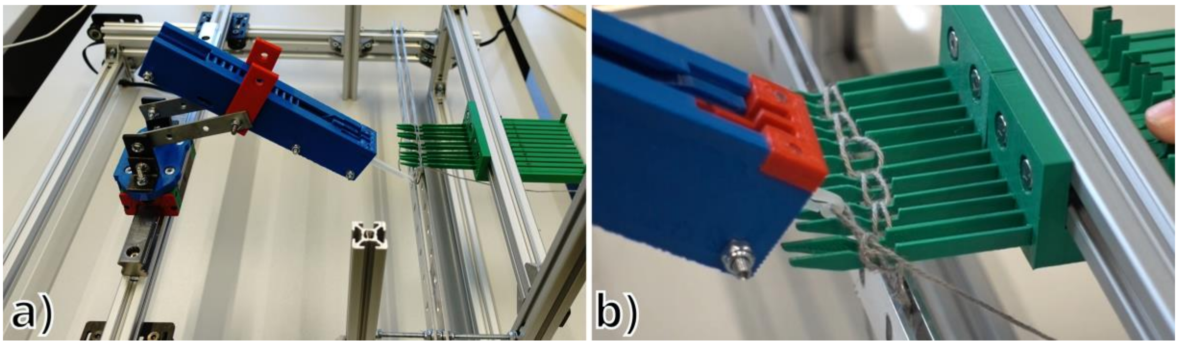

Figure 32. Refined prototype according to the fourth possible solution with auxiliary bars and 3D printed machine elements moved by hand in linear guides. **a)** Overview of the construction. **b)** CHs suspended on the auxiliary bars as special machine elements.

The slider or opening of the crochet needle is oriented downwards, as can be seen in Figure 31 and 32. This is necessary to improve the slipping of the LL onto the shaft of the crochet needle while it is inserted into a working stitch. Once the crochet needle passes the plane of the auxiliary needles, sideways and upward oriented forces act on the LL because it is placed over the auxiliary needles. As shown in Figure 33, this results in the LL sliding upwards on the hook of the crochet needle. To keep the LL on the crochet needle, the shaft must be positioned accordingly at the upper end of the hook, where the LL moves towards.

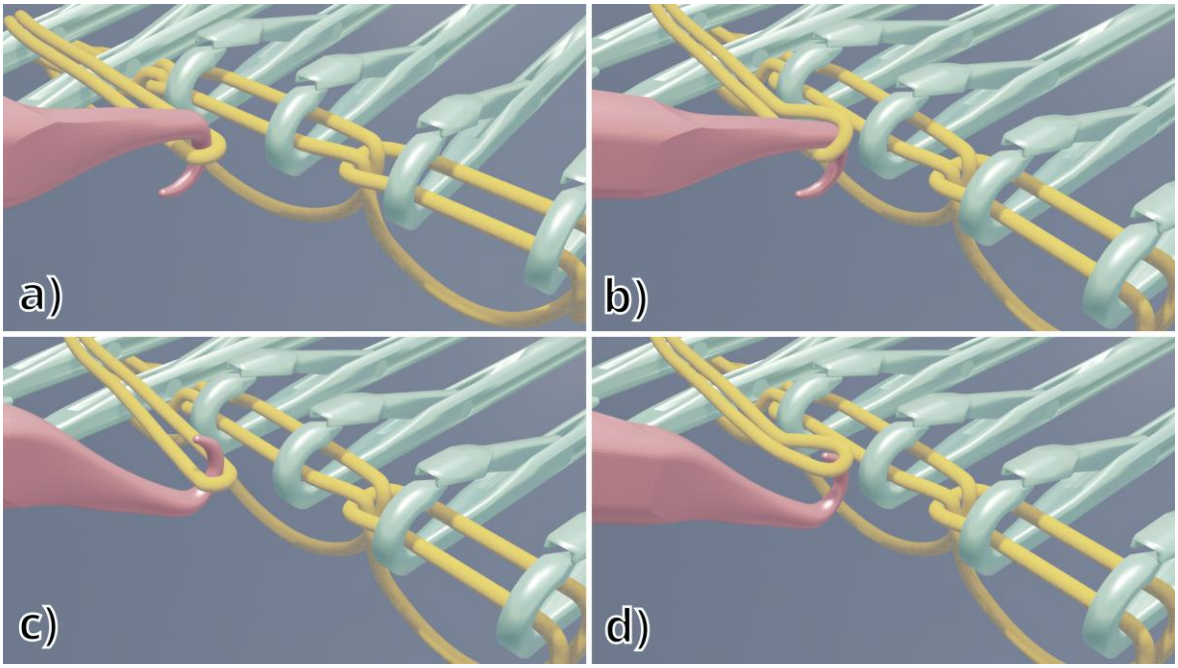

Figure 33. Inserting the crochet needle in a working stitch suspended on two conventional knitting machine needles. **a)** Slider and opening of the crochet needle's hook are oriented downwards. **b)** By extending the crochet needle along its longitudinal axis, the LL slips correctly onto the shaft. **c)** Slider and opening of the crochet needle's hook are oriented upwards. **d)** The LL slips off the crochet needle over its hook while inserting it into the working stitch.

However, the chosen orientation of the slider and opening of the crochet needle downwards, as it is schematically shown in Figure 31 b), leads to difficulties in extending it behind the crocheted textile. Due to moving the crochet needle above the plane of the auxiliary needles towards the needle bed, the LL tends to slip towards the open end of the hook (cf. Figure 34 a)) preventing it from slipping onto the shaft when the needle is extended. With the crochet needle rotated 180°, significantly fewer errors occur when extending behind the crocheted fabric. Nevertheless, as can be obtained from Figure 34 b), guiding the LL onto the crochet needle's shaft is not sufficiently ensured. From the situation shown in Figure 34, the LL may also slip off the needle over the hook.

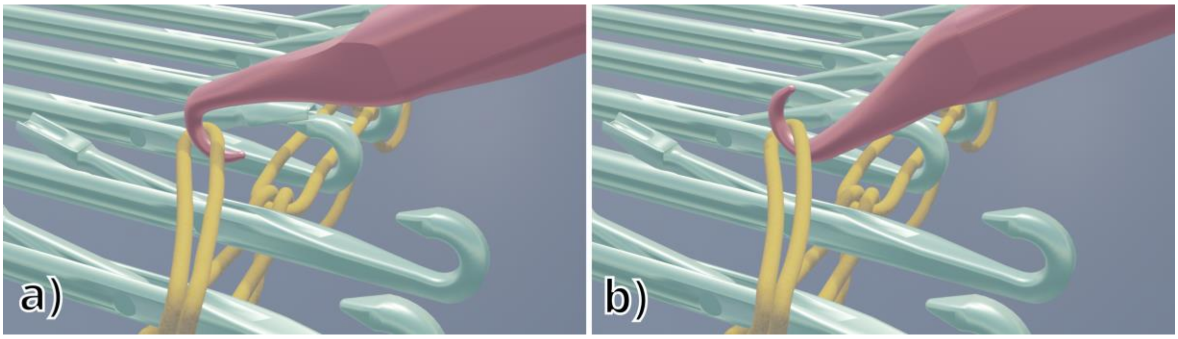

Figure 34. Situation of extending the crochet needle behind the textile with the opening of the hook facing downwards (**a**)) and upwards (**b**)).

To ensure deterministic and secure sliding of the LL on the shaft of the crochet needle during extension behind the crocheted fabric, the needle must be rotated around its own axis in such a way that the force vector acting from the LL on the needle points against the opening of the hook of the needle. With regard to Figure 34 b), this requires a slight clockwise rotation of the crochet needle.

The resulting appropriate crochet needle orientation is depicted in Figure 35 a). Following this principle of rotating the crochet needle against the direction of the LL and the corresponding force vector, the reliability of insertion into a working stitch and, in general, the movement of the crochet needle without the risk of losing the LL can be significantly improved. The rotated orientation of the crochet needle before insertion into the working stitch is illustrated in Figure 35 b). Compared to a straight downward orientation of Figure 33 b), this orientation of the crochet needle further increases the reliability of stitch formation and ensures that the LL always slides onto the shaft.

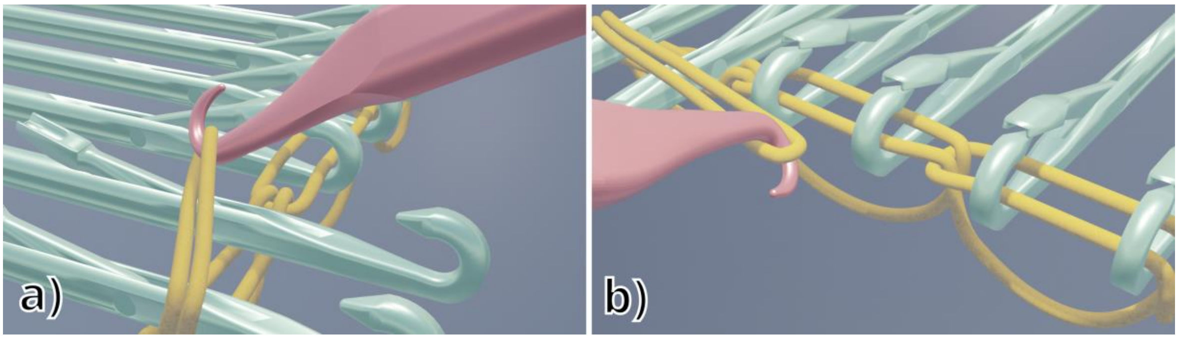

Figure 35. Rotation of the crochet needle to ensure reliable sliding of the LL on the needle shaft and preventing to lose the LL. **a)** Extending the rotated crochet needle behind the textile for a yarn over in the uninserted state. **b)** Rotation of the crochet needle while being inserted into a working stitch.

Further tests have shown that the variable rotation of the crochet needle at different steps of the stitch formation process is necessary for reproducible and reliable automation. Due to the required angled position of the crochet needle during insertion in a working stitch (cf. Figure 35 b)), the first two possible solutions for reliable insertion are rejected. When using transfer needles as auxiliary needles or a normal needle with an external spring clip in the form of a flexible beam, the crochet needle must be aligned exactly vertically with the opening of the head facing up or down. Since without the angled orientation of the crochet needle, it is not always possible to ensure error-free insertion, these variants do not meet this criterion formulated in terms of ideality. A further factor against variants 1 and 2 is that the machine elements wear out more quickly due to the necessary contact.

With regard to variant 1, it is worth noting that with the arrangement of the fundamental machine elements similar to a V-bed knitting machine, the formed stitch cannot be suspended in the way of the first crochet machine approach (cf. section 2.3.1) nor with the method presented in the following section (3.1.6). This is an additional reason for the decision against variant 1.

In order to decide between solution variants 3 and 4 for the optimal method of inserting the crochet needle, the prototype was further refined, in particular by adding a motorized movement of the fundamental machine elements. The corresponding setup with a rotation of the crochet needle, a simple yarn guide and the auxiliary bars of solution variant 4 is shown in Figure 36 a).

As can be seen in Figure 36 b), experiments revealed the problem of bending of the auxiliary bars due to the forces acting on them during automated stitch formation. Especially, the movement of the LL and its widening as it slides onto the shaft of the crochet needle provides lateral forces on the auxiliary bars which hold the previously formed stitches. Depending on the friction of the yarn on the machine elements and on itself, not enough required yarn can be delivered from the supply. As a result, the previously formed stitches contract as shown in Figure 36 b).

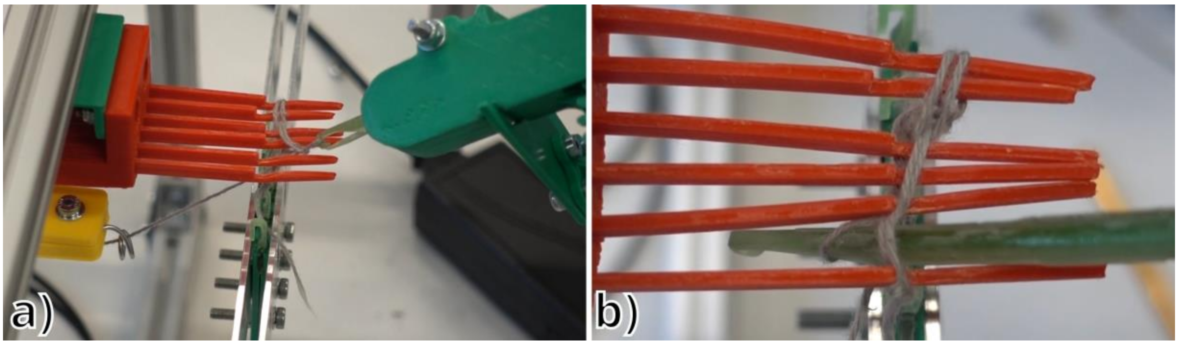

Figure 36. Extended prototype with auxiliary bars. **a)** Setup of the fundamental machine elements with rotational crochet needle and simple yarn guide as well as take-off. **b)** Bending problem of the 3D printed auxiliary bars.

On the one hand, the 3D printed auxiliary bars are not sufficiently stiff. On the other hand, unlike professional textile machine needles and yarn-carrying elements, they have too high friction coefficients. Therefore, to use auxiliary bars, it would be necessary to develop them according to industrial standards and manufacture them from metal. This effort and the associated costs are not justified against the background of the Ph.D. and the development of a cost-efficient crochet machine. As a consequence, solution variant 4 does not correspond to the defined ideality of the crochet needle insertion process, and according to the exclusion procedure, solution variant 3 has emerged as sufficiently ideal. In this case, it is particularly advantageous that commercial and proven machine elements in the form of latch or compound needles can be used.

3.1.5 Suspending stitches on auxiliary needles

Due to the selected method of secure insertion of the crochet needle with an oblique angle into a working stitch suspended on two conventional knitting machine needles as auxiliary needles, the process for suspending the newly formed stitch of the first crochet machine approach cannot be adopted. There, the working stitch is dropped from the auxiliary needle while the crochet needle is in the inserted state. Before new yarn is placed in the crochet needle and pulled through the working stitch, it is placed in the now free hook of the auxiliary needle.

With the arrangement of the yarn guide, which is currently still considered as a black box, below the level of the auxiliary needles, the simultaneity of inserting the new yarn into the crochet needle and suspending the new stitch is no longer achievable. According to the toolbox provided by TRIZ, the principle of separation, which is generally intended to resolve physical contradictions [182], is used to find a solution. The suspension of the formed stitch is separated both temporally and spatially from the insertion of the yarn into the crochet needle and is performed after the formation of a stitch. Also, dropping of the working stitch is principally performed after the formation of the new stitch. The latter is then suspended by laying its LL over the auxiliary needle pair (ANP).

Figure 37 illustrates the developed motion sequence for dropping the working stitch and suspending the new stitch on the same auxiliary needles with the example of an SL. In the situation shown in Figure 37 a), the SL has already been formed by drawing a new loop through the working stitch and through the old LL (cf. section 3.3.2 for the stitch building process).

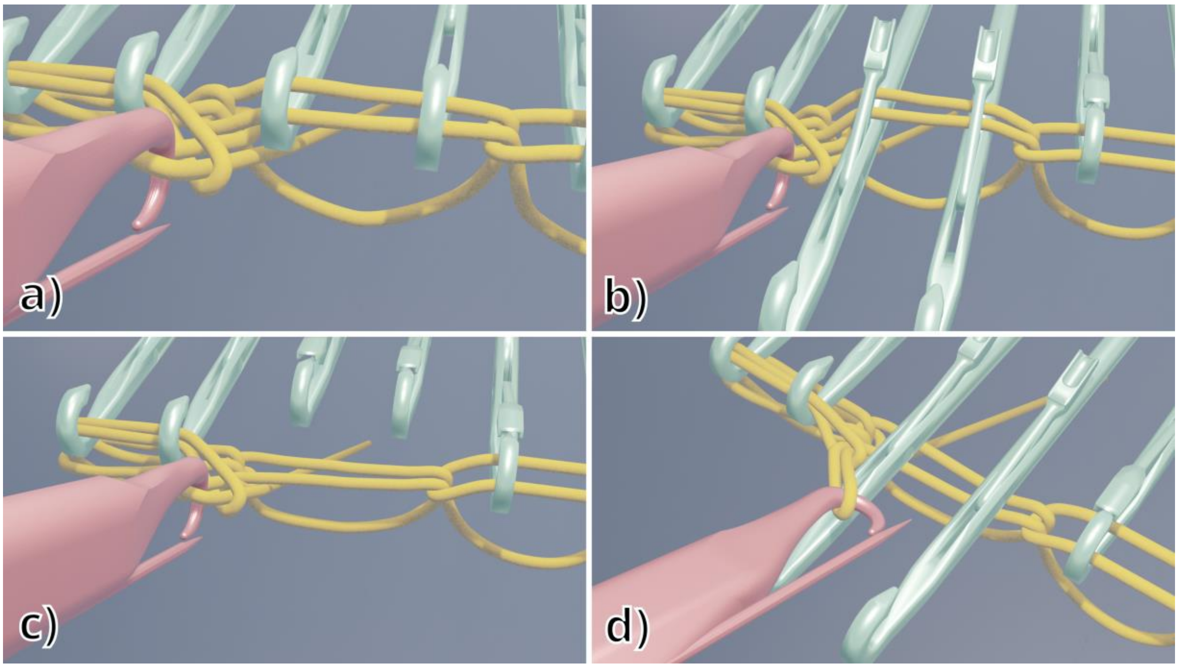

Figure 37. Developed procedure of casting-off the working stitch and suspending the new stitch on the auxiliary needle pair (ANP). **a)** Exemplary initial situation after forming a SL. **b)** Extending and retracting the ANP to let the working stitch slip on the shaft and knock it over, respectively. **c)** The working stitch is dropped. **d)** Rotated crochet needle lays the LL over the slightly extended ANP.

Before the new LL can be suspended on the auxiliary needles to secure the formed stitch, the working stitch must be dropped. To do this, the procedure familiar from weft knitting (cf. Figure 10 in section 2.2.1) is carried out with both auxiliary needles of the pair at the same time, in that they move forward to slip the stitch behind the latches onto the shafts before they are retracted. As shown in Figure 37 b), the latches of the auxiliary needles close automatically during retraction, due to contact with the stitch, so that it can slip over the hook of the needles.

After dropping the working stitch, the latches of the auxiliary needles continue to be closed, as can be seen in Figure 37 c). To subsequently place the LL over both auxiliary needles, as shown in Figure 37 d), the latches must be opened by a currently unspecified machine element. Alternatively, compound needles can be used for the auxiliary needles, which have a built-in mechanism for opening and closing the needle as required.

According to the illustration of Figure 37 d), the LL is laid over the ANP by moving the crochet needle in crochet direction perpendicular to the auxiliary needle bed and above the ANP. While doing so, as described earlier, it is rotated 90° so that the LL is positioned opposite the opening of the needle and cannot slip out of it during movement. After the LL has been placed over both auxiliary needles, they can retract to resume the standard position, and the crochet needle can be placed in front of the next working stitch to be inserted for forming the next stitch (cf. Figure 35 b) in section 3.1.5).

The presented method of laying a LL over two auxiliary needles has been established in numerous trials as the most suitable variant for suspending the newly formed stitch. It is particularly advantageous that laying the LL over a ANP is performed simultaneously with the movement of the crochet needle to the next working stitch. Another advantage is that the crochet stitches are formed in the orientation as in manual crocheting and not upside down as in the first crochet machine approach (cf. Figures 16 and 17 in section 2.3.1).

In rare cases, yarn is overlapped over two needles in warp knitting machines. In this regard, it is known that due to the joint knock-over of the needles connected via the shared overlap, great tensions are created on the machine elements and the yarn [117]. In order to ensure that the developed crochet machine variant of the overlap over two needles does not also cause such problems, more test runs with a further refined prototype are necessary. However, the overlap performed here differs from that of warp knitting on the one hand by the more complex motion sequence compared to the swinging motion (cf. Figure 13 in section 2.2.3) and on the other hand by the overlapping a whole loop. In general, laying a loop with hook and both legs over a needle is a novel method.

3.1.6 Yarn guide and patent

In order to thoroughly test the selected method of suspending the stitches on two conventional machine needles for a safe insertion of the crochet needle into the working stitch, a further refinement of the initial prototype is necessary. Especially conventional machine needles in their original size are used to test whether the overlap over two needles causes problems similar to those of a warp knitting machine. In addition, a reliable principle for inserting the yarn into the crochet hook must be found to design the yarn guide as a fundamental machine element.

The compound needle SN-N 115.118 G1 with slider SN-S 103.75 G1 from Groz-Beckert is used as the crochet needle, while the Vosata 105.83 G04 needles from the same manufacturer are used for the auxiliary needles. The latches of these are opened by a slanted brush when the needles are extended again to allow the LL to be laid over after the working stitch has been dropped (cf. section 3.1.6). With a simple weight as take-off, the crocheted textile is passed between the double knock-over verge. This setup of the refined initial prototype is depicted in Figure 38.

Yarn guide

Figure 38 shows also that the yarn guide, for which a simple punched sheet is used here, can be adjusted in height in addition to being moved transversely to the auxiliary needles. This additional, vertical axis of movement is necessary to ensure safe insertion of the yarn into the hook of the crochet needle for the different stitch types. The insertion process with regard to SLs is shown in Figure 38 and has similarities to an overlap on warp knitting machines (cf. Figure 13 in section 2.2.3).

The vertical movement of the yarn guide is particularly necessary for secure yarn overs in forming SCs and HDCs. There, the opening of the crochet needle hook faces downwards when it is inserted into a working stitch, while it is oriented upwards when the yarn over is performed in the uninserted state (cf. Figure 35 in section 3.1.5).

For the less complex SC, it is necessary to draw a first loop only through the working stitch and not also directly through the LL. This is because a loop from another yarn over, this time in a non-inserted state, must then be pulled through both the loop that emerges from the working stitch and the LL (cf. Figure 2 b) in section 2.1.1). Therefore, the crochet needle cannot be inserted into the stitch as with SLs, because during the SL crochet needle insertion, the LL slips out of the hook on the crochet needle's shaft and the newly grabbed loop is automatically pulled through the LL when the crochet needle is withdrawn from the working stitch.

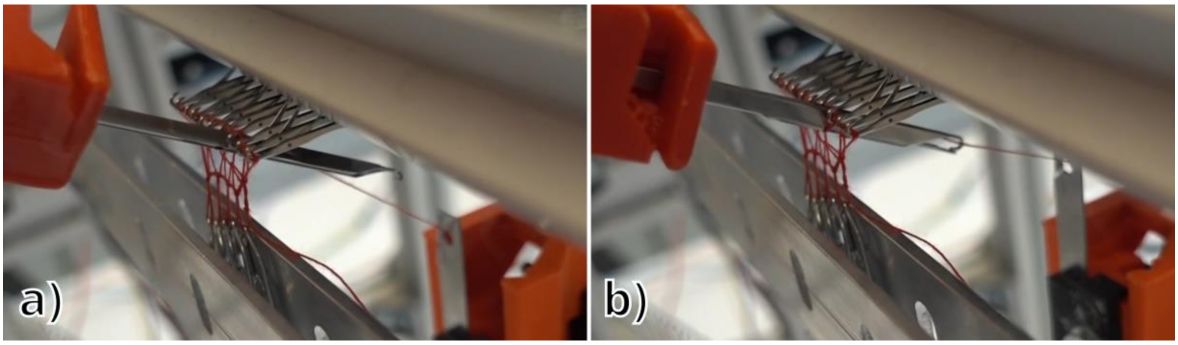

Figure 38. The fundamental machine elements of the refined initial prototype forming a SL. **a)** During insertion in the working stitch of the crocheted fabric, the LL slips on the shaft of the crochet needle, which can receive a new loop. **b)** The yarn guide moves the yarn in crochet direction under the crochet needle and rises to firmly place the yarn in the open hook. After closing the hook, the crochet needle is retracted to draw the yarn, which becomes the new LL, through the working stitch.

To prevent this and allow SCs to be formed, the LL must not slip onto the shaft when the needle is inserted into the working stitch. This is made possible by keeping the slider slightly closed while the crochet needle is inserted into a stitch to keep the LL in the hook of the needle, as shown in Figure 39 a) and b).

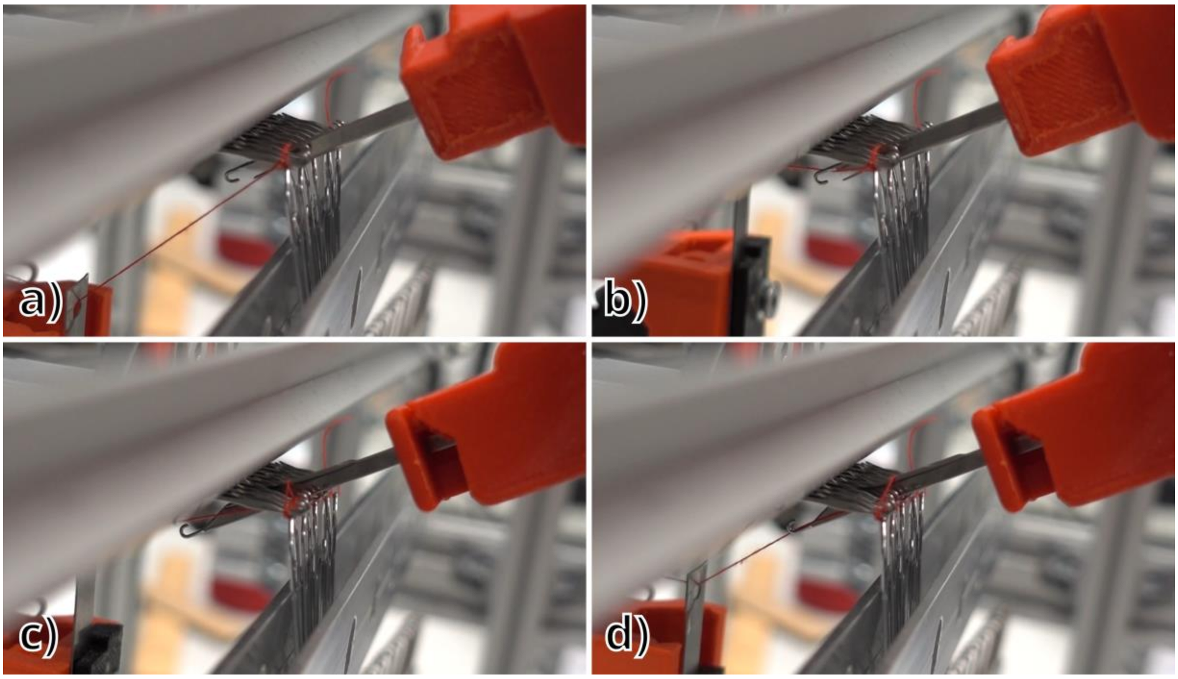

Figure 39. Placing yarn in the crochet needle with the refined prototype to form a SC. **a)** Crochet needle is inserted in a working stitch with half closed hook to prevent the LL from slipping on the shaft. **b)** The yarn guide is moved upwards after it moved past the crochet needle in crochet direction, to lay the yarn in the half open hook. **c)** Before the second yarn over in the uninserted state is performed, the crochet needle is extended behind the crocheted fabric with a fully open hook. **d)** The yarn is placed in the crochet needle's hook by an overlap in crochet direction.

In Figure 39 c) and d), it is demonstrated how the yarn over is performed in the uninserted state of the crochet needle. Here, the LL and loop of the first yarn over are intended to slip onto the shaft when the crochet needle is extended, which is why the hook is fully open. The yarn is passed in crochet direction over the open hook of the crochet needle, before the yarn guide is lowered to force the yarn into the crochet needle's hook. This has again similarities to an overlap performed by a warp knitting machine. However, instead of a swinging motion, the yarn guide is moved successively upwards, then in crochet direction and lastly downwards.

Patent

With this structure of the refined initial prototype, it becomes possible for the first time to automatically create SLs, SCs, HDCs as well as turns (with CHs) on the basis of a chain line. According to the requirements defined in section 3.1.3, the crochet needle is inserted under the two legs of the top loop, as the most common insertion point (see Figure 4 a) in section 2.1.1). The stitches are formed in the orientation of the manual crocheting and not upside down, as in the first crochet machine approach (cf. section 2.3.1). This is achieved by using conventional knitting machine elements for suspending the stitches and holding the LL. In addition to these requirements, which can be interpreted as fulfilled, the further elementary requirement of a robust stitch formation process is partially fulfilled, insofar as the process is more robust than with the first crochet machine approach, but still needs to be further optimized.

At this stage of development, the German patent ("Verfahren zum maschinellen Häkeln und Häkelmaschine", 10 2022 108 119.2) was filed in joint work with the HSBI and project partners. According to Koltze and Souchkov, such a protection of the IP is part of an industrially oriented innovation process [179]. The patent with a focus on the developed motion sequences of the fundamental machine elements marks the end of the concept phase of the innovation process. However, this patented version of the prototype crochet machine developed in this work does not yet represent the final state of the prototype designated as CroMat.

Problems regarding excessive tension on the yarn and machine elements due to suspending a stitch over two auxiliary needles have not occurred with the patent-registered prototype. In particular, the dropping of the common stitch simultaneously by both needles, which is considered critical in warp knitting machines [117], has not led to any problems here. Instead, during the tests continued after the patent application, a problem arose with regard to inserting the crochet needle into a stitch with the half-open slider (cf. Figure 39 a)).

3.2 Improvements beyond the patent

Regarding the patent-compliant prototype, there is a problem of reliably inserting the crochet needle into the working stitch to draw a loop through it while keeping the LL in the hook of the crochet needle. Against this background and the goal of an ideal stitch formation process with the lowest possible error rate, it is therefore necessary to solve this problem. Developing a respective solution can be classified according to the model of the phases of the innovation process (cf. Figure 23 in section 3.1.1) as the first step of the development phase. Since the basic structure of the initial prototype is optimized by improving the machine with respect to a more robust stitch formation process. In this regard, the developed stitch formation motion sequences and their technical implementation in the prototype mutually influence each other.

The problem of the prototype and the motion sequences of the patent regarding the first yarn over for SCs is described in section 3.2.1. Section 3.2.2 deals with the systematic search for a solution and section 3.2.3 describes its implementation and the resulting improvement of the prototype.

3.2.1 Analyzing the yarn feeding problem

The problems of inserting the crochet needle with a half-open slider into a working stitch during the formation of SCs are caused by the LL being caught between the slider and the needle shaft when the needle is driven out along its longitudinal axis. Due to this jamming, not enough yarn can be fed as the crochet needle advances further and the tension on the yarn becomes very high, which often leads to breaking the yarn. This occurs especially when coarser yarns than a sewing thread are used.

Figure 40 shows the respective situation of inserting the crochet needle with a half-closed slider. When the crochet needle is extended, the LL slides in the hook of the needle to the point where the shaft and slider meet (cf. Figure 40 a)). To be able to extend far enough to perform the yarn over, the LL must be lengthened, and the yarn must slide across the point of contact between the shaft and the slider. In case of friction being too high there, this will not succeed and the yarn will jam. One cause of high friction is that the slider is slightly pushed away from the shaft by the yarn slipping into the narrow spot. The point where yarn jamming starts to become critical is shown in Figure 40 b). If the needle is moved further with jammed yarn, either the yarn will break or the needle movement will be hindered, which can damage the machine parts.

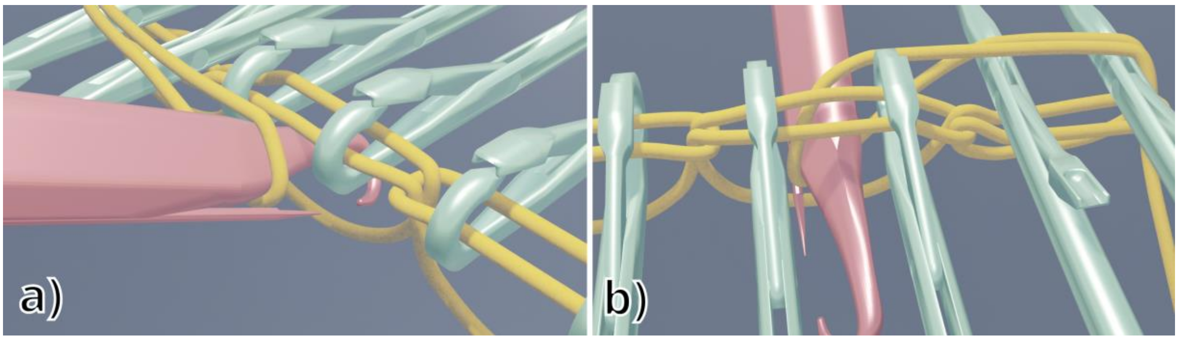

Figure 40. Inserting the crochet needle into the working stitch with half closed hook to retain the LL. **a)** Due to extending the crochet needle along its longitudinal axis, the LL slides to the contact point between slider and shaft. **b)** From this point on, it becomes problematic that the yarn is trapped between the slider and shaft.

A spontaneous idea for a solution would be to allow the LL to slide onto the crochet needle shaft when it is inserted into the working stitch, and then to allow the LL to slip back into the hook through an open slider when the crochet needle is retracted. To enable the LL to slip back into the hook, the slider must be open at the position where the hook of the crochet needle passes the clearance of the working stitch. In this case, however, there is a high probability that the hook of the crochet needle will get caught in the yarn of the working stitch. To prevent such entanglement, the slider must be closed at this point, but this causes the LL to slip over the hook when the crochet needle is retracted. Here, a systematic approach for creating a solution for the first SC yarn over is appropriate to avoid wasting further development resources.

3.2.2 Systematic identification of possible solutions

TRIZ provides such a systematic approach starting with the formulation of a contradiction with conflicting requirements on the system to address the underlying problem [182]. Here, a contradiction can be formulated that the crochet needle must simultaneously keep the LL in its hook by half closing the slider and must be inserted in the working stitch to allow for the yarn over in the inserted state. The crochet needle cannot do reliably both because the yarn often becomes jammed between slider and shaft resulting in high tensions that cause it to break or impair the function of the machine elements. This worsens the stresses on the machine elements and the yarn.

However, at the same time, the complexity of the system is very low, because drawing a new loop through the working stitch can be done by the crochet needle, and no further machine elements are required. Thus, the arrangement of the fundamental machine elements remains simple and the necessary motion sequences can be theoretically carried out swiftly. It is thus also possible to formulate a more general contradiction between the requirements that on the one hand the complexity of the stitch formation should remain low while on the other hand stress on the machine elements and the yarn should be avoided.

The ideal inventive solution is to overcome a contradiction by fulfilling both requirements without making any compromises [182]. The way to such a solution is systematically prepared by relying on innovation principles that, according to the results of the underlying patent analysis, have already solved similar problems in the past [182]. It is important that this is achieved on an abstracted level and that the conflicting requirements are generalized accordingly. The generalized requirements can then be assigned to an appropriate row and column of the contradiction matrix, which relates the contradictory requirements to possible innovation principles. Specifically, the contradiction matrix “Matrix 2003” is used here [183].

To generate possible solutions, the second, more primary contradiction is considered. The requirements are to avoid intense stresses on the machine elements and yarn, and also to keep the complexity of the fundamental machine elements required for the stitch forming process low. The improving parameter of low complexity is currently in contradiction with the deteriorating parameter in the form of the occurring tensions. The latter can be assigned to row 19 “Stress/Pressure” in the contradiction matrix “Matrix 2003”. With the improvement of the complexity of the system represented in column 45 of the matrix, it yields the following innovation principles to possibly solve the problem [183].

- Change of physical and chemical properties [182]: This principle inspires to change the material properties of the objects and to modify e.g., the elasticity, the concentration or even the state of aggregation;

- Coupling [182]: Similar or adjacent parts or functions are to be combined to couple the effect;
- Separation [182]: Here the negative feature should be removed by separating the corresponding part of the object or creating a new object with only the necessary and positive features;
- Principle of the mediator [182]: It is proposed to use a possibly new object as mediator, which temporarily transmits the required effect and can be removed afterwards, for example;
- Transition to other dimensions [182]: This innovation principle proposes to solve problems by exploiting the dimensions of space and, for example, arranging objects differently.

Change of physical and chemical properties as well as coupling

A change in the chemical and physical properties is not beneficial regarding the present problem. On the one hand, the given material properties of the needles are necessary so that they can fulfill their tasks in the crochet machine. On the other hand, a change in the material properties would contradict the requirement for the machine to use conventional machine elements. The innovation principle of coupling also does not provide suitable solutions because the problem to be solved lies already in the coupling of the tasks of holding the LL and drawing a new loop through the working stitch (first contradiction).

Separation and principle of the mediator

In contrast to the coupling, the separation offers a more suitable solution. Following this principle, the tasks of holding the LL in the hook of the crochet needle could be separated from the insertion and drawing through of a new loop using two different machine elements (first contradiction). For example, a machine element could be added which holds the LL while the crochet needle fetches the new loop, and which then transfers the LL back to the crochet needle. Alternatively, the crochet needle could stand still and hold the LL in its hook while an added machine element receives the yarn over and moves the resulting new loop through the working stitch before transferring it to the crochet needle. This approach is illustrated in Figure 41. The solution idea would also comply with the principle of the mediator, because a new object would be introduced that would temporarily take over one of the two conflicting tasks.

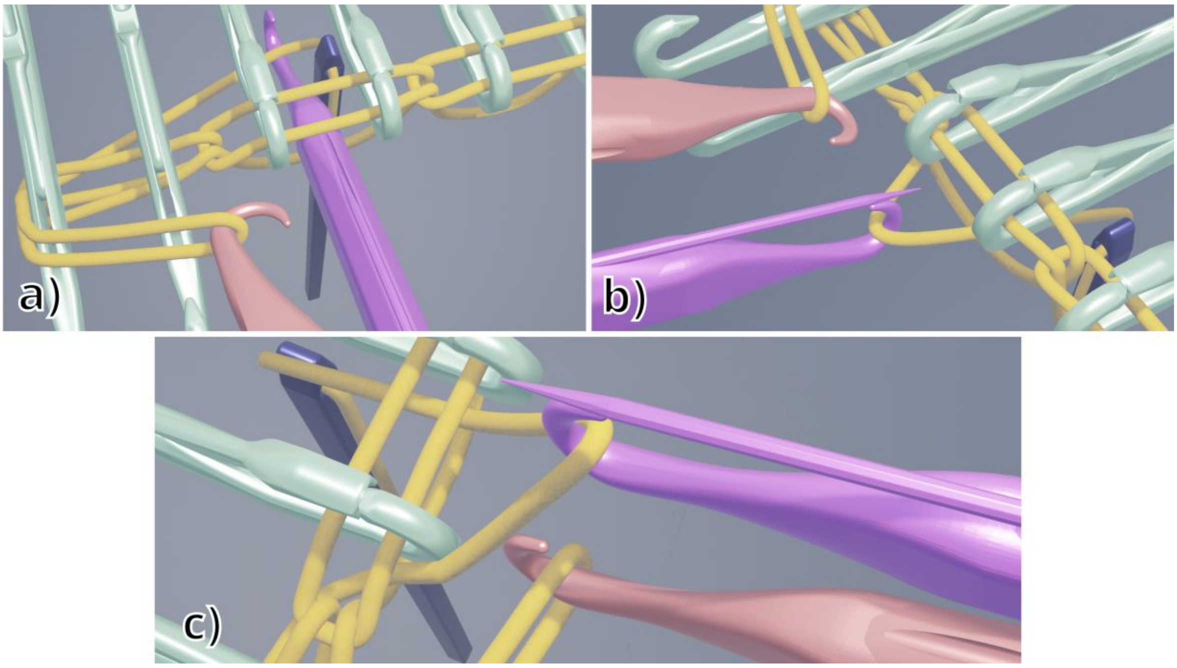

Figure 41. Illustration of the solution approach of drawing the loop of the first yarn over in creating a SC through the working stitch by an additional purple needle. **a)** The purple needle is inserted into the working stitch to receive the yarn over, while the crochet needle stands still and holds the LL. **b)** The new loop is drawn through the working stitch and must be past to the crochet needle. **c)** The purple needle is lifted to allow the crochet needle to grab the new loop with the hook, which is with the positions of the needles not possible.

According to the illustration of the approach of using another needle as a mediator in Figure 41, the problem in the transfer of the new loop becomes apparent. Thus, starting from Figure 41 c), the purple needle would have to be moved further up and additionally in crochet direction, so that the crochet needle can reach into the new loop. Afterwards, the purple needle has to cast off the new loop, which makes further movements necessary. In addition to requiring complex movements, another problem related to the technical implementation is that the linear guides will need space and thus the two needles probably cannot be moved that closely alongside each other as depicted in Figure 41 c). For the transfer of the new loop, it would be more practical if the additional machine element for moving the yarn was located on the other side of the textile in the area of the yarn guide. However, in this case, a needle would not qualify for such an element, because needles can only pull yarn and not push it.

Generally, the addition of another object contradicts the requirement for low complexity of the system. This is because an additional machine element for solving the task would necessitate additional components and motion axes. Also, the complexity of the motion sequences would be increased because an additional transfer of the LL or the new loop between crochet needle and the new machine element would be required. Thus, the low complexity property of the system, which is the improving parameter of the second contradiction, would be restricted. These possible solutions would therefore only lead to a compromise, which is not an ideal inventive solution according to TRIZ [182].

Transition to other dimensions

According to the last innovation principle generated from the second contradiction, another solution approach consists in a different spatial arrangement of the objects (transition to other dimensions). At first glance, a change in the arrangement of the machine elements seems unsuitable because their current arrangement is necessary to execute the various steps for forming the different stitch types. Thus, changing the arrangement in order to better execute the currently problematic process step inevitably results in hindering other process steps. However, this problem can be overcome according to the principle of the mediator by moving the machine elements to a different arrangement only temporarily, namely only to fulfill the current problematic process step.

The spatial arrangement of the LL cannot be changed without adding another machine element. Changing the arrangement of the crochet needle, e.g., a different angle to the auxiliary needles, cannot avoid the problem of the yarn jamming when it is inserted into the working stitch with the slider half-closed. Arranging the auxiliary needles differently so that the working stitch is effectively moved towards the crochet needle in order to insert the needle into the working stitch without moving it would be cumbersome and unfavorable, because the textile being produced should not be moved.

As the last fundamental machine element, the yarn guide can be arranged differently. Similar to the idea formulated above of using another machine element to move the new loop through the working stitch and transfer it to the crochet needle, the yarn guide can be used directly for this purpose. To do this, it must be temporarily arranged so that it can be inserted into the working stitch like an additional machine element. While the yarn guide is in the inserted state, the yarn over can then be performed at the front side of the fabric. In this way, the crochet needle holds the LL without problems and the loop of the first SC yarn over is moved through the working stitch. If the yarn guide is returned to the initial position after this process step, other process steps are not affected by this operation.

The disadvantage of this approach is that additional movements are necessary to spatially rearrange the yarn guide for this process step of feeding the new loop from behind through the textile. However, experiments have shown that this change of arrangement only requires a rotation of the yarn guide, which can be implemented by one additional movement axis. The shape of the yarn guide must be such that the eyelet can be passed through the working stitch.

3.2.3 Implementation of the most suited solution

Using the yarn guide to solve the problem of the first SC yarn over and both contradictions (cf. section 3.2.2) offers the great advantage that no further machine elements are required and therefore the complexity is only minimally affected. Also, the yarn guide is responsible for moving the yarn and feeding it to the crochet needle anyway, so it is appropriate to extend its possibilities in that the yarn can also be fed through the textile. Another advantage is that there is sufficient space below the auxiliary needle bed to install the additional motion axis for rotating the yarn guide easily. Moreover, passing the yarn from the back side through the textile allows a more straightforward placement of the new loop in the crochet needle compared to the solution variant shown in Figure 41 in section 3.2.2.

For the yarn over to form the new loop while the yarn guide is in the inserted state, it is necessary for the crochet needle to move relative to the yarn guide. This is because the freedom of movement of the yarn guide in the inserted state is just as restricted as for the crochet needle in the similar state. The principle of yarn feeding can be considered reversed for this process step, as the yarn with its guide remains stationary for a short time while the needle is moved (cf. section 3.1.7 and reference 184).

The principal arrangements and movements of the fundamental machine elements according to the developed solution concerning the first yarn over of a SC are illustrated in

Figure 42. For a SC, the first loop must be drawn through the working stitch but not through the LL (cf. Figure 2 b) in section 2.1.1). The loop for this first yarn over is moved by the yarn guide through the working stitch.

Similar to the photographs in Figure 39 in section 3.1.7, the arrangement of the yarn guide according to the patent is shown schematically in Figure 42 a). From this position it can be rotated, as shown in Figure 42 b), to enable the insertion into the working stitch from behind. The yarn guide in the inserted state is shown in Figure 42 c). The new loop is not yet formed, but the corresponding yarn segment is offered to the crochet needle. As shown in Figure 42 d), the crochet needle can catch this yarn segment by moving under it. If the yarn guide is now retracted, the yarn segment caught by the crochet needle forms the loop of the yarn over. This loop was thus passed through the working stitch by the yarn guide. Afterwards, the yarn guide can rotate back to the initial orientation.

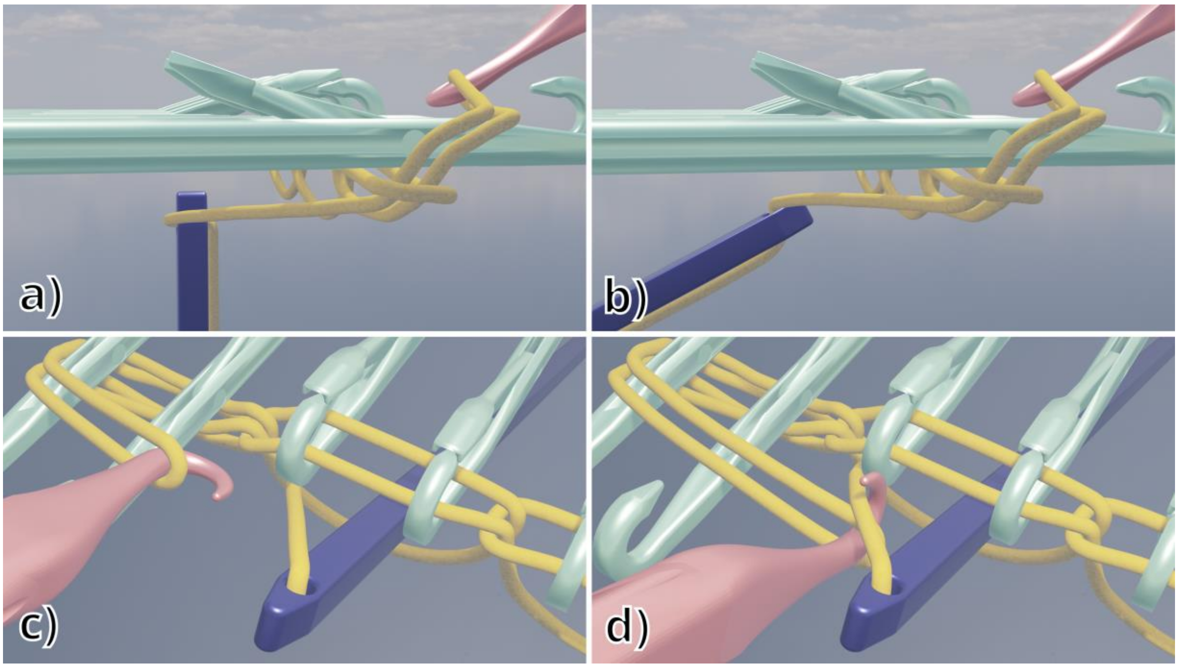

Figure 42. Demonstration of the developed solution for the problem of placing a new loop, which is to be drawn through the working stitch, in the hook of the crochet needle while keeping the LL in the hook. **a)** Initial situation with a yarn guide oriented vertically. **b)** Allowing the yarn guide to rotate, so it can be inserted in the working stitch from behind. **c)** Yarn guide feeds the yarn to the face of the crocheted fabric, to enable the crochet needle to grab it. **d)** Placing the yarn segment, which becomes the new loop, next to the LL by moving the crochet needle.

The developed solution presented in Figure 42 enables efficient implementation of the first yarn over of a SC, because the LL can be held by the crochet needle without stressing the machine elements and the yarn while the required movement sequences can be implemented efficiently. For example, the necessary positioning of the yarn guide for insertion from behind into the working stitch can be carried out in parallel with moving the crochet needle for suspending the LL at the previous ANP.

Whether this solution of the contradictions formulated in section 3.2.2 is an ideal inventive solution according to Koltze and Souchkov lies in the estimation of the change of the system's complexity (in relation to the second contradiction) by the additional necessary rotation of the yarn guide. If a significant change is assumed, the developed solution is only a compromise, because the negative effect (the stress on the yarn and the machine elements) can be avoided only by slightly limiting the positive effect (the low complexity of the structure). In any case, the crochet machine was significantly improved by the addition of one motion axis.

By passing the yarn guide from behind through the working stitch, the formation of HDCs can also be considerably improved. This is because HDCs also require a loop to be drawn through the working stitch, but not through the LL. A similar process step with the same problems, as explained in section 3.2.1, was necessary for this stitch type. In addition, for HDC, a yarn over must be performed with a loop that is not pulled through the fabric nor through the LL. This can be achieved now by extending the yarn guide behind and above the fabric (cf. section 3.3.4).

Furthermore, the added rotational axis of the yarn guide improves the yarn over operations in general. This is because the eyelet of the yarn guide can be moved closer to the hook of the crochet needle, which makes the insertion of the yarn much more secure. Thus, the yarn overs become more similar to the swinging motion for overlaps on warp knitting machines. The yarn guide is now mostly used in the angled arrangement and not at a right angle to the horizontal as described in the patent.

In accordance with the development phase of the innovation process according to Koltze and Souchkov, the design of the prototype and the motion sequences of the fundamental machine elements were optimized with the yarn guide improvement described in this section. In particular, the implementation of this improvement differentiates the CroMat prototype from the initial prototype described in section 3.1.7. This is because the CroMat prototype is characterized by a corresponding yarn guide that can feed yarn through a stitch from behind. Thus, the CroMat prototype represents an improvement over the crochet machine described in the patent.

In addition to this improvement, the motion sequences of the fundamental machine elements for reliable stitch formation were further improved in a process of iterative optimization characterized by practical trials. No further changes were made to the basic arrangement of the fundamental machine elements. However, the structure and technical implementation of the CroMat prototype were significantly revised compared to the initial prototype of the conceptual phase. The state of the CroMat prototype at the end of the development phase is described in section 3.3 with regard to the motion sequences of the fundamental machine elements and in section 3.4 regarding the technical implementation.

3.3 Automated crochet stitch formation

The basic motion sequences of the fundamental machine elements necessary for automating flat crocheting were developed within the scope of the CroMat crochet machine patent and are described therein [A5]. With the subsequent improvement of the yarn guide, which offers the possibilities of feeding a yarn segment through a working stitch or over the fabric, the motion sequences have also been improved. The improved motion sequences are implemented in the final development stage of the CroMat prototype. They can be seen as the result of the development phase of the innovation process model according to Koltze and Souchkov [179] and are among the major contributions of this work.

The stitch formation sequences are to be considered in a simplified way and independent of the specific machine implementation, which is illustrated in section 3.4, in order to emphasize their generality. Since, these motion sequences of the fundamental machine elements can certainly be implemented mechanically in a different way. Due to the description independent of the machine implementation, the developed principles and sequences provide a general basis for future developments in the field of automation of crochet technology.

Here it is shown for the first time in detail how the crochet stitch types SC (section 3.3.3) and HDC (section 3.3.4), turns with one or two CH (section 3.3.5) as well as INC (section 3.3.7) and DEC (section 3.3.8) according to the principle of flat crochet starting from a chain line can be formed by a machine. In addition, the first lay over (FLO) as the start of the machine process (section 3.3.1), the basic SLs (section 3.3.2) and the possibilities for open work crochet (section 3.3.6) are addressed. Moreover, further methods for shaping the fabric (section 3.3.9) and the issue of forming more complex stitches (section 3.3.10) are discussed.

3.3.1 Initial situation

The fundamental machine elements considered in presenting the stitch formation process are the auxiliary needles, the crochet needle and the yarn guide. Over two neighboring auxiliary needles (green), which are implemented as latch needles here, the LL of a stitch is overlapped to secure it. In a subsequent course, the suspended stitch can be used as a working stitch to crochet a new stitch. The crochet needle (red), which is a compound needle, holds the current LL in front of the needle bed at an angle of about 30° and works the yarn (yellow) into new stitches. Between the yarn storage and the suspended fabric is the yarn guide (blue), which aids the crochet needle regarding stitch formation by presenting yarn and wrapping it around the crochet needle (yarn over). As described in section 3.2, the yarn guide can rotate to enter the working stitch from behind and to generally improve the placing of yarn in the crochet needle's hook. The standard angled position of the yarn guide is shown in Figure 43.

Figure 43 a) depicts the initial situation of the crochet machine process with a manually crocheted course of CHs (the chain line) suspended on the auxiliary needles with the LL held by the crochet needle at the left side and the yarn that runs from one end of the LL through the eyelet (top down) and along the shaft of the yarn guide. Yarn storage, linear guides of the machine elements and the take-off, which can be a simple mass that needs to be hooked into the lower yarn segment of each CH, are not shown.

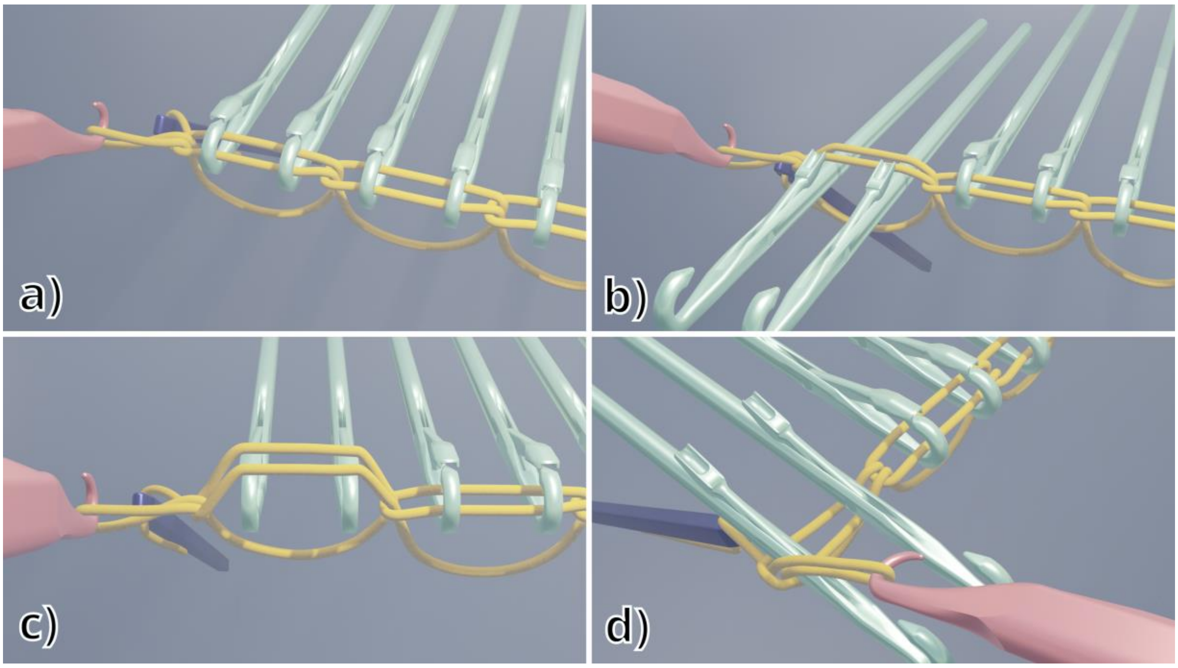

Figure 43. Illustration of the first lay over (FLO) process, which is the first machine production step, with casting off an old stitch and suspending a new one on the ANP. **a)** Initial situation with suspended CH course on the auxiliary needles in standard position and the LL held by the crochet needle. **b)** Extended position of the ANP for casting off the corresponding stitch. **c)** Retracting the ANP immediately before the CH slips completely over the closed latches. **d)** ANP above the dropped stitch in position for suspending the LL by laying it over the needles.

As the first step of the machine process, designated as first turn or FLO, the last created CH at the left end is to be cast off with the conventional latch needle motion known from knitting machines (cf. Figure 10 in section 2.2.1). The corresponding process of driving both auxiliary needles simultaneously forward until the yarn is behind the opened latch and then retracting the needles to knock the stitch over the closing latches is shown in Figure 43 b) and d). It is important to mention that in contrast to casting off a stitch in knitting, in machine-crochet casting off an old stitch and forming a new stitch are to be seen as separate processes.

After casting off, the crochet needle laps the LL over the two auxiliary needles, which are extended slightly with open latches, as depicted in Figure 43 d). An additional machine element (not shown here) is necessary to open the latches, because the yarn is already cast off and thus cannot rotate the latches. For secure overlapping, the crochet needle rotates clockwise by 90° and traverses afterwards across the hooks. Simultaneously, the yarn guide moves under the auxiliary needles also in right direction, which is set as the direction of the first course crocheted by machine (second course of the fabric). This first overlapping is special and called FLO. It secures the transition (T1) from the first CH course to the second course on the first ANP, so that it can serve as a working stitch for forming a stitch as part of the third course. The last CH of the first course is thereby used as the CH of the turn. This results in the peculiarity that beneath the first turn is no CH.

3.3.2 Slip stitch

The automated formation of a SL is depicted in Figure 44. After overlapping the first turn by laying the LL over the first ANP, which is shown in Figure 44 a), the crochet needle is positioned between the auxiliary needles of the second pair. As depicted in Figure 44 b), the opening of the hook of the compound needle faces downward at an angle in the direction of crochet. The angular position is necessary so that the LL slides onto the shaft of the crochet needle when it is extended and does not slide off the needle (cf. section 3.1.5). The opening of the hook is thus aligned against the force vector of the LL on the crochet needle.

In general, the slider of the crochet needle can be retracted to open the hook when the LL is moved, because the rotation of the crochet needle prevents the LL from being dropped. Also, even a closed slider cannot prevent the LL from slipping off the hook if the crochet needle is not oriented appropriately.

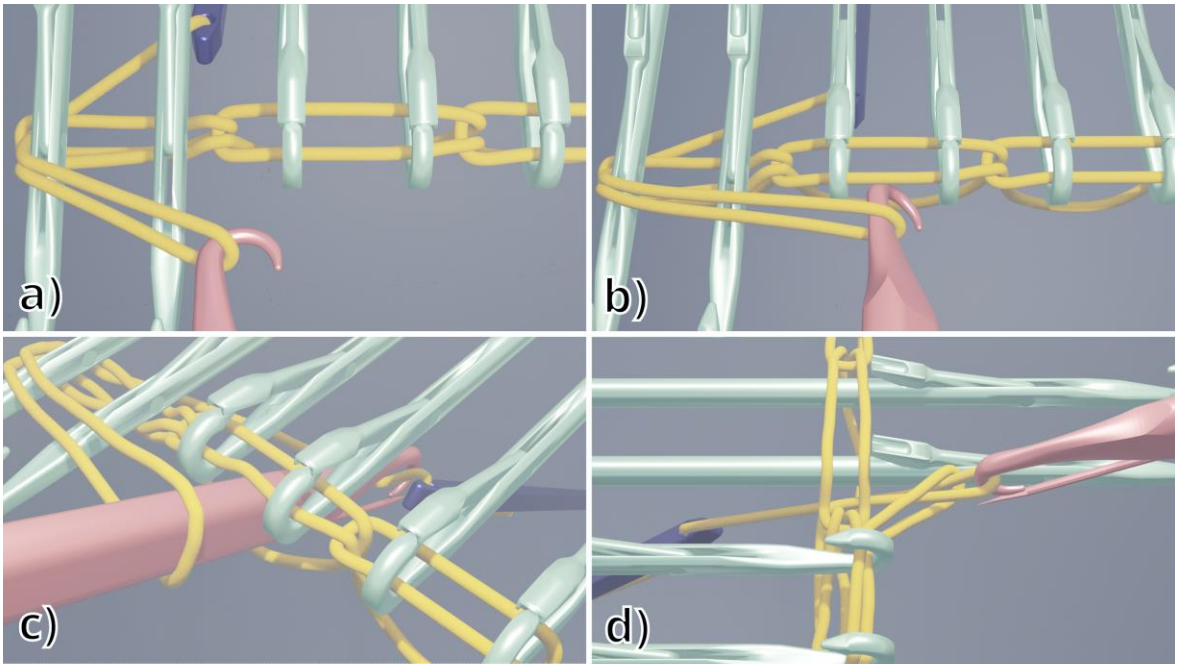

Figure 44. Frames of the motion sequences necessary to form SLs. **a)** Motion of the crochet needle in crochet direction to the working stitch after laying the LL over the extended ANP. **b)** Yarn guide and crochet needle in position before the latter is inserted into the working stitch. **c)** Crochet needle with closed hook after yarn over, which was performed by the yarn guide as an overlap. **d)** Retracted crochet needle holding the new LL, which was drawn through the working stitch and the old LL, while the previous ANP is in standard position and the ANP of the working stitch is in extended position for dropping it.

With an appropriate angle, the crochet needle is extended and inserted into the current working stitch, while the LL slips onto the needle shaft due to the open hook (cf. Figure 44 b) and c)). The yarn over is then performed by an overlapping movement of the yarn guide and a clockwise rotation of the crochet needle so that the hook's opening is facing downwards. The respective motion of wrapping yarn around the compound needle has similarities to the overlap known from warp knitting as it is shown in Figure 12 in section 2.2.2.

Figure 44 c) depicts the scenery after the yarn over and closing the hook with the slider before the crochet needle is retracted along its longitudinal axis. By the latter, the new loop, which is created from the grabbed yarn segment, is drawn by the crochet needle with a closed hook through the working stitch and through the old LL. Thus, a SL is created and a new LL, namely the new loop, is held by the crochet needle. The finished stitch and the ANP of the previous stitch driven into the standard position are shown in Figure 44 d).

In Figure 44 d) is also shown how the ANP is extended to place the used working stitch behind the latches in order to cast it off. Placing the new LL over the respective ANP is generally necessary for a created stitch to be suspended, and to be stored for the formation of a new stitch in the next course. The respective motion of casting off the working stitch and laying over the new stitch's LL was already shown in Figure 37 in section 3.1.6. In short, after retracting the ANP, it is extended again with opened latches above the dropped stitch, which is pulled down by the take-off. Before the crochet needle is driven horizontally in the crochet direction, it must rotate by 90° to align the hook's opening with the crochet direction.

A modeled exemplary machine-crocheted fabric consisting of SLs is depicted in Figure 45. In a), the crochet pattern of the fabric is represented in a crochet chart with international crochet symbols [27]. Here, for the machine-crocheted fabrics, the turns are placed within a course in contrast to the charts for manually crocheted fabrics (cf. Figure 5 in section 2.1.2 or Figure 103 in section 4.1.1). In the representation chosen here, it becomes clear that the working stitch from which each stitch emerges lies in the same column in the row below. One column corresponds to an ANP of the machine. The stitch connections according to the arrangement in the crochet chart are explained in more detail in Figure 96 in section 3.6.2.

The first course (bottom stitch row) consists of CHs (black outlined oval) and the turns are indicated by rotated CH symbols, which correspond to the vertical alignment in the fabric. A black dot is the symbol for a SL. Furthermore, the crochet pattern in Figure 45 a) depicts the missing CH beneath the first turn, which is characteristic for fabrics produced by the CroMat machine.

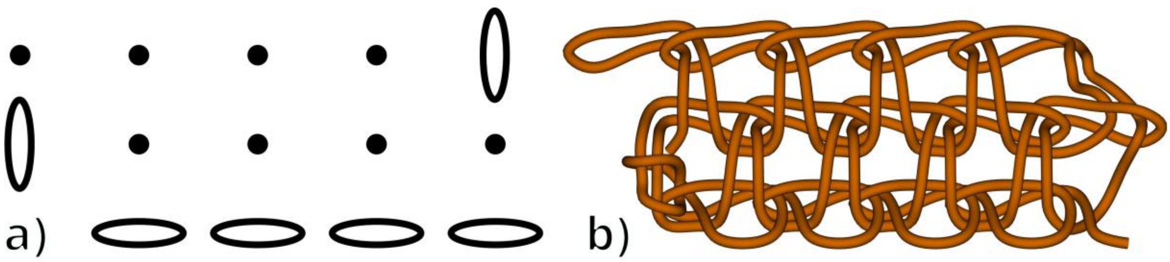

Figure 45. SLs in an exemplary fabric crocheted according to the CroMat machine. **a)** Crochet pattern showing the fabrics structure by international crochet symbols for CHs, SLs and turns. **b)** Model of the corresponding fabric, which is based on a topology-based approach on the meso-scale with parametric key points.

In Figure 45 b), the computer-generated topology of the fabric and stitches is shown. It is to mention, that the model features a simplified yarn path and does not show the relaxed state of the fabric. More details on the developed modeling are given in sections 4.1 and 4.3.

Next, Figure 46 illustrates the main stages of the SL formation process by modeling the yarn only. Figure 46 a) shows the initial situation with the LL and the working stitch, which is, like the neighboring stitch, suspended at the red marked position on the respective ANP. The new loop drawn by the crochet needle through the working stitch is illustrated in b), and in c) it is shown how this loop becomes the new LL after being drawn through the old one. Generally, during the formation of a new stitch and the suspension of its LL, the crochet needle and crochet hook have moved in total in the crochet direction by the distance between two pairs of needles, i.e., between two stitches.

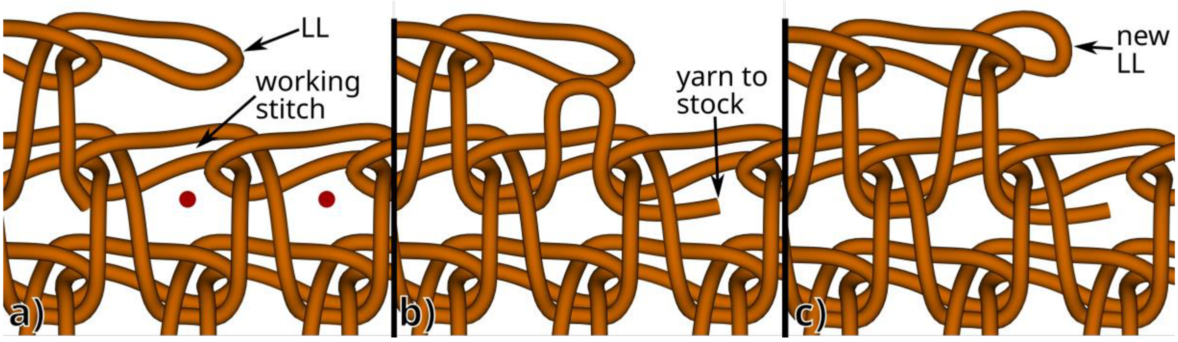

Figure 46. SL formation process illustrated in three steps by considering the fabric's model. Figure is under CC BY-NC-ND license taken without modification from reference A6 (Copyright © 2023, the Authors).

The described motion sequence for the automated formation of SLs complies with the patented process [A5]. The process is substantially different from the first approach to a crochet machine described in section 2.3.1, which is also capable of producing SLs. Thus, the novelty requirement of the new patent [A5] is met in relation to the old patent [18] of the first approach. The major differences of the SL forming processes are the suspension of a stitch by placing the new LL on two needles after stitch formation, the rotation of the crochet needle and the insertion of it from above at an angle of around 30° as well as the insertion of the yarn below the auxiliary needle plane. These improvements enable a substantially more secure SL formation process, in particular with regard to inserting the crochet needle into the working stitch.

3.3.3 Single crochet

With regard to manual crocheting and in contrast to SLs, SCs are created by drawing the loop of the first yarn over only through the working stitch, and by creating an additional loop by a further yarn over outside the fabric, which is then drawn through both loops wrapped around the crochet needle (cf. Figure 2 b) in section 2.1.1). In the developed motion sequences, the crochet needle is not inserted in the working stitch for the first yarn over. Instead, a yarn guide capable of providing yarn through the working stitch is used (cf. section 3.2.3).

This principle of providing yarn through the working stitch by inserting the yarn guide from below with a slightly steeper angle than the crochet needle is depicted in Figure 47 a). Due to this arrangement of machine elements, a yarn segment is created between the eyelet of the yarn guide and the left side of the working stitch, which can be gripped by the crochet needle with the open hook pointing upwards. After moving the crochet needle in the displayed position, the yarn guide can be retracted to form the loop placed next to the LL on the hook. As a result of this method, a loop is moved through the working stitch as if the crochet needle had drawn the loop through the stitch.

The crochet needle must then move out of the way of the ANP, which needs to cast off the working stitch. In contrast to the SL process, here, the working stitch is cast off before the formation of the SC is finished. This is done to avoid stretching the loops held by the crochet needle, which would occur if the crochet needle had to move further in the crochet direction next to the non-retracted ANP. After casting off, the ANP remains retracted so that the crochet needle can be positioned as shown in Figure 47 b).

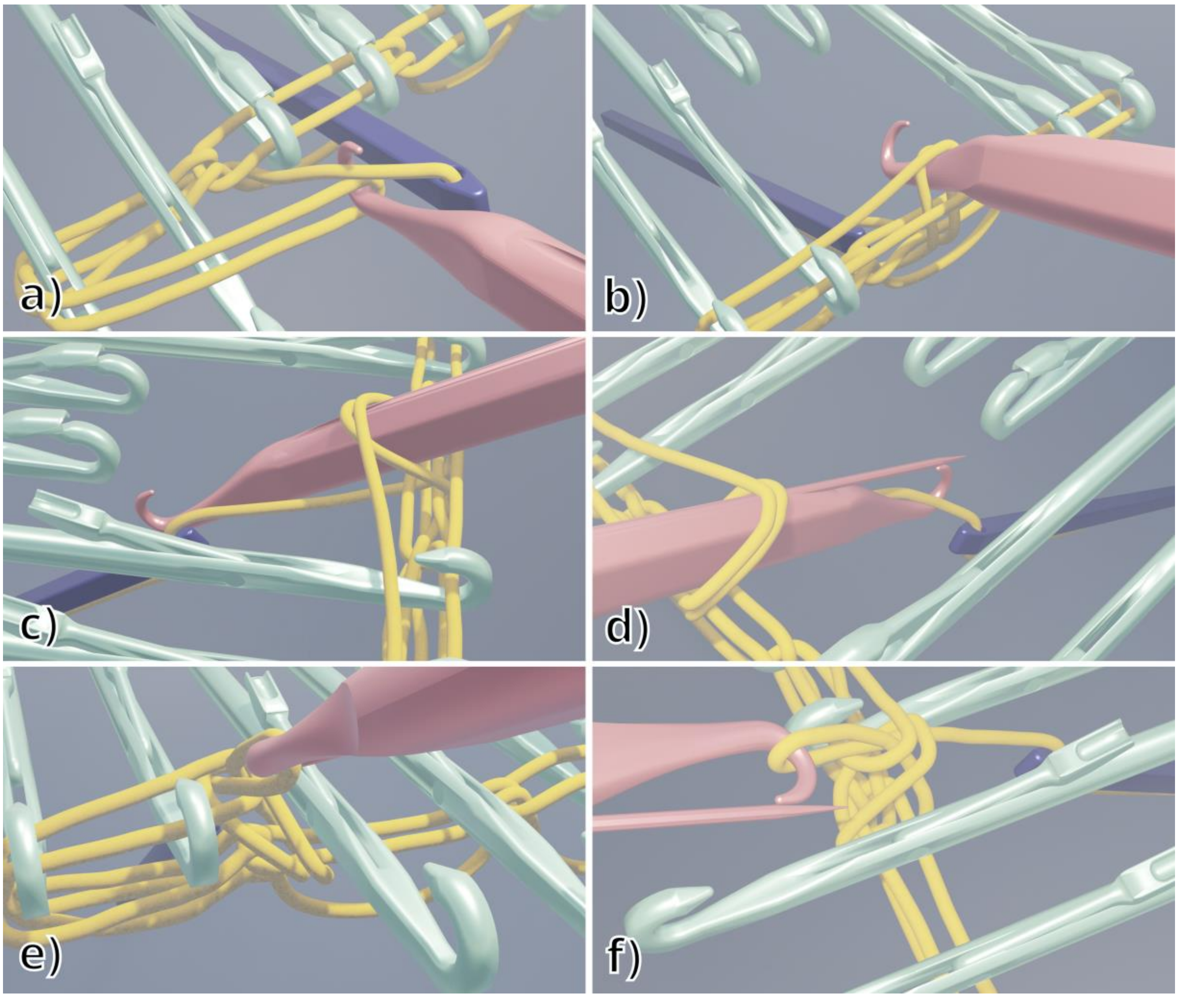

Figure 47. Developed machine process for the formation of SCs. **a)** First yarn over by grabbing a yarn segment provided by the yarn guide through the working stitch with the crochet needle. **b)** Position of the fundamental machine elements after knocking over the working stitch and before driving the crochet needle forward along its longitudinal axis. **c)** Crochet needle in extended position above the crocheted fabric with the LL and the loop from the first yarn over slid up on the shaft. **d)** Closed hook after the second yarn over by the yarn guide. **e)** Situation with extended ANP, after drawing the loop from second yarn over through both loops around the crochet needle. **f)** Same situation as e) from a different perspective showing the new LL to be subsequently laid over the ANP.

The crochet needle is positioned over the crocheted fabric as shown in Figure 47 b), before it is extended along its longitudinal axis to bring the hook under the auxiliary needle plane. For this movement, the opening of the hook is oriented upwards with a slight slant in crochet direction. As described in section 3.1.5, this is necessary, to ensure appropriate sliding of the loops on the crochet needle's shaft.

Figure 47 c) shows the crochet needle in the extended position with the loops positioned at the shaft above the auxiliary needle plane and the yarn guide at the left side of the crochet needle. For the second yarn over, the yarn guide rotates its eyelet in a plane above the crochet needle's hook. Afterwards, the yarn guide moves in the crochet direction to place the yarn over the hook. With a subsequent rotation, which compensates for the previous rotation, the yarn is wrapped around the hook and the yarn over is finished. This process is similar to the overlap in warp knitting, which is described in Figure 12 in section 2.2.2. The situation after the second yarn over and after closing the hook with the slider of the crochet needle is illustrated in Figure 47 d).

To finish the stitch, the loop of the second yarn over, now becoming the new LL, is drawn through the loop of the first yarn over and through the old LL by retracting the crochet needle along its longitudinal axis. To finish the machine operation for building a SC, the ANP, whose latches must be open, is to be extended over the dropped old working stitch, to allow the crochet needle to suspend the SC's LL. For this, the crochet needle must first be moved out of the way to the left side of the ANP. Also, it rotates to let the hook's opening face in the crochet direction for the subsequent overlap. This situation is presented by Figure 47 e) and f) from different perspectives.

Figure 48 depicts SCs in an exemplary crocheted fabric as crochet pattern and model. In comparison to the SLs depicted in Figure 45 in section 3.3.2, the additional loops of the slightly higher SCs can be seen in the lower part of the stitches. The intermeshing of the upper part is similar to the SLs. Also, the topology of a turn with one CH (T1, cf. section 3.2.4) can be derived by this illustration.

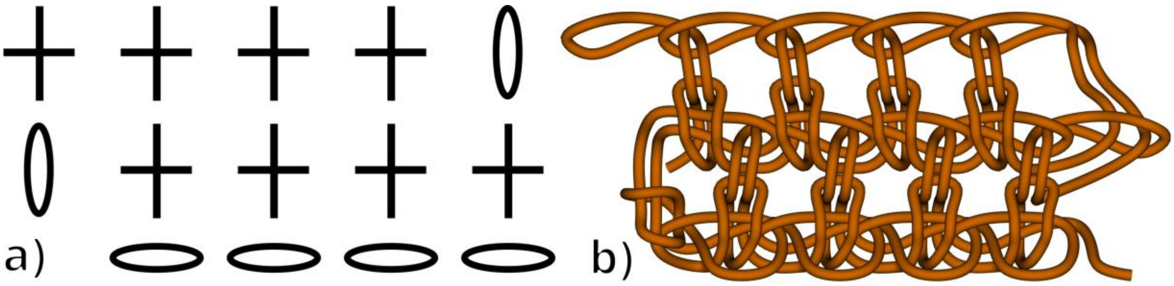

Figure 48. Crochet pattern and model of SCs arranged in a simple crocheted fabric. **a)** Crochet pattern with international stitch symbols. **b)** Model of the fabric showing the topology of the SCs.

3.3.4 Half double crochet

The HDC adds a layer of complexity by an additional yarn over before performing the first yarn over known from SCs. Hence, an HDC incorporates an additional loop. The loop of the additional yarn over is not to be drawn through the working stitch and must therefore be guided above the crocheted textile. Apart from this difference, the processes of stitch formation are identical.

An efficient first yarn over for an HDC can be achieved if yarn is provided by the yarn guide above the level of the auxiliary needles, as shown in Figure 49 a). While moving in crochet direction and suspending the LL of the previously formed stitch, the crochet needle can grab the presented yarn segment. The latter runs from the previous stitch to the yarn guide's eyelet, which is positioned between the ANP where the LL is suspended and the ANP of the working stitch. After placing the yarn into the crochet needle's hook next to the LL, the yarn guide can retract to complete the loop formation of the first yarn over.

As next step, the second yarn over is performed as illustrated in Figure 49 b). Similar to the first yarn over of SCs, a yarn segment is provided by extending the yarn guide through the working stitch. This segment can then be wrapped around the hook by moving the crochet needle under it, as depicted, and afterwards retracting the yarn guide.

Now, the fundamental machine elements need to be positioned to enable the final yarn over. For this, the working stitch is dropped from the associated ANP, which requires driving the crochet needle against the crochet direction out of the way. Then, the ANP remains in the retracted position to leave room for the crochet needle, which again moves in crochet direction. Thereby, it also slightly rotates clockwise to ensure a correct sliding of the three loops in the hook onto the shaft in the next step. This situation is depicted in Figure 49 c). It is also shown that the ANP of the previous stitch position was moved to the standard position.

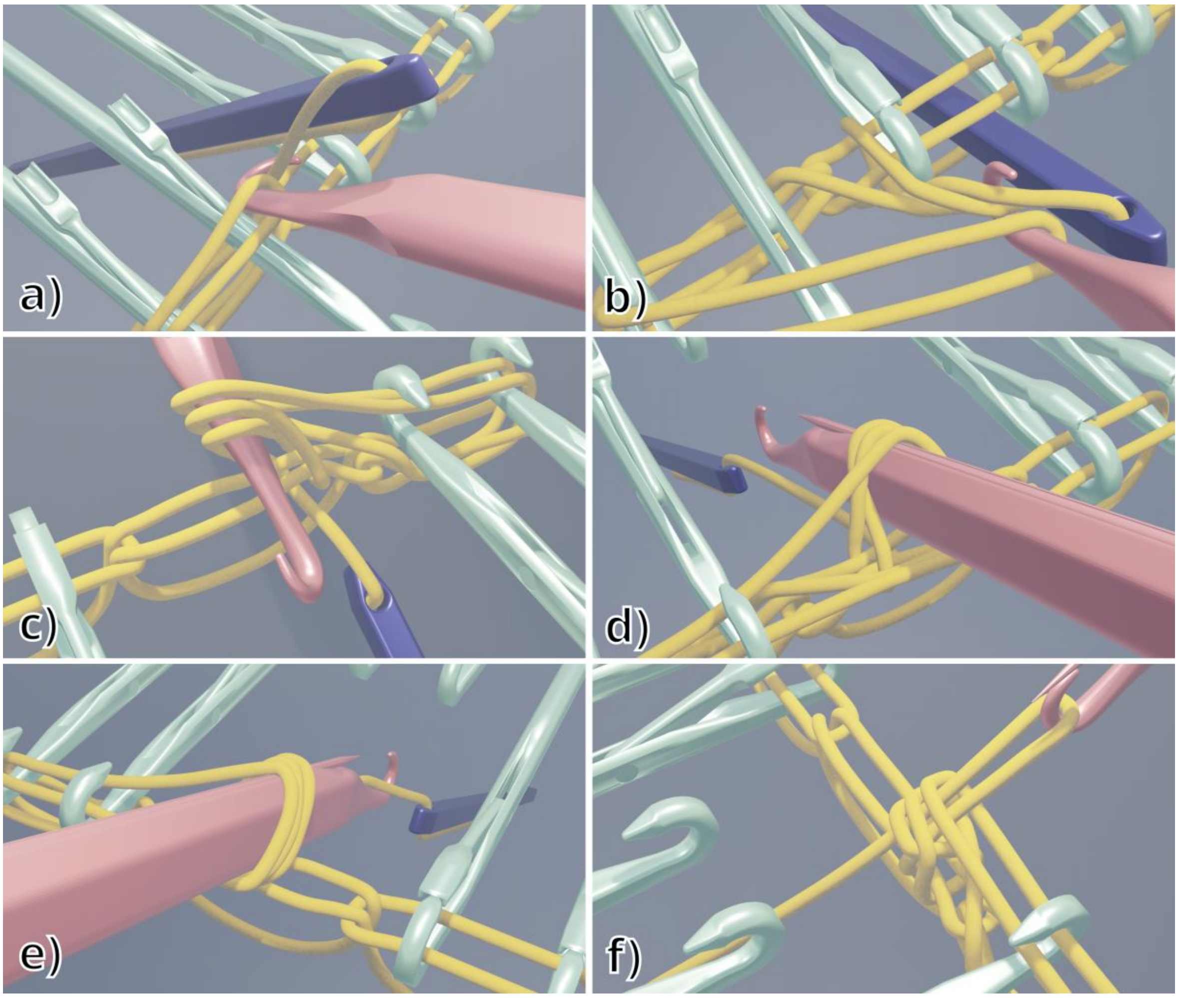

Figure 49. Fundamental machine elements performing the motion sequence for building an HDC. **a)** First yarn over consisting of feeding a new loop above the crocheted fabric. **b)** Second yarn over as moving another loop through the working stitch by the yarn guide, similar to the first yarn over of a SC. **c)** Machine element positions before extending the crochet needle along its longitudinal axis above the fabric. ANP has knocked over the working stitch and remains in the retracted position while the ANP of the previous stitch position has moved in the standard position. **d)** Crochet needle in extended position with the three loops slid on the shaft and yarn guide in position for overlap. **e)** Yarn guide on the other side of the crochet needle, whose slider is closing the hook, after performing the overlap. **f)** Finished HDC with new LL held by the crochet needle after drawing it through the loops on the crochet needle.

The crochet needle is driven along its longitudinal axis above the fabric to receive the final yarn over and to let the three loops from the hook slide up the shaft. As can be seen in Figure 49 d), the hook's opening faces upwards to aid the subsequent overlap performed by the yarn guide in a swinging motion from the left side to the right side of the crochet needle. The yarn guide's position after the overlap is depicted in Figure 49 e).

After closing the hook by moving the slider, the crochet needle is retracted to draw the loop from the last yarn over, which becomes the new LL, through the three loops on the shaft. This is illustrated in Figure 49 f). It completes the HDC formation, however, the machine must perform further steps to secure the new stitch at the corresponding ANP. In this regard, the ANP is moved forward to the overlay position above the dropped working stitch while the crochet needle is laterally moved against the crochet direction out of the way. Subsequently, the LL is placed over the ANP with a movement in crochet direction.

The topology of HDCs and their interlooping can be derived from Figure 50. In contrast to SCs (cf. Figure 48 in section 3.3.3), HDCs feature an additional loop and are slightly higher. Also, a turn with two CHs (T2) is used to connect the courses, which is common in crocheting to match the height of the stitches. However, the first turn still consists of only one CH, because the beginning of the automated crochet process is characterized by placing the last CH of the first course (CH line) at the first stitch position of the second course. Since this involves only one CH, it is T1.

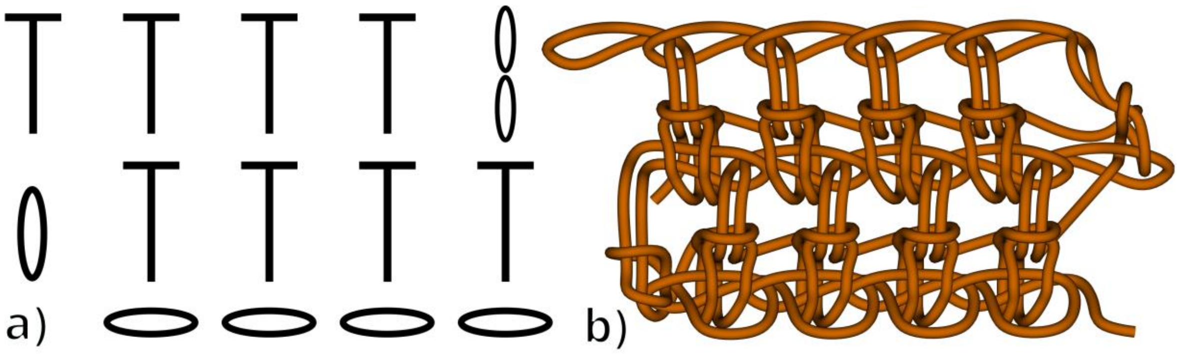

Figure 50. Crochet pattern and model of an exemplary HDC fabric. **a)** Symbolic representation as crochet pattern. **b)** Topology-based model of the corresponding fabric.

3.3.5 Turn

Two subsequent crochet courses are connected by a turn, which consists of one or multiple CHs. T1 designates a turn with one CH, which can be seen in Figure 48 in section 3.3.3 and is used for SLs or SCs in the next course, while T2 refers to two CHs, which can be seen in Figure 50 in the previous section and corresponds to higher HDC stitches in the subsequent course.

After forming the last stitch in a course, one or two CHs are created in the same direction. Then the crochet direction is reversed, and the CH's LL is laid over the first ANP of the current course, which corresponds to the last stitch position of the previous course. Due to the turn being secured at the first ANP, the turn is to be seen as the first stitch of the new course. Thus, the turn is here defined as the first element of each course. However, the first CH course has no previous course and does not start with a turn as an exception.

To finish the exemplary course before performing the turn, Figure 51 illustrates the creation of a second SL at the last ANP of the course. This process proceeds from the SL formation shown in Figure 44 in section 3.3.2. After laying the LL of the previous stitch over the ANP (Figure 51 a)), the crochet needle is inserted into the working stitch (Figure 51 b)), which is the first CH of the previous course and suspended at the last stitch position of the current course. Then, for finishing the SL, the loop from the yarn over is drawn through the working stitch and through the old LL, and the working stitch is to be cast off (Figure 51 c)). As a difference to the normal procedure, now the new LL must not be laid over the ANP and it can remain retracted, because a turn is to be performed.

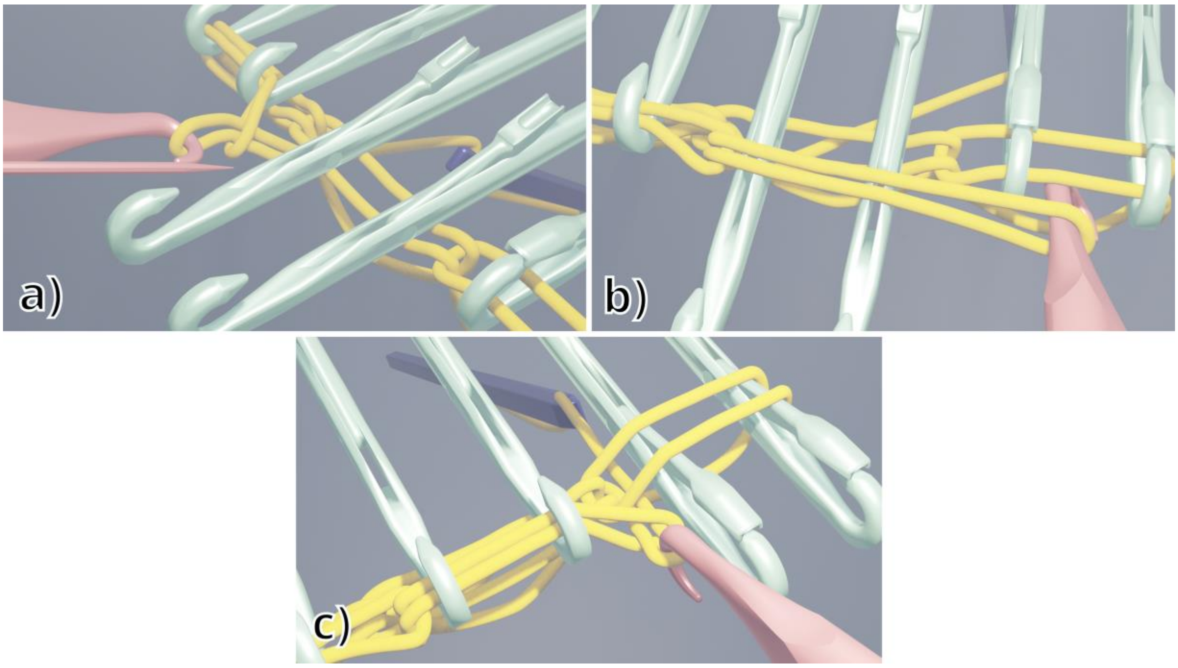

Figure 51. Process of building a second SL. **a)** Start of laying the LL of the previous created SL over the corresponding ANP. **b)** Position of fundamental machine elements before inserting the crochet needle in the working stitch. **c)** Casting off the working stitch after forming the second SL by drawing the new LL trough the working stitch and the old one.

The process of forming a turn with the crochet machine is illustrated by the example of a T1 to the left with the formation of one CH. The latter is created next to the last ANP of the current course, which is retracted as depicted by Figure 52 a). With an angle and position of the crochet needle similar to SL, the crochet needle is moved along its longitudinal axis, but without penetrating a stitch. The subsequent yarn over corresponds to the procedure known from SLs. In Figure 52 b) it is shown how the new loop is only drawn through the old LL by the crochet needle with a closed hook. As a result, a CH is produced.

Next, the crochet direction is reversed, and the LL of the CH is laid over the first ANP of the new course. For this, the retracted ANP is extended above the CH as shown in Figure 52 c). The crochet needle is rotated anticlockwise until the opening of the hook faces in the new crochet direction. With a turn at the other end of the manufactured textile, the needle would rotate clockwise until it points to the right. After this rotation for changing the crochet direction, the LL is laid over the ANP, as depicted in Figure 52 d) to finish the T1. Thus, the turn is secured at the first stitch position of the new course and the subsequent stitch can be built at the next ANP.

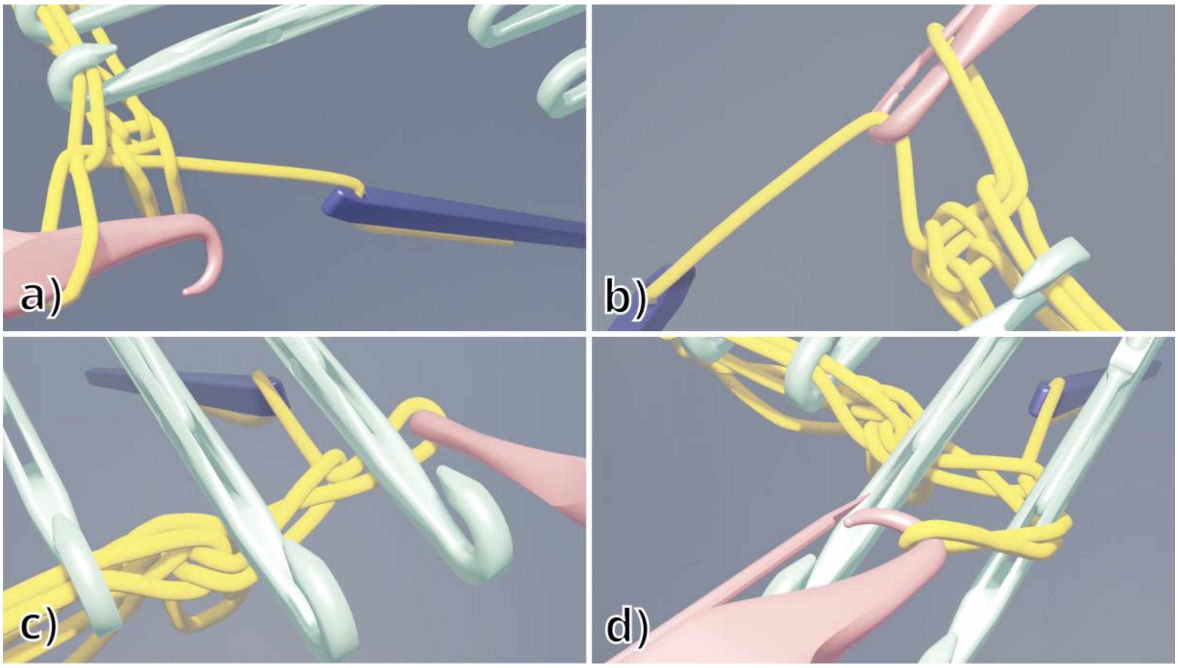

Figure 52. A turn with one CH (T1) to the left. **a)** ANP of the current course's last stitch is retracted while the crochet needle is moved in position. **b)** Drawing the new loop from the yarn over through the old LL. **c)** Positioning the ANP above the turn's CH in the position for suspending the LL. **d)** Moving the crochet needle in the direction of the new course.

3.3.6 Chain stitch and skipping a stitch within a course

With the fundamental machine elements of the CroMat it is also possible to produce a CH within a course and not only at its end. The corresponding process is presented in Figure 53. Firstly, the not used working stitch must be cast off. The respective ANP remains in the retracted position. Hereafter, the crochet needle is positioned as if a SL is to be produced (cf. Figure 53 a)). The motions of the following yarn over beneath the auxiliary needle plane and the drawing of the new loop through the old LL (cf. Figure 53 b) and c)) are similar to the process of SL creation illustrated in section 3.3.2. However, the loop becoming the new LL is only drawn trough the old LL and not also through a stitch. Subsequently, the ANP is driven forward above the crocheted fabric in the position for suspending the CH's LL on it. This is shown in Figure 53 d).

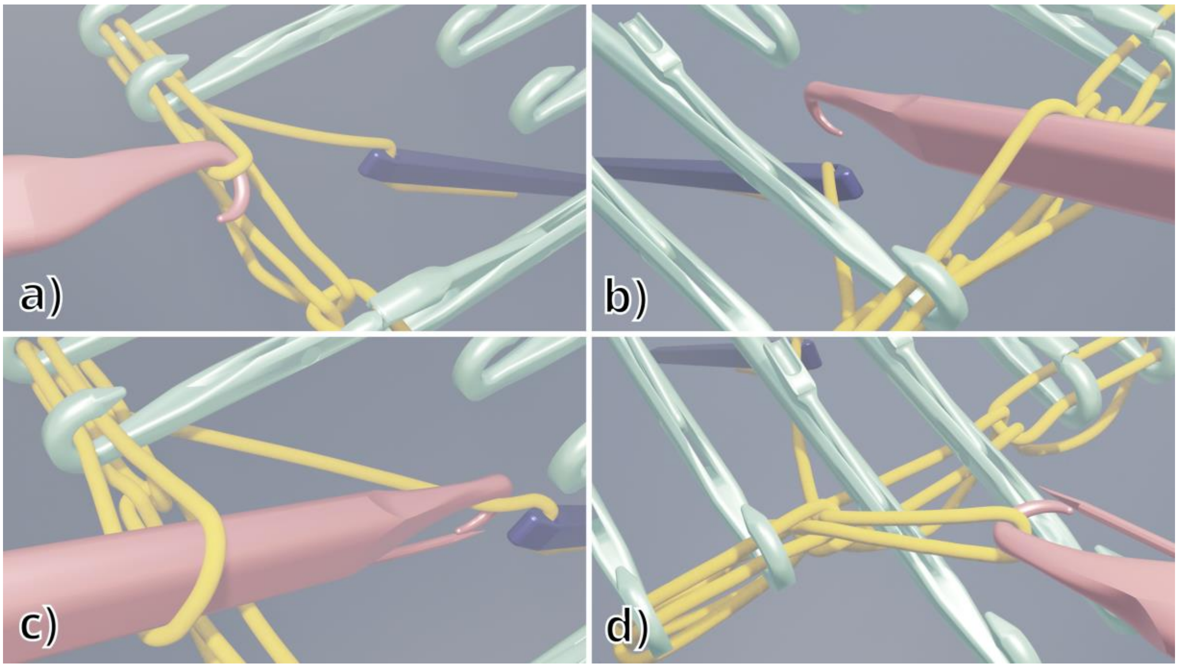

Figure 53. Process of creating a CH within a course. **a)** Retracting the ANP after casting off the old stitch and positioning the crochet needle. **b)** Extending the crochet needle along its longitudinal axis passing over the fabric. **c)** Yarn over by overlap motion of the yarn guide and begin of retracting the crochet needle with closed hook. **d)** Laying the new LL of the CH over the ANP.

An example of incorporating CHs within a course is given by Figure 54 where CHs alternate with SCs. To represent a CH within a course symbolically, the common CH symbol is used as shown in a). In b), the missing connections of the CHs within a course to the stitches beneath is illustrated. This results from not drawing the LL of the CH through a stitch of the previous course.

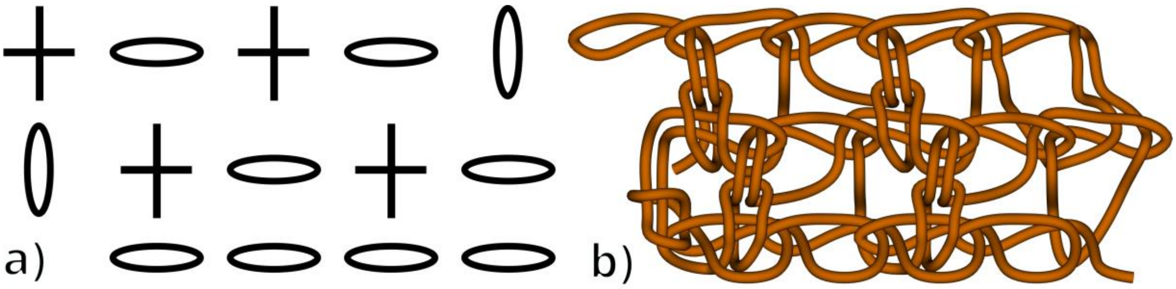

Figure 54. Exemplary crocheted fabric featuring four CHs within the courses. **a)** Crochet pattern. **b)** Corresponding model.

With such CHs within a course (cf. Figure 54), an openwork crochet can be produced. This type of patterning is achieved by not working all stitches of the current course into the previous course, hence by creating CHs [11], since with a CH, the interlooping or linking to the previous course at the respective stitch position is omitted. Commonly in open work crochet, several CHs are aligned consecutively to form a short chain, which is then reconnected to the course below by forming another stitch type [11].

Alternatively, a disconnection to the previous course can be created by skipping a stitch position and not building a new stitch at the respective ANP. Instead, the LL of the previous stitch is prolonged and laid over the ANP after casting off the working stitch, with which no intermeshing was performed.

Figure 55 illustrates this skipping of a stitch without building a new one. As can be seen in Figure 55 a), the old stitch at the current stitch position was cast off by motions of the ANP. The LL previously laid over the previous ANP is then elongated and also laid over the ANP at the current position. This is shown in Figure 55 b). In contrast to the formation of a CH within a course, no new stitch is created within this process.

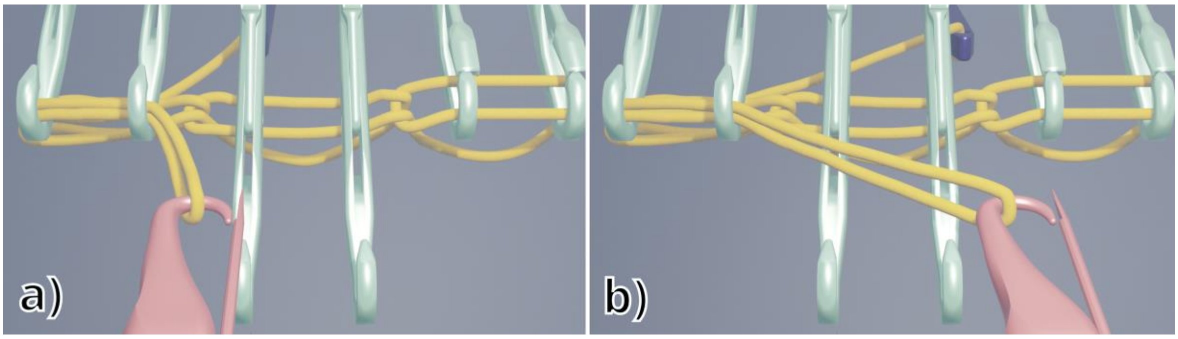

Figure 55. Process of skipping a stitch by extending the LL of the previous stitch beyond the current stitch position. **a)** Fundamental machine elements after casting off the working stitch at the current position. **b)** Laying the old LL over the respective ANP.

The crochet structure resulting from skipping a stitch by prolonging the LL is shown in Figure 56. Since the CYC does not provide a symbol for such an operation, which is rather uncommon in manual crocheting, a horizontal line was chosen to represent this operation in the crochet pattern. It is to mention, that this operation is treated as a regular stitch regarding the automated production, although no stitch is formed.

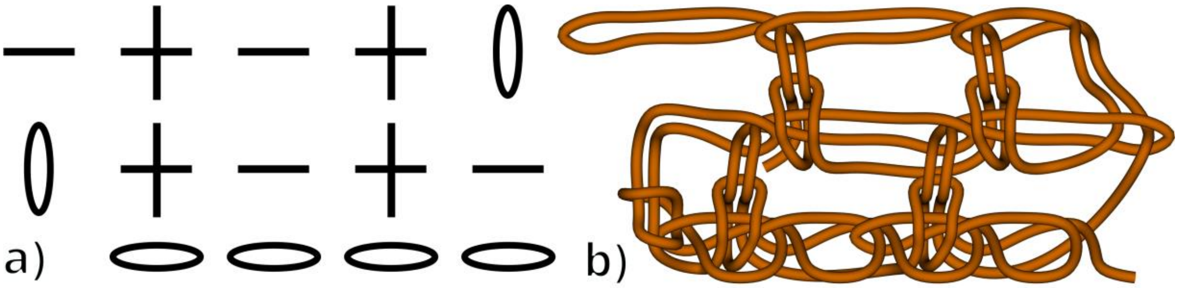

Figure 56. Example of an automatically crocheted fabric featuring multiple operations of skipping without building a stitch. **a)** Crochet pattern with the horizontal line as designated symbol for this operation. **b)** Topology-based model of the fabric's structure.

3.3.7 Increase stitches

In crochet, as described in section 2.1.1, the fabric is widened with INC by working multiple stitches in one working stitch of the previous course. Hence, loops for different stitches are drawn through the same working stitch. The fundamental machine elements allow the adding of one stitch at the beginning of a course by such an operation. Since, during the turn a new ANP can be added for the additional stitch without the need of stitch transfer.

As can be seen in Figure 57 b), the turn's LL is suspended on this added ANP. This offers the possibility to suspend the LL of the first stitch, which is built on the first working stitch of the new course, at the ANP where the turn's LL would be placed normally (cf. Figure 57 e)). Based on the same working stitch another new stitch can be created, which is suspended at the working stitch's position after it has been cast off. This entire process, shown in Figure 57, requires the crochet needle to move more than one stitch position against the crochet direction. Therefore, the yarn feeder (cf. section 3.4.6) must be able to retract yarn to ensure a defined, constant yarn tension.

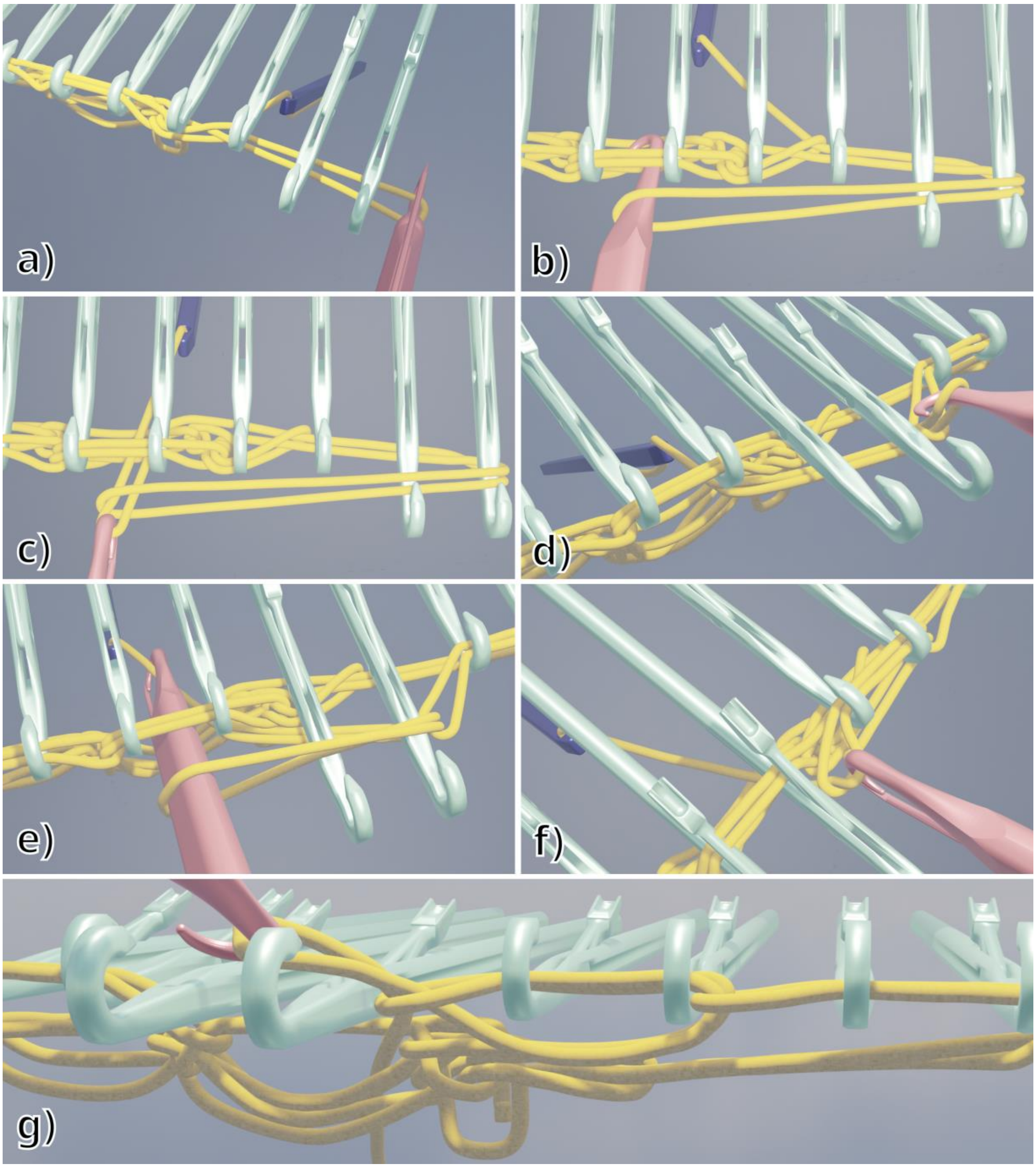

Figure 57. Principle of making an increase (INC) with two SLs after the turn with the fundamental machine elements to add a stitch to the course. **a)** After forming the CH of the turn, one additional ANP is brought in position for laying the LL over. **b)** The crochet needle is moved by two stitch position to be inserted in the working stitch after the turn is suspended on the additional ANP. **c)** A loop becoming the LL of the first SL is pulled through the working stitch and the old LL. **d)** This first SL is suspended on the previously crossed ANP after the first ANP is driven in the standard position. **e)** The crochet needle is inserted in the same working stitch again to form the second SL. **f)** Casting off the working stitch for suspending the new LL at the respective ANP. **g)** Laying over the LL of the second SL to finish the INC.

Figure 58 depicts an example of a crochet structure with INCs based on SCs. The two SCs worked in the same stitch of the previous course have slightly different symbols to distinguish them from the standard SCs. By representing one stitch rotated by 45°, its parent in the course beneath is made clear. This illustration differs slightly from the symbols defined by the CYC for manually crocheted INCs, where both stitch symbols would be rotated so that they point to a common origin at their center [27]. However, with the chosen representation, the parent stitch in the previous course is also clearly recognizable while the uniform structure with one stitch per position (ANP) is maintained.

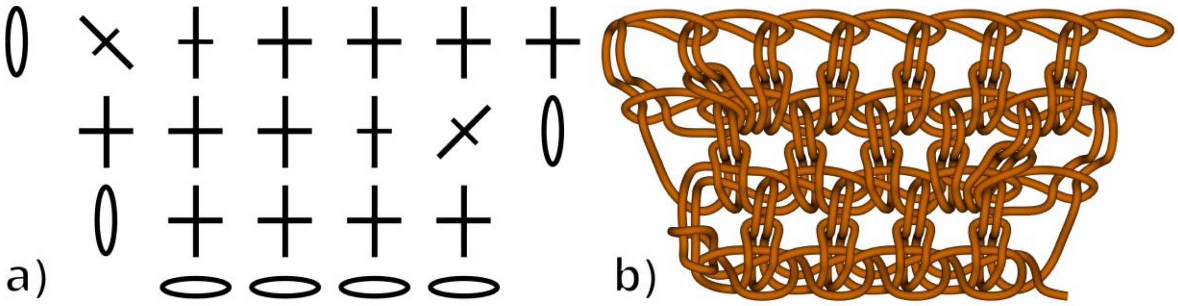

Figure 58. Crochet pattern and model for INC with SCs. **a)** Symbolic representation with slightly altered symbols used for the SCs involved in the INC. **b)** Model of the corresponding fabric.

Furthermore, SLs used in an INC are depicted in Figure 59. The structure of the model (b)), differs from an INC with SCs and is somewhat looser, with the first SL of the INC resembling a CH within a course (cf. Figure 54 in section 3.3.6). This results from grabbing the yarn running from the first SL to the yarn supply for drawing it through the LL of the first SL for the formation of the second SL. Accordingly, the yarn runs through the old stitch in the course beneath more like expected for a normal stitch and less like the INC with two SCs, which is shown in Figure 58 b).

For representing the SLs of INCs in the crochet pattern, new symbols are introduced to depict, similar to INC with SCs, the origin of the stitches, as can be seen in Figure 59 a). The use of a black oval as a symbol for an SL is common in crochet, as is the use of a circle. Here, a black circle denotes a normal SL. Moreover, it is also possible to perform INCs with HDCs by the machine. In this case, the process and structure are similar to the use of SCs.

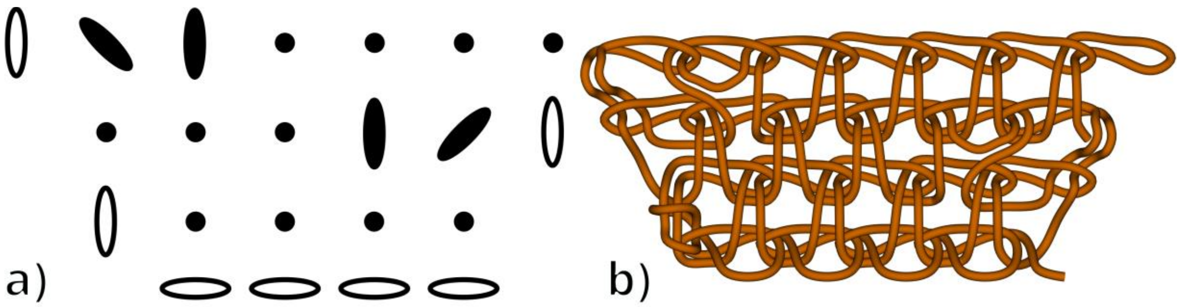

Figure 59. Example of using SLs for INC. **a)** Crochet pattern with alternative symbols for the SLs required for the INC. **b)** Corresponding model.

Performing multiple INCs in one course to add multiple stitches is not possible with the CroMat prototype, because this would require transferring already produced stitches to other ANPs to enable suspending the additional stitches. Transferring of stitches cannot be done with the fundamental machine elements and is currently not implemented in the CroMat. However, creating one INC is possible due to the opportunity of suspending the LL of a turn at an outward additional needle pair. Placing the turn's LL at one further outward needle pair and building a third stitch in the same working stitch, is not possible. This is, because the turn's LL would be stretched too far, which, due to yarn friction, would subject the crochet needle to strong forces acting transversely to its longitudinal direction of extension.

In weft knitting, loop transfer is commonly performed in rib structures with two needle beds by transferring a loop from one bed to the other combined with racking movements of one bed [111]. The corresponding process for V-bed weft knitting machines with specially designed latch needles is depicted in Figure 11 in section 2.2.1. Alternatively, it is also possible to transfer a stitch within one bed to an adjacent needle, which is known as plain needle loop transfer. This is generally less common and usually implemented in straight bar frames [111]. It is done by additional machine elements, called transfer or fashioning points, which can take the loops from several adjacent needles and transfer them to other needles with a lateral movement [106]. Loop transfer in one bed can also be done with V-bed knitting machines by transferring a loop to the second bed and then retransfer it to the first one at a different needle with racking the needle bed [185].

The crochet needle of the crochet machine cannot perform a transfer because it must always hold the LL and the stitches to be transferred cannot be placed using the principle of overlaying the LL over an ANP. This principle, though, is necessary to ensure a failure-free suspension. A valuable future improvement of the CroMat would be to add machine elements similar to the transfer points of straight bar frames for allowing stitch transfer and to enable multiple INCs as well as DECs in one course.

The Croche-Matic approach [14,15] of a circular crochet machine presented in section 2.3.2 can execute INC and DEC, due to a lack of a system for suspending and securing the stitches. However, this also results in a very high error rate [14,15].

3.3.8 Decrease stitches

As the second basic method for altering the shape of crocheted fabrics, DEC is also automated by the developed CroMat prototype. Due to the currently missing capability of transferring stitches, DEC is limited to be executed at the end of a course. Also, similar to the case of INC, only one stitch can be manipulated to avoid excessive forces on the crochet needle. These would occur if the LL would be stretched over too many needle positions for involving several stitches in DEC. Another common feature is that the crochet needle must also move by at least one ANP against the actual crochet direction, while keeping the yarn tension constant.

The discarding of a stitch by DEC with the fundamental machine elements is shown in Figure 60. According to the principle of the first yarn over of SCs, loops are drawn through the last two working stitches of a course (Figure 60 a) and b)). Then, both working stitches are cast off (first the one further out, then the closer one), while the ANP of the second working stitch is discarded (Figure 60 c) and d)), and the stitch position is removed from the course. The second yarn over typical for SCs is afterwards performed at the stitch position of the first working stitch (e) and a new loop is drawn through all three loops on the crochet needle (f). Finally, the new LL can be suspended at the ANP of the first working stitch, or the turn is performed at this position and the resulting LL is placed over this needle pair in the direction of the new course.

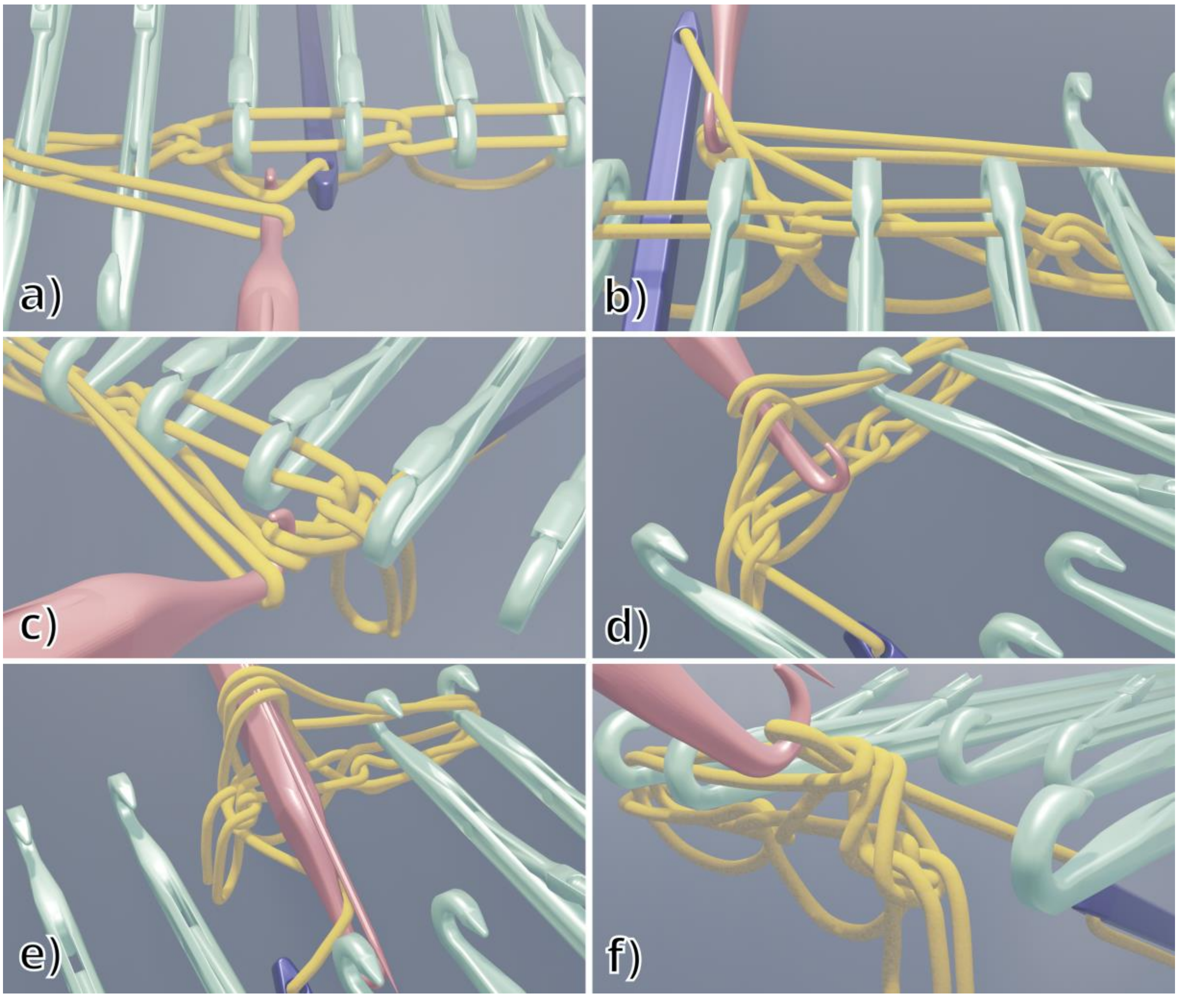

Figure 60. Process of decrease (DEC) with SCs illustrated with the fundamental machine elements. **a)** First yarn over by providing a yarn segment through the first working stitch. **b)** Second yarn over with yarn provided by the yarn guide driven through the second working stitch. **c)** Situation after casting off the second working stitch and removing the respective ANP from the course. **d)** Positioning of the machine elements after casting off the first working stitch and before the final yarn over. **e)** The final yarn over is performed by the yarn guide. **f)** In contrast to a conventional SC, the loop becoming the LL is drawn through three loops.

Regarding the symbolical representations of the DEC operations in Figure 61 a) and 62 a), it can be seen that the same tilted symbols are used as for representing INC (cf. Figures 58 and 59 in section 3.3.7). For DEC, these also indicate how the stitches are connected to each other. The angle of the symbols therefore also depends on the crochet direction of the row, hence both INC and DEC are not associated with unique symbols. Instead, the symbols for the operations clearly result from the local structure of the crochet pattern.

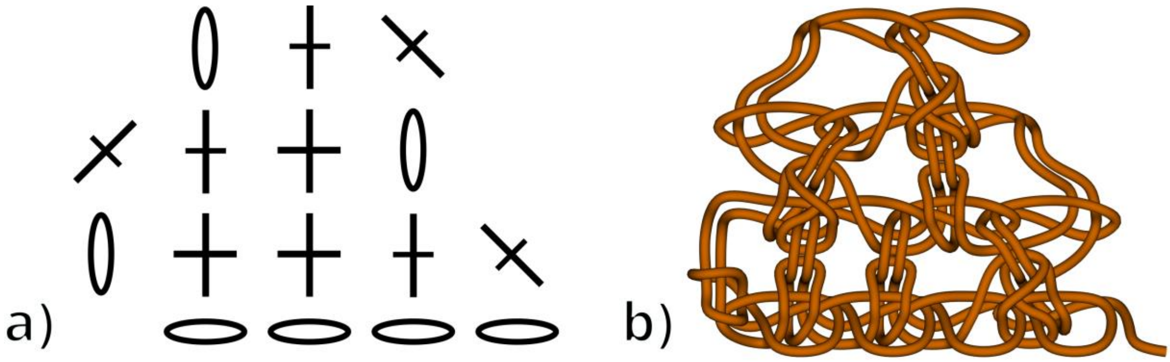

Figure 61. Representation of DECs with combining SCs with a crochet chart in **a)** and with a corresponding model in **b)**.

Figures 61 b) and 62 b) show that the topology differs between DEC with SC and with SL in that SL has one loop less involved in the structure. This results from the fact that in SL, the loop drawn through the second working stitch is also drawn directly through the other loops on the crochet needle. However, the way in which the first loop is drawn through the first working stitch by the crochet needle is the same for both stitch types. Joining two stitches via DEC is in conventional crochet instructions sometimes described as sc2tog or sl2tog, depending on the stitch type.

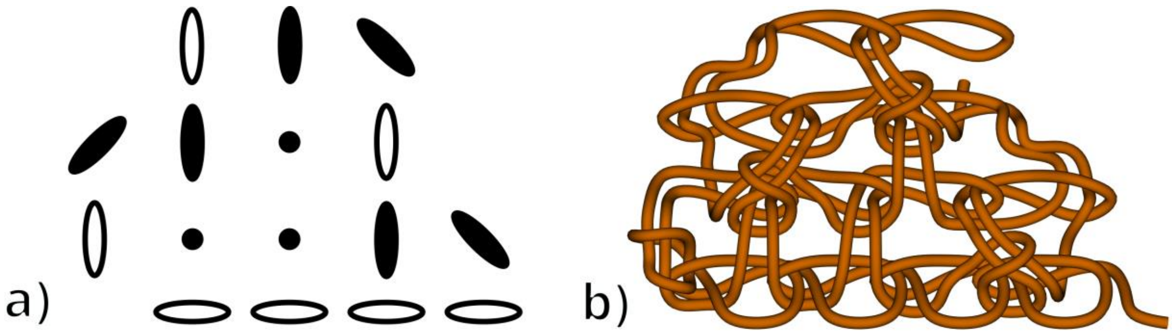

Figure 62. Example fabric of DEC with SLs presented by a crochet chart in **a)** and by a topology-based model in **b)**.

3.3.9 Further methods for changing the fabric's width

With INC and DEC, the number of stitches in a course can be changed. Furthermore, the fundamental machine elements are capable of four additional methods to alter the fabric's shape by adding and removing stitches. The first and most simple way for changing the fabric's width is to remove a stitch at the end of the current course (RSTE). For this, the last stitch of a course is cast off and no new stitch is created at this position. Consequently, the respective ANP is not used anymore in the current or next course. Of course, in later courses, the ANP can be used again by operations that increase the width of the fabric. By running several RSTEs in succession, any number of stitches can be discarded while reducing the fabric's width accordingly.

With knitting machines, such simple dropping of a stitch and taking the needle out of action is not possible, because all stitches of the last row are open there and the fabric would unravel at this point [186]. Therefore, in knitting, the stitches must be transferred to needles that are still active before the needle is no longer used. This would correspond to a DEC in crochet. In crochet, only the last stitch formed is ever open, which is why a RSTE can be performed without problems. This is a good example of the greater flexibility offered by crochet technology.

As a second method, the number of stitches in a course can be reduced by removing a stitch at the beginning of a course (RSTB). In contrast to RSTE, a new stitch is worked into the working stitch before it is cast off and the corresponding ANP is no longer used. Thus, the machine performs the operation of removing the last created stitch as part of the turn. The CH associated with the turn is then suspended on the ANP next to the removed stitch position which is accordingly one needle pair further inward than with a usual turn. Therefore, the stitch of the last course suspended at this position must also be cast off before the LL of the turn is laid over.

This transfer of the turn to an adjacent position limits the method in the number of removed stitches, to preferably one. Although an RSTB of multiple stitches is possible with the CroMat, more than one would stretch the length of the turn's LL unreasonably across the corresponding multiple stitch positions.

Analogous to the removal of stitches, stitches can also be added at the beginning or at the end of a course to modify the fabric's width. Generally, adding a stitch is done by building and securing a CH on a new ANP. By adding a stitch at the beginning of the course (ASTB), this CH is formed at the position of the last stitch in the previous course after the turn is laid over an additional ANP. Thus, a transfer of the turn to an adjacent stitch position is required similar to RSTB. Resulting from this, it is again preferable to change the width of the fabric only by one stitch per course with this method. ASTB is generally similar to INC (cf. section 3.3.7), except that a CH is added instead of an SL, SC or HDC.

As the fourth method, a stitch can be added at the end of a course (ASTE). In this regard, the CH is added at a new ANP after the machine has processed the former last stitch of the course. The subsequent turn can then be placed at this added stitch position. Thus, the turn is placed in the crochet pattern above the added CH and a transfer of the CH like for ASTB and RSTB is not necessary. As a result, more than one stitch can be added by ASTE. ASTB can be clearly distinguished from a CH within a course (cf. Figure 54 in section 3.3.6) in that there is no stitch in the course below at the position of the added CH, while there is a stitch in the case of CH within a course.

The number of addable CHs by ASTE is limited with respect to a properly functioning take-off, because with more than three added CHs, the stitches tighten too severely to subsequently allow the crochet needle to be inserted into them without error. This is because the newly added stitches are laterally offset from the stitches on which the force of the take-off acts directly. If only one stitch is added, it is not necessary to insert the crochet needle into it because it is dropped as the last element of the current course in order to suspend the following turn at this position.

Figure 63 provides an overview of the crochet patterns resulting from the described four additional methods of changing the fabric's width. The first CH course and turn are depicted in blue and form the equal foundation for all four displayed exemplary fabrics. According to the respective method, in each course one stitch is added or removed. An exception of this is that regarding the first turn, no stitch is added or removed at the beginning of the course, due to the start of the machine's crochet process (cf. section 3.3.1). Additionally, the used ANPs are indicated with red numbers beneath the stitch positions. In Figure 63 a) and b) it can be seen that for ASTB and RSTB, the turn of the new course is not above the last stitch of the previous course. The turn being placed above the last stitch of the previous course is the normal case, which is also true for ASTE and RSTB as can be derived from Figure 63 c) and d).

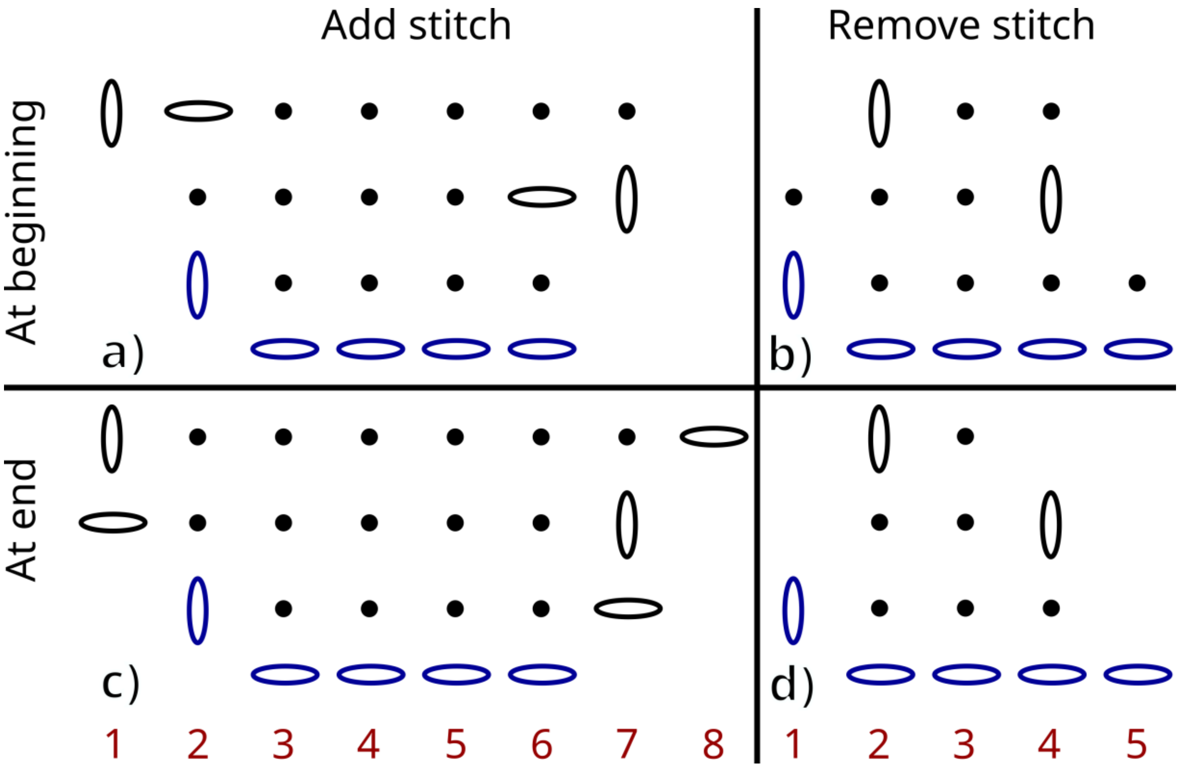

Figure 63. Overview of the possibilities to change the fabric's width by considering exemplary crochet patterns. The red numbers mark the ANPs necessary for the fabric construction. **a)** Add stitch at the beginning (ASTB). **b)** Remove stitch at the beginning (RSTB). **c)** Add stitch at the end (ASTE). **d)** Remove stitch add the end (RSTE). Based on Figures S1 and S2 of the supplementary materials of the CC BY licensed reference A7.

Models corresponding to the patterns presented in Figure 63 are illustrated in Figure 64. Based on this figure, the structure of the fabrics can be compared in terms of topology. However, the models do not allow comparing the true shapes, do not consider forces, and present a simplified yarn path (cf. sections 4.1 and 4.3). In Figure 64 a), with respect to ASTB, it can be seen that the LLs of the stitches after the turns (with the exception of the first turn) were not drawn through the previous course, characterizing them as CHs. Regarding RSTB, which is depicted in Figure 64 b), the prolonged LLs of the turns resulting from their transfer to the neighboring stitch position are striking. In Figure 64 c), the increased tightening of the CHs added by ASTE is displayed. Lastly, Figure 64 d) shows that according to RSTE no stitches are formed in the last stitch of each course (except for the first CH course).

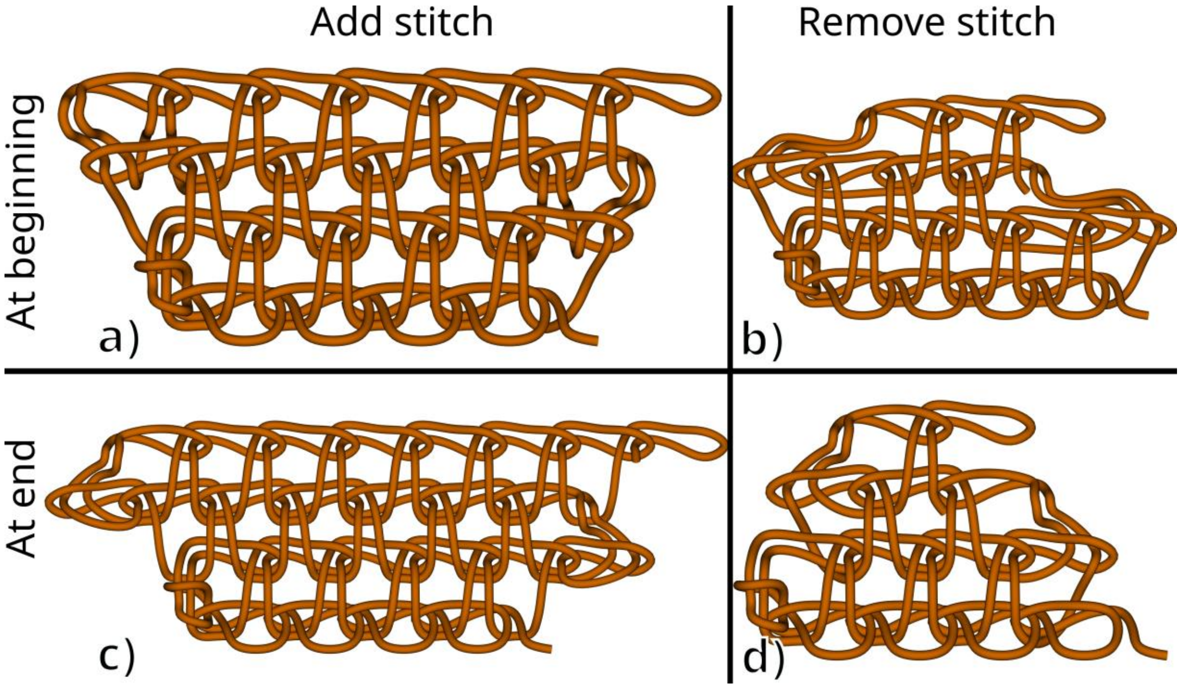

Figure 64. Modeling of the methods for changing the fabric's width based on the crochet patterns of Figure 63. **a)** ASTB. **b)** RSTB. **c)** ASTE. **d)** RSTE. Based on Figures S1 and S2 of the supplementary materials of the CC BY licensed reference A7.

The possibilities of the developed CroMat crochet machine for width-wise shaping during production are based on the variation of the number of used ANPs (see also sections 3.3.7 and 3.3.8). This principle is common in weft knitting and involves transferring of loops as described above [185]. With widening in knitting, a group of loops is transferred outwards about one needle, while narrowing can be performed by transferring loops by multiple needles [185]. Moreover, weft knitting provides shaping possibilities by altering the stitch structure, for example by tuck/miss stitches or elastic inlays, or by changing the stitch length (*L*) [185]. The CroMat prototype can also change the stitch type as well as the *H* in a limited range via the yarn tension (cf. section 3.4.6).

3.3.10 More complex stitches

HDC is the most complex crochet stitch that can be formed with these fundamental machine elements of the CroMat. For more complex stitches, like double crochets, it would be necessary to draw the loop of the last yarn over of an HDC not through all loops on the needle, but only through the foremost one. Then, the loop of an additional yarn over would need to be pulled through the remaining two loops. This selective drawing through only a distinct loop is not possible with a compound needle as crochet needle. Since, a loop is always drawn through none or through all loops wrapped around the compound needle. For selective drawing, a second position or hook on the needle is necessary for securing or releasing specific loops. The patented idea of a corresponding design originating from the author is shown in Figure 65 [A5]. Using a 3D printed variant and the initial prototype described in section 3.1.5 (cf. Figure 29), double crochet stitches were successfully formed.

Figure 65. Alternative design of a crochet needle with two hook or positions to separately secure loops.

As can be seen in Figure 65, both recesses, in which loops can be stored separately, can be closed with the same slider. With such a needle, a double crochet can be principally built according to the motion sequences of HDC formation (cf. Figure 49 in section 3.3.4) with the following differences. During the first yarn over both, the LL and the new loop, are transferred in the rear recess of the crochet needle. The loop of the second yarn over, which is to be drawn through the working stitch, is then placed in the front recess. This is because the loop of the second yarn over must slip on the shaft when extending the crochet needle for the third yarn over while the LL and the loop of the first yarn over remain in the closed rear recess. As a result, the loop from the third yarn over can be drawn through only the loop of the second yarn over and not through the other loops. For the fourth yarn over, which distinguishes a double crochet from an HDC, the LL and loop of the first yarn over are placed on the shaft while moving the crochet needle with a fully opened slider along its longitudinal axis. Then, the loop of the fourth yarn over is placed in the first recess and pulled through the two loops wrapped around the crochet needle's shaft with a fully closed slider. This last created loop in the first recess becomes the new LL and the double crochet is finished.

Additionally, two compound needles working together and placed side by side, so they can rotate around their joint central axis, could be used to form double crochets by machine. With the mutual rotation and by considering the directions of the legs of a loop held by one needle, the loop can be transferred to the second needle by inserting it through the loop's legs. To finish the transfer, the first needle must then cast off the loop. With such a handover, loops, through which a new formed loop must not be drawn, can be stored in one needle, while the other one draws loops through each other. Thereby, double crochets can be formed with the above-described process by considering each recess as a different needle. A more detailed description (in German) can be found in the patent [A5].

According to the principles of multiple recesses in one needle or multiple crochet needles, more complex stitches than double crochets can be built by adding more recesses or needles. For example, a treble crochet as next complex stitch would require one needle with three recesses or three needles, because a further step of selectively drawing of a loop through distinct loops is necessary. However, this work and the developed CroMat machine focuses on building stitches up to the complexity of HDCs. One reason for this is that stitches like double or treble crochet would necessitate the development of special needles or a much more complex mechanical construction. The automation of these complex stitches based on the approaches developed here is a task of a future project.

3.4 Technical implementation of CroMat prototype

This section describes the technical implementation of the CroMat prototype at the end of the development phase according to Koltze and Souchkov [179]. The CroMat prototype fulfills all basic functions and requirements but does not yet represent a production-ready industrial machine. Such an industrial prototype is being developed by the project partners based on the CroMat prototype.

First, an overview of the structure of the CroMat prototype is given in section 3.4.1. Then the components of the fundamental machine elements consisting of the auxiliary needles (section 3.4.2), the crochet needle (section 3.4.3) and the yarn guide (section 3.4.4) are described in detail. In section 3.4.5, the forces occurring at selected points in the stitch formation process are considered theoretically to give an impression of the stress on the components. Furthermore, difficulties regarding the yarn tension are highlighted in section 3.4.6. Finally, section 3.4.7 addresses the electronics installed in the prototype to control the machine.

3.4.1 CroMat machine overview

To enable the implementation of the movements of the fundamental machine elements for stitch formation as described in the previous section, the CroMat crochet machine prototype must have a certain number of movement axes. The axes result directly from the necessary motions of the fundamental machine elements (cf. section 3.3) and specify the structure of the prototype. According to the requirement of low complexity of the ideal crochet machine, only the necessary minimum of motion axes is implemented. The machine's complexity increases with each axis, and with it the susceptibility to errors as well as the costs. In this context it is advantageous that during the development of the motion sequences of the fundamental machine elements attention was already paid to perform movements as simple as possible and implement them with as few motion axes as possible.

Schematic overview

Figure 66 gives a schematic overview of the movement axes and the basic CroMat prototype structure. The crochet needle (1) in its housing (2) can be moved transversely to the auxiliary needle bed (4) via the X-axis and towards and away from it via the Y-axis. Additionally, a rotation of the crochet needle around its own axis according to W is possible. The crochet needle is arranged at a fixed angle α of about 30° with respect to the auxiliary needles (3) and can be moved accordingly via the R- and S-axes. S moves the shaft of the crochet needle, which is designed as a compound needle, while R moves the slider. More detailed descriptions about the implementation of the movements of the crochet needle are given in section 3.4.3.

The ANPs (3) on which the crochet stitches are suspended are guided in the auxiliary needle bed (4). They can be brought into any position along their longitudinal axis by means of the movement axis P. The P-axis can be positioned with respect to different ANPs by the movement of carriage 5 along the V-axis behind the needle bed. This method of moving the P-axis via the carriage 5 gives an indication that mechanical multiplexing is used for the movement of the auxiliary needles and not a cam system known from knitting machines. More details are described in section 3.4.2.

Besides V, the U-axis is also parallel to the X-axis and enables the movement of the yarn guide (6) below the plane of the auxiliary needles. The eyelet of the yarn guide, which moves the yarn (10), can be changed in its angular position relative to the auxiliary needles with T and can be moved along Z. With this combination of rotation and translation, the yarn guide can be inserted into a working stitch from behind and can generally perform yarn overs. The assembly of the yarn guide is addressed in section 3.4.4.

The yarn (10) is provided by the feeder (8) with a defined thread tension and is manipulated into stitches by the yarn guide, the auxiliary needles and the crochet needle, which are acting as fundamental machine elements. Section 3.4.6 describes the feeding and tensioning of the yarn in more detail. The crocheted fabric (9) formed from the yarn is guided through the double knock-over verge (7). The latter is necessary to keep the crocheted fabric in a position that favors the insertion of machine elements into the working stitch as well as the casting off the stitches. For the CroMat prototype a simple mass is hung in the crocheted fabric and used as a take-off.

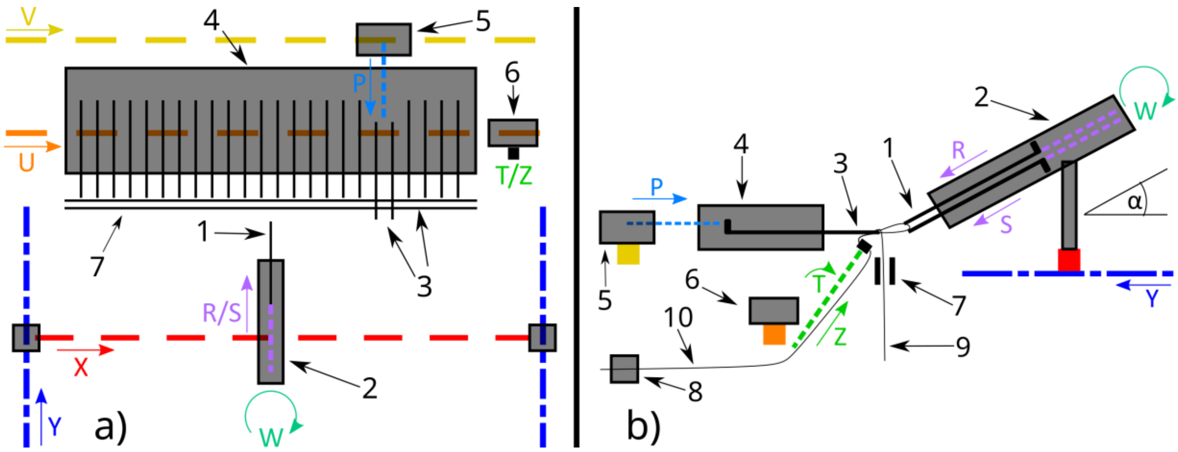

Figure 66. Schematic structure of the crochet automaton (CroMat) prototype crochet machine with movement axes and numbered components. **a)** Top view. **b)** Side view. 1: crochet needle, 2: crochet needle housing, 3: auxiliary needles, 4: auxiliary needle bed, 5: auxiliary needle movement carriage, 6: yarn guide carriage, 7: double knock-over verge, 8: yarn feeder, 9: crocheted fabric, 10: yarn.

Given the structure of the crochet machine shown in Figure 66, the movements of the fundamental machine elements presented in section 3.3 are made possible by ten axes of motion. The presented fundamental structure is independent of the actual technical implementation of the assemblies. Therefore, the schematic structure also serves as the basis for the industrial crochet machine, which is located between the elaboration and production phases in the innovation process, and in the design of which the author of the present work is involved.

Motion axes compared to other crochet machine approaches

Compared to the first crochet machine approach, which has four motion axes to automate the formation of SLs (cf. section 2.3.1) [6,18], the further developed CroMat prototype is considerably more complex with ten motion axes. The larger number of motion axes is necessary to form not only SLs but also SCs, HDCs, turns as well as INC and DEC by machine. The motions of the auxiliary needles and of the crochet needle along their longitudinal axis as well as the lateral movement of the crochet needle in front of the auxiliary needle bed have similarities to the first crochet machine approach. Differences are that the CroMat prototype requires an additional moving carriage for the movement of the auxiliary needles and that the vertical movement of the auxiliary needle bed is waived. Also, additional axes are added for the movements of the slider of the crochet needle, its rotation and for the movement of the crochet needle towards the auxiliary needle bed. The other additional axes are required for the movement of the yarn guide.

In terms of the number of movement axes, the CroMat prototype has similarities with the Croche-Matic prototype (cf. section 2.3.2) for automating circular crochet, which has nine axes [14,15]. There, similar to the crochet needle of the CroMat prototype, the crochet hook can be moved along its longitudinal axis and can also be rotated. Four of the other axes move the already crocheted fabric. In the CroMat prototype, the fabric is only moved indirectly when auxiliary needles drop a stitch. Needles or other machine elements to constantly support the formed fabric are not used in the Croche-Matic approach.

In comparison to the necessary ten movement axes of the CroMat machine elements, simple weft knitting machines have one main movement axis, namely the movement of the cam system over the needles in the needle bed (see section 2.2.1). Thereby, the yarn guide is also moved. Moreover, further DOFs are added regarding the cam system, e.g., to enable tuck or miss stitches [187], as well as further possible elements for patterning, e.g., a single needle selection. Such additional configuration options, which are often implemented mechanically [104], are not required for the CroMat crochet machine, because the patterning is performed by means of different movements of the machine elements on the ten movement axes.

CroMat construction

The specific structure of the CroMat prototype is shown as a CAD model in Figure 67, which Christoph Döpke assisted to model within his employment in the *HaekelMasch* project. There, it can be seen that the framework of the machine is constructed from 20 mm aluminum extrusion profiles, which are frequently deployed in prototype construction. These allow, on the one hand, a sturdy structure and, on the other hand, a modular exchange and fine-tuning while mounting the assemblies. Accordingly, RP and the performance of experiments are made possible with the CroMat prototype. A structure based on 20 mm aluminum profile rails is also used, for example, for mass-produced 3D printers of the Ender series from Creality [188].

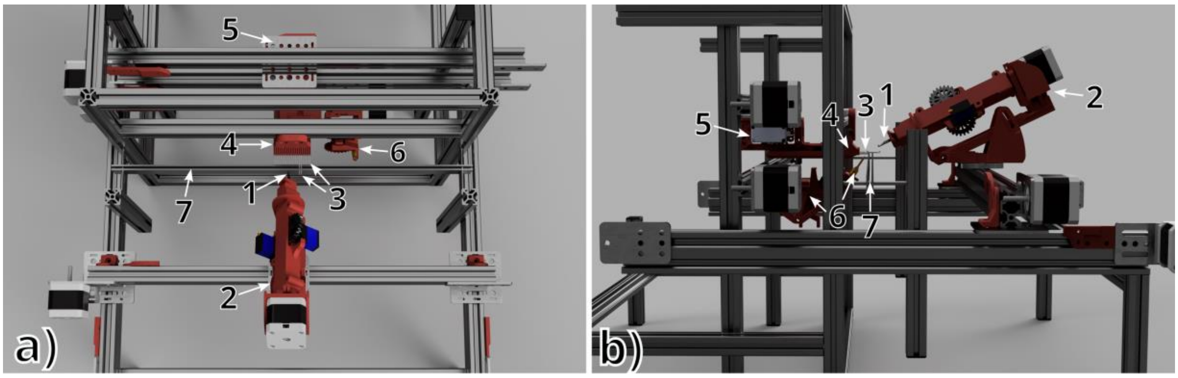

Figure 67. CAD model of the CroMat crochet machine prototype. **a)** Top view and **b)** side view. 1: crochet needle, 2: crochet needle housing, 3: auxiliary needles, 4: auxiliary needle bed, 5: auxiliary needle movement carriage, 6: yarn guide carriage, 7: double knock-over verge. 3D printed parts are displayed in red and the micro servo motors in blue.

A further similarity to consumer 3D printers is the usage of V-slot pulleys (belt driven carriages guided by rollers in V-shaped grooves of aluminum rails, cf. section 2.4.2). Figure 68 shows the implementation of this type of linear guide for the right side of the Y-axis, which moves the X-axis via two motors and V-slot pulleys. Regarding the X-axis, which is also moved via a V-slot pulley, the deflection pulley for the belt drive can be seen in Figure 68 a). The belts are driven by a gear with the desired transmission ratio, which is mounted on the shaft of an electric motor, see Figure 68 b). In addition to the X and Y axes, the U and

V axes are also implemented via such V-slot pulleys. The axes have limit switches, similar to the one visible in Figure 68 a), to determine the origin.

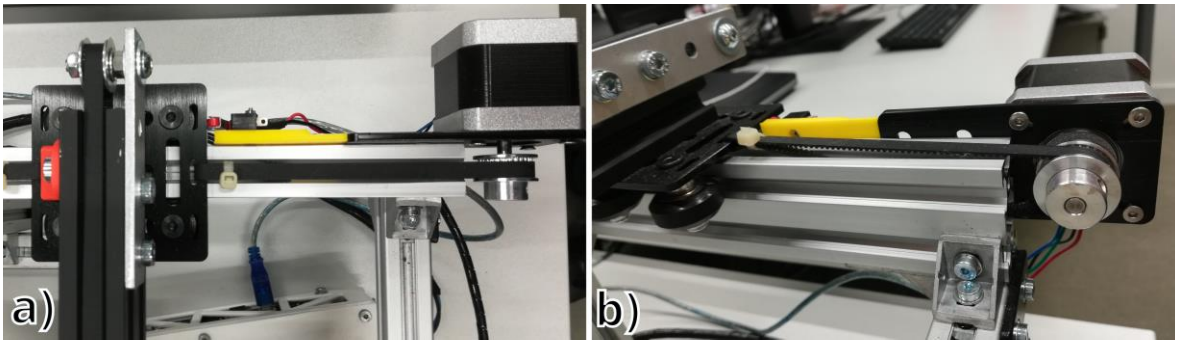

Figure 68. Linear guide of the Y-axis as belt driven V-slot pulley. **a)** Top view of the moved carriage, on which the right side of the X-axis is mounted. **b)** Side view of the V-slot pulley system with the rollers of the carriage shaped according to the groove of the aluminum rail.

Alternatively, ball screw drives, which are common for high speed machine tools [189,190], could be used to transmit the rotational motion of the electric motor to the linear motion of the carriage. Compared to belt drives, which are also widely used in industrial applications, these have the advantage of higher positioning accuracy of the moving element [191]. However, ball screw drives are more difficult to manufacture and correspondingly more expensive than belt drives [191,192]. Belt drives have an uncertainty in the position of the carriage due to the elasticity of the belt when only the angular position of the motor is known [191]. This is particularly significant at high accelerations [191].

In view of the necessary accuracy of the positioning of the machine elements and the limitations of the many 3D printed components (shown in red in Figure 67), the disadvantage of belt drives is considered to be of little relevance for the CroMat prototype. The prototype is intended to demonstrate the basic machine implementation of the motion sequences from section 3.3 and is not to be used for production, so high-speed stitch formation, which inevitably involves high accelerations, is not the goal. Therefore, severe deviations in the positioning for the use case of the prototype are not to be expected. The fact that the movements of the axes X, Y, U and V via belt drives are sufficiently accurate and adequate for the prototype was confirmed by the production of a large number of crochet samples (cf. section 4.5). For an improved prototype, such as the industrial prototype, which is planned with precisely manufactured metal parts, ball screw drives should be installed so that accurate positioning is possible even at high speeds.

As can be seen in Figure 68, the belt drive is propelled by an electric motor in the standardized NEMA 17 design. Specifically, this motor driving the Y-axis is a two-phase stepper motor with a step angle of 1.8° with an accuracy of ± 5% (cf. section 2.5.1). The torque of the used model 17HS4417 from ACT Motor GmbH [193] is with a holding torque of 0.4 Nm more than sufficient for the movement of the X-axis in Y-direction. However, it has to be considered that two of these motors (right and left of the X-axis) are used for the Y-axis. These are connected in series to save on motor drivers. Since an operating voltage of 24 V is used and the motors are also designed for 12 V, this is possible without any problems. Beneficial is the simple construction and the guaranteed right-angled alignment of X- and Y-axis even during movement.

The same NEMA 17 motor type is used for the rotary axis T. The axes X and V are also equipped with NEMA 17 motors, namely steppers of the type 1704HS168A-OB [194]. Furthermore, the types 17HS19-1684D [195] and 17PM-K374BN01CN [196] are used for the axes U and W, respectively.

These NEMA 17 motors all have very similar torques and characteristics. In terms of their application in the CroMat prototype, they are sufficiently accurate and are capable of moving the machine elements for the stitch forming operations. In general, such NEMA 17 motors are often used in 3D printers or CNC mills (cf. section 2.4.2).

The other axes, namely for moving both the crochet needle and the yarn guide along their longitudinal axes, are equipped with micro servo motors from TowerPro (cf. section 2.5.2). Specifically, the slider and shaft of the crochet needle are driven by MG92B motors and the yarn guide by an MG90S. These are advantageous in terms of their low mass and small volume. For example, the two MG92B micro servo motors can rotate with the crochet needle around its axis (cf. Figures 67 and 69). This enables a simple, reliable and lightweight construction.

Figure 69 shows the functional and final structure of the CroMat prototype. As in Figures 66 and 67, the most important machine elements are marked to ensure comparability of the actual structure with the schematic overview and the CAD model. It should be noted that the prototype is designed for a modular exchange of components in the sense of prototyping and not for an industrially producing machine. The 3D printed auxiliary needle bed offers currently the possibility of suspending 18 stitches per course. If required, auxiliary needles can be added.

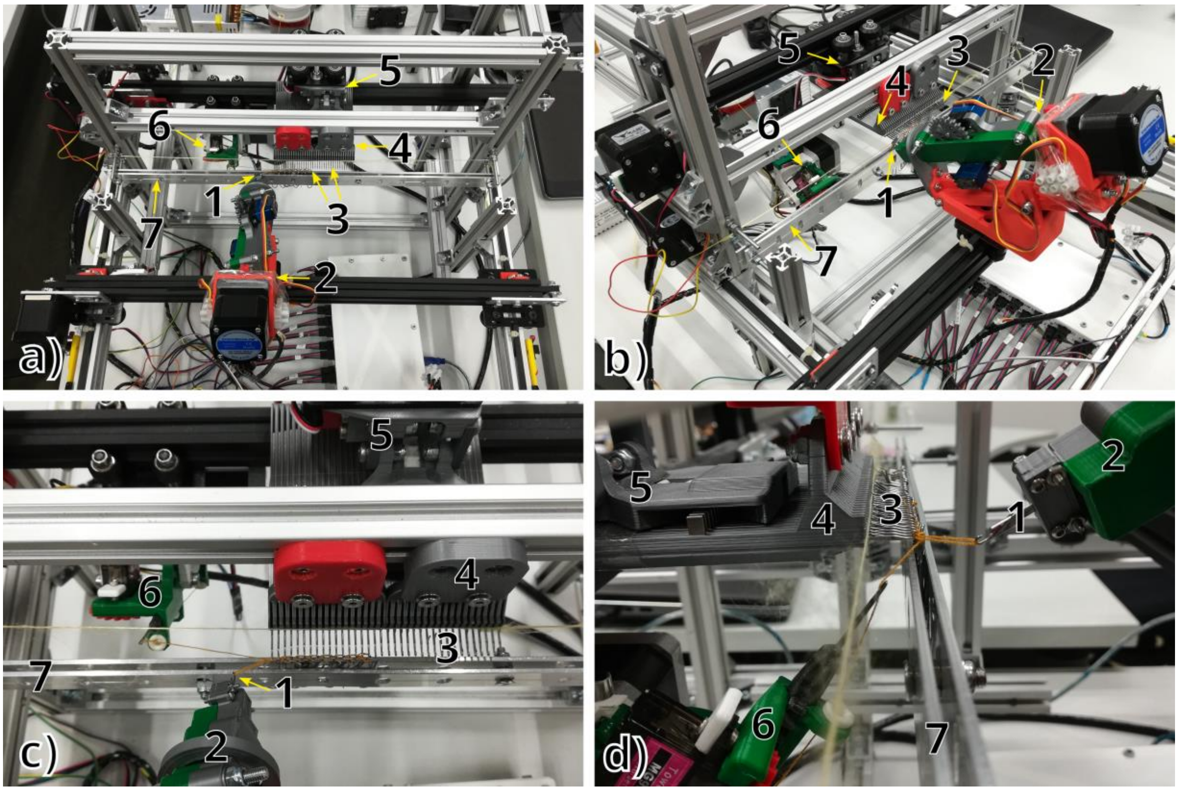

Figure 69. Photographs of the functional and final CroMat prototype. **a)** Overview from above. **b)** Overview from the side. **c)** Close-up view from above on the fundamental machine elements. **d)** Side view on the fundamental machine elements. 1: crochet needle, 2: crochet needle housing, 3: auxiliary needles, 4: auxiliary needle bed, 5: auxiliary needle movement carriage, 6: yarn guide carriage, 7: double knock-over verge.

Figure 69 c) and d) also show the yellow polyester sewing thread (M 782) from Gütermann (Gütermann GmbH, Gutach-Breisgau, Germany, [197]) used as standard for most trials. This is slightly thicker than classic sewing threads and is well suited for processing into all stitch types with the machine. Thicker and coarser yarn is problematic in terms of thread tension for the complex HDC stitches, but can be processed well for SLs, for example. Section 3.4.6 addresses processible yarn in more detail.

Similar to the abstracted model of the fundamental machine elements shown in Figure 43 in section 3.3.1, the initial situation with the specific implementation of the machine elements is shown in Figure 69 d). In the following sections, the assemblies of the auxiliary needles, the crochet needle and the yarn guide are explained in more detail.

3.4.2 Auxiliary needles

The auxiliary needles fulfill the purpose of holding the stitches formed last at each stitch position (each ANP) so that these can be used as working stitches for stitch formation in the next course. In this respect, the two auxiliary needles, over which a stitch is placed, ensure that the insertion point for the crochet needle or for the yarn guide is always in the same place, which is free of yarn. As with knitting machines, the textile produced is held in a defined position by these needles. This is necessary to ensure reproducible and error-free stitch formation. The fact that a suitable fixation of the formed textile is necessary becomes clear from the example of the Croche-Matic crochet machine. There is a lack of appropriate needles and a defined positioning of the textile and therefore the stitch formation is error-prone [14,15].

For the CroMat prototype, a double 5-gauge with five ANPs per inch was selected. Thus, the ANPs have a spacing of 5.08 mm to each other, while the individual needles have a spacing of 2.54 mm as with a 10-gauge pitch. A gauge of 5 was chosen because it is the smallest possible gauge in view of the machine elements used and the necessary motion sequences. For smaller gauges, smaller needles are required, which also necessitates extensive adjustments to the sequence programs. If larger gauges are desired, only the needle distances have to be increased, which involves relatively little effort.

Needle positions

The ANP of the working stitch must be able to be positioned in the four main positions described in Figure 70 during stitch formation. The positions of a) and b) are necessary to cast off the working stitch. For this, the ANP must be extended so far that the working stitch slides safely behind the open latches. In direct succession, the needle pair is then retracted by L_1 plus L_2 to cast of the stitch. Afterwards, combined with a movement about L_1 and L_3, another position (c)) must be taken to lay over the new LL. For SLs, this is done directly in the next step. In the case of SCs and HDCs, the working stitch is dropped before the new stitch has been completely formed and the ANP remains in the retracted position for a few steps (b)). After placing the LL on the ANP, it returns to the standard position. This usually happens while the next stitch is being formed. The exact timing depends on the type of this subsequent stitch.

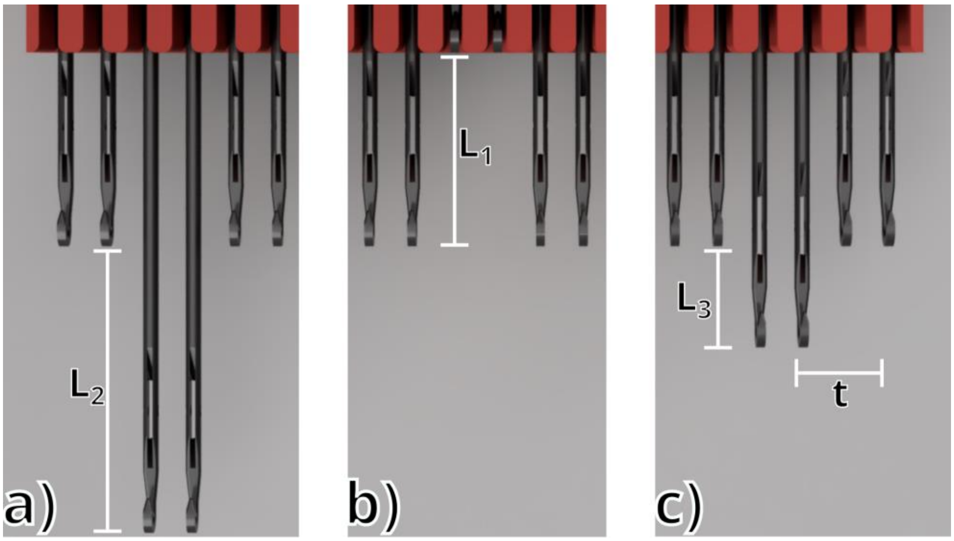

Figure 70. Main positions of the auxiliary needles necessary for stitch formation. **a)** ANP is fully extended to bring the working stitch onto the needle shafts behind the open latches that are not shown here. **b)** ANP is completely retracted to cast off the working stitch. **c)** ANP is in position for laying over the LL of the new stitch. L_1: The distance from the tip of the needle to the auxiliary needle bed in the standard position (11.5 mm). L_2: Distance by which the auxiliary needles are extended from their standard position to move the working stitch onto the needle shafts (17 mm). L_3: Distance from the position for placing the new LL on the auxiliary needles and their standard position (6 mm). t: The distance between two pairs of auxiliary needles (5.08 mm) corresponding to a gauge of 5.

Usually, all pairs of auxiliary needles used for a course go through the positions shown in Figure 70 one after the other in the crochet direction. This is due to the sequential stitch formation and the necessity of dropping an old stitch before suspending a new one. In this context, the DEC operation is an exception, because there an ANP is skipped. Thus, the following one casts off the stitch before the skipped ANP cycles through the positions shown in Figure 70. In general, while a ANP is moved, the remaining pairs of auxiliary needles remain in the standard position.

Moving the needles

The auxiliary needles are always moved in pairs. In order to drive the ANPs according to the defined positions, the following three possible solutions were considered:

- Knitting cams: With the well-known principle of a reciprocating cam carriage, which moves over the auxiliary needle bed as in flat knitting machines, the auxiliary needles can be moved in a fixed sequence via their butts and a corresponding track in the carriage [184];
- Driving every ANP by an individual motor: As suggested for some implementations of weft knitting machines, each needle can be equipped with an individual motor [198];
- Mechanical multiplexing: According to this principle, an input can be connected to different outputs in a similar way to the electronic component. Thus, the movement of a motor can be transferred to several components with the help of additional control inputs. Regarding the CroMat, the control inputs can be understood as the positions of the pairs of auxiliary needles to be moved. To give this control input, the motor is positioned for the actual movement of the auxiliary needles with respect to the desired ANP by moving it with an additional motor.

The main advantages and disadvantages of the three considered options related to the application for moving the auxiliary needles of the CroMat are shown in Table 1.

Table 1. Overview of the advantages and disadvantages of the three considered ways of moving the auxiliary needles.

	Pro	Contra
Knitting cams	Proven principle. Only one motor necessary.	Sequence of needle positions is fixed. The two crochet directions need mirrored cam tracks.
Individual motors	Maximum flexibility of movement of auxiliary needles. A pair can be moved while the surrounding ones are at rest.	High effort and high costs due to many motors.
Mechanical multiplexing	One ANP can be moved. Only two motors necessary.	Less flexible than one motor for each needle.

With regard to the use of a conventional knitting cam system, the disadvantages outweigh the advantages when used in the CroMat. With a fixed sequence, DEC and RSTE operation cannot be performed. With these it is necessary that the next ANP casts off the stitch before the current one does. This is because, unlike the normal sequence, a loop has already been pulled through the working stitch of the next ANP. If the current ANP were to cast off the old stitch, the pair could not be extended above the crocheted fabric, but would collide with the LL of the stitch formed before the DEC. Also, changing the crochet direction requires mirroring the cam track, which cannot be symmetrical according to the positions shown in Figure 70. This would lead to a complex construction of the cam system, increasing the overall complexity.

Furthermore, a cam system would require a distance between the ANPs that is more than twice as large as the distance between the auxiliary needles of a pair so that the next ANP can remain in the standard position during the movement of the current one. If the next ANP is already moved, it is not guaranteed that the crochet needle (or yarn guide) can be safely inserted into the working stitch.

The minimum possible distance between the auxiliary needles of a pair is determined by the size of the crochet needle that has to be inserted at an angle into the working stitch (cf. Figure 44 in section 3.3.2) without the machine elements colliding. The distance of less than 2.54 mm between the needles of an ANP, which results from the gauge of 5 and from which the auxiliary needle width must be additionally subtracted, is just sufficient for inserting the crochet needle. Reducing the distance to less than 2.12 mm, which corresponds to a gauge of 6, would significantly increase the probability of collision of the CroMat's machine elements and thus the susceptibility to errors in stitch formation.

In order for the next ANP to remain in the standard position while the current ANP is extended by L_2 (cf. Figure 70 a)), the areas of the cam track corresponding to the positions of Figure 70 c) and b) must lie between the ANPs. In addition to the width of each of these two areas of about 5 mm (the exact dimension may be slightly reduced depending on the width of the auxiliary needles used), the width of the three pitch sections between the positions is added. Increasing the distance between the ANPs would result in an increase in stitch width, which is not desirable in view of the already large stitches in relation to the suitable yarn diameters.

With the solution variant of equipping each ANP with an individual motor, maximum flexibility in the movement of the auxiliary needles can be achieved. However, the large number of motors required for this is not only associated with high costs, but also with a high level of design effort in the transmission of the movement to the needles. On the one hand, this contradicts the rapid implementation of the necessary functions during prototyping, and on the other hand, this contradicts the demands of the ideality that the CroMat should be as simple as possible.

The third variant, based on the principle of mechanical multiplexing, combines the advantages of both solutions so that the pairs of auxiliary needles can be moved separately from one another and only two motors are required for this (regardless of the number of pairs of auxiliary needles). The restriction in flexibility is expressed in the fact that the current ANP must necessarily be moved to the standard position before the next ANP can be moved. This is because the groove in the slider rack, which is used to move the butts of the auxiliary needles, must first align itself with the groove in the carriage before the latter can move on. Another advantage of this solution is that any position between the four main positions (cf. Figure 70) can be taken. This means that the assembly does not have to be rebuilt if other positions become necessary during optimization or for additional machine operations. A quick adjustment via the software is possible.

Due to the groove in the carriage, which is moved above the auxiliary needle bed and which is shown in Figure 71 a) from below, the surrounding auxiliary needles are held in position. On both sides of this groove are slanted edges which align the butts of the needles in their standard position. This prevents jamming if an auxiliary needle happens not to be in exactly the right position. This guidance of the auxiliary needles in the central groove of the carriage is very similar to the principle of knitting cams. For the movement of a ANP along the P-axis, the corresponding butts, which are located in the recess of the slider rack, are guided by it. The teeth of the white slider rack are shown with a view of the carriage from above in Figure 71 b).

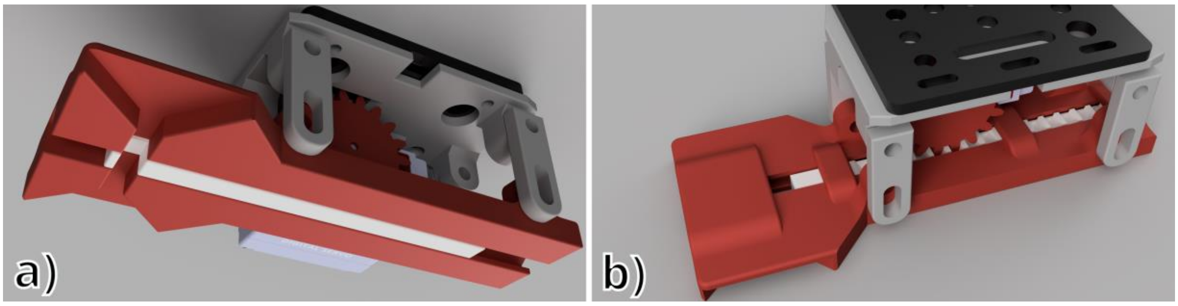

Figure 71. Design of the developed carriage, which is to be moved above the auxiliary needle bed, for driving the auxiliary needles according to the principle of mechanical multiplexing. **a)** View of the bottom side with the white slider rack aligned with the groove in the carriage through which the auxiliary needle butts slide. **b)** View of the carriage with a retracted slider rack from above.

The servo motor shown in Figure 71 moves the slider rack, which is positioned to grip the butts of the ANP, along the P-axis. Specifically, a Miusei MS24 servo motor with a torque of about 1.9 Nm [199] is used to apply sufficient force to move the slightly preloaded needles in the 3D printed needle bed. For such a movement, the slider rack must be positioned exactly above an ANP. If another ANP is to be moved, the entire carriage is moved along the V-axis (cf. Figure 66) to the position of the corresponding ANP. During this movement, the slider rack remains in the default position, which corresponds to the default position of the auxiliary needles.

Figure 71 shows the base plate of the V-slot pulley in black. The rollers, which run in the groove of a V-slot aluminum profile, are screwed to this plate. The whole assembly is designed to be suspended so that the carriage can be moved with an air gap of about 1 mm close above the auxiliary needle bed. It should be noted that the assembly was designed for manufacturing using FDM 3D printing. Accordingly, some tolerances and gap dimensions were chosen larger than for machining metal parts.

Needle type

Corresponding to the above descriptions of auxiliary needles, latch needles have been selected as the needle type for them. This type of needle, first patented in 1806 [30], is the most widely used type of needle in weft knitting machines [30]. Compared to the alternative types of compound and bearded needles, this one has the advantage of being self-acting and does not require any other machine elements to open/close its hook when performing the knitting action [30]. The obsolete bearded needles need an additional machine element for closing, which pushes the beard, and the compound needles need an additional drive for the movement of the slider for opening and closing [30].

When used in the CroMat, the latch needles have the disadvantage that the hooks are closed after the stitch is dropped, but these need to be open in order to be able to place the LL over the auxiliary needles. Thus, they are not completely self-acting here and require an additional device to open them before suspending the LL. Opening brushes are often used as devices for opening latches in weft knitting machines [187]. A corresponding brush was tested with respect to the crochet machine prototype (cf. Figure 38 in section 3.1.7) and found to be not sufficiently reliable in opening the latches. A more reliable device for opening the latches was found to be an aramid thread placed in such a way that the latches of the auxiliary needles are opened by it when they are extended.

For the use of compound needles, it would be necessary to add another axis of motion with a corresponding motor. This would increase the complexity of the crochet machine considerably more than attaching a tensioned yarn. Thus, it was decided to use latch needles and to attach an additional stationary machine element, namely the yellow aramid yarn, which can be seen in Figures 69 and 72.

In the CroMat prototype, the aramid thread is mounted above the auxiliary needles, directly in front of the auxiliary needle bed. The advantage over a rigid element such as a metal blade, which could be attached in the same way, is the flexibility of the thread. This is because, when the latch needles are extended, their raised shaft section passes the edge of the auxiliary needle bed. If a blade were attached corresponding to the level of the latches, it would collide with the raised section of the shaft. To avoid grinding the needle shaft to a uniform height, a tensioned aramid thread is used which, unlike a metal blade, can flexibly follow the elevation of the shaft. However, due to the wear and tear of the aramid thread, a rigid blade is preferred for the industrial prototype with possible necessary grinding of the auxiliary needle shafts to a uniform height.

The auxiliary needles are implemented in the CroMat prototype as Vosata 105.83 G04 latch needles from Groz-Beckert. These were chosen because their dimensions fit well with the selected crochet needle. It was necessary to make the decision dependent on the crochet needle, because the respective range of suitable needle types was in comparison much more limited (see section 3.4.3). The Vosata has a 2.3 mm high hook, and a 1.35 mm high shaft. Advantageously, this needle is a friction needle due to its slight flex bend, which is well suited for the open cam system of the CroMat prototype's carriage [30].

The standard position of these Vosata auxiliary needles is defined so that the aramid thread lies just behind the opened latches (cf. Figure 72). The aramid thread must be behind the latches so that it is not caught by the hooks when the auxiliary needles are retracted. In general, the auxiliary needles should be retracted as far as possible in their standard position in order to be guided and stabilized as firmly as possible by the auxiliary needle bed. With the distance from the open latches to the tip of the needle being 11.3 mm, this standard position was defined with a distance of 11.5 mm between the auxiliary needle bed and the needle tips (see L_1 in Figure 70). For dropping a working stitch, the auxiliary needles are retracted by L_1 (11.5 mm) from the standard position so that they are positioned close behind the yarn and the yarn can open the latches during subsequent extension.

With regard to this chosen standard position of the auxiliary needles, it is advantageous that the crochet needle also has sufficient space below the auxiliary needle bed for being extended for a yarn over in the non-inserted state without colliding with it. In a hypothetical further retracted standard position, depending on the thickness of the auxiliary needle bed, it can be problematic to extend the crochet needle along the 30° angle α far enough without causing collisions (cf. Figure 66 in section 3.4.1).

Figure 72 shows the implementation of the needle bed, the auxiliary needles, and the carriage for their movement in the CroMat prototype. In particular, the realization of the motion sequences for dropping a working stitch after the formation of an SL, which was shown in Figure 37 in section 3.1.6, is depicted. For this, the auxiliary needle positions described in Figure 70 are adopted. Also, the embodiment of the crochet needle as a compound needle, which will be discussed in more detail in the next section, can be seen.

In the course of practical trials carried out with the CroMat prototype using various yarns, it occurred on rare occasions that the latches got caught in the loops placed on the Vosata auxiliary needles. This can happen especially with yarns consisting of two or more twisted threads and having larger diameters (larger than 1 mm). After the auxiliary needles have been extended and the working stitch has been placed on the shafts, it can happen that the loops do not slip suitably under the latches to close them, but that the latches pierce into the yarn. In this case, the auxiliary needle gets caught in the working stitch. These errors where not observed with the sewing thread M 782 from Gütermann, used as a standard here.

In order to avoid this error and to expand the range of yarns that can be used with the CroMat crochet machine in the future, auxiliary needles with spring-loaded latches can be used. With these, the latches of the needles are never completely open nor completely closed due to internal spring mechanisms. This means that the angle between the needle shaft and the open latch is greater, so that the probability of yarn being pierced by the latch is significantly reduced. A specific needle model with overall suitable specifications is, for example, the Vosa 80.75 G 036 from Groz-Beckert. This needle type is planned to be used for the auxiliary needles in the industrial prototype.

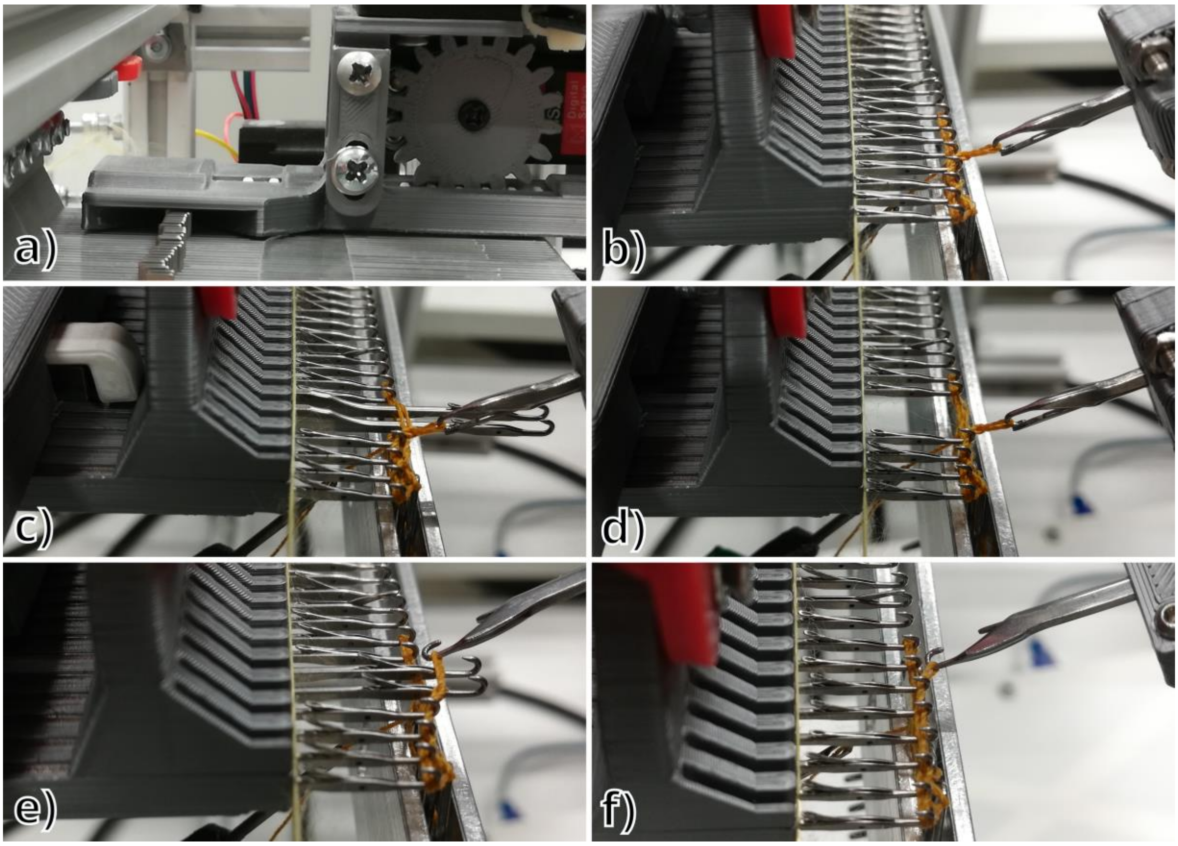

Figure 72. Photos of the auxiliary needles, the corresponding carriage and the main positions along the P-axis necessary for stitch formation. **a)** Auxiliary needle carriage with sliding rack and driving gear. **b)** Standard position of the auxiliary needles with suspended stitches using sewing thread M 782 from Gütermann. **c)** Auxiliary needles extended by distance L_2 as first step for casting off a working stitch. **d)** Auxiliary needles retracted by L_1 with respect to standard position and dropped working stitch. **e)** Auxiliary needles in position (L_3) for yarn over with latches opened by the yellow aramid yarn tensioned in front of the auxiliary needle bed. **f)** Auxiliary needles in standard position after placing the LL.

3.4.3 Crochet needle

The requirements for the CroMat's crochet needle regarding the necessary movement axes were described in section 3.1.3. The fact that a compound needle is used for this has also already been mentioned. This needle type exists since 1856 and is often used in warp knitting machines [30].

Needle type

In the first crochet machine approach, a latch needle with a modified protruding tip was used to perform the tasks of the crochet needle (cf. sections 2.3.1 and 3.1.2). Practical trials with this old approach have revealed that, due to the latch, there are often errors in the stitch formation. In these, the latch, which moves in a relatively large arc, easily gets caught in the yarn of the formed textile into which the needle is inserted.

With regard to the use of a latch needle as a crochet needle in the CroMat prototype, it is also problematic that it is not possible to directly control whether the hook is open or closed. This means, for example, that the first yarn over in HDCs (cf. section 3.3.4) cannot be performed because the hook must be open. However, the hook would be closed because the yarn would have been pulled through the old working stitch with the needle in the previous step.

For a suitable compound needle as embodiment of the crochet needle, the three designs from Groz-Beckert shown in Figure 73 were considered. Two of them (a) and b)) have protruding tips similar to the first crochet machine approach. In addition to their overall small size, these needles have a very small hook with which it is difficult to hold three loops securely (which is necessary for HDCs). For this reason, and because the protruding tip is no longer necessary with the developed principle of inserting the needle into a stitch suspended on two auxiliary needles (see section 3.1.5), it was decided against these two compound needle types. Thus, needle c) from Figure 53 was chosen as the embodiment of the crochet needle. The company Maschinenfabrik HARRY LUCAS GmbH & Co. KG, as a partner of the *HaekelMasch* project, provided support in the selection and acquisition of the needles.

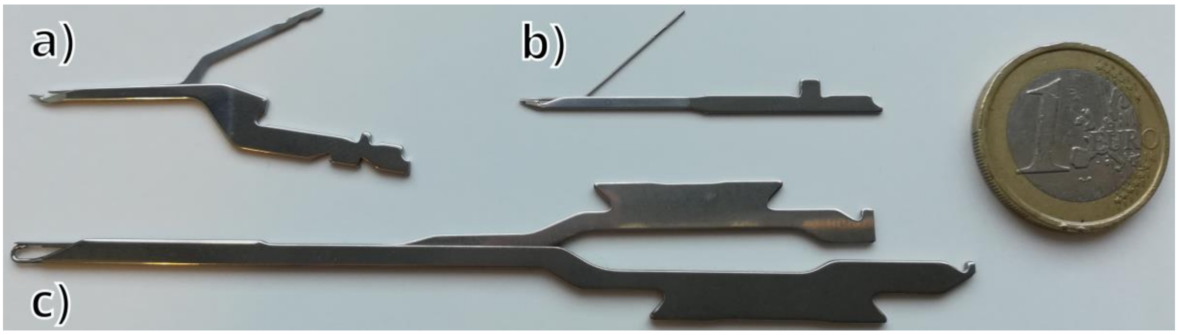

Figure 73. Compound needle types from Groz-Beckert considered for the implementation of the crochet needle. **a)** Spec 47.89 G 103 with slider Spec 33.44 G 101. **b)** Spec. 44.58 G101 with slider Spec. 20.28 G502. **c)** SN-N 115.118 with slider SN-S 103.75 G1.

The selected compound needle SN-N 115.118 with slider SN-S 103.75 G1 from Groz-Beckert features a hook height of 2.35 mm, in which several loops with a reasonable yarn diameter can be inserted without any problems. The relatively long shaft is also beneficial in terms of inserting the needle into a working stitch and interacting with the yarn in this state.

However, there is a problem with this compound needle, caused by the relatively sharp increase in the thickness of the needle from a diameter of 0.6 mm to about a 1.16 mm by 3.17 mm cross-section. When the needle is extended above the crochet for the final yarn over of a HDC, there are three loops in the hook that have to widen considerably in order to slide onto the shaft. This problem is described in more detail in section 3.4.5. At this point it is important to mention that sometimes the crochet needle could not be fully extended because the driving force was not sufficient to widen the loops properly. This is due to the hindrance caused by the friction of supplying yarn for the necessary widening.

Extending the crochet needle with a higher force would lead to more stress on the yarn and the machine elements. Instead, the problem was approached at its root. By reducing the increase in needle thickness, the loops do not need to widen as much, and the resulting resistance forces are reduced. Therefore, approx. 1 mm of material was removed from the underside of the compound needle in the shaft area with a height of 3.17 mm. The result of the adjustment can be seen in Figure 74 b). Based on trials, it could be confirmed that the reduction of the needle thickness indeed leads to an easier sliding of the three loops on the shaft during the extension for the final yarn over of HDCs and thus to a strong reduction of the error probability.

Figure 74. Modification of the crochet needle by grinding off approx. 1 mm on the underside in the area of the higher needle thickness. **a)** Original compound needle (SN-N 115.118 with slider SN-S 103.75 G1). **b)** Modified crochet needle.

Interestingly, the compound needle used here as crochet needle is also employed as needles in the crochet knitting machine Acotronic 8B/600 from Comez [200]. This is a warp knitting machine which, like the crochet galloon machines (see section 2.2.3), cannot form true crochet stitches.

Assembly and guides

The crochet needle is the machine element with the most axes of motion. Thus, the needle must be able to be moved along the X- and Y-axes, rotate along W and be extended along its longitudinal axis, with the shaft and slider being driven separately. These movements are implemented so that the assembly shown in red in Figure 75 can be moved along the X-axis by a belt drive, which in turn is moved by the Y-axis belt drives. In order to be able to extend at a suitable angle and have some flexibility for prototyping, the angle α of the crochet needle to the horizontal can be manually adjusted. For the rotation of the needle around its own axis, its housing including the two micro servos for extending the needle is moved by the stepper motor. Here, the small installation space and the low mass of the MG92B micro servo motors are advantageous.

As can be seen in Figure 75 b), the movements of the micro servos are transmitted to the shaft and the slider of the crochet needle via gearwheels and racks. The racks hold the corresponding butts and slide in the recesses of the two 3D printed housing parts (one half is shown in Figure 75 b)). The crochet needle is guided through a small recess in the front of the housing. Accordingly, the crochet needle can be moved along its axis more than 50 mm by the servos. To ensure that the slider and shaft of the needle are moved evenly, the micro servos need to drive the racks simultaneously.

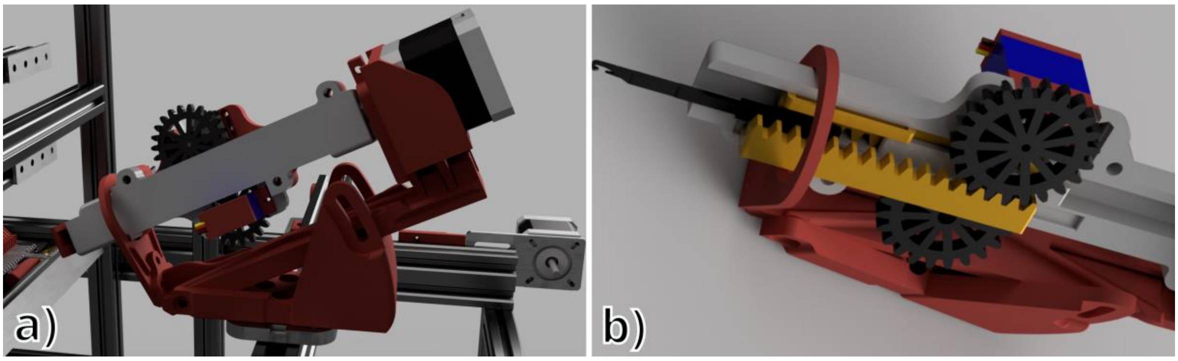

Figure 75. Model of the assembly of the linear guide of the crochet needle. **a)** Lateral view of the assembly in the model of the CroMat prototype. **b)** View of the opened housing of the linear guide of the crochet needle.

The design shown in Figure 75 allows all the necessary movements of the crochet needle. As with the control of the auxiliary needles, changes and additions can be easily made via software without having to change the mechanical design. The developed motion sequences are designed robust enough to enable reliable stitch formation despite the slight play of the 3D printed guide of the crochet needle. In an improved version of the CroMat crochet machine, such as the industrial prototype, the linear guide of the crochet needle should be made of metal parts to reduce backlash and permit precise positioning. Suitable bearings should also be used to minimize friction.

Main crochet needle positions

As can be seen from the descriptions of the motion sequences of the fundamental machine elements (cf. section 3.3), the crochet needle must perform a large number of movements. To describe all the respective positions is beyond the given scope, so only the implementations of the most important ones are shown below. These are primarily determined by the necessary yarn overs of the stitch building processes. Basically, there are five variants of forming a new loop with a yarn over with the CroMat, resulting in different crochet needle positions:

1. Inserting the crochet needle into a working stitch for a yarn over by placing yarn around it. This is especially necessary for SLs;
2. Yarn over performed by the yarn guide with a crochet needle extended behind the crocheted fabric. This is done for the final yarn over for SCs and HDCs as well as for creating a CH within a course;
3. Extending the crochet needle next to the crocheted fabric to perform a yarn over for building a CH as part of a turn;
4. Positioning of the crochet needle to place yarn in the hook, which is provided by the yarn guide driven through the working stitch. This is necessary for the formation of SCs and HDCs;
5. Picking up yarn, which is provided over the crocheted fabric by an extended yarn guide, with the crochet needle. This corresponds to the first yarn over for HDCs.

In addition, there are the positions of the crochet needle for laying a new LL over an ANP. This process is necessary for all stitch types and a corresponding implementation is shown in Figure 72 in section 3.4.2. Furthermore, there is a multitude of intermediate positions and movements. These ensure, for example, that the inserted loops remain in the hook of the crochet needle. Another common type of these additional movements is to move the crochet needle out of the way in respect of the extension of the auxiliary needles to avoid collisions and entanglement of the yarn.

The first category of positioning for a yarn over is shown in Figure 76 regarding the insertion of the crochet needle into a working stitch for the formation of an SL. In a) it can be seen how the crochet needle is positioned directly in front of the working stitch, with its angular position as described in section 3.1.5 ensuring a secure sliding of the LL onto the needle shaft. The yarn placed in the crochet needle can then be drawn through the working stitch and through the LL. The exact procedure for forming SLs is described in section 3.3.2.

Moreover, in Figure 76 it can be seen that a bent paper clip is hooked into each CH of the first course. These are passed through the double knock-over verge, and weights, like those used for manual flat knitting machines, can be hooked into the bent paper clips underneath. Such a fabric take-off is necessary so that the stitches are expanded far enough for the crochet needle or yarn guide to be inserted into them.

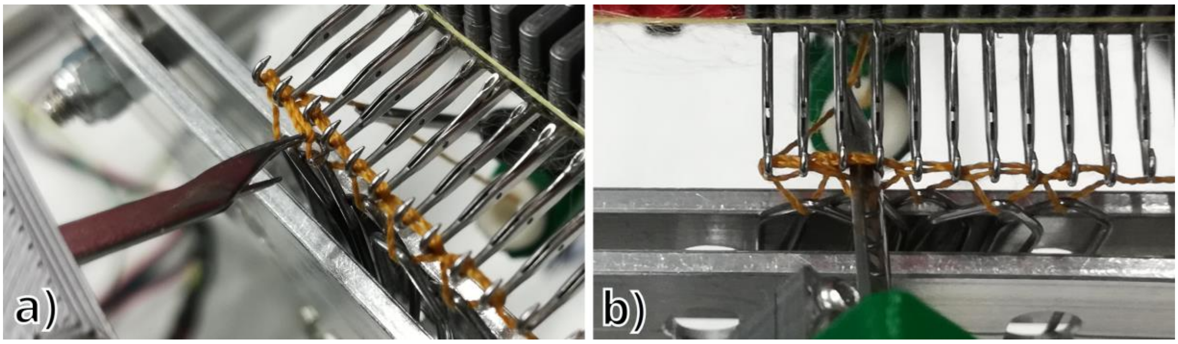

Figure 76. Inserting the crochet needle into a stitch using the example of an SL. **a)** Position before the working stitch. **b)** Position in the inserted state with yarn placed in the hook.

Figure 77 illustrates the second variant of the yarn over with the crochet needle extended behind the crocheted fabric. For this, the working stitch is cast off and the auxiliary needles remain retracted to allow to position the crochet needle's hook above the fabric, as can be seen in a). This positioning and the subsequent placement of yarn in the extended crochet needle are identical for SC and HDC. As can be obtained from Figure 77, the only difference is the additional loop on the crochet needle for HDC.

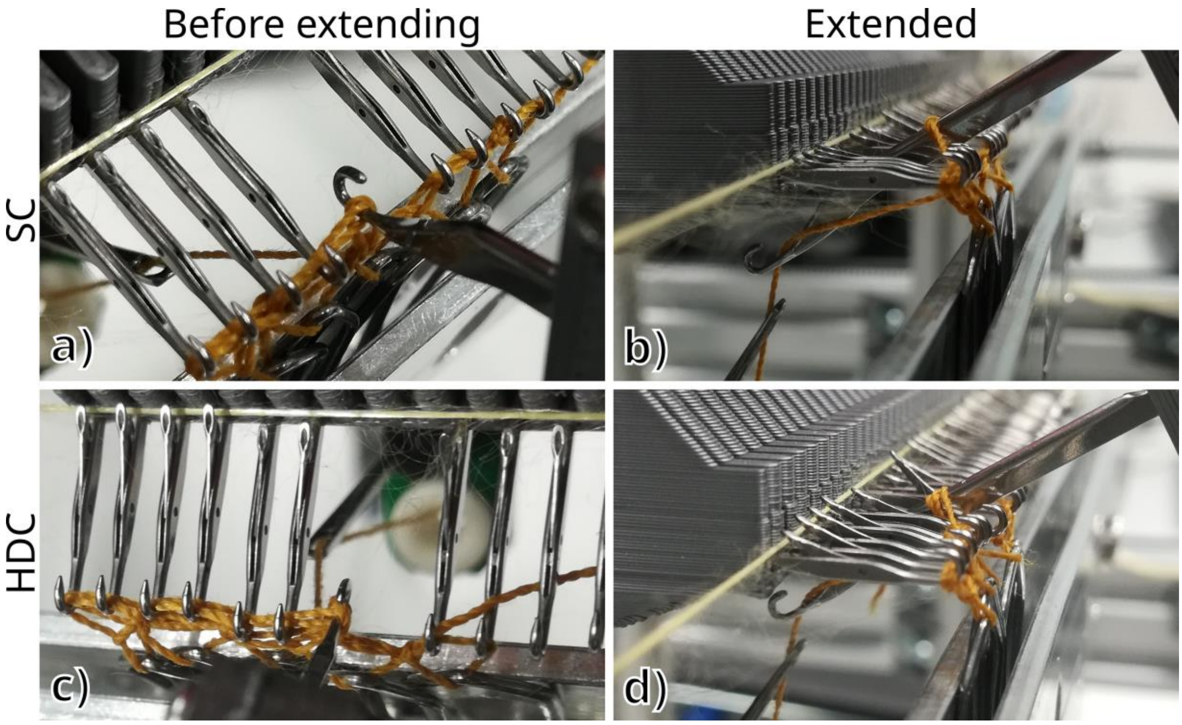

Figure 77. Extending the crochet needle behind the crocheted textile for a yarn over in the uninserted state. **a)** and **b)** show the photographs of forming a SC, while **c)** and **d)** show respective photographs regarding HDC.

The third yarn over variant is to extend the crochet needle next to the crocheted textile, as shown in Figure 78. Here, the crochet needle is with respect to the Y-Axis positioned similarly to the first variant and the subsequent yarn over is also similar. However, due to being positioned next to the fabric, the crochet needle is not inserted in or driven out behind a stitch. Another difference is that the ANP of the last stitch is retracted. The LL of the CH being formed is then placed over this in the new crochet direction (in this case to the left) to complete the turn.

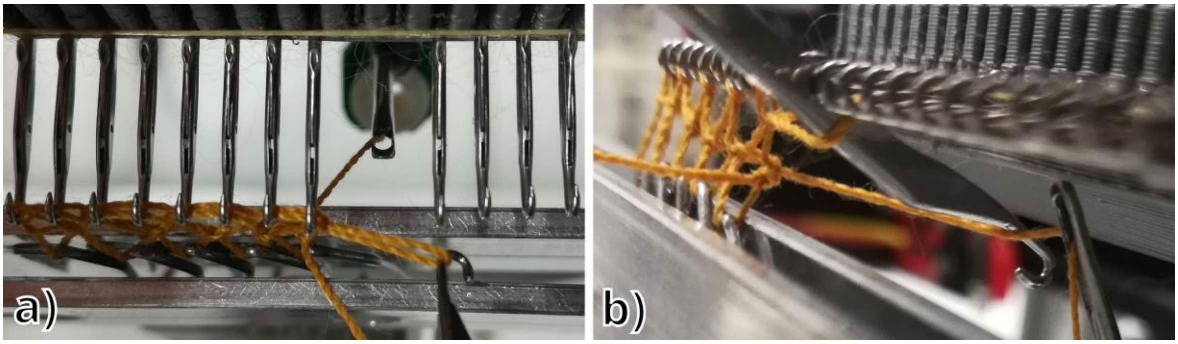

Figure 78. Important crochet needle positions for the third yarn over variant. **a)** Position next to the crocheted fabric to form a CH. **b)** Extended crochet needle with wrapped yarn around the hook.

Figure 79 illustrates the crochet needle positions for the fourth yarn over variant. Again, the implementations for SC and HDC differ only in the number of loops that are already in the hook of the crochet needle. Figure 79 b) shows that the crochet needle is moved against the crochet direction to slightly tension the yarn segment that becomes the inserted loop. This is necessary to prevent the yarn segment from jumping off the hook when the yarn guide is subsequently retracted. Such positioning is exemplary for the further necessary movements mentioned above to ensure that the loops remain securely in the hook. Furthermore, this positioning illustrates that the machine elements do not perform uniform, continuous movements.

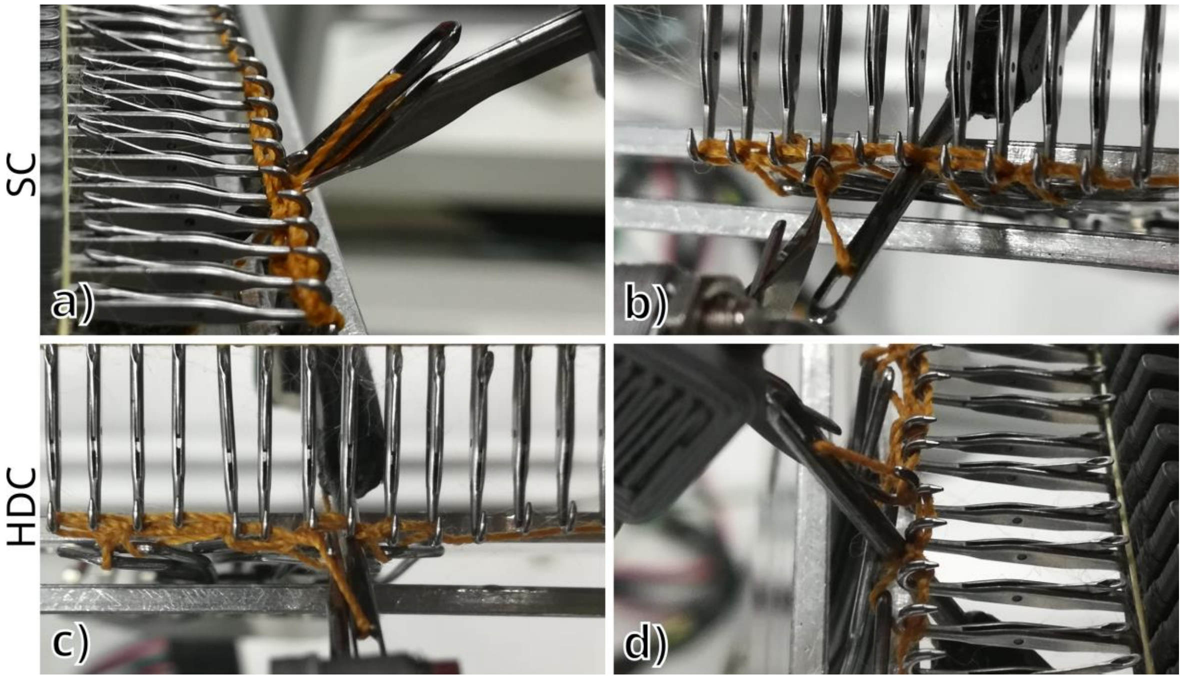

Figure 79. Positions of the crochet needle for a yarn over with a penetration of the yarn guide through the working stitch. **a)** Using an SC as an example, the positioning of the crochet needle's hook under the yarn presented by the yarn guide is shown. **b)** Crochet needle is moved slightly against the crochet direction in order to place the loop securely in the hook when the yarn guide is subsequently retracted. **c)** Crochet needle in position for inserting a yarn segment fed by the yarn guide for an HDC (in a similar position as a)). **d)** Changing the position of the crochet needle for better inserting the yarn.

Regarding HDC, it can be observed in Figure 79 c) how an auxiliary needle is bent. This occurs there due to the high friction forces and the difficulty of resupplying yarn. The reason for this is that two loops are already inserted in the crochet needle, both of which have to be widened so that the crochet needle can be positioned accordingly for the second yarn over. The insertion of the second loop as part of the first yarn over is shown in Figure 80 (the first loop is the LL). From the bending of the needle in Figure 79 c) it can be concluded that due to the yarn tension and the frictional forces, not enough yarn can be supplied to extend the two loops, which is why the auxiliary needle flexes in the crochet direction. The problem of forces building up in HDC is considered in more detail in section 3.4.5.

This problem can be mitigated somewhat by pulling the loops slightly larger during the first yarn overs by moving the crochet needle. This makes the yarn a little looser overall for positioning according to Figure 79 c). A proper solution to the problem would be to dynamically adjust the yarn tension so that during the initial yarn over and subsequent positioning, the forces on the yarn are reduced overall. This is described in more detail in section 3.4.6.

The fifth and last variant of the yarn over is shown in Figure 80. There, the crochet needle grabs a yarn segment, which is passed by the yarn guide over and not through the fabric, while it lays over the LL of the previous stitch. This is only performed as the first yarn over for HDCs. It should be noted that the yarn guide is extended between the needle pairs of the previous stitch and the current working stitch.

Figure 80. Fifth yarn over variant of the CroMat with the yarn guide being extended behind the crocheted textile. **a)** The crochet needle, which is in the position for laying over the LL of the last stitch, is moved towards the presented yarn segment. **b)** The hook catches and pulls the presented yarn segment. **c)** With the retraction of the yarn guide, the new loop is placed securely in the crochet needle's hook. Also, the LL is laid over the ANP.

With the illustrations shown regarding the implementation of the most important positions of the crochet needle, it is noticeable that the crochet needle is often extended relatively far out of the housing. This is often necessary to prevent a collision of the crochet needle housing with the auxiliary needles. In order to increase the reliability of stitch formation, the crochet needle should be guided more securely by being further retracted in future improvements to the CroMat. For example, the housing could be modified so that it is slimmer at the front and therefore less likely to collide with the auxiliary needles.

3.4.4 Yarn guide

As already explained in section 3.2.3, the CroMat crochet machine uses a special yarn guide. In addition to performing overlaps similar to a warp knitting machine, this can also be moved from diagonally below through the plane of the auxiliary needles in order to present a yarn segment to the crochet needle. This can be done either through a stitch or above the textile.

Construction

Like most of the assemblies of the CroMat prototype, the yarn guide is also based on 3D printed parts. The 3D model of the corresponding design is shown in Figure 81. The yarn runs from the yarn feeder through the eyelet in the tip of the yellow rack from bottom to top. This eyelet can be suitably positioned by the remaining components for the necessary steps in stitch formation. For this purpose, the rack can be moved along the Z-axis by the red gear driven by the micro servo. The angle (T) of this axis can be changed by the NEMA 17 stepper motor via another red gear (cf. Figure 81 b)). The entire structure is suspended to allow it to be positioned below the auxiliary needle bed along the U-axis (implemented as a V-slot pulley).

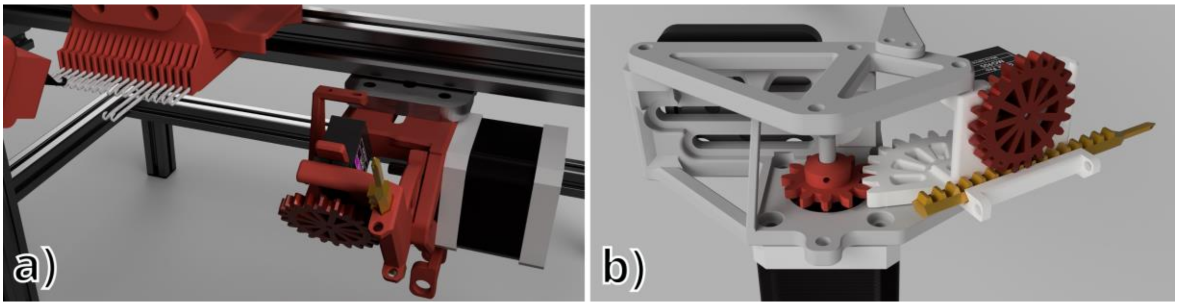

Figure 81. CAD model of the yarn guide assembly. **a)** Arrangement in the overall structure of the CroMat prototype. **b)** Detailed view of the implementation of the rotation axis T and translation axis Z.

Figure 82 shows that the yarn runs through the eyelet on the tip of an approx. 20 mm long metal shaft, which is glued into the 3D printed rack. The eyelet was selected so that it can be moved between the auxiliary needles and, when extended, is far enough above the plane of the auxiliary needles that the crochet needle can grip the yarn segment. Figure 82 a) also shows the bent paper clips guided through the double knock-over verge. A weight is not attached in this illustration. Figure 82 b) shows how the yarn is guided underneath the rack through the white ceramic eyelets to keep friction low while still providing secure guidance. Behind the yarn guide, the yarn runs freely to the yarn feeder, which regulates the yarn tension.

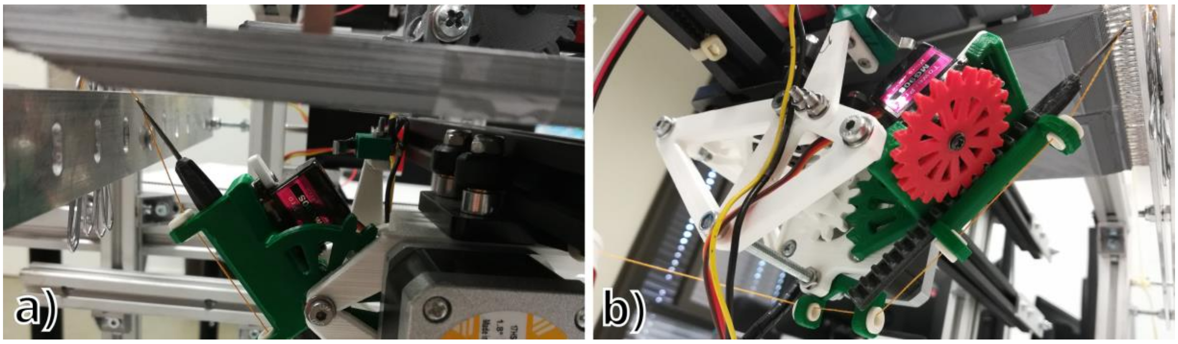

Figure 82. 3D printed structure of the yarn guide in the CroMat prototype. **a)** View of the yarn guide, which can travel directly under the auxiliary needle bed, from the right side. **b)** Guiding the yellow yarn through the white eyelets in a view from diagonally below.

Main positions

In general, the yarn guide follows the movements of the crochet needle. In this way, the yarn overs can be performed in crochet direction. As with the crochet needle, the main positions of the yarn guide are determined by the insertion of yarn into the crochet needle and the corresponding formation of a loop. Accordingly, the five variants of yarn over with the CroMat crochet machine introduced in the previous section are also considered here with regard to the yarn guide.

The movements of the yarn guide for wrapping the yarn around the hook of the crochet needle, which is inserted into the working stitch, correspond to the first yarn over variant and are illustrated in Figure 83. This type of yarn over is similar to the second of the two methods of yarn feeding defined by Spencer, namely the movement of the yarn feeder past a stationary needle [184]. Also, this yarn over is similar to the swinging motion of the warp guide during an overlap on warp knitting machines [117]. Accordingly, the loop is formed by Spencer's third method of loop formation by wrapping the yarn from the guide around the needle [184]. In the implementation in the CroMat prototype, the yarn guide additionally moves slightly against the crochet direction after insertion in order to wrap the yarn around the hook as securely as possible.

Figure 83. Movement of the yarn guide for the first variation of yarn over with a crochet needle inserted into the working stitch. **a)** Starting position of yarn guide and crochet needle. **b)** Moving the yarn guide in crochet direction with slightly changing the angle (T-axis) to place the yarn into the hook. **c)** Further change of angle with slight extension along Z and subsequent small movement against crochet direction to press the yarn securely into the hook. Crochet needle has changed its angle along W, closed the hook with the slider and begins to retract.

Regarding the yarn guide, the third yarn over variant, with an extension of the crochet needle next to the fabric to form a CH as part of a turn, corresponds to the first variant. This is because the same movements are performed with the yarn guide (possibly at a different position on the X-axis).

Figure 84 shows the yarn guide movements for the second yarn over variant. As in the first variant, the new loop is formed below the auxiliary needle plane by the movement of the yarn guide around the crochet needle. Here the similarities to the swinging motion of a warp knitting machine overlap are even more pronounced. The crochet needle is extended above the working stitch and is closer to the auxiliary needle bed with respect to the Y-axis. This requires yarn guide positions that differ in detail from those of the first variant. The biggest obvious difference is that the opening of the hook of the crochet needle points upwards here.

Figure 84. Movement of the yarn guide for the third variant of the yarn over using the example of a SC. **a)** Initial situation. **b)** Yarn guide changes angle and extends slightly to move closely over the open hook of the crochet needle and guide the yarn over it. **c)** Yarn guide retracts and moves slightly against crochet direction to push yarn into hook.

The remaining two yarn over methods are based on the principle of the yarn guide, which has been specifically developed for the CroMat and which presents the yarn segment to the crochet needle above the level of the auxiliary needles in order to form a new loop. As shown below, the crochet needle grabs the yarn segment presented. This is because the yarn guide cannot perform any overlap movements when it is extended, as its mobility along the X-axis is prevented by the auxiliary needles on both sides or is severely restricted by the working stitch.

Accordingly, yarn over methods four and five, with a movement of the needle relative to the stationary yarn feeder, are more similar to Spencer's first yarn feeding method [184]. There, the loop is not formed by an overlap, but is created by the retraction of the yarn guide after the crochet needle has gripped the yarn segment. This is illustrated in Figure 85 for the fourth method with a yarn guide inserted into the working stitch using the example of an SC.

Figure 85 also shows how the crochet needle's hook is moved under the yarn segment to be grabbed, which has already been moved through the working stitch. To support this and to provide space for the crochet needle, the yarn guide moves 0.8 mm in crochet direction after insertion into the working stitch. Also, the angle of the yarn guide (T-axis) is slightly adjusted when the crochet needle is below the yarn segment to push it into the hook (compare Figure 85 a) and b)).

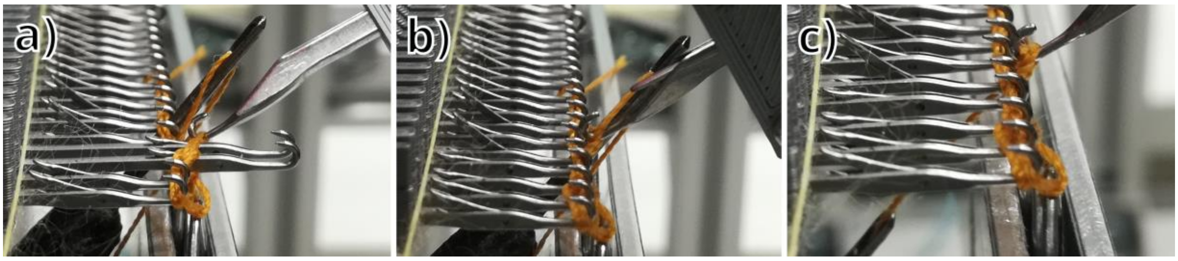

Figure 85. Fourth variant of yarn over with the insertion of a yarn segment guided through the working stitch into the crochet needle using the example of an SC. **a)** Yarn guide was inserted into the working stitch and offers the yarn segment to the crochet needle. **b)** Crochet needle moves under the yarn segment and yarn guide changes the angle for safe insertion. **c)** The yarn guide retracts while the crochet needle is stationary to form the loop.

The fifth yarn over variant differs from the fourth variant in that the yarn guide feeds the yarn segment above the crocheted fabric and is not inserted into the working stitch, but between two auxiliary needles from different pairs. Except for the extension and retraction, the yarn guide remains at rest and only the crochet needle carries out the movements for placing the yarn. The fifth yarn over is illustrated in Figure 80 in section 3.4.3.

3.4.5 Stress on yarn and machine elements

Due to the complexity of the stitch formation with many sub steps and discontinuous movements (cf. section 3.5.2), a calculation of the loads on the machine elements is extremely complex. This is further heightened by the complicated intertwining of the yarn in the crochet stitches and the generally complex non-linear behavior of the yarn [201].

It is also important to note that the CroMat prototype still corresponds to a very early stage of an industrial machine and that many details are not yet ideally implemented. An in-depth analysis of the loads on the machine elements during automated crocheting is therefore probably more appropriate for an optimized version of the CroMat crochet machine, such as the industrial prototype.

Situation of laying the LL over after forming a SL

To still offer some insight into the forces involved, Figure 86 considers the simplest case of moving the crochet needle after forming an SL to lay the LL over the auxiliary needles. As a simplification, only the yarn segment from the yarn guide to the crochet needle is considered. The segment that runs into the fabric as the other half of the LL, where it forms the loop of the old stitch through which the LL was pulled, is assumed to be rigid.

The force F_{CN} required by the crochet needle to move the LL or to pull the respective yarn out of the yarn feeder can be calculated using an extended form of the Euler-Eytelwein formula. The Euler-Eytelwein formula generally describes the ratio of the forces on a rope before and after running around a cylinder drum [202]. A similar situation arises with the angles β and γ shown in Figure 86. Here, these describe the angle of deflection of the yarn at the respective points. Since the yarn is not deflected via a cylinder drum, but via another yarn segment, an extension of the Euler-Eytelwein formula is necessary, because in this case, the diameter of the cylinder drum, or generally of the deflecting object, is not significantly larger than the rope diameter. Instead, both diameters are equal, which is why the yarn's bending stiffness is no longer negligible [202].

Specifically, the Garbaruk formula, represented by equations 1 and 2, is used as an extension of the Euler-Eytelwein formula [203]. The Garbaruk formula is generally used to describe the forces in knitting machines. The force F_1 after deflection can be calculated from the force F_0 before deflection, taking into account the bending stiffness B, the diameter of the yarn d_{yarn}, the coefficient of yarn-to-yarn friction μ and the contact angle α.

$$F_1 = (F_0 + B/d_0^2)e^{\mu\alpha} - B/d_0^2 \quad (1)$$

$$d_0 = 2d_{yarn} \quad (2)$$

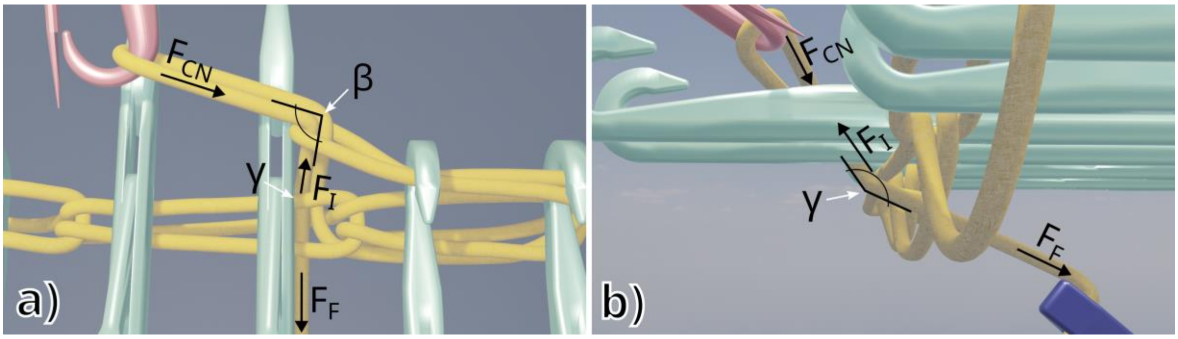

Figure 86. Simplified depiction of the force F_{CN} acting on the crochet needle during movement in the crochet direction as a function of the thread tension F_F and the yarn contacts β and γ. **a)** Top view and **b)** side view.

The Garbaruk formula can be used to describe the situation shown in Figure 86 as follows. Note, that F_I represents the force between the two yarn contact points.

$$F_{CN} = (F_I + B/d_0^2)e^{\mu(\pi-\beta)} - B/d_0^2 \quad (3)$$

$$F_I = (F_F + B/d_0^2)e^{\mu(\pi-\gamma)} - B/d_0^2 \quad (4)$$

The yarn tension F_F is usually 6.3 cN and is applied to the yarn by the yarn feeder. The angles β and γ (cf. Figure 86) must be considered in radians and subtracted from π to derive the contact angle of the yarns. Literature values regarding a non-absorbable braided polyester wound sewing yarn are used for the remaining parameters [204]. Processing of such medical yarns represents a promising future field of application for the crochet machine. With a bending stiffness of 2.86 nNm and a coefficient for yarn-to-yarn friction of 0.056, the medical yarn with a diameter (d_{yarn}) of 0.81 mm [204] results in an F_{CN} of about 0.2 N. Thus, during the overlay and movement to the new insertion point of the next working stitch, the crochet needle is subjected to about 0.2 N.

However, due to the strong simplifications and the angles assumed from an ideal position of the machine elements and yarns, this estimation is to be taken with a grain of salt. It should be noted that during stitch formation, the positions of the object constantly change and therefore the force will also fluctuate slightly. Also, the static friction that is assumed to be higher is not taken into account. Moreover, this calculation completely ignores the friction of the yarn on the crochet needle and the yarn-on-yarn friction of the contacting legs of the LL near β. Thus, it can be assumed that the friction and thus necessary force is higher in reality.

Situation of laying the LL over after forming an HDC

In Figure 87, similarly to Figure 86, the situation of placing the LL over the ANP after forming an HDC, as the most complex stitch type that can be produced, is shown. It can be seen that the yarn segment from the crochet needle to the yarn feeder has an additional point of contact (point 2). Also, there is no direct point of contact of this yarn segment to the working stitch, but instead to a loop that was pulled through the working stitch as part of the HDC. The exact position of the three loops through which the yarn segment passes can hardly be determined without an elaborate simulation, which is outside the scope of this work. The situation shown in Figure 86 is chosen to be well-arranged and does not necessarily correspond to the real conditions. For this reason, the yarn contact points (1 to 3) for the Garbaruk formula cannot be reasonably determined.

If, however, the force opposing the crochet needle is to be estimated, it might be somewhat higher than 0.2 N. This is because the course of the yarn segment and the angles of contact points 1 and 3 are basically the same as described for the SLs (compare Figures 86 and 87). Contact point 2 has a contact angle of zero according to the illustration, because the yarn segment of the LL under consideration is not deflected by the respective loop. Thus, the Garbaruk formula cannot be applied there to determine the assumed increase in friction of this contact point.

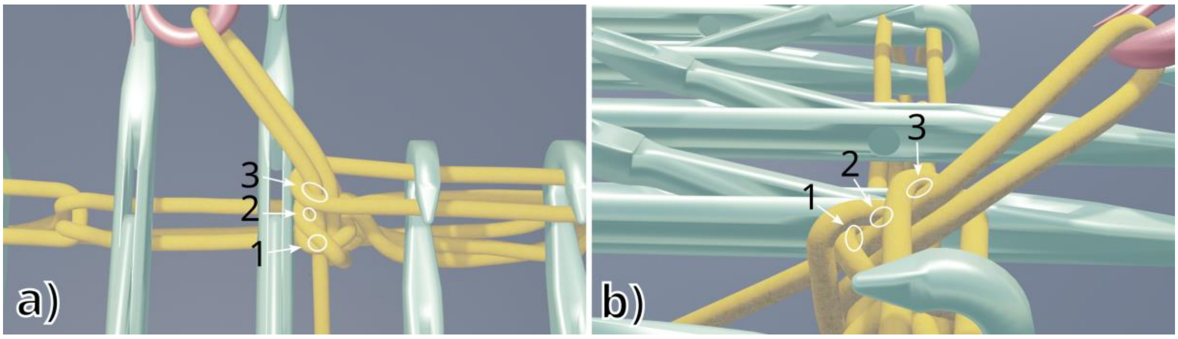

Figure 87. Idealized illustration of the position of the loops and machine elements after formation of an HDC and during overlapping of the corresponding LL. The contact points of the yarn segment between the yarn storage and the crochet needle (1 to 3). **a)** Top view. **b)** View from the side.

Situation before extending the crochet needle for the final yarn over of an HDC

Furthermore, the theoretical consideration of the forces on the crochet needle immediately before extension for the final yarn over at HDCs is worthwhile. This is where most of the problems of high forces on the machine elements have been observed. It is hardly possible to move the crochet needle, which holds three loops, further in the crochet direction from the position shown in Figure 88. For this reason, in HDCs (and also in SCs) the working stitch is cast off before the crochet needle is extended for the final yarn over (cf. section 3.3.4 and Figure 49). This allows the crochet needle to be extended in the area normally occupied by the auxiliary needles of the working stitch without having to move too far in the crochet direction.

Figure 88 shows an idealized representation of the corresponding situation and the forces acting on the needle via the loops (F_2, F_3 and F_6). Additional, intermediate forces and the respective contact points with other yarn segments or needles that deflect the corresponding yarn segment are also indicated. The forces on the crochet needle depend on each other. F_2, which results from F_F via F_1, is the input of F_3, which in turn influences F_6 via F_4 and F_5. To enable the crochet needle to move, yarn must be supplied for the top loop (F_6), which must move along the entire path via the other two loops and all six yarn contact points.

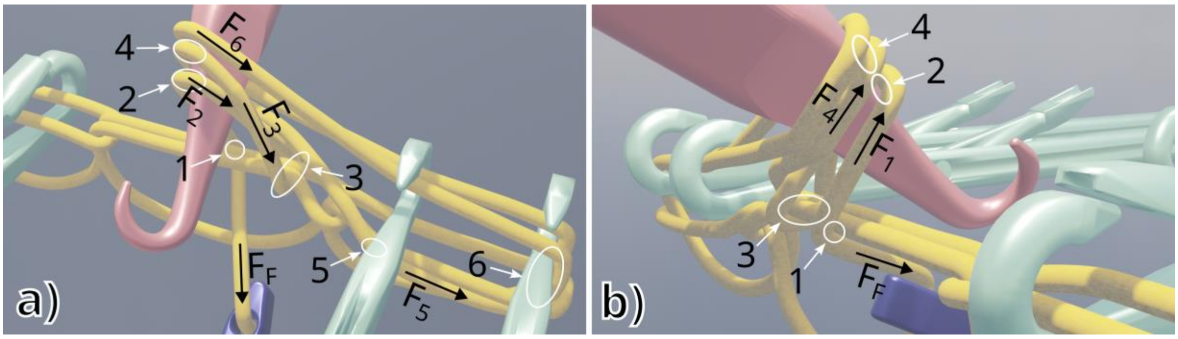

Figure 88. Simplified situation before the crochet needle is extended for the final yarn over at HDC. The forces F_2, F_3 and F_6 together act as F_{CN} against the movement of the crochet needle in crochet direction. The yarn contact points 1 to 6 considered with respect to friction are indicated as well as the further forces between them. In **a)** and **b)** the same situation is shown from different angles.

By simplifying the idealized yarn path and the six yarn contact points and neglecting the friction of parallel yarn segments, the dynamic friction and resulting forces of Figure 88 can be described using the Garbaruk formulas according to equations 5 to 11. In this respect, the same yarn parameters as above are used and the same diameter d_{yn} is assumed for all yarn contact points to needles, based on a needle diameter of 1.5 mm. The yarn contact angles are again simplified.

$$F_{CN} = F_2 + F_3 + F_6 \qquad 5$$

$$F_1 = \left(F_F + B/d_y^2\right)e^{\mu_{yy}\alpha_1} - B/d_y^2 \qquad 6$$

$$F_2 = \left(F_1 + B/d_{yn}^2\right)e^{\mu_{yn}\alpha_2} - B/d_{yn}^2 \qquad 7$$

$$F_3 = \left(F_2 + B/d_{yy}^2\right)e^{\mu_{yy}\alpha_2} - B/d_{yy}^2 \qquad 8$$

$$F_4 = \left(F_3 + B/d_{yn}^2\right)e^{\mu_{yn}\alpha_2} - B/d_{yn}^2 \qquad 9$$

$$F_5 = \left(F_4 + B/d_{yn}^2\right)e^{\mu_{yn}\alpha_3} - B/d_{yn}^2 \qquad 10$$

$$F_6 = \left(F_5 + B/d_{yn}^2\right)e^{\mu_{yn}\alpha_2} - B/d_{yn}^2 \qquad 11$$

with:

$$d_y = d_{yarn} + d_{yarn} = 2 \cdot 0.81\ mm \qquad 12$$

$$d_{yn} = d_{yarn} + d_{needle} = 0.81\ mm + 1.5\ mm \qquad 13$$

$$d_{yy} = d_{yarn} + 2 \cdot d_{yarn} = 3 \cdot 0.81\ mm \qquad 14$$

$$\propto_1 = 70° \qquad 15$$

$$\propto_2 = 180° \qquad 16$$

$$\propto_3 = 20° \qquad 17$$

In addition to yarn-to-yarn friction μ_{yy}, which corresponds to the friction assumed above, there is friction of yarn to the crochet or auxiliary needle. The coefficient for this yarn-to-needle friction μ_{yn} is assumed to be 0.24. This value is based on the one hand on a measurement of the coefficient of polyester yarn to metal friction of 0.244 [205] and on the other hand on the measurement of the coefficient of friction between polyacrylonitrile (PAN) yarn and a conventional knitting machine needle with a diameter of 1.5 mm of 0.24 [206].

With these values and according to the equations 5 to 17, the calculations result in a force of 17.7 N, which counteracts the movement of the crochet needle. In this case, therefore, the force acting on the needle is estimated approx. two orders of magnitude higher than in the case of laying the LL over.

Besides the movement of the crochet needle in the crochet direction, the movement of it along its longitudinal direction is also occasionally restricted by the three held loops. This is because during this movement, the three loops on the hook must slide onto the shaft of the crochet needle. For this, the loops need to be widened because the shaft diameter is larger than the diameter of the hook. Due to the forces exerted by the loops on the needle, in rare cases, the crochet needle is prevented from being extended behind the crocheted fabric.

With regard to this movement along the longitudinal axis, the crochet needle is driven by a TowerPro MG92B servomotor with a torque of 0.3 Nm. Corresponding to the conversion into a linear motion via a rack and pinion with a pitch diameter of 33 mm, the definition of torque from force times lever results in a force of 18.2 N. This force is only slightly greater than the force F_{CN} acting on the crochet needle. However, F_{CN} acts mainly against the movement of the crochet needle in crochet direction along the X-axis, so that the portion acting against the extension of the needle in longitudinal is unknown.

The crochet needle can be moved with a force of approx. 60 N (90 N during start-up) on the X-axis. This results from the 1704HS168A-OB stepper motor [194] with a torque in normal operation of about 0.3 Nm (0.45 Nm during start-up), which drives the carriage of the crochet needle via a belt and gearwheel with a pitch diameter of 10 mm. Thus, the driving force is theoretically significantly higher than the counteracting force F_{CN} and the movement should be feasible without any problems. However, the movement of the crochet needle in the crochet direction, starting from the situation shown in Figure 88, has proved to be problematic in practical trials in that first the auxiliary needles bend and then the movement is prevented entirely. For this reason, F_{CN} must therefore be significantly larger in reality.

The discrepancy between the real and the calculated force can be explained by the literature value of the coefficient of yarn-to-yarn friction of braided polyester yarn of 0.056 used for the calculation [204]. This value is significantly lower, especially in comparison with the used coefficient of the friction of polyester yarn on metal or PAN yarn on knitting machine needles of 0.24 [205,206]. In general, the literature values of the parameters used are probably different from the yarn used for the tests with the CroMat prototype. For these, a polyester sewing thread (M 782) from Gütermann was used [197].

Koncer et al. [207] report a coefficient of friction of 0.381 for a polyester sewing thread. If this coefficient is used for both μ_{yy} and μ_{yn} with respect to equations 5 to 17, the F_{CN} results in 190.9 N. This resisting force is realistically high in that it would prevent movement of the crochet needle in the crochet direction and would also result in bending of the auxiliary needles. It should be noted that in this case the assumed bending stiffness does not necessarily match the other parameters of the yarn.

Measured forces and discussion

In order to be able to estimate the real forces resulting from the friction, a spring balance (Camry, Hong Kong, China) was used to pull on the LL in the crochet direction as shown in Figure 88. After overcoming the static friction, the LL was pulled for a very short distance with approx. 1 N until the LL was jammed, the force exceeded the measuring range of 40 N and the auxiliary needles began to bend.

The force of about 1 N measured for a short time corresponds to the force measured with the spring balance when the LL is placed over the auxiliary needles for SLs (corresponding to the situation in Figure 86) and for HDCs (corresponding to the situation in Figure 87). Approx. 1 N was also measured for SCs. Thus, the force acting on the crochet needle due to sliding friction during the step of placing the LL of a new stitch on the auxiliary needles can be realistically expected to be 1 N.

Interestingly, the calculation of F_{CN} according to the situation of overlaying the LL after forming an SL (cf. Figure 86) yields 1.4 N when the friction coefficient of 0.381 is inserted as μ in the equations 3 and 4 with otherwise equal values. This calculated force is very similar to the measured force considering the accuracy of the measurement and the assumptions made. Thus, the supposed coefficient of friction of 0.381 seems to be realistic, and also the simplified mathematical description of the situation seems to be reasonable.

However, the calculations performed in this section are highly simplified and the results are therefore not very reliable. They should rather be seen as a rough estimate of the magnitude of the forces. For a more precise calculation, it is on the one hand necessary to measure the relevant properties of the sewing thread used. On the other hand, the situation would have to be modeled e.g., with an FEM tool to simulate the actual angles and acting forces in this complex scenario. Both are beyond the scope of this work and are to be addressed in future studies.

The forces acting against the movement of the crochet needle along its longitudinal axis during extension for the final yarn over of HDC (see Figure 88) cannot be reliably assessed. It is only possible to assume that in some cases these must be greater than 18.2 N, because the extension of the crochet needle is then inhibited. The obvious solution to this problem is to use a stronger motor or a smaller lever arm for a more favorable translation of torque into force. However, this would continue to stress the machine elements and yarn with the acting forces, resulting in increased wear. The better solution would be to prevent the high forces from building up.

To prevent large forces from arising due to the three yarn loops wrapped around the crochet needle, these must be as loose as possible around the crochet needle so that they can be easily widened by the larger diameter of the needle shaft. This can be achieved if the yarn tension is lower before and during needle extension. Setting the yarn tension lower overall is no possible solution because the default thread tension of 6.3 cN is required at other stages of the stitch formation process. Thus, dynamic adjustability of the yarn tension during stitch formation is necessary. This will be covered in more detail in the following section.

3.4.6 Yarn tension

By varying the yarn tension, *H* (stitch height) can be affected. However, the adjustment possibilities for the *H* are limited in that the yarn tension must ensure reliable stitch formation. To maintain a constant yarn tension for secure stitch formation processes of the CroMat, a yarn feeder with the function of retracting yarn is necessary. This is because during stitch formation, frequent movements of the crochet needle and yarn guide against the crochet direction are necessary. Without a yarn feeder with integrated yarn take-up system, which can provide constant yarn tension, the yarn would become too loose and could not be placed securely. The likelihood of the yarn slipping out of the crochet hook would greatly increase.

For example, in the fourth yarn over variant, the crochet needle is moved against the crochet direction before the yarn guide is retracted in order to tension the yarn segment (see Figure 79 in section 3.4.3). Also, in yarn over variants 1 to 3, the yarn guide is moved about 3 mm against the crochet direction after insertion of the yarn in order to press the yarn into the hook. Furthermore, the crochet needle must be moved against the crochet direction after the final yarn over for SLs, SCs, and HDCs to clear space for the auxiliary needles to be extended (cf. Figure 44 in section 3.3.2 or Figure 47 in section 3.3.3).

With regard to the initial prototypes in the concept phase (cf. section 3.1.7), a yarn tensioning head from a Silver Reed flat knitting machine, which can take in some yarn with a spring, was used for the yarn tension. However, the yarn tension, especially when moving the yarn guide or crochet needle against the crochet direction, was too fluctuating for reliable stitch formation.

The requirement for constant yarn tension, even during yarn take-up, can be met by using an EFS 920 yarn feeder from Memminger-Iro (Dornstetten, Germany). This yarn feeder is designed for modern flat knitting machines, has a yarn accumulator which allows a total of 70 cm of yarn to be retrieved and regulates the yarn tension electronically [208]. For this purpose, the yarn feeder is mounted between the yarn stock and yarn guide on the aluminum profile frame of the CroMat prototype, and the desired yarn tension is set.

Yarn feeder problems

The constant yarn tension also poses a problem in view of the complex stitch formation processes. This is because, especially with HDC, the yarn tension that is necessary at one point is too high at another point, so that strong tensions and forces build up on the yarn and the machine elements, as explained in the previous section.

A relatively low yarn tension is especially necessary when moving the crochet needle in crochet direction after a new loop has been placed in the hook with yarn over variants 4 or 5. This is because the force, which is increased by friction, must be low enough to lengthen all loops in the hook of the crochet needle without bending the auxiliary needles as shown in Figure 79 (section 3.4.2). With a lower yarn tension, the loops are less tight around the hook, making it much easier to widen them with the shaft of the crochet needle during extension. The default value of 6.3 cN is too high at this point, as shown by the occurrence of bending the auxiliary needles and the occasional failure of the crochet needle to widen the loops appropriately. In this context, it would be also advantageous to reduce the yarn tension when the crochet needle is extended for yarn over variants 1 to 3.

Furthermore, widening the LL is also necessary when laying it over an ANP, so that a lower yarn tension could also be selected for this step. With a yarn tension that can be set more or less at will in this step, the loop height can be influenced independently from the yarn tension required during loop formation. This is because the *H* is influenced in particular by the yarn tension during the suspension of the LL. With a looser thread, the stitch to be suspended is drawn larger by the take-off.

These advantageous low tensions contrasts with the steps in the stitch-forming operations, where a relatively high thread tension is required. For example, when retracting the yarn guide in yarn over variants 4 and 5 with the standard M 782 sewing thread from Gütermann, a thread tension of at least 6.3 cN is required to ensure that the inserted yarn remains in the hook of the crochet needle. With a lower thread tension, the yarn is drawn in more slowly than the yarn guide is retracted, so that a free-standing loop is formed for a short time, which usually moves over the hook and is therefore not placed in it when the yarn is drawn in. For this reason, a relatively high yarn tension is also necessary when moving the crochet needle against the crochet direction. Such a movement is necessary, for example, for INC or generally for making space with the crochet needle for the extension of the auxiliary needles before the LL is laid over. If the thread tension is too low, the loops will not stay tight in the hook and can therefore easily come out of it.

The EFS 920 yarn feeder offers the possibility of setting a higher yarn take-up tension. Corresponding attempts to solve the problem with this function have been made but have not led to any success. This is probably due to the fact that a higher yarn tension is not beneficial for every yarn take-up.

Moreover, the EFS 920 offers an interface for dynamic adjustment of the yarn tension via external signals. This provides the solution of the physical contradiction of both high and low yarn tension necessary for the stitch formation according to the principle of separation in time as described by Koltze and Souchkov [182]. Consequently, the appropriate yarn tension can be specified for each step of the stitch formation. This allows the developed sequence programs to be further optimized.

During the development of the CroMat prototype, a corresponding interface was not implemented. This is due in particular to the motherboard used in the CroMat prototype (cf. section 3.4.7), which does not offer a suitable communication interface. The implementation of the interface is planned for the optimized industrial prototype, for which a customized motherboard including firmware is developed by the project partners.

Another future improvement regarding yarn tension is to optimize the construction of the yarn guide so that fewer yarn contact points are needed which increase the set yarn tension. This would probably also reduce problems with maintaining loop tension when moving the crochet needle against the crochet direction or retracting the yarn guide.

Usable yarns

With regard to the tests carried out and crochet samples produced with the CroMat prototype, a compromise was found with a constant yarn tension of 6.3 cN using the M 782 sewing thread from Gütermann. Based on numerous tests, this tension has proven to be both sufficiently low and sufficiently high, so that corresponding errors occur only very rarely. The formation of SCs and HDCs is only possible with this sewing thread and yarn tension. In contrast, with SLs, different yarn tensions and different yarns can be used without problems. This is probably due to the fact that for SLs only one loop is always held by the crochet needle. Thus, the *H* of SLs can be adjusted by changing the yarn tension (cf. section 4.5.3).

For example, an approx. 0.58 mm thick cotton yarn with 1786 dtex (Rico Essentials Crochet, idee. Creativmarkt GmbH & Co KG, Paderborn, Germany), used for the study presented in section 4.2, is suitable for the production of SL textiles with the CroMat. In Figure 89 a) it is shown that, with the standard yarn tension, the stitches are relatively large in comparison to the diameter of the yarn, despite the fact that the yarn is relatively thick. In manual crochet, the corresponding yarn would result in smaller stitches.

Figure 89 b) shows how much space three loops of this yarn take up in the hook of the crochet needle when forming HDCs. Three loops of a thicker yarn might fit in the hook, but yarn would probably be impaled by it. In general, the formation of HDCs and SCs does not work well with the yarn shown because of high tensions and forces, probably due to high yarn friction. To use this yarn for these types of stitches, a variably adjustable yarn tension of the yarn feeder would be necessary.

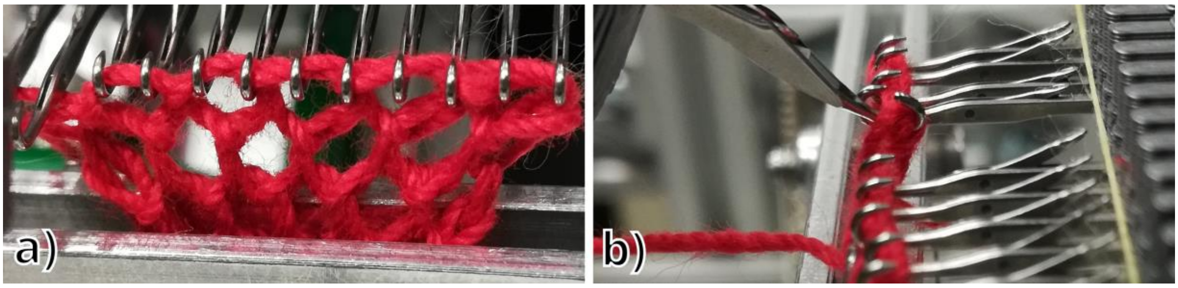

Figure 89. Photos showing the use of an approx. 0.58 mm thick cotton yarn (1786 dtex) in the CroMat prototype. **a)** An automated crocheted textile consisting of SLs. **b)** Three loops in the hook of the crochet needle during the formation of an HDC.

With SLs and thicker yarns than those shown in Figure 89, the problem often arises that the latches of the non-spring-loaded latch needles are too tight on the shaft in the open position when the stitch is to be cast off, causing the yarn to be impaled by them. When using spring-loaded latch needles for SLs, it can be assumed that yarns up to a diameter of about 0.8 mm would be usable.

In addition to the yarn diameter, the bending stiffness can also be limiting regarding crochetability with the CroMat. With higher bending stiffnesses of the yarns, the movability of the inserted loops is made more difficult by the crochet needle and problems arise regarding the yarn feeder, which cannot correctly retrieve the yarn. For example, a relatively stiff yarn with a thickness of about 1.2 mm could not be inserted into the yarn feeder.

3.4.7 Firmware and motor control

According to the mechatronic structure and the movement of the machine elements via numerous electric motors, motor drivers, a microcontroller and firmware similar to CNC milling machines or 3D printers are required. The microcontroller firmware must be able to interpret the G-codes of the sequential programs and to send appropriate commands to the drivers, which apply voltage to the stepper motors to move them. In addition, PWM interfaces are needed to control the micro servos used in the CroMat prototype. Also, the signals (closing or opening circuit) of the simple mechanical limit switches must be processed. These basic functions are combined in 3D printer controller boards.

For the CroMat prototype, an appropriate motherboard must have sufficient connections for the motors and, ideally, be able to be operated via open-source firmware. In this context, open source offers the great advantage that time and costs can be saved, especially with regard to prototyping, because a large number of ready-to-use software and instructions are available on the Internet [150]. Due to the similarities of the CroMat prototype approach to 3D printers and the large online community regarding these, a firmware common to 3D printers was chosen. The open-source firmware Marlin 2.0, which is designed for 3D printers and is free for all use with a GPLv3 license [165], offers numerous features and configuration options [141]. All real-time activities of the machine are managed by the Marlin firmware running on the motherboard [141].

The Bigtreetech SKR V1.4 Turbo Control Board (Bigtree-tech, Shenzhen, China) was selected as the hardware to go with this firmware. This motherboard, which is common for 3D printers, is available as a preset in Marlin, so that only relatively few configurations must be made. In order to be able to connect enough stepper motors, the expansion board BTT EXP-Mot V1.0 (Bigtree-tech) is additionally used. The motherboard has a 32-bit LPC1768 CPU of the Cortex M3 series from ARM (advanced RISC (reduced instruction set computer) machines). The motherboard and the electric motors are powered by 24 V DC. Fredric Meyer participated in the development of the electronics under the guidance of the author as part of his employment for the *HaekelMasch* project. The interaction of the electronic components of the CroMat prototype is shown schematically in Figure 90.

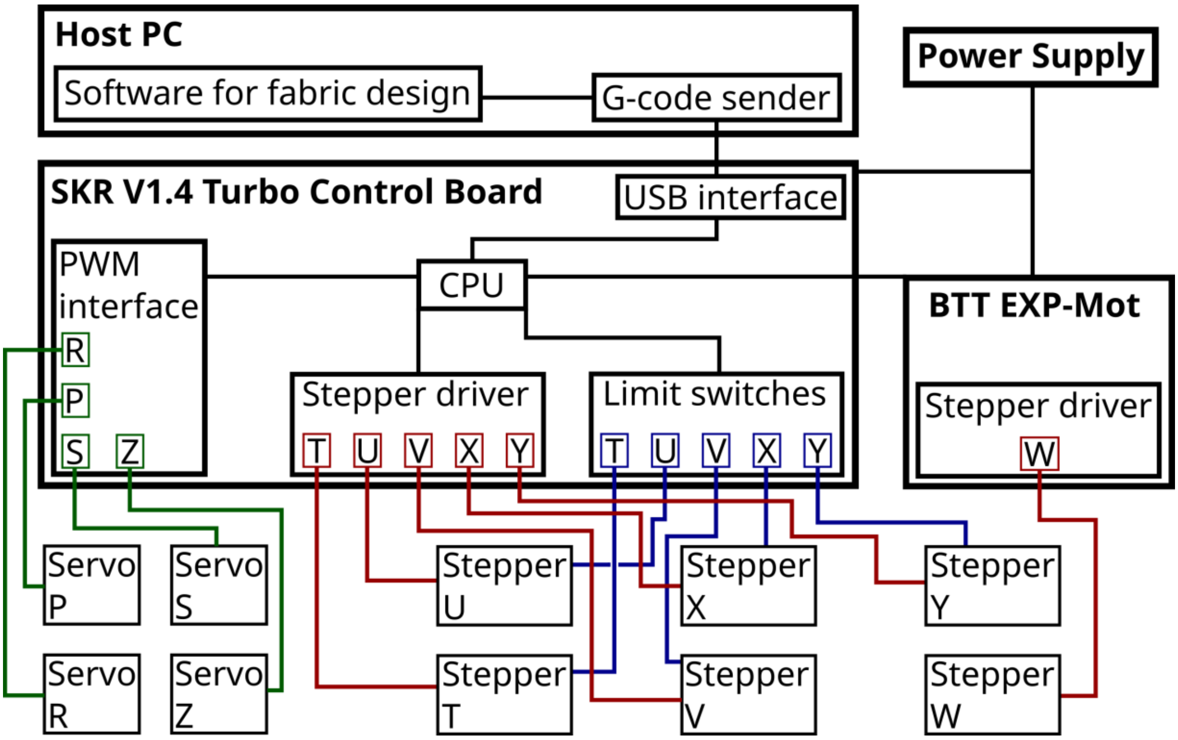

Figure 90. Schematic overview of the electronic components of the CroMat prototype.

Using a personal computer (PC) and the specially developed tool for designing machine-crocheted textiles (cf. section 3.6), the crochet program to be executed is created. This consists of a sequence of G-code commands (cf. section 2.5.3) to control all the necessary movements in the correct order, as described in more detail in section 3.6.5. To execute the commands, they are sent to the motherboard of the CroMat using a G-code sender via a USB connection. The freeware program cncjs [209] is used for this, in which G-code macros for executing each stitch type and operation can be created and accessed via buttons. The motherboard is flashed with the Marlin firmware so that the CPU can process the received G-codes.

As the CPU also receives signals from the limit switches, it can zero the position of the stepper motors when the corresponding carriages are moved to the limit switches during initialization, which is performed after each machine startup. The NEMA 17 motor of the W-axis is the only stepper motor of the CroMat prototype that does not have a limit switch. This is because it must be possible to rotate the crochet needle around W in both directions from the zero position, making it difficult to construct a mechanical stopper for the limit switch. Its position must be manually turned to the home position after initialization.

To control the motors, the CPU sends signals to the periphery. The servo motors are controlled via PWM. According to the duty-cycle communicated via the signal line, i.e., the time share of the high state in the period duration, the servo takes a fixed angle (cf. section 2.5.2). Beside this line, there is a power and a ground line to each servo motor. Photos of the lines connected to the motherboard via connectors to all motors and to the limit switches are shown in Figure 91.

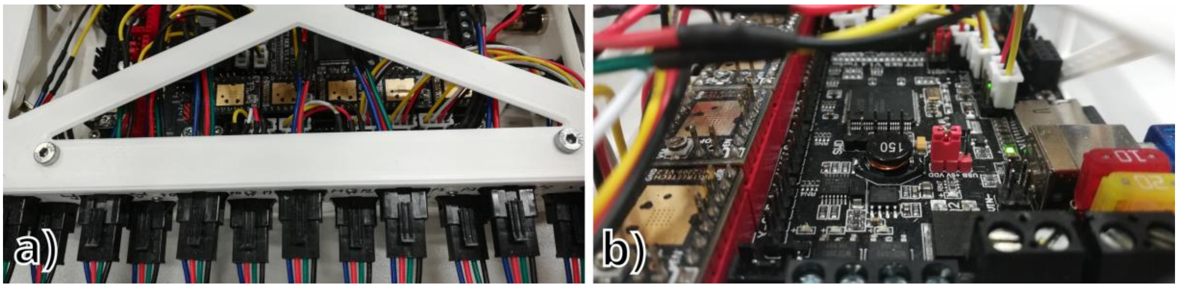

Figure 91. Photos of the Bigtreetech SKR V1.4 board with cables connected in the 3D printed case with the lid removed. **a)** The connectors to the motors and switches can be seen on the bottom side. **b)** Close-up of the motherboard.

Here, M-codes are also used to position machine elements driven by servo motors. The servo motors R and S must be moved in parallel to drive the crochet needle with slider. With the firmware a direct parallel movement like the stepper motors is not possible. As a workaround, the servos are alternately driven by 1°, so that the viewer perceives a smooth movement. The delay, i.e., the time the CPU provides for the servo to move into position, was adjusted accordingly in the firmware. However, due to the stepwise procedure the movement of the crochet needle is relatively slow.

For controlling the bipolar hybrid NEMA 17 stepper motors, the CPU communicates via universal asynchronous receiver-transmitter (UART) with the TMC2209 (Trinamic Motion Control, Hamburg, Germany) drivers. A driver polarizes the coils of the two phases via two lines each (four lines in total) of a stepper motor to rotate it by the desired number of steps. With linear axes, this results from the desired motion in millimeters and the ratio of steps/mm entered in the firmware as a function of the transmission ratio. The positions of all stepper motors are tracked starting from the zero position via the steps already performed. Because no feedback is required, this is an open-loop control system [150]. The TMC2209 drivers support microstepping (with 16 microsteps here), so that a higher accuracy can be achieved than specified by the step angle of 1.8° of the NEMA 17 motors (cf. section 2.5.1).

3.5 Crocheting with the CroMat prototype

This section provides an insight into the process of automated crocheting of fabrics with the CroMat prototype. For this purpose, section 3.5.1 shows how an exemplary textile is produced and section 3.5.2 illustrates the necessary movements of all axes to produce a single SC of the fabric.

3.5.1 Producing an exemplary crocheted fabric

To illustrate the operation of the CroMat crochet machine, the process for producing a small sample fabric is shown. The freeware cncjs is used to control the machine, in which the programs for forming each stitch type are stored as macros with buttons (cf. section 3.4.7). Here, the buttons are activated by the user in the correct order stitch by stitch. A more advanced method, better suited for an industrial application, was also developed and is described in section 3.6.

As a preparatory step, the first CH course (with crochet direction to the left) must be crocheted manually on the ANPs of the machine. Note that the turns also require a needle pair. If, as in this example, a course is to be six stitches wide, this is to be understood as six stitches and one turn and thus seven ANPs. Accordingly, seven CHs are crocheted on, whereby the position of the CH on the left end must correspond to the programmed start position of the machine. Here, this coincides with the leftmost ANP. The stitches should be formed a little looser than usual for manual crochet, so that the crochet needle can be inserted into them without difficulty. A bent paper clip or similar utensil should now be hung in each CH and passed through the double knock-over verge (cf. Figure 92). A weight, which serves as a take-off here, can then be attached underneath.

The first three steps required for automated crocheting after switching on the CroMat prototype are illustrated in Figure 92. First, a homing has to be performed, where all axes are moved to their limit switches, so that the controller can track the position of the axes with stepper motors starting from these zero positions. Second, the crochet needle is moved to a position next to the first ANP so that the LL of the last CH of the first course can be inserted manually in the hook (cf. Figure 92 b)). Then the yarn feeder is to be switched on for the thread tension. Third, the special first turn, called FLO, must be performed to cast off the outermost CH used as the first turn and to bring the crochet needle into position for overlaying the LL (c)).

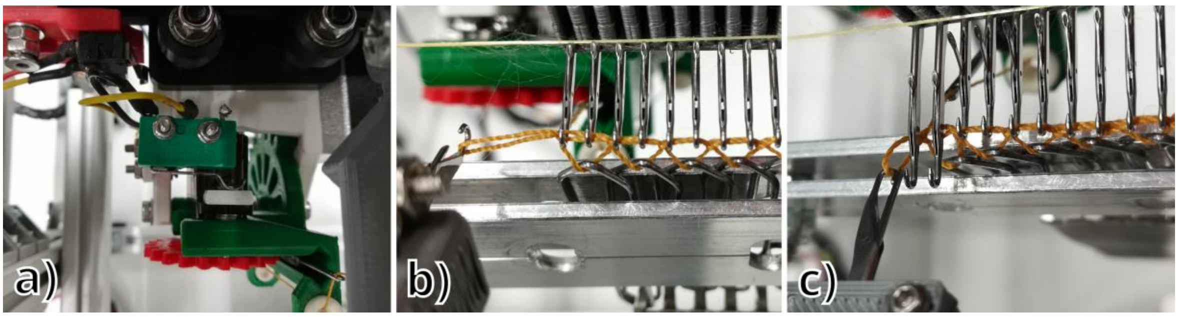

Figure 92. Steps of initialization of CroMat before crocheting. **a)** Axes move to their limit switches for homing. **b)** Insert the LL of the CH course into the crochet needle. **c)** Execution of the FLO as the first turn.

The G-code macro for forming a stitch or turn ends before its LL is placed over the corresponding ANP (cf. Figure 92 c)). This is necessary because HDCs, unlike the other stitches, already perform a yarn over of variant 5 during suspending the LL (cf. Figure 80 in section 3.4.3). The machine elements take identical or definite starting positions (one *L* further in crochet direction) after each stitch, so that the stitches can be formed in any order. This is because the stitch macros are programmed with relative movements (cf. section 2.5.3). A dependency to the previously formed stitches exists only in the correct sequence for crocheting the desired fabric.

The production of the exemplary textile with the CroMat is illustrated in Figure 93. A turn with two CHs after an SL course, which were formed based on the initial CH course, is shown in a). The subsequent HDC course formed to the left is shown in b). In c) the crochet needle is shown again on the right side after crocheting a SC course and performing the turn for the next row. The fabric's final SL course is shown in d).

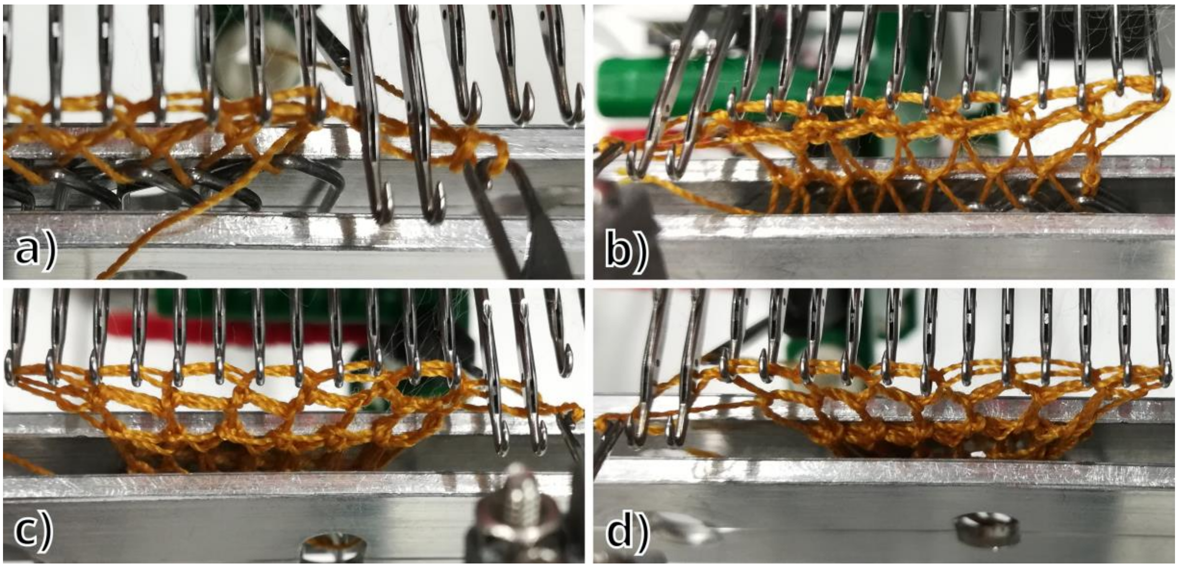

Figure 93. Row-by-row production with the CroMat prototype. **a)** Turn after the first SL course to the right. **b)** HDC course to the left. **c)** SC course to the right. **d)** Final SL course to the left.

After crocheting the last course of a textile, it can be removed from the machine manually, or a RSTE (cf. section 3.3.9) can be performed for each stitch for casting off successively. Forming an additional CH as a final turn, as shown in Figure 93 d), is optional. For removing the fabric, the yarn end to the yarn guide can be cut. To prevent unraveling, the loose yarn end can simply be drawn through the last stitch. A photo of the fabric produced is shown in Figure 94. Textiles produced with the CroMat prototype are addressed in more detail in section 4.5.

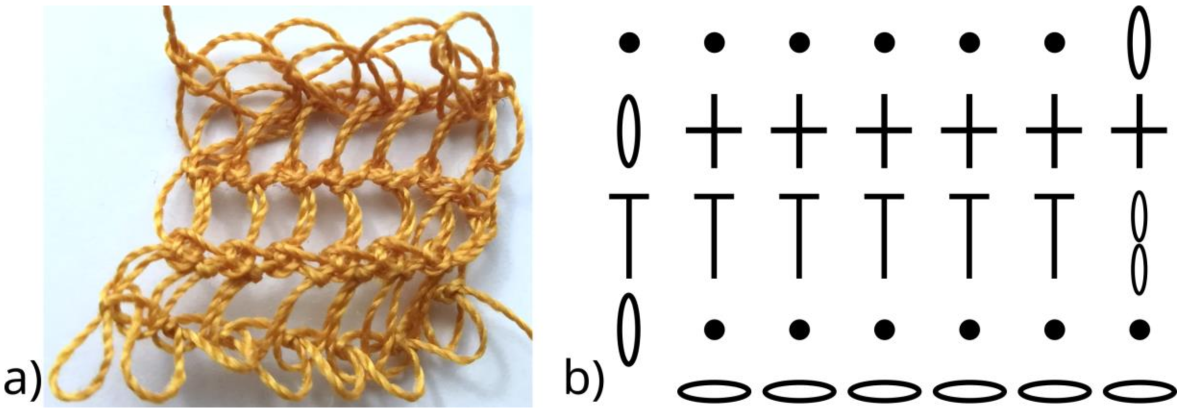

Figure 94. Exemplary fabric crocheted with the CroMat prototype. Photograph in **a)** and respective crochet chart in **b)**.

In the future, the first CH course could also be crocheted onto the auxiliary needles automatically with the machine. Only the first stitch would have to be crocheted manually onto the corresponding ANP. After transferring the LL to the crochet needle, the machine can theoretically crochet the rest of the CH line. However, before further rows can be formed on top of this, the fabric take-off must be attached manually. During the practical tests with the CroMat prototype, it turned out to be easier to crochet the CH course by hand onto the auxiliary needles first and to start automated production after all manual working steps have been completed.

3.5.2 Movements for SC formation

To illustrate the crochet machine's operation and the complexity of stitch formation, the necessary movements of all axes of the CroMat prototype to form a single SC going to the right are shown here. For this, 40 steps, each consisting of one or more simultaneous movements, are necessary. The movements of the crochet needle, which actually consist of several 1° steps as explained in section 3.4.7, have been combined in this consideration. As a simplification, the movement of the shaft and slider are assumed to be parallel. The changes in positions relative to the initial positions as the positions in the end of the previous stitch formation are considered.

The necessary sequence of the positions of the machine elements has resulted from numerous tests with the CroMat prototype. Compared to the positions, the speed at which the steps are performed is less relevant, provided that no excessive speed results in position errors. The executed movements are plotted on the basis of the positions relative to the initial one over the 40 steps at equidistant distances in Figure 95. How long a movement takes or how long a position is held is not evident from this representation, which is why the slopes of the position changes do not allow any conclusions to be drawn about the speeds of the movements.

The designations of the axes and the signs of the movements are based on the schematic representation of Figure 66 in section 3.4.1. Accordingly, a clockwise rotation of the crochet needle around its own axis by W is considered positive. For T, a rotation in positive direction is characterized by moving out of the vertical zero position (90° from horizontal, where the limit switch is). When comparing the movements shown in Figure 95, it is important to note that the divisions of the ordinates differ. This is because the crochet needle, auxiliary needles and the yarn guide are driven over considerably larger distances than the X, Y, U and V axes are moved.

The first steps in forming a SC are characterized by positioning the crochet needle, auxiliary needles and yarn guide. The latter is extended in step 6 to penetrate the working stitch from behind, which is shown for example in Figure 47 a) in section 3.3.3 or in Figure 79 in section 3.4.3. As long as Z is at 22.1 mm, the crochet needle is moved to reproducibly place the presented yarn segment into the hook, while the yarn guide is barely moved. In these movements of the fourth variation of the yarn overs to step 18, it is noteworthy that the crochet needle is gradually retracted as it is moved along the Y-axis closer to the auxiliary needle bed. Finally, in step 18, it is moved in the negative X-direction (against crochet direction) to tension the yarn segment inserted in the hook (as illustrated in Figure 79 in section 3.4.3) before the yarn guide is retracted along Z in step 19.

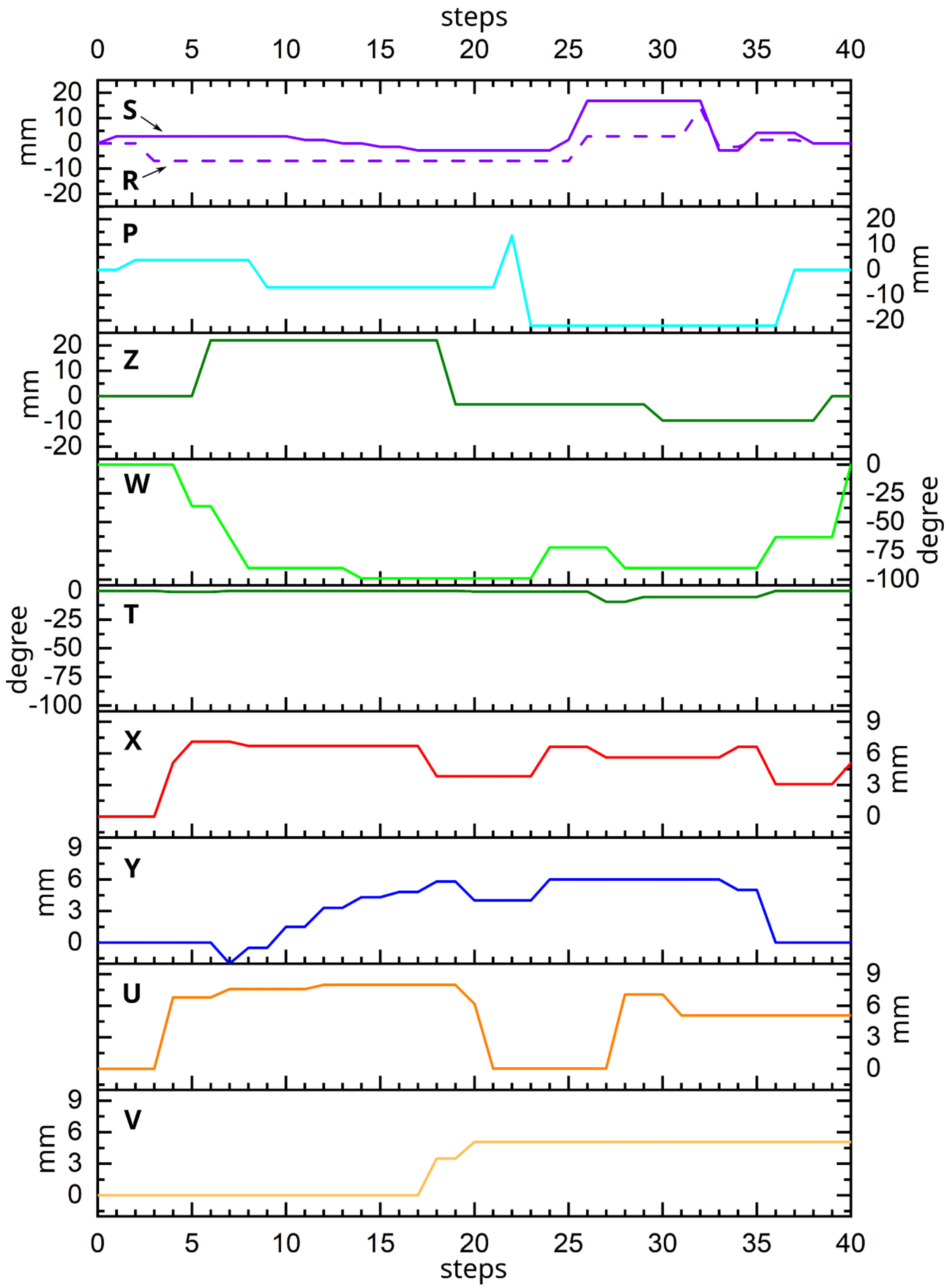

Figure 95. Position changes of all axes of the CroMat prototype related to their initial position for the formation of one SC going to the right. Image created in Origin by Marius Dotter based on the data prepared by the author.

The next operation necessary for SC formation is to extend the crochet needle behind the crochet in order to be able to perform a yarn over of variant 2. To do this, the ANP must be retracted beforehand in order to cast off the working stitch and make room for the crochet needle. In this context, the peak of the P-axis at step 22 represents the extension of the

ANP by L_2 according to Figure 70 a) in section 3.4.2 (see also Figure 72 c)). From step 23 to 36 the needle pair remains in the retracted state.

After retracting the ANP, the crochet needle is moved along X, Y and W to be positioned for the extension in step 26. Previously, the carriage of the yarn guide was moved along U against the crochet direction to perform the yarn over of version 2 in the crochet direction as shown in Figure 84 in section 3.4.4. The swinging motion of the yarn guide is reflected in the position changes of U, T and Z. The yarn over is completed by the yarn guide. The completion of the yarn over is marked by closing the hook of the crochet needle by extending the slider along R in step 32.

To support drawing the new LL through the two loops on the shaft of the crochet needle and to drop these loops, the crochet needle is moved slightly in the positive X direction and negative Y direction after it has been retracted (step 33). The crochet needle is then extended again by a few millimeters, moved further in the negative Y direction and in the negative X direction to position it for the extension of the ANP to the starting position in step 37. The new LL can then be placed over this needle pair in the crochet direction. However, the G-code macro ends before the actual suspension of the formed stitch. Up to step 40, final positioning of the crochet needle is carried out, which prepares the laying over (such as a rotation over W) and brings elements such as the yarn guide back to the starting position.

Overall, the V-axis performs the simplest movement during stitch formation. The total movement is distributed to several steps to allow parallel motion without the movement of V slowing down other, parallel movements. Like X and U, V ends at 5.08 mm, which corresponds to the pitch of the machine. The movement of these axes therefore corresponds to the main movement of the machine. All other axes return to their starting position. For the P-axis, it should be noted that the starting position with respect to the stitch formation does not correspond to the standard position (distance L_1 to the auxiliary needle bed, cf. Figure 70 in section 3.4.2), which allows the carriage to move along V.

The Croche-Matic prototype (cf. section 2.3.2), as the only other machine capable of producing SCs, needs 30 movements for forming one SC [14,15]. In comparison, the 40 steps of the less error prone CroMat prototype are of a similar scale.

Regarding the CroMat, the ability to combine several movements into one step is limited by the servo motor driven motions, to which no other movements can performed in parallel. In a future improvement of the CroMat crochet machine, it should therefore be ensured that all movements can theoretically be executed in parallel in order to optimize the stitch formation in terms of speed. Machine-related restrictions, such as that V may only move while P is in the standard position, and the general workflow according to the basic motion sequences (cf. section 3.3.3) must of course still be taken into account.

3.6 Development of CroMat crochet design tool

In addition to the development of a crochet machine, the control of the machine and the design of crocheted fabrics that can be produced automatically with it are also addressed. Without a dedicated design tool, future acceptance and application of the CroMat crochet machine in the industrial sector is not possible. This is because existing methods for controlling and designing suitable textiles cannot be directly adopted for this novel textile machine. Therefore, a straightforward and extensible software tool for the design of machine-crochetable fabrics and for the corresponding control of the CroMat crochet machine was developed. The concise structure of the tool's GUI with international crochet symbols and error checking allows users that are unfamiliar with crochet to easily develop a fabric to be crocheted by machine. The CroMat design tool has been published in the open access journal *Communications in Development and Assembling of Textile Products* [A6] under a CC BY-NC-ND 4.0 license (Copyright © 2023, the Authors). The present section of the thesis is based on this paper called *Design tool for automated crocheting of fabrics*.

Section 3.6.1 gives an introduction to designing crocheted textiles, while 3.6.2 presents the GUI as a user interface. Error checking, the creation of a preview and the generation of G-code are presented respectively in sections 3.6.3, 3.6.4 and 3.6.5. Finally, the design tool is discussed in section 3.6.6 and compared with similar approaches.

3.6.1 Tool overview

Conventionally, manually crocheted fabrics are designed by writing instructions in text form or by drawing symbols representing the stitches on paper. Besides designing, such instruction texts or crochet charts are also used to communicate the crochet patterns [16]. For an easier design and more standardized communication, there are also a few dedicated software tools for manually crocheted textiles [16]. Examples of such programs are StitchFiddle [210], CrochetChart [211] or My Crochet Designer [212]. As a more elaborated approach, Seitz et al. [16,17] have developed a domain-specific tool with a graph-based language for crochet patterns. With this tool 3D crochet charts can be created, and text instructions are generated automatically.

For the automated generation of manual crochet instructions, further tools are presented in the literature. Çapunaman et al. [92] propose a computational framework to generate crochet patterns corresponding to 3D objects as inputs, which can be designed with common CAD tools. With an alternative approach, Guo et al. [19] also compute text-based instructions for crochet patterns based on input 3D geometries. In this regard, stitches are represented by tiles, which are arranged automatically, to model and visualize the 3D textile to be crocheted. Furthermore, Nakjan et al. [20] created a tool to specifically design amigurumi (3D crocheted dolls) by 2D sketches interpreted as 3D primitives (sphere, tear drop or cylinder), which are then compiled into crochet instructions.

Regarding the design of machine-produced textiles, commercial design systems are commonly used for versatile V-bed weft knitting machines [101]. M1plus from Stoll and KnitPaint from Shima Seiki are prominent examples of such and provide pixel-based programming interfaces [101,113,114]. Such systems often provide visualization and assistance with automatic error detection [101,104,114].

3D previews of the designed textile and its patterns are state of the art and facilitate the development process [213,214]. A simple approach for generating such a preview is to describe an idealized spline-interpolated yarn center path at the meso scale, while taking into account the correct topology (relative orientation of the yarn segments to each other)

[A1,213,215,216]. This approach is further described in section 4.1 and is, for example, implemented in the commercial Warp Knitting Pattern Editor 3D from TexMind [217].

Developing an easy-to-use and extensible tool for designing machine-crocheted planar fabrics starting from a chain line according to CroMat prototype is necessary, because existing tools are not applicable to this new type of textile machine. Also, in addition to the hardware, software that enables the use of the machine must also be made available to potential users. Such a tool can demonstrate the possible structures of machine-crocheted fabrics and can aid potential users, which are unfamiliar with crochet, in accessing this new type of textile technology.

3.6.2 User interface

A pixel-based GUI was chosen to correspond to the industrial standard programs [101,113,114] and to benefit from potential users being in principle familiar with the interface. Also, it's tabular structure suits well the two-dimensional fabric structure. The existing approaches of design tools regarding manual crocheting [19,20,92] cannot be adopted, because they deal with circular, 3D crocheting. Circular crocheting differs significantly from flat crocheting starting from a chain line (cf. section 2.1.1) and the CroMat machine implementation also imposes some deviations to manual crocheting.

The chosen approach of representing machine-crocheted fabrics with international crochet symbols, considering the crochet machine's operation, is presented in Figure 96. More information on computer representation of crocheted fabrics is given in section 4.3.1. As can be seen, international crochet symbols of the CYC [27] are used to label stitches for the developed GUI, similar to the previous crochet charts depicted in this work. The technical front is considered for designing the fabric. It is to note that all representations in this work refer to the technical face, unless otherwise stated.

Here, a slightly different crochet chart representation is used in contrast to some crochet chart depictions of manually crocheted fabrics, where the transitions are outside the stitch columns, which are for example used in Figure 5 in section 2.1.2 or Figure 103 in section 4.1.1. Hence, the transitions are within the courses and thus the construction of the fabric is more concisely represented. In this way, it is intuitively comprehensible how the stitches are intermeshed with those above and beneath and on which ANPs they can be formed. The intermeshing is indicated in Figure 96 by the red arrows, which also illustrate the stitch formation by drawing loops both from the previous stitch in the same course and from a stitch in the course below at the same wale. Consequently, wales correspond laterally to needle pair positions and courses chronologically to the stitches formed successively at the same needle pairs.

As usual, the top course corresponds to the last produced course. The first transition from course 1 to course 2 is a special case called FLO and does not have any stitches beneath it. This is due to the workflow of manually crocheting the first CH course onto the needles of the machine and putting the leading loop in the crochet machine's hook before the automated production starts.

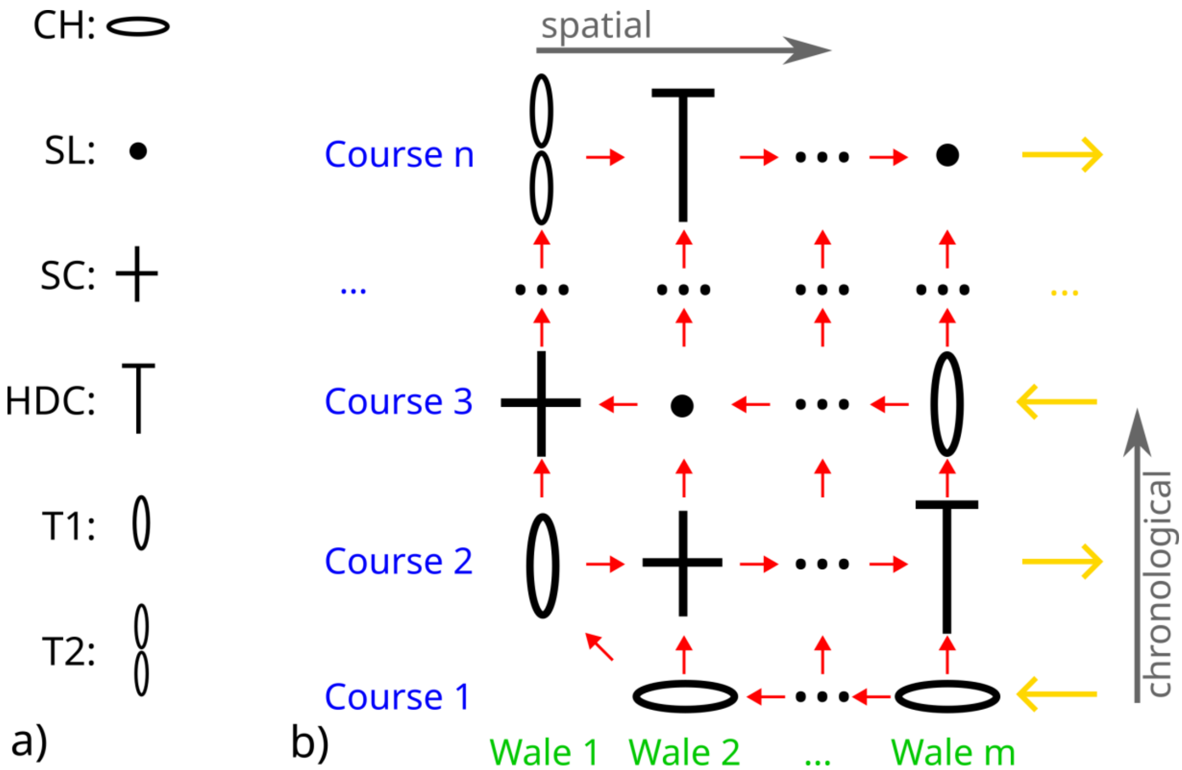

Figure 96. Description of the symbols used (**a)**) and illustration of the representation of crochet fabrics in the graphical user interface (GUI) with exemplary stitches (**b)**). Yellow arrows denote the crocheting direction of each course and red arrows show the connections of the stitches according to the crochet procedure. The ellipsis indicates further possible courses and wales. The machine's ANPs are associated with the wales. Figure is under CC BY-NC-ND license taken without modification from reference A6 (Copyright © 2023, the Authors).

Figure 97 presents the developed GUI, which is, in principle, similar to conventional pixel-based programming interfaces [218]. The ANPs on which the stitches of the wales are created are defined by the needle indicator (NI) at the bottom of the GUI. According to the wale position, a stitch is automatically assigned to a specific needle position in the machine. This allocation based on the topology also remains in the underlying array data structure. Due to the lack of stitch transfer possibilities of the CroMat prototype, no specific algorithms for needle scheduling or transfer planning are needed, which are for example discussed by McCann et al. [113] or Lin et al. [219] regarding knitting machines. The user can simply change the needle allocation in the GUI.

A stitch type can be selected via the toolbar and a position in the fabric can be assigned by clicking on the respective tile. Stitches can be erased with the "blank tile" tool. This selection at the toolbar is implemented with buttons, while the tiles in the canvas region are label widgets. By clicking on these modifiable labels, the internal representation in the data array is changed to the selection, if that operation is determined to be valid by the program. This data array matches spatially the data displayed in the canvas region. By clicking the border regions surrounding the tiles, the canvas is automatically expanded and the course indicator (CI) as well as the NI are updated accordingly. For example, by clicking the left border region, a column of modifiable labels is added in between the left border column and the inner area containing the tiles, while the NI would be adjusted. If a row or column next to the border region contains no more stitches, it will be deleted automatically.

The whole design tool is implemented in Python 3 and built as cross-platform software. Correspondingly, the Python version Tkinter [220] of the open-source GUI toolkit Tk was used for programming the GUI.

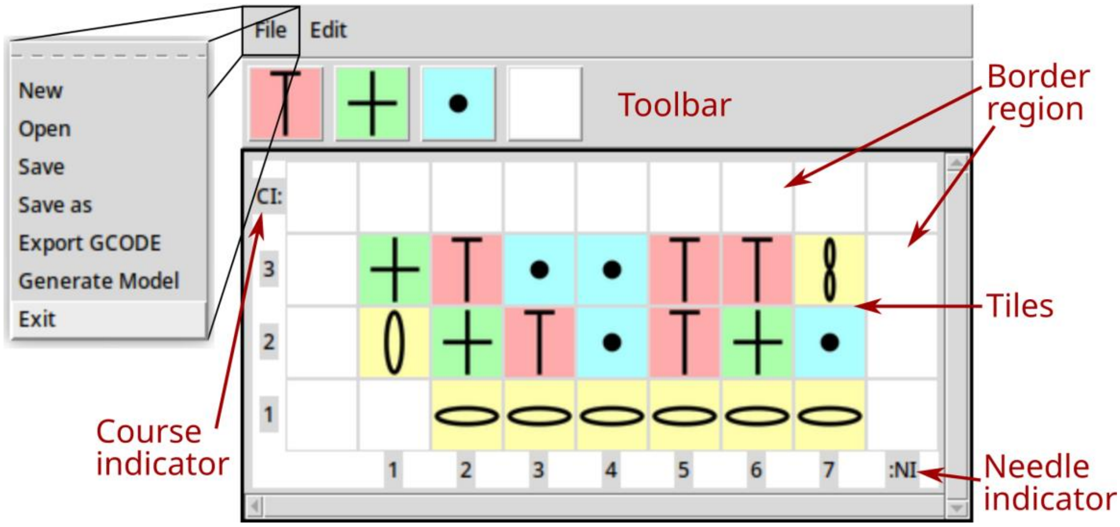

Figure 97. Overview of the developed GUI with the computer representation of an exemplary crocheted fabric. Figure is under CC BY-NC-ND license taken without modification from reference A6 (Copyright © 2023, the Authors).

The structure of the designed machine-crocheted fabric is saved in a text file. Each stitch or transition is labeled with a short string and the topology is maintained by saving the courses in rows of an array, whereas the columns correspond to the stitch sequence of the GUI representation. An example of such an array representation of a crocheted fabric together with the respective GUI is depicted in Figure 98. It is to note that due to the peculiarity of the machine at position 1/1 is no stitch. Because the CH, which was suspended there, is used as the CH of the first turn (FLO).

All necessary information about the fabric's structure is contained in the simple array representation shown in Figure 98. The used string labels correspond to the standard international crochet stitch representation in text form [27]. These strings can be mapped via dictionary data structures to G-code macros for automatically producing the corresponding elements or to the key point representation of the unit cell for modeling.

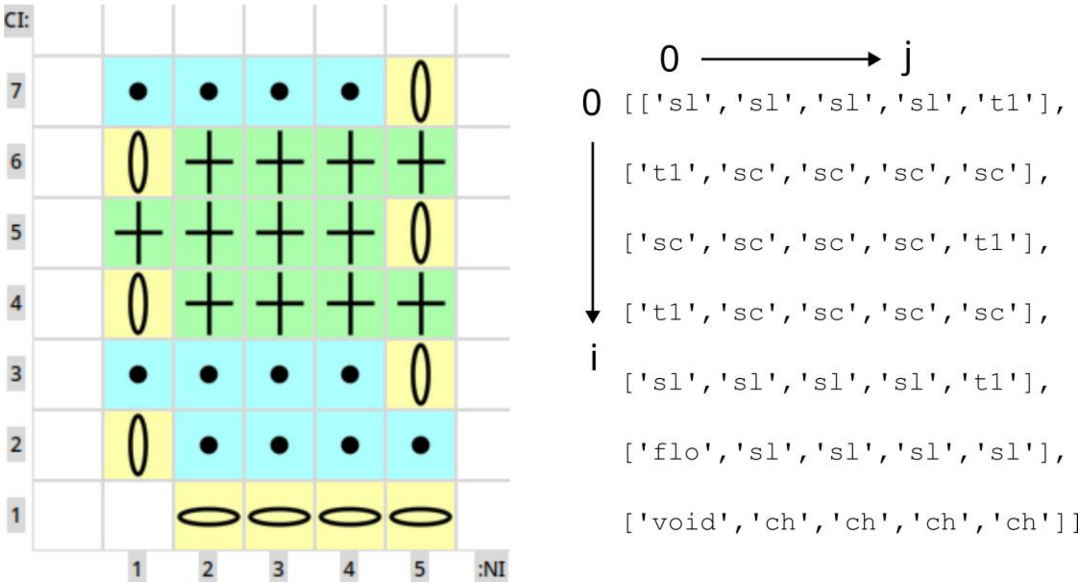

Figure 98. Computer representation of a crocheted fabric graphically illustrated in the GUI at the left side and in an array with stitch label strings as the basic data structure at the right. The model generated from this information is shown in Figure 118 in section 4.3.1. Figure is under CC BY-NC-ND license taken without modification from reference A6 (Copyright © 2023, the Authors).

3.6.3 Error checking

To ensure the producibility of the designed fabrics with the CroMat prototype, an error checking module was developed for the tool. Like the GUI in the current prototype state, this refers only to rectangular crocheted fabrics without width changes. Thus, not all possibilities of the CroMat machine are considered yet. A simple extensibility in terms of adding INC and DEC (as well as the further possibilities to influence the number of stitches per course) was considered in the programming of the design tool and can be implemented with relatively low effort. The developed modeling (cf. section 4.3.1) and the proposed approach for the automated generation of crochet patterns based on shapes of 2D polygons (cf. section 4.4) already take into account the CroMat's shaping possibilities (cf. section 4.3.2).

Regarding the current state of the error checking the following rules are considered:

- Only production of SLs, SCs, HDCs and transitions with one as well as two CHs are possible (constraint **a**);
- First course of CHs is to be manually crocheted from right to left with no CH beneath the first transition called FLO (**b**);
- Second course is always crocheted to the right by the machine (**c**);
- Fixed width, no increase or decrease (**d**);
- A stitch or transition must have a previously formed stitch or transition beneath (with FLO as exception) (**e**);
- Before each stitch in a course (according to the direction) has to be a previously created stitch or transition (**f**);
- Before a start position of the course, which must be a transition, there must not be another transition or stitch (**g**).

These constraints are checked by the tool to aid users in designing crocheted fabrics with the GUI. Error checking is performed on the abstract GUI representation. A section of the program for error checking is shown as Python-based pseudocode in the supplementary materials of reference A6. Generally, the errors are marked by a text output and by a red border around the corresponding tile. Error resolving is currently left to the user to avoid correcting an error contrary to the user's intent when there are multiple causes. The user can also start the error checking at any time by clicking an option in the edit menu.

In principle, error checking is based on completely traversing the array with the crochet pattern (as shown in Figure 98 in section 3.6.2) once, checking for any possible error that conflicts with the constraints. Thereby all possible errors can be found, which are considered. According to the machine-specific and general crochet rules reflected in the error checking, the machine-crochetability is defined.

Regarding the verification of compliance with general crochet rules, it is, for example, checked that the crochet direction alternates with the courses or that HDCs follow on T2 while SLs or SCs follow on T1. The latter is implemented by inspecting the parent stitch beneath the transition and the target stitch (next stitch in crochet direction). Usually in manual crocheting each course starts with a transition, nevertheless, this rule is additionally reflected in constraint **g** because it is a strict limit of the machine.

Constraint **g** is checked by calculating the correct position of the transition of each course. There can only be one transition per course. Also, everything that is not a void (no entry) and is positioned before the transition (according to the crochet direction) is recognized as an error. The locations of the transitions correspond to the alternating crochet direction of each course. This pattern is based on the definition that the transition of the FLO is on the left and the corresponding course is heading to the right. Thus, this complies with the constraint **c**. Furthermore, this also results in the direction of the first CH course to the left, which is a part of constraint **b**.

Regarding **b** and the special case of the first transition as the start of the automated production, it is controlled that there is no CH but a void in the crochet pattern under FLO. In general, as part of the error checking and for compliance with constraint **e**, it is checked for each stitch that there is a parent stitch in the course beneath it. Here the CH course is an exception, because it is the first course with no parent stitches.

The CH course is also taken as the basis for the fixed width of the fabric (restriction **d**) by checking that there are no more stitches in the other courses than the number of CHs + 1 (considering the special case of the missing CH under the FLO). Together with the calculation of the correct positions of the transitions, this ensures that the designed fabric has a constant width.

Moreover, constraint **f** is respected by searching for voids between stitches within a course. If there are voids between stitches, the rule is broken that before a stitch there must be previously formed stitch or transition, and an error is raised.

Compliance with constraint **a** is ensured by providing only the stitch types that can be created by machine for selection. Thus, algorithms for error checking are not needed in this case. As a further method for error prevention, the CHs of the first course are automatically set depending on the user assigned stitches in the second course. Also, a transition is automatically set when a stitch is assigned to a previously unoccupied tile above the existing stitches, whereby a new course is instantiated.

3.6.4 Preview of the fabric

To provide a preview of the designed crocheted fabric similar to the approaches described in section 3.6.1, the developed modeling of machine-crocheted fabrics explained in section 4.3.1 is applied. This modeling can also be used independently of the GUI of the design tool, provided that a text file similar to the GUI output array (cf. Figure 98 in section 3.6.2) is used as input.

To generate a preview with a model of the designed fabric, the GUI output array, which represents the fabric structure, is iterated beginning with course 1 in wale m. Depending on the course's direction, the strings (such as 'sl') are mapped to left or right pointing variants of the unit cells of the stitches. According to the topological position of the string labels in the array, corresponding translation vectors are added to the key point coordinates of the unit cells. Also, the key points are modified to match the required L and H. The adjusted key point coordinates are appended in a monolithic list following the iteration of the array in the crocheting sequence. Regarding the assignment of the correct unit cell for a transition, the succeeding and previous stitches are considered to ensure appropriate intermeshing. The final key point list and yarn diameter are saved in comma-separated value (CSV) files, which can, for example, be opened with the freeware TexMind Viewer [221] for spline-interpolation and visualization.

3.6.5 Generating G-code

As described in section 3.4.7, the CroMat is controlled by G-codes. To form a stitch, multiple G-code commands have to be executed. Accordingly, the programs for forming each type of stitch with a distinction of the crochet direction are stored in G-code macros.

Movements are specified in relative coordinates so that stitches can be executed in any order (respecting the machine-crochet rules). To fabricate the textile designed with the tool, the macros must be appended in a single file in the correct order.

The generation of a corresponding G-code program is based on the error checked GUI output array containing the information about structure and topology (cf. Figure 98 in section 3.6.2). Analogous to the generation of the preview (cf. section 3.6.4), the array is traversed according to the crochet sequence. Depending on the direction of each course, the exact stitch type (such as SL to the left or T2 to the right) is assigned as a string for each entry of the GUI output array. These specific strings are mapped utilizing dictionary data structures to human-readable text files containing the required G-codes for each stitch type as macros.

Starting with the second course (due to the manual building of the first CH course), the G-code instructions read for each stitch are appended consecutively and the result is written into a new text file. To save computing time, the G-code text file for each stitch type is read only once and stored in a dictionary, from which the data for subsequent stitches of the same type can be obtained.

Because the tool operates on the stitch level, a flexible interchangeability of the macros with the machine instructions is ensured. On the one hand, this is advantageous regarding the machine under development, and on the other hand, it enables the design tool to be used for potential alternative crochet machines in the future. The stitches could also be mapped to text files with instructions for manual crocheting to generate crochet patterns in text form.

The G-code generated by the presented tool can be directly executed by the CroMat prototype to produce a corresponding crocheted fabric. Currently, the freeware program cncjs [209] is used to send the G-code commands from a laptop to the CroMat prototype via an USB interface (cf. section 3.4.7).

The workflow of using the tool to design a fabric to be produced with the CroMat is illustrated in Figure 99. During designing, an error check can be performed at any time highlighting errors for the user. Similarly, a topologically correct 3D preview can be created at one's convenience to be displayed with the TexMind Viewer. The CSV files of the models and the structure of the GUI can be saved for later use or rework. Once the design process is complete, the G-code can be generated automatically. The respective macros with a distinction between right and left oriented stitches are shown in pseudocode. As comparison conventional crochet instructions in text form are also given.

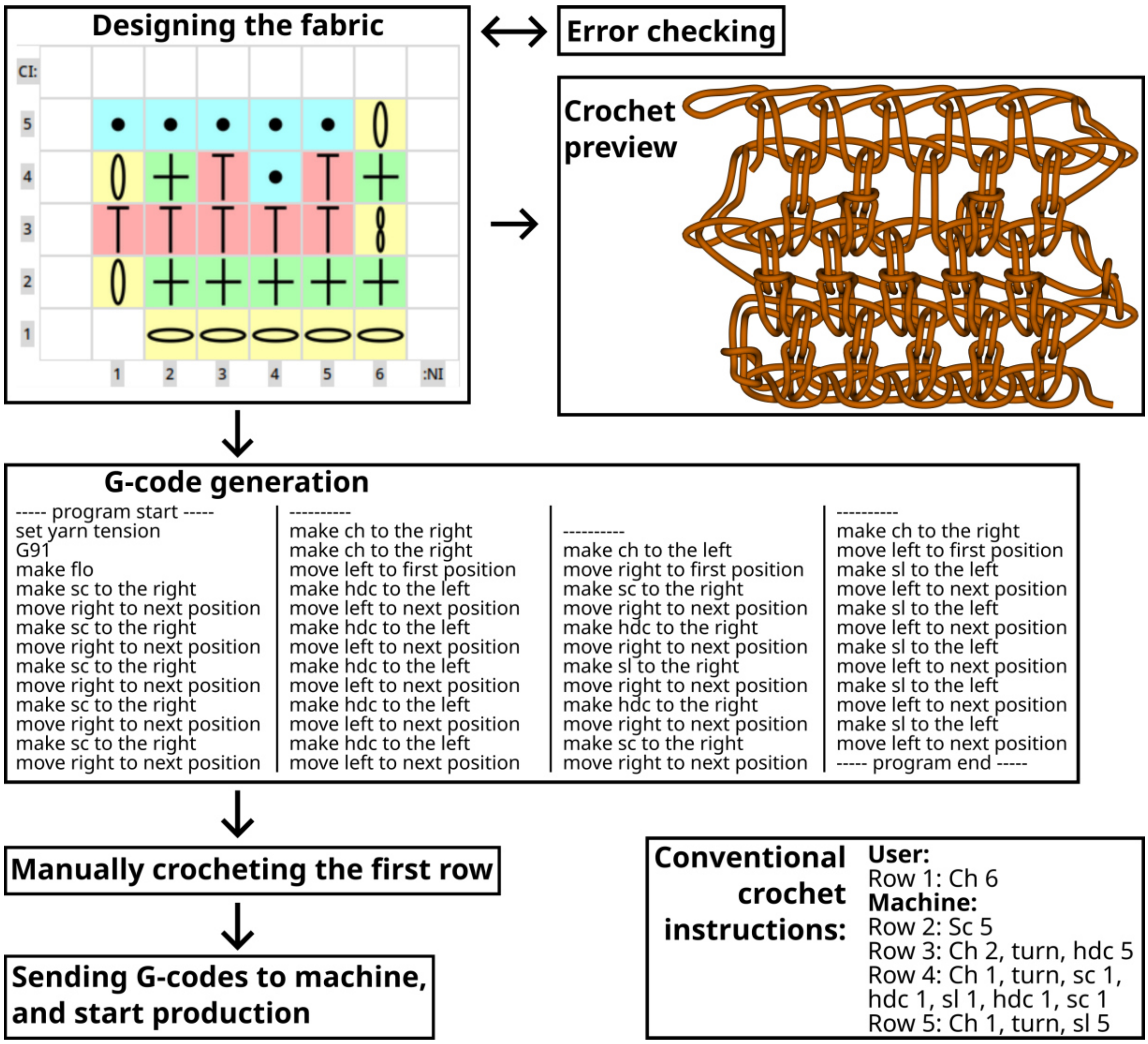

Figure 99. Workflow of using the developed design tool in an exemplary application. Figure is under CC BY-NC-ND license taken without modification from reference A6 (Copyright © 2023, the Authors).

3.6.6 Discussing the design tool

The concept of the first developed design tool for a true crochet machine is, in principle, similar to commercial design tools for knitting machines (such as M1plus or KnitPaint) with pixel-based programming, preview and error detection. However, the range of the prototype tool's functions is much more limited. According to the limitation of the CroMat to only produce flat fabrics, the approach differs from tools presented in scientific literature to design 3D textiles for manual circular crocheting [19,20,92]. Thus, in contrast to the literature, 3D objects cannot be processed to represent them with crocheted stitches and to generate instructions on how to crochet them. An alternative approach of processing of two-dimensional shapes to automatically generate machine-producible crochet patterns is presented in section 4.3. It is planned to integrate this approach in the design tool.

Moreover, the tools from references [19,20,92] refer to crochet in the round and not to planar crochet, which is performed by the crochet machine. However, similar to the work of Guo et al. [19], a 3D model of the crocheted textile is also created. Similarities to Çapunaman et al. [92] are that the intrinsic characteristics of the production process are taken into account and instructions for production are generated.

With the modeling it is possible to rapidly generate a preview, which is advantageous in terms of design processes [213,222]. Especially regarding crocheted fabrics, which are rather unknown to potential designers in the technical field, this is of great advantage. In addition to visualization, the automatically generated models can also be used for further simulative investigations [A1,216,223], as it is done by means of FEM in section 4.1.2. This enables the model-based development of crocheted fabrics. However, with the design tool it is not possible to combine several stitches into a cluster, as is often done in crochet [97].

Besides being specific to automated flat crocheting based on a chain line, the design tool is also specific to the CroMat prototype, because it is the only machine capable of producing planar crocheted fabrics. The implemented error checking is partly related to general crochet rules but is also machine specific. However, the focus on individual stitches of the presented tool offers an approach for future expansion into a general, machine-independent design tool, which is the research trend regarding established knitting machines [93,113,114]. This is because, independent from the specific machine, the sequence in which the stitches are formed, given by the principles of crocheting, remains the same. Thus, when generating instructions for a specific machine, the stitches can be mapped simply to other text files with the appropriate machine commands. Therefore, instructions for other machines with a similar operation principle could be generated with the same GUI and tool. Assuming that alternative crochet machines also form the stitches only from one side, the topological modeling can also be seen as generally valid, because the topology of the stitches, alongside the production sequence, are given by the principles of crochet.

A potential applicability of the tool for future alternative crochet machines is a commonality with the design tool for manually crocheted textiles developed by Seitz et al. [16,17]. This is because they note that their tool could also be used to generate machine instructions in the future [17]. To use their tool for the CroMat, a suitable mapping of the graph representation to the G-code macros would have to be created. The validity checking of Seitz et al. would also have to be adapted to the limitations of the machine. In Seitz et al. the validity of the textiles is ensured by allowing the user to select only appropriately valid operations for each step according to the sequence of manual crocheting [16,17]. Also, Seitz et al.'s representation of SLs would have to be changed. This is because they do not add any height to the textile in their tool and cannot be used as working stitches of future rows [16,17]. The reason for this is the focus on manual crochet, where SLs are typically not used as working stitches. In contrast, CroMat allows the creation of whole fabrics from SLs only.

A similarity to Seitz et al. is that the instructions regarding the production of the designed textiles are also generated by traversing the data structure according to the crochet order [16,17]. Overall, the crochet chart-based editor of Seitz et al. offers more possibilities for creating diverse 2D and 3D crochet patterns. However, one advantage over the editor created by Seitz et al. is that stitches that have already been set can be changed here without having to undo all the operations performed after the corresponding stitch.

3.7 CroMat requirement fulfillment

The finalized CroMat prototype marks the end of the development phase according to Koltze and Souchkov [179]. The prototype is functional in that all functions as well as the motion sequences developed for mechanized stitch formation can be demonstrated. Furthermore, crochet samples can be crocheted automatically with the prototype (cf. section 4.5). However, it is to note that the prototype construction resembles still an early design stage with much room for improvements regarding the assemblies and G-code programs.

The error-proneness of automated stitch formation depends on the type of stitch. The simple SLs can be formed almost error-free, while SCs and especially HDCs experience more problems. These are, as described in sections 3.4.5 and 3.4.6, due to the large friction with multiple loops in the hook of the crochet needle and the limitations of the yarn tension. Because of the lower stiffness of 3D printed parts compared to metal parts, the susceptibility to failure is amplified in the case of forces acting while forming HDCs. Also, the generally higher inaccuracies of FDM 3D printing compared to milling metal makes it more difficult to achieve accurate positioning during static mounting of the components as well as during their dynamic movement. In addition, wear occurs where the plastic parts contact each other directly, such as in the front bearing when the housing of the crochet needle rotates around its own axis. These are all side effects of a first prototype, which is not intended as an optimized machine, but which can nevertheless fulfill all the required functions. With the further development to an industrial prototype in the elaboration phase, these problems can be solved by minor design improvements, while the essential processes of automated stitch formation can be retained.

Due to these minor problems of the CroMat prototype, the error rate of the stitch formation processes is affected. Therefore, the requirement defined in section 3.1.3 for a robust stitch formation process with a low error rate can be seen as not yet completely fulfilled. This is because in the formation of SCs there is usually one error per 100 stitches, whereas for HDCs it is more likely to be one error per 40 stitches. The robustness of the stitch formation process is thus limited. However, in the case of SLs, far more than 100 stitches can be formed consecutively without errors. Generally, the CroMat prototype does not have the claim to be used as a production machine. In this respect, it can also be argued that the requirement for robustness of stitch formation is met with respect to the purpose of the prototype and with respect to the use of inexpensive components. The latter is also a requirement imposed on the CroMat prototype, which can be considered fulfilled.

The material costs of the CroMat prototype without yarn feeder and without needles can be estimated at under 1100 €. Also, the costs of the 3D printed parts are not included, because during the prototyping the consumption of PLA filament and the printing times were not recorded. The NEMA 17 stepper motors cost about 15 € each, while the servos cost between 3.50 € and 20 € depending on the type. The motherboard with drivers and the expansion board is a little over 100 €. In addition, there are the parts for the linear guides such as limit switches, cables or timing belts as well as the aluminum profile rails, angles and screws of the frame. All in all, a functional crochet machine can be built with relatively low costs and a simple consumer 3D printer (in addition to standard tools such as screwdrivers or soldering irons).

Scalability to an industrial machine was taken into account during development. However, with regard to the motion sequences, safe stitch formation was prioritized over a high production speed. With the speed used for most tests, which does not reflect the maximum possible speed, the formation of an SL requires about 7.7 s. According to the increasing complexity, it takes about 12.8 s for a SC and about 15.4 s for an HDC. The production speed of the CroMat prototype is limited in particular by the relatively low speed of the servo motors, which cannot be moved in parallel to other motors (cf. section 3.4.7). If these are replaced by stepper motors or enabled to move in parallel in an industrial machine, the speed can be increased, and an additional optimization potential can be exploited in terms of parallel movements. With more parallel movements, more time can be saved.

The production speed can be further increased if the motors are moved at a higher speed and acceleration. Due to the many discontinuous movements, acceleration is estimated to be the limiting factor here. An increase in acceleration requires more powerful motors and a stiffer structure, as well as possibly further measures to minimize vibrations. Certainly, the developed G-code programs themselves offer further optimization potentials for more efficient implementation of the movements and reduction of travel distances. This potential can be exploited with regard to an improved industrial machine that will in any case require adjustments to the G-code programs of stitch formation.

Regarding the scaling to an industrial machine, it is advantageous that the needles of the prototype are already professional machine parts, which have proven themselves in knitting machines, and can be directly adopted for a future machine. Considering the compound needle selected for the crochet needle (cf. section 3.4.3), the smallest possible gauge was implemented so that the smallest possible stitch size can be produced by machine according to the specified requirement. With this compound needle, a smaller stitch size is hardly possible, because it needs enough space to be inserted into the working stitch between two auxiliary needles. The necessary angle of the crochet needle during insertion is to be considered regarding the possible spacing of the auxiliary needles.

Due to the restrictions of the yarn tension and the limitation of the formation of SCs and HDCs to the sewing yarn M 782 from Gütermann, the yarn thickness is relatively low in relation to the stitch size (cf. section 3.4.6 and section 4.5). In manual crochet, much thicker yarn would be used for the stitches with a width of about 5 mm. In addition to the yarn tension, the thickness of the yarns that can be used is also limited by the fact that three loops must be able to be securely inserted into the hook of the crochet needle. With regard to SLs, the yarn that can be used is less restricted compared to SCs and HDCs, and it has been found that yarns with a diameter of up to about 0.6 mm can be used well.

The CroMat prototype can successfully implement SLs, SCs, HDCs, turns with one or two CHs, INC with SL and SC, DEC with SL and SC, as well as other methods to change the width of the manufactured textile. Also, by forming a CH in a course or skipping a stitch, open work crochets, which are characterized by not stitching in every stitch of a course, can be formed (cf. section 4.5.2). The developed control system supports that these operations can flexibly and almost arbitrarily follow each other (restrictions exist especially to the possibilities of changing the width of the textile). All operations have in common that they are based on the most widely used insertion point (under the two legs of the top loop) and that each textile is built on a chain line of manually formed CHs. The developed software for the design of the machine-crocheted textiles and for their modeling allows an easy operation of the machine, suitable also for persons who are unfamiliar with crochet (cf. section 3.6 and section 4.4).

The fabrics crocheted automatically with the prototype in T- and double-T-beam (I-beam) shape (cf. section 4.5.2) show the great potential of the future use of a CroMat crochet machine for the production of complex near net-shaped composite reinforcements. With regard to their production, which is becoming increasingly important in the wake of the climate crisis and rising costs for energy and raw materials [1], innovative, suitable technologies are required (cf. section 2.6.2). The assumed good suitability of crochet technology could also be confirmed in machine implementation, because it is possible to produce complex, coherent 3D textiles with a removing and re-hanging of the fabric as in manual crochet. This potential can be exploited by future developments based on the CroMat prototype. Thus, the prototype also fulfills the corresponding requirement of enabling the production of complex structures.

Furthermore, the CroMat prototype can be used for joining textiles. This is demonstrated in section 4.5.2 by the production of the tubular fabric, where the final course is formed based on two courses, which are connected by it. Thus, to join two textile components, it is in principle possible to suspend the stitches of two or more textiles on the same ANPs of the machine and join them by forming SLs, SCs, or HDCs. Depending on the intended application, it is possible that future machines specializing in such joining can be derived from the CroMat crochet machine.

Against the background of TRIZ theory, the CroMat prototype fulfills the law of completeness of a system formulated by Altschuller in the context of his theory of evolution of technical systems [182]. This is because the prototype has the four necessary system components: drive, transmission, working unit, and control unit. Since the CroMat prototype offers more functionality compared to the initial crochet machine approach (more possible stitch types and shaping options) and is significantly less error-prone compared to the Croche-Matic approach, Altschuller's law of increasing ideality is also satisfied [182]. Furthermore, the development status of the CroMat complies with the law of unequal development of system parts because the subsystem of professional knitting machine needles is significantly more mature than, for example, the subsystem of the 3D printed guide of the crochet needle [182]. It is interesting to note that the CroMat prototype does not conform to the law of completeness of the upper system because there is no infrastructure yet for operating a corresponding crochet machine or for selling the machine-crocheted textiles produced [182]. However, this is necessary for the machine to fit into the upper system and generally for being used in an industrial context in the future.

Overall, the requirements formulated in section 3.1.3 are considered to be fulfilled. Based on the properties presented in section 4.5, application areas of such textiles can be derived so that a future industrial crochet machine can be better integrated into the upper system. Building upon the detailed descriptions of the structure and operation, further development of the CroMat technology into an industrially applicable, production-ready machine is significantly facilitated. Besides the preview of a possible crochet machine construction, the developed control system also provides a basis for future developments. Especially the novel design tool together with the modeling and the developed algorithm for automated crochet pattern generation (cf. section 4.4) are relevant in this regard. Without such a design option appropriate for users unfamiliar with crochet, the obstacles to the application of a future, industrial crochet machine would be much higher.

4 Research on crocheted fabrics

This section presents the research and development performed beyond the creation of the CroMat crochet machine. As indicated, some of these sections are based on publications in scientific journals that were done as part of the doctoral research. Section 4.1 presents an approach to modeling manually crocheted fabrics and shows the possibilities of FEM simulation based on this approach. The basic, so far unexplored mechanical properties of manually crocheted textiles are investigated in section 4.2. Section 4.3 deals with the modeling of fabrics produced with the CroMat crochet machine as an extension of the modeling presented in section 4.1. The CroMat design tool presented in section 3.6 is extended in section 4.4 with a possibility to automatically generate producible crochet patterns according to the shapes of input 2D polygons. Finally, some crochet samples produced with the CroMat are presented in section 4.5.

4.1 Modeling and simulation of manually crocheted fabrics

This section is based on results published in the *Journal of Industrial Textiles* with the title *Topology based modelling of crochet structures* under a CC BY-NC 4.0 license (Copyright © 2022, the Authors) [A1]. As a first step towards the digitalization of crocheting, a novel approach to model crocheted fabrics considering the topology of CH, SL and SC using sware from the company TexMind [224]. In terms of virtual investigation of crocheted textiles for a potential future technical context, the applicability of the model for FEM simulations with software such as LS-DYNA was considered and confirmed.

Section 4.1.1 gives a brief introduction to the modeling of textiles. The framework developed in this work for modeling crochet structures is presented in section 4.1.2. Finally, section 4.1.3 addresses the possibilities of further FEM simulations based on the models.

4.1.1 Modeling approaches for textiles

Generally, textiles are modeled for education, design, engineering and research purposes [225]. Virtual preliminary tests can save on practical trials and valuable production time [213,214]. Models of textiles can be distinguished by three scales [213]. The micro-scale as the finest level considers the underlying fiber-fiber interactions that, for example, are responsible for the accurate cross section of a yarn within a larger textile structure [213,226]. The meso-scale focuses on the (mechanical) properties of the yarns and their topology or geometry in relation to each other while neglecting the micro-scale [213]. For this, a textile is often subdivided into unit cells with repeating yarn patterns [213,226]. In the coarse-grained view of the macro-scale, the (mechanical) properties of the entire textile structure are taken into account, for example by representing it as a continuum membrane or plate [213,226].

For the developed modeling approach, the meso-scale was chosen due to a compromise between complexity, practicality and visualization potential of crochet structures. The intermeshed yarn in a unit cell can be described geometry- or topology-based. Regarding a geometrical representation, the exact yarn path can be calculated, and mechanical conditions can be considered e.g., by factoring in minimization of energy [213,226-228]. In contrast to this complexity, a topology-based representation focuses the information on the textile's topology – namely how a yarn segment extends relative to others without precisely defining the exact curvature or position [213,215,229]. Here, Kyosev's definition of topology as "the knowledge of the orientation and positions of the yarns (or their axes), related to the other yarns in the same structure" is applied [215]. Due to the simplifications, a topology-based model is less accurate, but allows a more general use and is more suitable for industrial CAD applications [215]. For instance, a model can be used for yarns with different properties by assigning these during a subsequent FEM simulation [A1,215].

To gain a correct topology in a unit cell, the yarn paths' center lines can be defined by key points which are coordinates in 3D space [213,216,229]. The shape between neighboring key points can be formed by spline interpolation [213,230]. In this regard, Kochanek-Bartels splines are suitable because of the possibility to adjust the spline shape based on the tangents d_i and d_{i+1} at the key points p_i and p_{i+1} [231]. The tangents are calculated according to equations 1 and 2 with respect to the tension (t) as a parameter for the tangent vector lengths, to their directions influenced by the bias (b) and with respect to the continuity (c), namely the sharpness of the connections of the tangent vectors. Moreover, a possibility to obtain a more realistic representation is to optimize the key point positions by mechanical or geometric considerations [213,230,232]. By sweeping volume along the yarn paths a 3D model is created.

$$d_i = \frac{(1-t)(1-b)(1-c)}{2}(p_{i+1} - p_i) + \frac{(1-t)(1+b)(1+c)}{2}(p_i - p_{i-1}) \quad 18$$

$$d_{i+1} = \frac{(1-t)(1-b)(1+c)}{2}(p_{i+2} - p_{i+1}) + \frac{(1-t)(1+b)(1-c)}{2}(p_{i+1} - p_i) \quad 19$$

Due to the high complexity of intermeshed textiles, FEM, in contrast to analytical methods, is considered suitable for further simulative investigations [213,214,225,233]. For this purpose, according to the principle of FEM, the previously generated model is meshed in finite elements. Described by differential equations, changes of these elements can be solved numerically, and thus the total change of the model can be calculated [213,232,233]. For textiles an explicit approach is often used, which is suitable for large deformations and efficient in computing time [213,233,234]. Simple elements as trusses and beams are suitable for fast calculating simulations while 3D elements with no limitations on the DOFs can provide more accurate results [230,233,235]. To model different yarn types, the material properties can be changed within the FEM tool.

4.1.2 Developed modeling of crochet structures

Explaining the modeling

In the developed modeling approach at the meso-scale, a single stitch (CH, SL or SC) is considered as a unit cell and the corresponding key points are defined parametrically via a Python program. The basic key points of a SL unit cell are presented in Figure 100, and their relations in dependence on the shaping parameters L, H and stitch depth (D) are given by equations 20 to 24 [A1]. Since L also defines the distance between two stitches (or unit cells), two SLs, a and b, are considered.

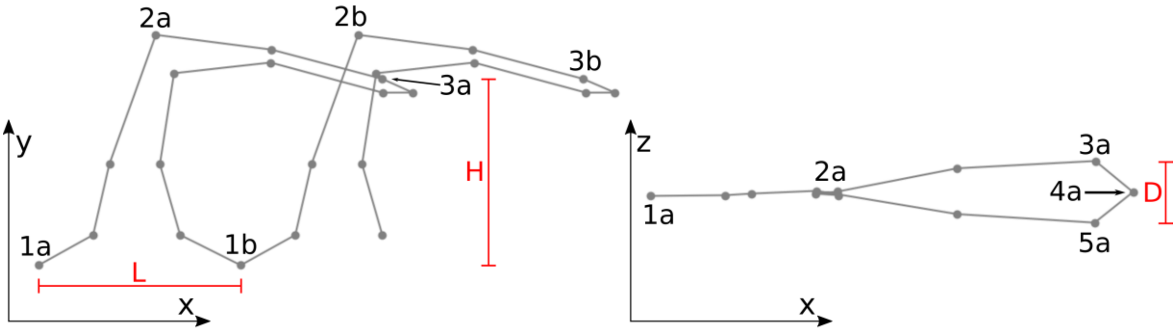

Figure 100. Topology-based representation of a SL by key points with shaping parameters and marked key points used in equations 20 to 24. On the left side both SL *a* and *b* are shown and on the right side only SL *a*. Figure is under CC BY-NC license and taken from reference A1 without modification (Copyright © 2022, the Authors).

$$L = 1b_x - 1a_x = 2b_x - 2a_x = 3b_x - 3a_x \tag{20}$$

$$4a_x - 1a_x = 1.85 \times L \tag{21}$$

$$H = 3a_y - 1a_y \tag{22}$$

$$2a_y - 1a_y = 1.23 \times H \tag{23}$$

$$D = 3a_z - 5a_z \tag{24}$$

To virtually assemble a course of *i* stitches, $L \times i$ can be added to the x-coordinates of the key points as a translation vector. The calculated coordinates of the stitches can be appended to one list representing the entire yarn path. Following this principle of displacement in virtual 3D space and paying attention to a correct meshing of all possible combinations, different stitches can be arranged to form a whole textile. The order of the stitches in the list of all key points corresponds to the sequence in manual crocheting. An example of the arrangement of stitches is given in Figure 101.

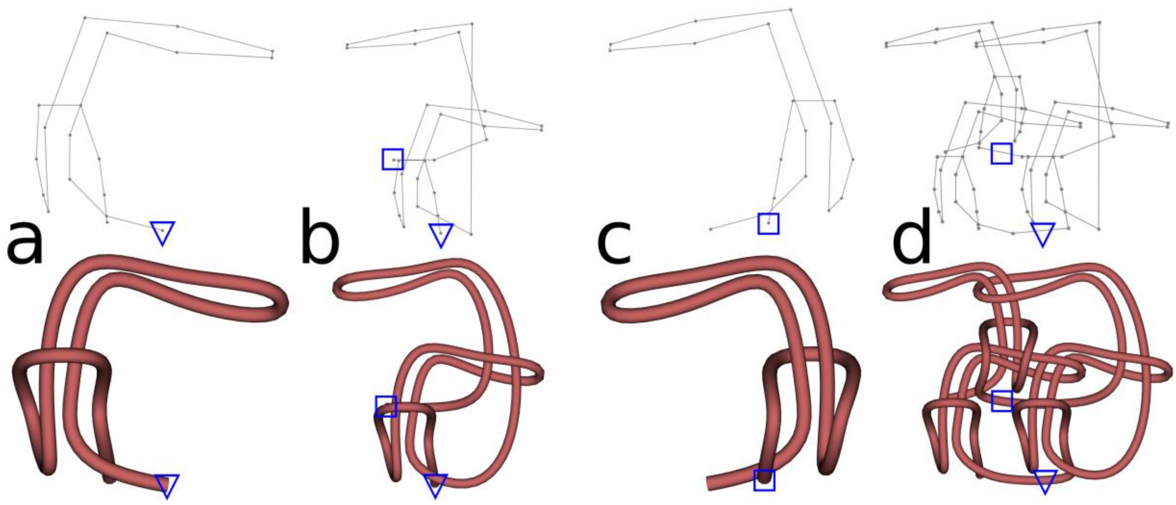

Figure 101. Example of arranging unit cells of a SC and a turn in virtual space with marked transitions between them by blue triangles and squares. At the top, the key point representation is shown and at the bottom the corresponding spline interpolated models visualized by the TexMind Viewer. **a)** SC facing in the right direction. **b)** SC with turn to the left direction featuring a CH. **c)** SC facing in the left direction. **d)** Assembled part of a crocheted fabric. Figure is under CC BY-NC license and taken from reference A1 without modification (Copyright © 2022, the Authors).

The appropriate intermeshing of different unit cells can be seen in Figure 101. Thereby, the stitch of b) is shifted by *L* in x-direction compared to a) and the stitch of c) is shifted in x- and y-direction depending on *H*. The simple approach does not take into account any further constraints nor relationships between individual unit cells, allowing the modeling to be flexibly extended to include additional stitch types. By taking the number of courses and wales as well as the stitch types per course as inputs, the developed Python program generates according to the described principle the topology-based model of the corresponding fabric in the form of a key point list saved in CSV files. As further inputs the yarn diameter and the shaping parameters *L*, *H* and *D* can be changed.

Creating the spline interpolation of the key point connections and adding the volume along the yarn center path like shown in Figure 101 can be performed with the TexMind Viewer (freeware) [221]. The viewer can open a created CSV file with a key point list and display the 3D model along with exporting images. For more options and output to common FEM tools like LS-DYNA, the TexMind Warp Knitting Pattern Editor [217] can be used.

Discussing the modeling

The limitations of the topology-based model with respect to replicating a truly realistic yarn path are illustrated by Figure 102. This figure shows an exemplary modeling of a manually crocheted fabric. A striking deviation of the model are the large distances between yarn segments, while the loops in the real textile are mostly considerably tighter. Thus, when comparing Figure 102 c) with d), it appears that the yarn course in the model corresponds more to the course of the marked, irregularly larger loop of the real fabric. Likewise, the turns on the left and right edges are too extensive. In the real fabric, they are more tightly spaced and arranged vertically rather than horizontally. These deviations result from the principle of topology-based modeling, which assumes an idealized yarn path and constant yarn diameter [216]. Also, the modeling does not consider influences such as yarn tension, which is responsible for the contraction of the loops in manually crocheted fabrics.

However, as it is demonstrated by the comparison of textile and model shown in Figure 102, the topology is correctly reproduced, and the structure of the crocheted textile is illustrated. The yarn tension in the manufacturing process can be taken into account indirectly by making the stitches correspondingly smaller via the shaping parameters. Optimization of the key point positions is possible in the future in order to represent the yarn path more realistically, e.g., at the turns. In general, realistic deformations of the topology-based model due to external influences can be simulated using FEM [A1,216].

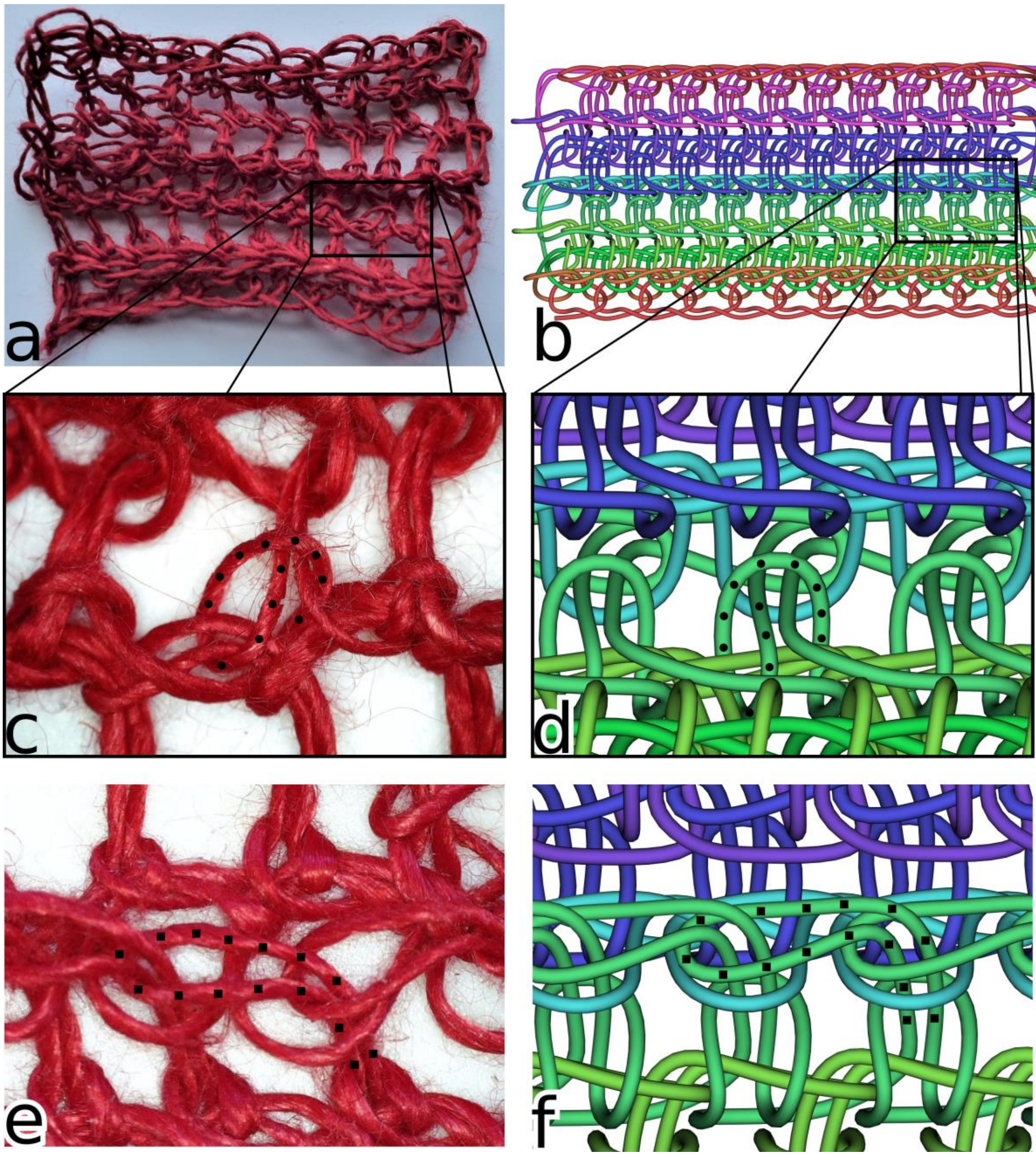

Figure 102. Comparison of the generated model visualized with TexMind Viewer with a crocheted fabric, which is (from the bottom) consisting of one CH course, two SL courses, two SC courses, one SL course, three SC courses and one SL course. **a)** Photograph of the manually crocheted fabric. **b)** Topology-based model with differently colored courses. **c)** Magnified section of the fabric with a loop marked by black dots. **d)** Corresponding section of the model and the likewise marked loop. **e)** Magnified section from the back of the fabric with a marked upper loop of a SC. **f)** Identical section of the model. Figure is under CC BY-NC license and taken from reference A1 without modification (Copyright © 2022, the Authors).

The modeling workflow is illustrated in Figure 103. First, the structure of the fabric to be modeled (Figure 103 a)) must be analyzed, as shown in Figure 103 b) with symbols of the CYC. This structure along with the yarn diameter of approx. 0.5 mm and an *L* of approx. 5 mm is passed to the developed Python program which generates a topologically correct key point list of the yarn path (cf. Figure 103 c)). A spline interpolated representation (cf. Figure 103 d)) can then be generated with the TexMind Viewer or Warp Knitting Pattern Editor. Using the export option to LS-DYNA of the latter, the model can be transferred to a

FEM tool and meshed with a suitable material type and beam elements as shown in Figure 103 e) and f).

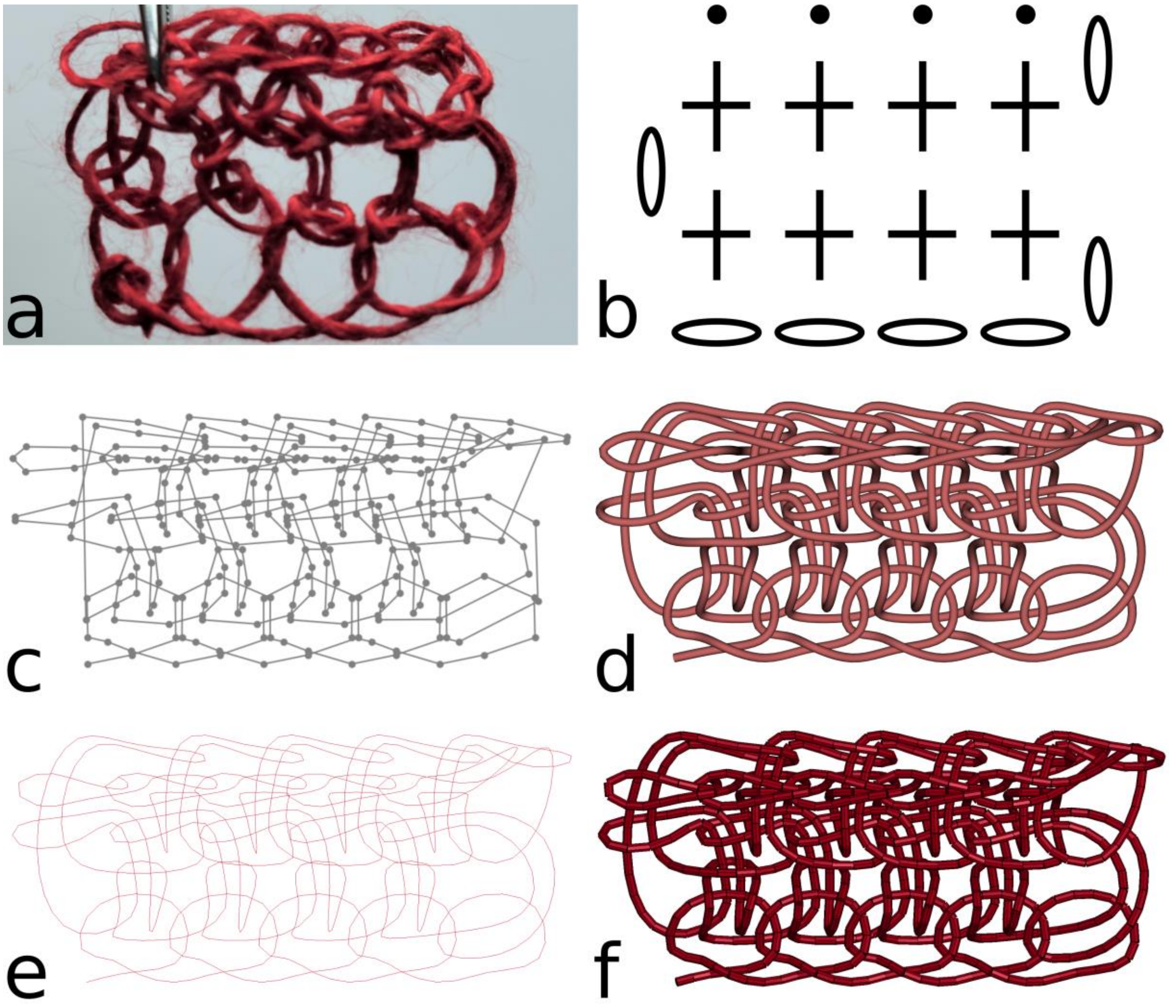

Figure 103. Exemplary topology-based modeling of a manually crocheted fabric. **a)** Photograph of the fabric. **b)** Abstraction with symbols of the CYC. **c)** Key point model generated by the developed Python program. **d)** Spline interpolated model visualized by TexMind Warp Knitting Pattern Editor. **e)** and **f)** Meshed finite element method (FEM) model with beam elements viewed in LS-PrePost with center path and volume filled beams, respectively. Figure is under CC BY-NC license and taken from reference A1 without modification (Copyright © 2022, the Authors).

Few approaches to modeling crocheted textiles are known from the scientific literature. In a comparable approach at the meso-scale, Guo et al. [19] have developed a set of tiles that represent parts of different stitches as unit cells. A modeled crocheted textile can be composed of these tiles, considering dependencies. In addition, 3D meshes (like a cube) can be automatically recreated with corresponding 3D crocheted structures. These can then be used to generate instructions on how to crochet them manually. In comparison to the approach presented here, the yarn course is modeled more realistically. However, applicability of the model in FEM simulations was not considered.

Similar to Guo et al., Çapunaman et al. [92] also developed a generation of 3D crocheted structures based on input geometries. The individual influence of a crocheter is additionally taken into account by evaluated crochet swatches so that the textiles to be manually crocheted based on the generated text instructions represent the input 3D objects as accurately as possible. In this case, the computer model is limited to an abstract mesh, which does not reflect the structure and topology of crocheted textiles. A visualization of a crochet to be designed is therefore not provided. Another study deals likewise with generating crochet patterns based on input sketches, which are interpreted as 3D objects, rather than with building a computer model [225].

The modeling framework presented here offers a fast and flexible way to generate computer representations of planar crocheted fabrics and is to be seen in an industrial context. Due to the fast model generation and visualization, the possibility to estimate the required yarn length [A1] as well as the suitability for subsequent FEM investigations of the material properties (cf. next section), the presented approach can enhance the productivity in design processes [214,230].

4.1.3 FEM investigations

Regarding the suitability for FEM simulations of the widest possible range of models that can be generated using the approach developed here, the spacing of the yarn segments was chosen to be as large as possible for the modeling design. Since when changing the ratio of yarn diameter to stitch size, interpenetrations of different yarn segments can occur, which have a negative effect on the FEM simulation [232,236]. A wide spacing increases the range of possible yarn diameter to stitch size ratios. At the current stage of modeling, a ratio of up to 1/10 is possible without such intersections arising [A1].

In the context of a simple and fast approach to design crocheted fabrics, beam elements common to textile models are used to keep the calculation time low [223,229]. The latter is under 10 min for displacement simulations with one clamped and one moved end of the fabric of about 10 mm. Further details on the performed FEM simulations can be obtained from reference A1.

Figure 104 displays an example of such an FEM simulation with the commercial explicit solver LS-DYNA and the modeled fabric of Figure 103 in section 4.1.2. With this, the stress in a crocheted fabric during elongation is simulated for the first time with FEM. The propagation of the von Mises stresses through the textile during displacement in wale direction can be traced by the fringe plot in Figure 104. Initially, the stress is focused on the CH course moving downwards until it begins to contact the course above. From then on, the stress spreads quickly and evenly throughout the fabric. The hourglass shape in the end is similar to that of knitted textiles in a tensile test [237].

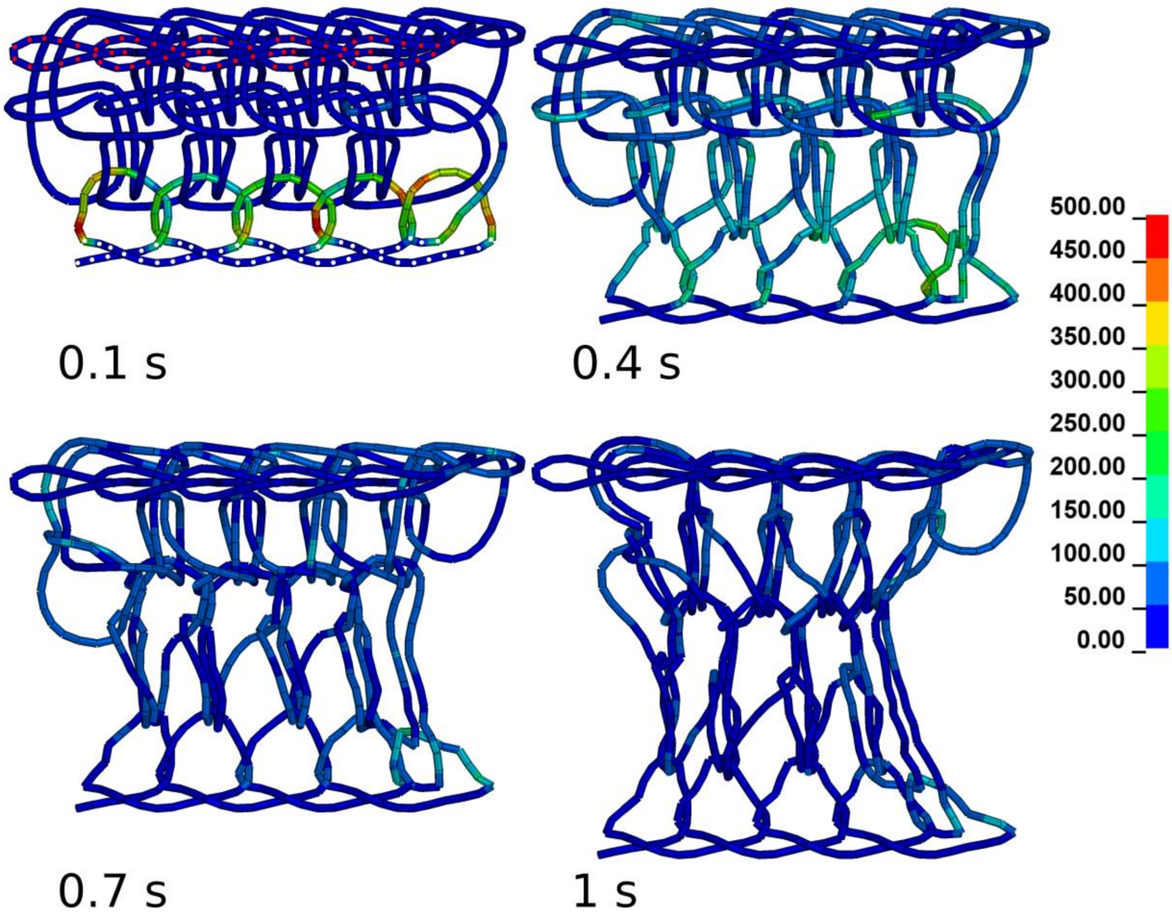

Figure 104. Displacement simulation in wale direction of a crocheted fabric with LS-DYNA at four time frames. The von Mises stresses are indicated as fringe plots with the scale in Pa. The red marked upper stitches (at 0.1 s) are restricted in movement while the elements marked in white of the bottom course moves downwards with 11.7 mm/s. Figure is under CC BY-NC license and taken from reference A1 without modification (Copyright © 2022, the Authors).

Besides the wale direction, the course direction is also characteristic for a crocheted fabric and thus a corresponding displacement simulation is shown in Figure 105. The indicated displacement of 1.17 mm is reached after 0.1 s. Compared to the displacement in wale direction (cf. Figure 104), the von Mises stress is already distributed over large parts of the material at this time. The faster distribution of the stress in course direction is due to the more closely spaced stitches and the different structure of these in course direction. This indicates anisotropic behavior for crocheted fabrics, like it is common for knitted ones [225,237].

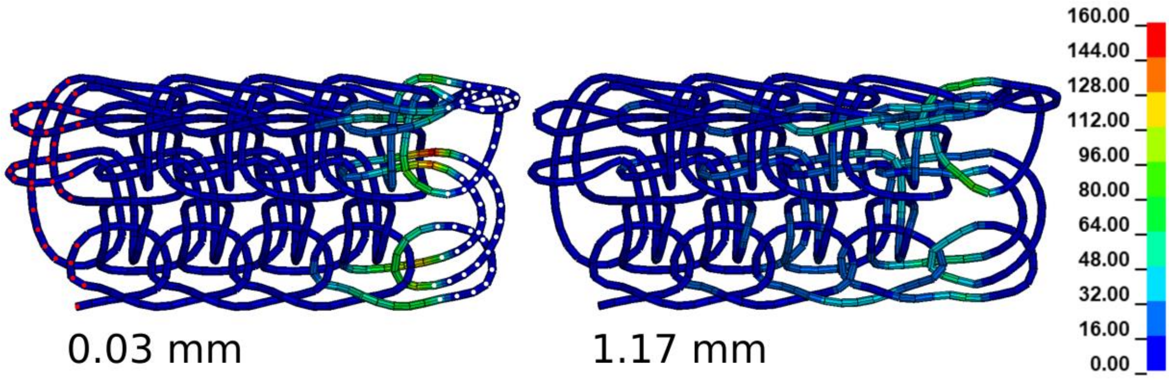

Figure 105. LS-DYNA simulation of displacement in course direction of the model shown in Figure 103 (in section 4.1.2) and 104 with indicated displacements. The von Mises stresses are indicated as fringe plots with the scale in Pa. The red marked elements on the left side are virtually clamped, while the elements marked with white dots at the right side moves with 2.1 mm/s. Figure is under CC BY-NC license and taken from reference A1 without modification (Copyright © 2022, the Authors).

To the best of the author's knowledge, these are the first published results on FEM simulations of crocheted textiles. The results show the possibility to perform FEM simulations with a simple modeling of complex textile structures to gain first insights into their mechanical properties. Based on this, crocheted fabrics can be investigated with more sophisticated FEM simulations in the future to engineer them.

The presented approach is similar to published FEM investigations on knitted textiles at the meso-scale, where the unit cells of the underlying models were often also defined by key points [213,216,229,230,232]. With such an approach, Kyosev [229] simulated in LS-DYNA the displacement of a weft knitted textile, which was modeled topology-based with key points and meshed with brick elements. Such 3D elements result in a high computational cost that is unsuitable for industrial applications [229]. However, simple elements like beams, which follow the simplification of the topology-based key point approach, are much faster to calculate but limited in the accuracy of the simulation.

Beyond this problem, other factors exist that generally hinder the use of FEM simulation of textiles in an industrial context. In particular, the variable cross-section as well as irregularities of a yarn are difficult to simulate and require a high effort [213,229]. Specially trained personnel are required for corresponding FEM simulations due to the complex programs [213]. Also, the properties predicted by simulations differ from real measured ones even with elaborate approaches [225]. Presumably, more accurate FEM simulations, e.g., with multi-scale approaches, can be effectively used for industrial applications in the future due to the increasing computing capacity [233]. Currently, the shortcomings of simulative studies require real measurements of the textile properties, whether in an industrial or academic context.

4.2 Mechanical characteristics of manually crocheted fabrics

In parallel to the development of the CroMat prototype, the properties of manually crocheted fabrics were investigated in order to gather fundamental knowledge about crocheted fabrics and to investigate novel technical fields of application. This is important because, to date, little scientific research has focused on crocheted textiles and their mechanical properties (cf. section 2.1.4). The content from this section is based on the scientific article *Principle capabilities of crocheted fabrics for composite materials* published in the open access *Journal of Engineered Fibers and Fabrics* [A2] under a CC BY 4.0 license (Copyright © 2023, the Authors) as part of the work.

Section 4.2.1 provides a brief introduction before the conducted experiments are described in section 4.2.2. The results regarding the influence of the crocheter on the mechanical properties of the fabrics are presented in section 4.2.3, while the influence of the crochet structure is addressed in section 4.2.4. Section 4.2.5 presents the results of the investigated composites with crocheted reinforcements. Finally, the results of the study are discussed in 4.2.6.

4.2.1 Study overview

To explore suitable fields of future application of crocheted fabrics and to justify further investments in the automation of crocheting, more knowledge about the basic mechanical properties of crocheted fabrics needs to be obtained first, since there is generally little knowledge about the technical properties of these. So far, the curling behavior of crocheted fabrics [88] as well as their sound absorption behavior [23] was investigated, and it was found that crochet is suitable to mimic the complex-shaped tendons and ligaments of the human hand due to various stitch types and shapes [89,90]. In addition, other promising applications include a crocheted textile as a part of a scaffold to mimic the human skin for tissue engineering [22] or a crocheted textile sensor for measuring elbow joint flexion [21]. Scholarly attention has also been paid to the complex hyperbolic shapes that can be formed with crocheted textiles [7-9].

Here, the basic tensile properties of manually crocheted fabrics consisting of SCs or HDCs, were investigated by uniaxial tensile tests with strain in course and in wale direction, also taking into account reproducibility. The goal is to examine the general applicability of crocheted fabrics as composite reinforcements, since crochets are potentially suitable as reinforcements for (near) net-shaped composites due to the various possibilities to crochet complex 3D structures. Information on composites is given in section 2.6.

Compared to knitting, where float or tuck stitches are the main variation possibilities [2], crochet offers a wider variation in producible structures. In addition, due to the fundamentally similar, stitch-based construction, a similar drapability of crocheted fabrics can be assumed. Here, simple aramid/epoxy composites were fabricated with crocheted reinforcements via vacuum-assisted hand lay-up, and their mechanical tensile properties were analyzed. Weft knitted double jersey fabrics served as references for the investigations.

4.2.2 Materials and Methods

The experiments performed are briefly explained here. A more detailed description can be found in reference A2. Crocheted fabrics were handcrafted by three different crocheters with a 2 mm crochet hook. A mercerized cotton yarn with 1786 dtex (Rico Essentials Crochet, idee. Creativmarkt GmbH & Co KG, Paderborn, Germany) was used. This yarn corresponds to the one used in Figure 89 in section 3.4.6 and to Figures 16 and 18 in section 2.3.1. As a technical para-aramid roving, Twaron Type 2040 with 1100 dtex and a density of 1.45 g/cm³ (Teijin Aramid GmbH, Wuppertal, Germany) was used [238]. The conventional cotton yarn was intended for the comparisons of the basic mechanical properties of the textiles. In a second step, promising structures have been made with the aramid yarn for composite materials.

As a reference, knitted fabrics were produced by a V-bed hand knitting machine gauge E5.6, with a medium stitch size. Double jersey was used to prevent curling of the samples. In wale direction, which is the test direction (TD) for all knitted samples, the required sample lengths of about 100 mm were cut and sewn after fabrication. For each sample, five specimens were produced and measured. Table 2 lists all investigated samples.

Table 2. Samples overview. The added number in the column of the number of wales indicates the number chain stitches (CHs) made during the turn (1, 2 or 3). To better distinguish the crocheted fabrics, the half double crochet stitch (HDC) fabrics tested in wale direction are highlighted in green, while those tested in course direction are marked by blue. Single crochet stitch (SC) fabrics tested in wale direction are highlighted in orange and SC fabrics tested in course direction in yellow. The table is under a CC BY 4.0 license and taken from reference A2 with slight modification (Copyright © 2023, the Authors).

Sample	Main Stitch type	Number of courses	Number of wales	Material	Crafter	TD
Crochet 1	HDC	51	10 + 2	Cotton	A	wale
Crochet 2	HDC	21	10 + 2	Cotton	A	wale
Crochet 3	HDC	21	10 + 2	Cotton	B	wale
Crochet 4	HDC	21	10 + 2	Cotton	C	wale
Crochet 5	SC	33	10 + 1	Cotton	A	wale
Crochet 6	SC	33	10 + 1	Cotton	B	wale
Crochet 7	SC	33	10 + 1	Cotton	C	wale
Crochet 8	HDC, with turn 3	21	10 + 3	Cotton	A	wale
Crochet 9	HDC	8	35 + 2	Cotton	A	course
Crochet 10	HDC, without SL stitch course	7	35 + 2	Cotton	A	course
Crochet 11	SC	14	33 + 1	Cotton	A	course
Crochet 12	SC, without SL stitch course	13	33 + 1	Aramid	A	course
Knit 1	Double jersey	40	11	Cotton	Machine	wale
Knit 2	Double jersey	40	14	Cotton	Machine	wale
Knit 3	Double jersey	50	13	Aramid	Machine	wale
Composite 1	SC, without SL stitch course	13	33 + 1	Aramid/ epoxy	A	course
Composite 2	Double jersey	50	13	Aramid/ epoxy	Machine	wale

The tensile tests carried out are based on the strip test method from the European norm (EN) ISO 1421 [239,240]. However, there were deviations in the width of the fabrics in order to comply with the available clamp width of 40 mm of the tensile testing machine used (Zwick-Roell 1455, ZwickRoell GmbH & Co. KG, Ulm, Germany). Also, the jaw distance was reduced to approx. 45 mm (before pretension) in order to be able to test fabrics with a length of approx. 100 mm. A test with Crochet 1 (not shown here, cf. reference A2) has proven that this adjustment allows reasonable measurements. For the statistical evaluation, results of different samples were regarded as significantly different if they differed by more than one standard deviation (SD).

According to EN ISO 1421, the speed of the moving clamp was set to 100 mm/min and a pretension setting with 2 N was chosen as mounting state. The latter corresponds to the specifications of EN ISO 13934-1 [241], which also served as the basis for the test procedure used here. Due to the pretension setting of 2 N, which is necessary to load the specimens reproducibly in the machine, the textile specimens were stretched by an unknown amount before the actual start of the measurement. The clamp distance at the start of the measurement was not recorded by the machine (manually this was not possible due to the direct start of the measurement after reaching the pretension), so that the original specimen lengths are unknown. Also, the cross-sectional area of the textile samples, required for calculating the stress, is unknown and cannot be determined by the measured dimensions. Therefore, stress-strain curves cannot be calculated for the textile samples, and force-elongation values are considered instead.

Composites were produced by vacuum-assisted hand lay-up technique with epoxy resin (Epoxy resin L and hardener CL mixed 10:30 per weight, R&G Faserverbundwerkstoffe GmbH, Waldenbuch, Germany). Tensile testing of the produced composites was based on the National Aeronautics and Space Administration (NASA) standard test methods for textile composites [242] and on the American Society for Testing and Materials (ASTM) D3039 standard [243], respectively. To ensure greater stability due to the continuity of the fibers [244,245], non-cut composites were produced, and the reinforcements were molded individually. Testing speed was set to 2 mm/min. However, as a deviation from the standard, the size of the samples was adjusted to the dimension of the crocheted fabrics. As a further deviation, no strain gauge or extensometer was used, instead the traverse path of the machine was considered. The ultimate tensile strength (σ_{ult}) of the composites was calculated according to equation 25 [242], where P is the maximum force, w is the sample's width perpendicular to TD, and t the sample's thickness. The Young's modulus E was calculated according to equation 26 [242], where l the jaw distance and $\Delta P/\Delta l$ is the slope in the linear region of the force elongation curve.

$$\sigma_{ult} = \frac{P}{w \cdot t} \qquad (25)$$

$$E = \frac{\Delta P}{\Delta l} \cdot \frac{l}{w \cdot t} \qquad (26)$$

4.2.3 Influence of the crocheter

The influence of the manual crafting of crocheted fabrics by different persons (Crocheter A, B and C) on the fabric's dimensions and mechanical properties is investigated by comparing Crochets 2 to 7. Significant deviations occurred regarding dimensions and the required yarn lengths of manually crocheted fabrics crafted by different persons according to the same construction (for more details see reference A2). The influence of the crocheter can be seen in Figure 106 especially with respect to the regularity of the stitch structure (compare A and B). In this figure, the deformations of the stitches due to the tensile tests in comparison to the areas held by the clamps are also clearly recognizable. HDCs and SCs deformed similarly, and parallel yarn segments aligned in TD between the tightened loops of different stitches.

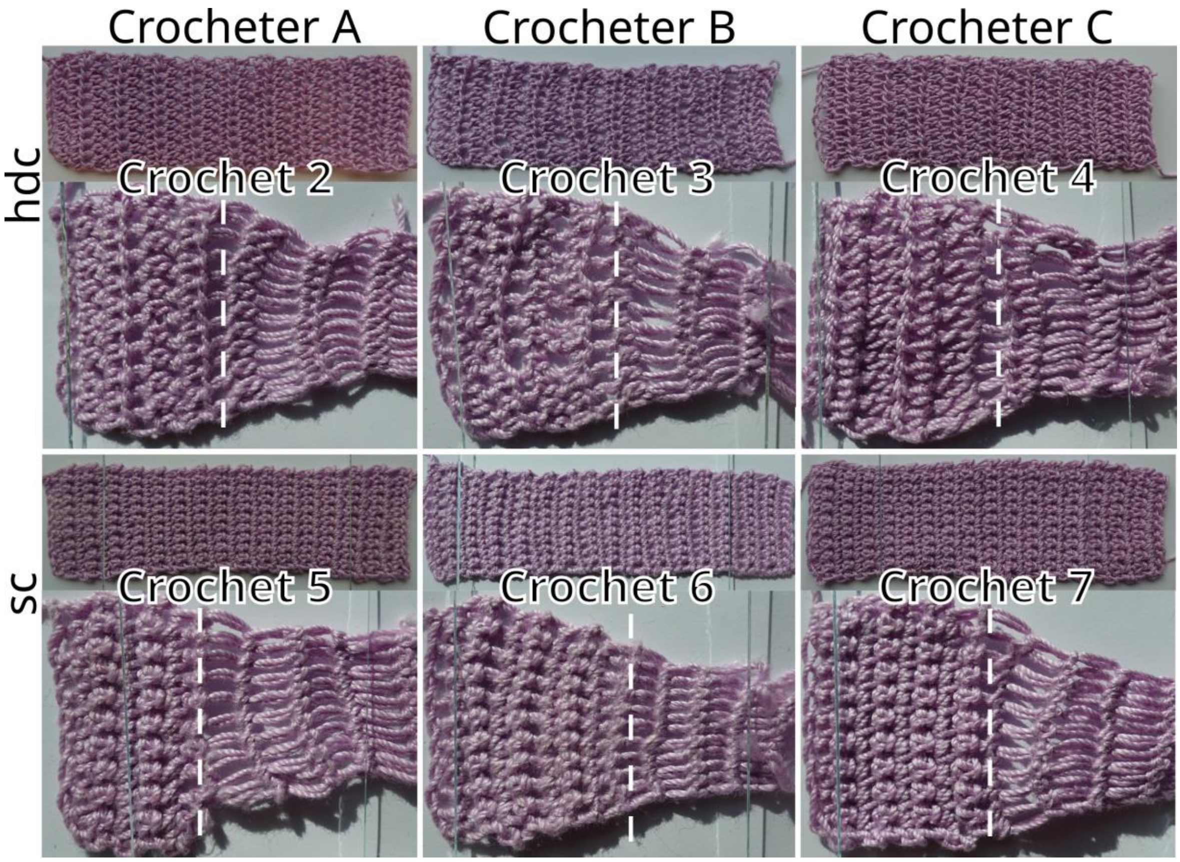

Figure 106. Photographs of fabrics (held down by glass slides) crocheted by different crocheters with HDCs and SCs as main stitch types before (upper parts) and after tensile tests (lower parts). Specimens were clamped on the left sides of the dashed lines during tests. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

In Figure 107, the results of the tensile tests of Crochets 2 to 7 are displayed. Remarkably, despite the significant differences in the dimensions and yarn length of these samples, no significant differences were measured in the forces and elongations of the HDC crochets. Regarding the SC crochets, Crochet 6 differed significantly from 5 and 7 in the forces and elongations at break as well as at maximum. This case of higher forces with lower elongations is probably connected to the higher stitch density (number of courses or wales per cm) and less consumed yarn of Crochet 6. Overall, the significant influence of the crocheter on the fabric's tensile properties could be confirmed. However, the SDs as a measure of the variation of individual specimens are adequately small, despite the manual production, to allow reasonable comparisons of the properties of samples from the same crocheter. Thus, all further samples were produced by crocheter A.

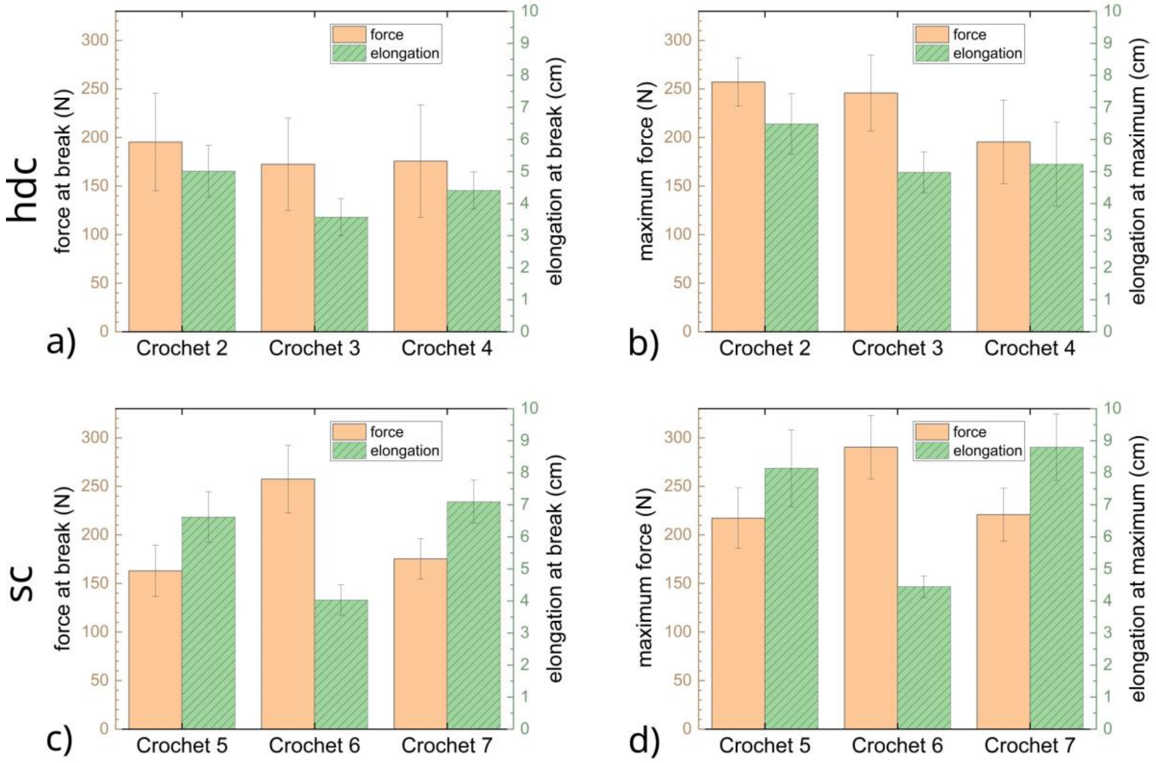

Figure 107. Comparison of tensile forces and the corresponding elongations of Crochets 2 to 7, manufactured by different crocheters, with mean values and standard deviations (SDs) as error bars. **a)** Force and elongation at break of Crochets 2, 3 and 4 with HDC as main stitch type. **b)** Maximum force and elongation of Crochets 2, 3 and 4. **c)** Force and elongation at break of Crochets 5, 6 and 7 with SC as main stitch type. **d)** Maximum force and elongation of Crochets 5, 6, 7. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

4.2.4 Influence of the crochet structure

Next, the influence of the stitch type (SC or HDC) and of the measurement direction (wale or course) on the tensile properties are investigated. Regarding the deformations after tensile testing, distinct differences occurred with the wale (Crochet 2, 9 and 10) or course direction (Crochet 5 and 11) as TD. In case of applied strain in course direction, both crochets with HDCs and SCs as the main stitch types (Crochets 9 and 11 in Figure 8) do not form parallel yarn segments aligned to TD, as observed in case of deformation in wale direction (Crochets 2 and 5 in Figure 5). As apparent in Figure 108, the loops of the HDCs and SCs tighten less and appear in the elongated form more similar to the knitted loops. The knitted reference was only tested in wale direction, to which a stiffer behavior is attributed [225,246,247].

To ensure that the width of the samples with different TDs and structures is comparable and suitable for the tensile testing machine, the number of stitches perpendicular to TD differ (cf. Table 2). The measured forces and elongations were therefore in the following (as indicated) normalized to the number of wales or courses per cm perpendicular to TD (the stitch density in width) to provide comparability of the samples.

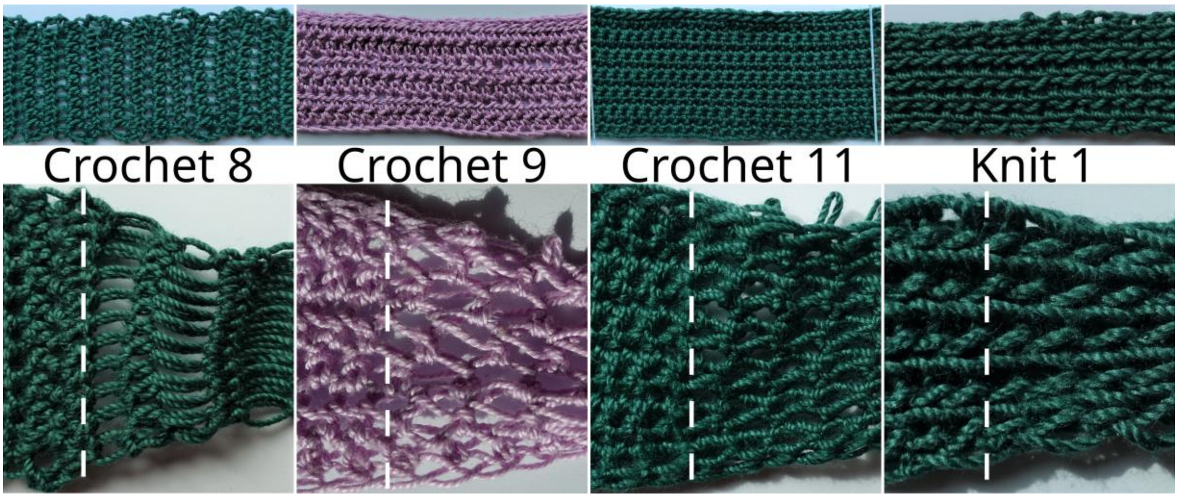

Figure 108. Photographs of exemplary fabrics of Crochet 8, 9 and 11 as well as Knit 1 with different structures. The upper part illustrates the fabrics before tensile testing and the lower part afterwards with indicated clamped region left from the dashed line. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

The orientation of a crocheted fabric in the tensile test with respect to wale or course direction led to significant differences in the mechanical properties, as can be seen in Figure 109. Regarding HDC, the normalized forces and elongations were significantly larger in course direction (Crochet 10) than in the wale direction (Crochet 2). Also, with SC, the course direction (Crochet 11) showed a significantly higher normalized maximum force compared to the wale direction (Crochet 5). Here, the normalized elongation at first break was significantly shorter for Crochet 11 than for Crochet 5, which corresponds to an early breaking of the SLs of the fabric's last course.

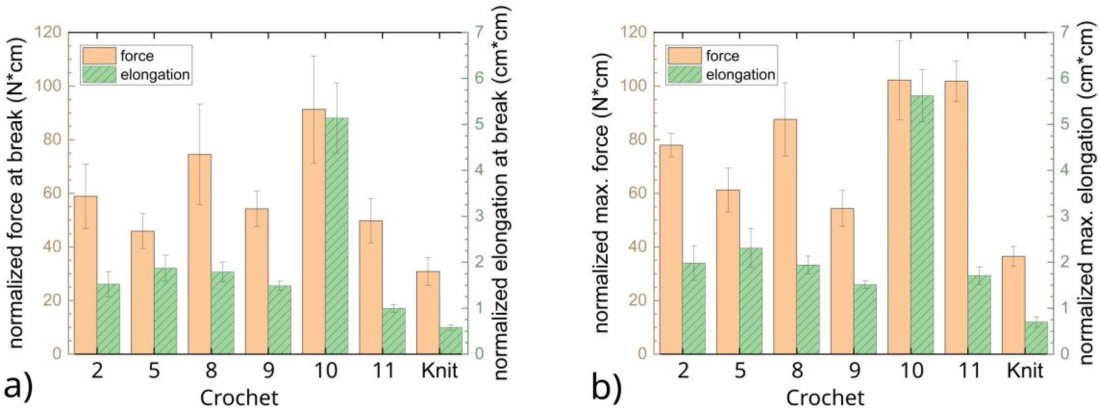

Figure 109. Tensile forces and respective elongations normalized to the stitch densities in width as mean values with SD error bars of Crochets 2, 5, and 8 to 11 as well as of the averaged knitted fabrics. **a)** Normalized force and elongation at break. **b)** Normalized maximum force and elongation. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

The early breakage of the SL course is also observed in HDC fabrics. Thus, significantly higher deformations and forces were measured with Crochet 10, which was produced without the SL course, than with Crochet 9 with a similar structure but an SL course. Apparently, SLs are less deformable.

When comparing SCs with HDCs in course direction, Crochet 10 (HDCs) and 11 (SCs) resulted in similar normalized maximum forces, while the normalized maximum elongation of Crochet 10 was significantly higher than that of Crochet 11. This shows a lower deformation of SCs compared to HDCs in course direction.

By comparing the crochets to the knitted reference (averaged from Knit 1 and 2), it is striking that the normalized forces and elongations of all crocheted samples were significantly higher than those of the knitted fabrics. However, the representation normalized to courses or wales per cm (depending on which is perpendicular to TD) may be unsuitable here, because it does not consider the inhomogeneities of crochets consisting of turns, CHs, and SLs besides SCs or HDCs. Also, for Crochet 2 and 5 with the same number of stitches in width perpendicular to TD the difference in the normalized maximum force is significant, while it is not significant considering the measured force (cf. Figure 107 b) and d)). Therefore, it is reasonable to additionally compare the non-normalized measured mechanical properties via an equal number of stitches in width.

In Figure 110, Knit 1 (11 stitches in width) can be compared to Crochet 2 (HDC, wale) as well as Crochet 5 (SC, wale). These comparisons reveal fewer significant differences in contrast to the normalized values. However, Knit 1 had still a significantly shorter elongation than Crochet 2 and 5, as well as a significantly lower maximum force than Crochet 2. Knit 2 (14 stitches in width) is comparable to Crochet 11 (SC, course), which displayed a significantly higher maximum force and elongation.

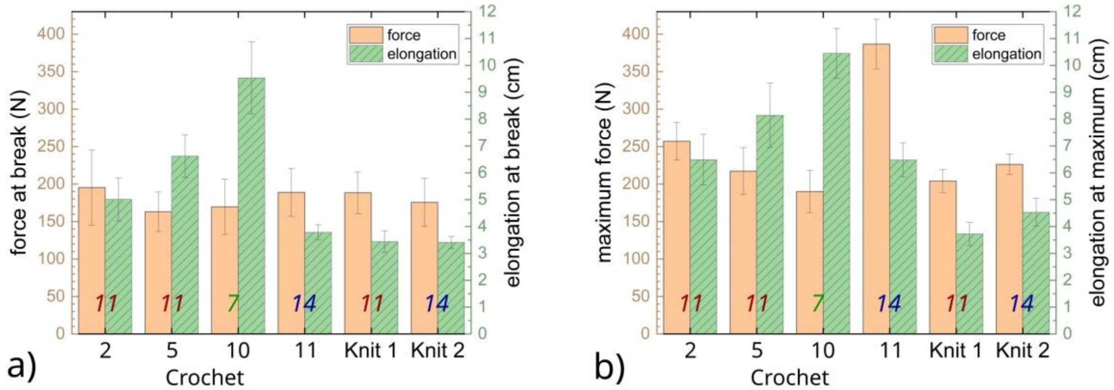

Figure 110. Non-normalized measured mechanical properties for comparison of Crochet 2, 5, 10 and 11 as well as Knit 1 and 2. The colored numbers in italics indicate the number of stitches in the width and thus designate the comparability of the specimen. **a)** Force and elongation at break. **b)** Maximum force and corresponding elongation. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

In both comparisons, the crocheted samples showed a tendency toward greater resisted forces at larger elongations compared to the knitted samples (Figure 109 and 110). The obvious explanation for this is the intrinsically different structure of the crocheted compared to the knitted stitches. Presumably, the anchoring of a crochet stitch in two previous stitches, instead of one previous stitch as in knitting, is relevant in this context [11,12].

Also, by considering the normalized and measured tensile properties, the course direction exhibited a higher elongation than the wale direction regarding HDC crochets. Contrastingly, a tendency towards higher elongations in the wale direction can be assumed for SCs.

4.2.5 Crochet composite

The structure of SCs with course as TD was chosen as most suitable for a composite reinforcement. This is because it resembles a promising combination of resisting high maximum forces at little elongations. The SL course identified as a weak point was omitted.

Accordingly, the aramid fabrics of Crochet 12 and Composite 1 were produced in this configuration. As references, aramid knits (Knit 3 and Composite 2) were made with the same number of stitches perpendicular to TD as the crochets.

Tensile properties of the crocheted and knitted aramid fabrics are compared in Figure 111. Crochet 12 had a significantly higher force at first break compared to Knit 3, while no further significant differences were measured. This confirms the observed tendency of higher mechanical stability of the crocheted in contrast to a knitted fabric. Compared to the conventional cotton yarn, the aramid yarn resulted in significantly higher measured forces and significantly less maximum elongation for crocheted and knitted fabrics alike (cf. Figure 110 in section 4.2.4 and Figure 111). Thus, the expected trend of higher resisted forces at lower elongations due to the aramid yarn was observed.

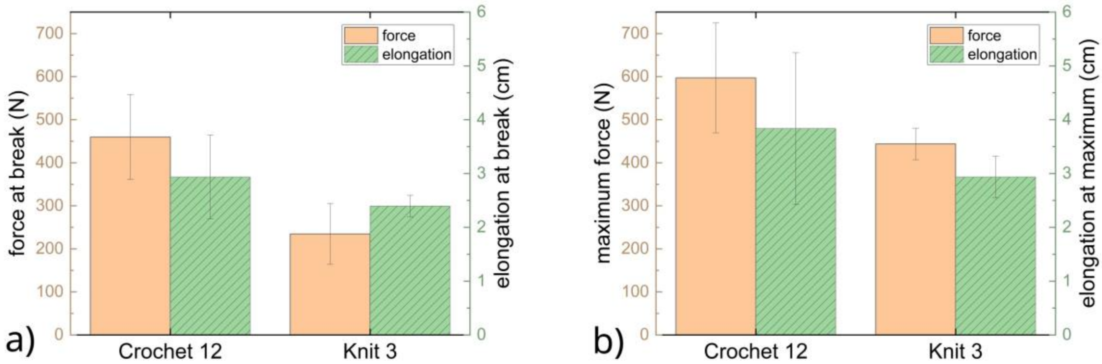

Figure 111. Measured tensile properties of the aramid fabrics Crochet 12 and Knit 3. **a)** Force and elongation at first break. **b)** Maximum force and elongation. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

Figure 112 depicts the novel crochet composite. Relatively large resin rich regions can be seen, especially in the bottom CH course. The microscopic image in b) shows several air bubbles in the resin matrix, which calls for a necessary improvement of the manufacturing process in the future. Air bubbles are known defects that occur due to the hand lay-up method and negatively influence the mechanical properties as well as the scatter of the measured values [174]. Since the air bubbles are evenly distributed throughout the composite, the mechanical properties are also affected evenly. In Composite 2, a uniform distribution of air bubbles was likewise observed.

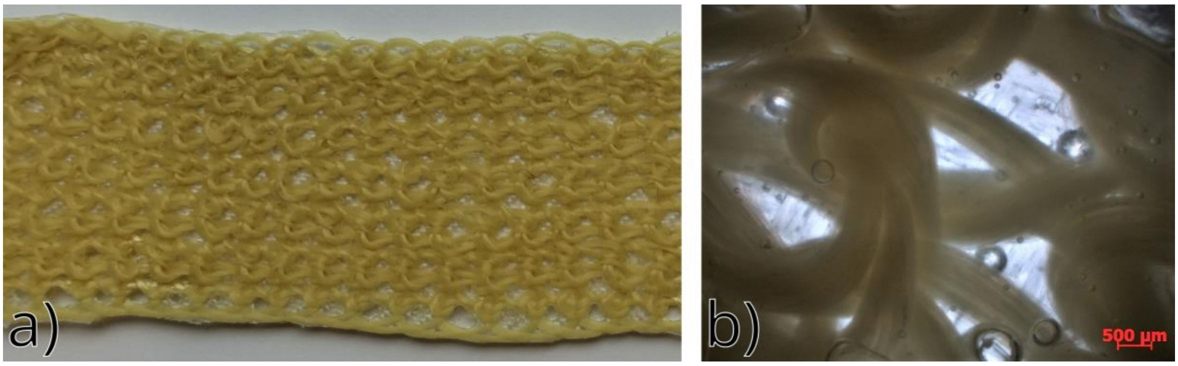

Figure 112. Composite 1 with aramid crochet. **a)** Photograph. **b)** Transmissive light microscopic image. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

The engineering stress and strain can be calculated for the composites, because the cross-sectional area can be calculated and no pretension for the measurements was necessary. The stress-strain curves of the specimen with the highest ultimate tensile strengths of

Composite 1 and 2 are compared in Figure 113. As can be seen from these typical curves, in contrast to the textile specimens, the maximum force was measured at the first break for the composites. The crocheted reinforcement resulted in a higher resisted stress at lower strain compared to the knitted reinforcement.

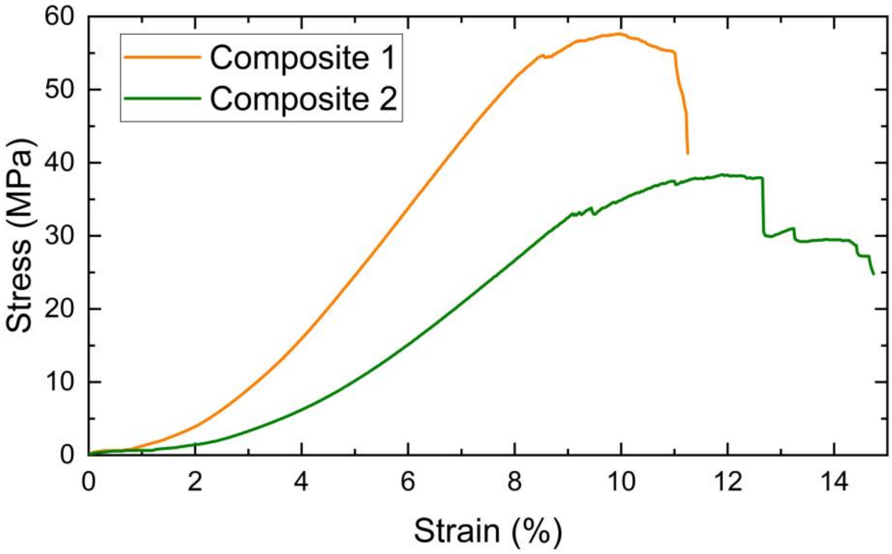

Figure 113. Stress-strain curves of Composite 1 (crochet) and 2 (knit) of the specimens with the highest ultimate tensile strength. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

In Figure 114, the results of the tested composites are shown. The crochet reinforcement (Composite 1, (32.2 ± 1.8) mm wide and (1.4 ± 0.1) mm thick) withstood a significantly higher force than the knitted one (Composite 2, (26.8 ± 0.8) mm wide and (2.4 ± 0.3) mm thick) at similar maximum elongations. For Composite 1, the calculated maximum stress (ultimate tensile strength) was also significantly higher than for Composite 2. The respective strain values differ not significantly. However, for Composite 1 the Young's modulus was with (830 ± 99) MPa significantly higher than that of Composite 2 with (386 ± 90) MPa. Thus, the crochet reinforcement resulted in a higher composite stiffness compared to the knitted reinforcement.

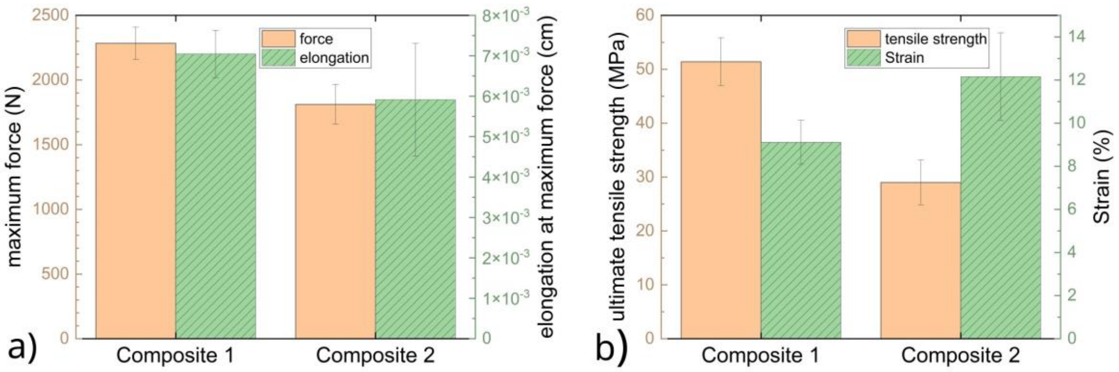

Figure 114. Mechanical properties of the crochet (Composite 1) and the knit composite (Composite 2). **a)** Measured maximum forces and elongation. **b)** Calculated ultimate tensile strength and strain of the composites. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

A possible reason for the higher tensile strength and Young's modulus of Composite 1 could be the significantly higher fiber volume fraction of Composite 1 with (31.2 ± 4.5)% in contrast to Composite 2 with (17.7 ± 2.5)% (determined by weighing and considering the densities of the materials). This is because it is known for knitted composites that a higher fiber volume fraction also tends to increase the tensile strength and Young's modulus [166]. Thus, with crocheted fabrics, a higher fiber content can be achieved with comparable dimensions of the composites, which positively affects the properties. A tendency towards higher mechanical stability under tensile load due to the crocheted reinforcements can be identified.

The fracture modes were similar for Composite 1 and 2 and occurred perpendicular to TD. Fractures initiated with matrix cracks and extended across the entire width of the composites. Such fractures perpendicular to the force direction for loading in wale and course direction are a typical phenomenon for knitted aramid/epoxy composites [169,245]. The crocheted and knitted composites differ in the wideness of the fractures. Regarding Composite 1, the parts of the specimen were generally drawn further apart than with Composite 2, as shown in Figure 115 a) and d). In Composite 2, the matrix was equally ruptured, but fewer fibers were torn. Fiber breaks can be seen in Figure 15 f) as well as b) and c). From the microscopic images, it is also recognizable that fiber bundles have separated from the matrix, which has broken into small pieces around these. Such delamination is known for fractures of aramid/epoxy composites [169].

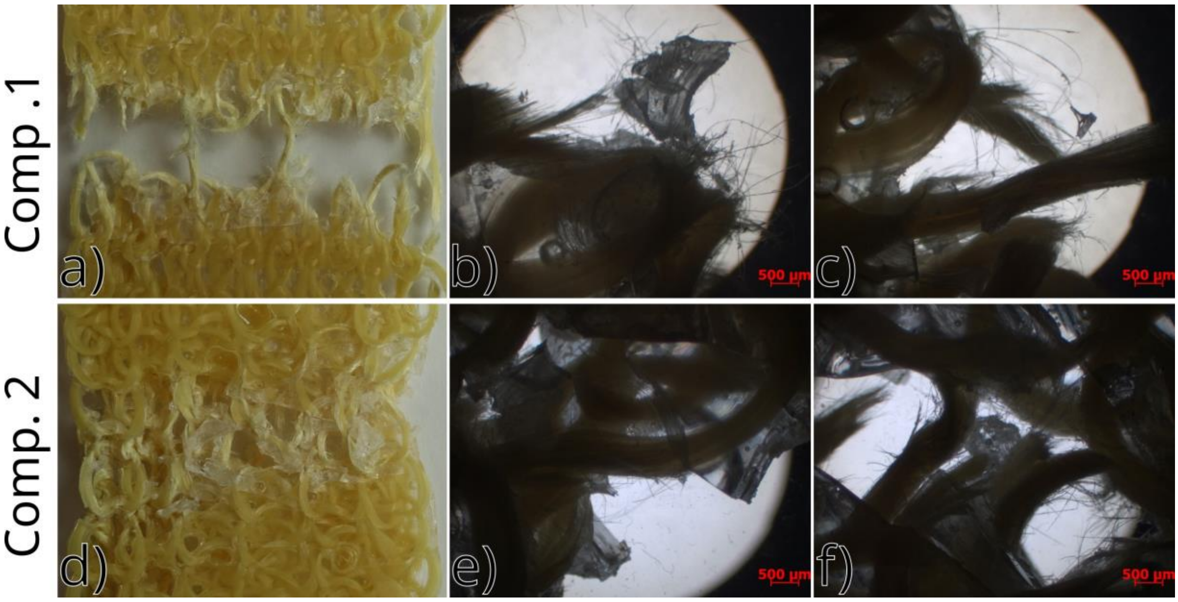

Figure 115. Exemplary composite fractures after the tensile tests. **a)** Photograph of the fracture of Composite 1. **b)** and **c)** Microscopic images of the corresponding fracture edge. **d)** Photograph of the fracture of Composite 2. **e)** and **f)** Microscopic images of the corresponding fracture edges. Figure is under a CC BY 4.0 license and taken without modification from reference A2 (Copyright © 2023, the Authors).

4.2.6 Evaluation of the results

The influence of manual production by different persons on the properties of the fabrics was identified as a significant factor. Xu et al. [90] also observed relatively large variations in the dimensions and mechanical properties of crocheted specimens for an anatomically correct testbed hand due to the manual fabrication process. The lack of reproducibility in the production prevents crocheted fabrics from being used as technical textiles. An automated and thus reproducible production with consistent quality is necessary in this regard [248,249]. Also, considering the time-consuming sample preparation (over 45 min per specimen), a machine-based production is necessary to boost productivity and to be economically feasible [248,249].

Despite the manual production, the basic tensile properties of crocheted fabrics could be sufficiently investigated for the first time. The anisotropic properties in wale and course direction of crocheted fabrics indicated by the simulative investigations from section 4.1.2 can be confirmed based on the tensile tests performed here. In this, crochets have a common characteristic with knitwear [225,246,247]. Regarding weft knitted fabrics, the wale direction is associated with higher strength and stiffer behavior [172,225,246,247]. Contrastingly, with crochets consisting of SCs or HDCs, the course direction tends towards higher maximum forces. A tendency towards higher resisted forces at longer elongations of the crochets compared to the knits was noticeable.

With the generally similar properties of crocheted and knitted fabrics, and the tendency to a stiffer tensile behavior, crochet composites may be able to overcome the known disadvantages of the relatively weak mechanical in-plane properties of knit composites [2,168]. To evaluate this more thoroughly, the out-of-plane properties of crochet composites need to be investigated in the future. The measured properties indicate a basic suitability of plain crocheted fabrics as composite reinforcements. However, the complex 3D structures that can be crocheted (by machine) are probably most promising for future technical applications with respect to near net-shaped composites (cf. section 4.5.2).

4.3 Modeling and simulation of machine-crocheted fabrics

Machine-crocheted textiles have a different structure than manually crocheted ones due to drawing loops only to one side. Similar to the manually crocheted textiles, a modeling framework for automatically crocheted ones was developed based on the CroMat crochet machine. This is to contribute to the digitalization of crochet technology in view of technical applications. Section 4.3.1, which describes this modeling, is based on the results presented in the paper *Design tool for automated crocheting of fabrics*, published in the open access journal *Communications in Development and Assembling of Textile Products* with a CC BY-NC-ND 4.0 license (cf. section 3.6) [A6].

The modeling of the crochet fabric shaping operations like INC or DEC are described in section 4.3.2. The corresponding material was published in the open access journal *Tekstilec* as a paper named *Numerical optimization of polygon tessellation for generating machine-producible crochet patterns* under a CC BY license (Copyright © 2023, the Authors) [A7]. More details about this publication are presented in Section 4.4. Finally, the models of the machine-produced and manually crocheted textiles are compared in section 4.3.3 with respect to FEM simulations.

4.3.1 Modeling machine-crocheted fabrics

The developed modeling of textiles crocheted by the CroMat is directly based on the developed modeling of the manually crocheted textiles shown in section 4.1. To match the topology and appearance of the machine-formed stitches, the unit cells of CHs, SLs and SCs were modified. New unit cell variants for HDC and a corresponding turn with two CHs were added. Furthermore, the possibility was added to line up different stitch types in arbitrary order in a course. Also, in the new Python program the data array as output of the GUI of the design tool (cf. section 3.6.2) can be used as input for the modeling of the corresponding fabric. With this, a preview based on the modeling framework can be created for the design of machine-crocheted fabrics.

According to the pitch of the CroMat's needle bed of 5.08 mm, the distance of the stitches in x-direction (*L*) are set to 5 mm. A realistic yarn diameter is approximated to be 0.6 mm. To assemble a course, unit cells of different stitches can be shifted horizontally with multiples of the same translation vector. Unit cells shifted to form a course of three stitches of each type with a crochet direction to the left are shown in Figure 116.

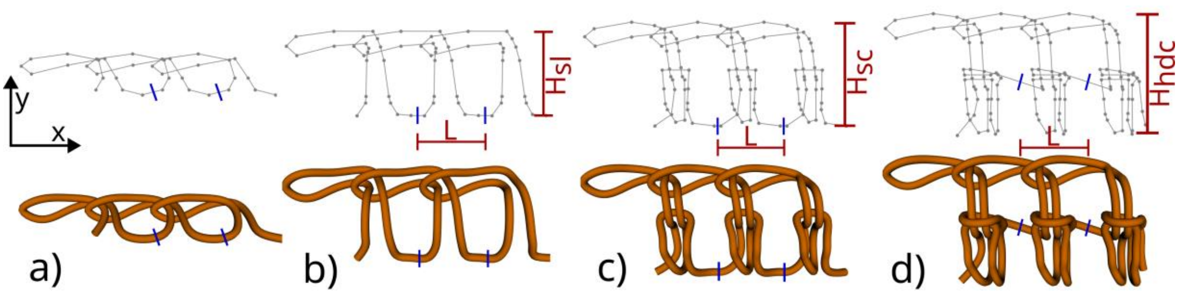

Figure 116. Unit cells of the machine-crocheted stitches as key point representation with the coordinate system (top) as well as spline-interpolated and volume-swept models displayed with the TexMind Viewer (bottom). The blue lines separate the three unit cells shown as a course in each case. The heights and widths of the stitches are indicated. **a)** CH. **b)** SL. **c)** SC. **d)** HDC. Note that the CHs are not directly in the x-y-plane, but slightly tilted to get a more realistic interlooping to the following course. Figure is under CC BY-NC-ND license and taken without modification from reference A6 (Copyright © 2023, the Authors).

If different stitch types are in a course, the height of all stitches is adjusted to the highest type in that course. This is because, on the one hand, the machine's take-off elongates the stitches evenly and, on the other hand, a uniform H is needed for a suitable connection to the next course in the modeling. The translation vector for vertical shifting and thus the spacing between courses depends on the height of the previous course. Additionally, the H depends on the yarn tension factor (YTF) according to equations 27 to 29, where H_{sl}, H_{sc} and H_{hdc} are the heights of the SLs, SCs and HDCs, respectively (cf. Figure 116). L denotes the stitch's width on which the height is based for a realistic stitch size.

$$H_{sl} = YTF \cdot 1.25 \cdot L \tag{27}$$

$$H_{sc} = YTF \cdot 1.5 \cdot L \tag{28}$$

$$H_{hdc} = YTF \cdot 1.75 \cdot L \tag{29}$$

Modeling of the maximal yarn tension is restricted by the minimal H, which ensures that all possible models are free of intersecting yarn segments. As default for the H, a YTF of 1 is used. This default is compared in Figure 117 to higher stitches representing lower yarn tensions. As can be seen, the vertical distances between the interlooping regions, which are not altered to prevent intersections, are increased for higher stitches. Intersections have a negative effect on FEM simulations and must therefore be prevented (cf. section 4.1.3 and A1). Also, the CH course's height is not influenced because it is not produced by the CroMat machine.

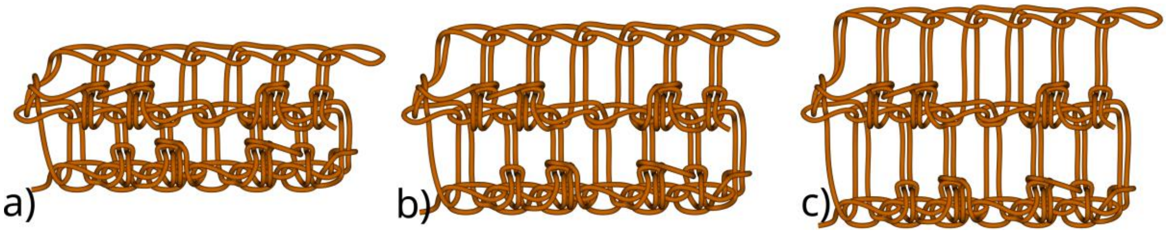

Figure 117. Comparison of different Hs to enable modeling of different yarn tensions during manufacturing. The modeled fabric consists of all available stitch types and its structure is depicted in Figure 97 in section 3.6.2. Note that the technical back is shown here. **a)** Lowest intersection free H with yarn tension factor (YTF) of 1 used as default. **b)** YTF of 1.25. **c)** YTF of 1.5. Figure is under CC BY-NC-ND license taken without modification from reference A6 (Copyright © 2023, the Authors).

Similar to single jersey weft knitting machines and plain fabrics [107], machine-crocheted fabrics have a technical face and a technical back. This is because, in stitch formation, yarn is always drawn from the back to the front creating face loops. The structural difference to manually crocheted fabrics, where face loops are created on both sides by turning the textile after each course, is illustrated in Figure 118. By considering the SCs in the fabric's centers, the two sides of the machine-crocheted fabric (a) and b)) can be clearly distinguished, while in the manually crocheted one (d) and e)) they cannot be differentiated based on the SCs.

In the side view of the manually crocheted fabric (Figure 118 f)), the alternating side, from which the loops are drawn to form the stitches, can be easily observed in the SLs (courses 2, 3 and 7), which are aligned almost perpendicular to the previous course. In the machine-crocheted fabric, the SLs are more stretched (cf. c)) due to the fabric take-off. Furthermore, regarding machine-crochet, the loops of the SCs in the second course are drawn through the first course of CHs differently than in manual crochet, which can be seen in the different shapes of the lowest courses of a) and d). These differences have to be considered in the design of automatically crocheted fabrics. The modeling of such fabrics is used throughout the whole work to illustrate various crochet structures.

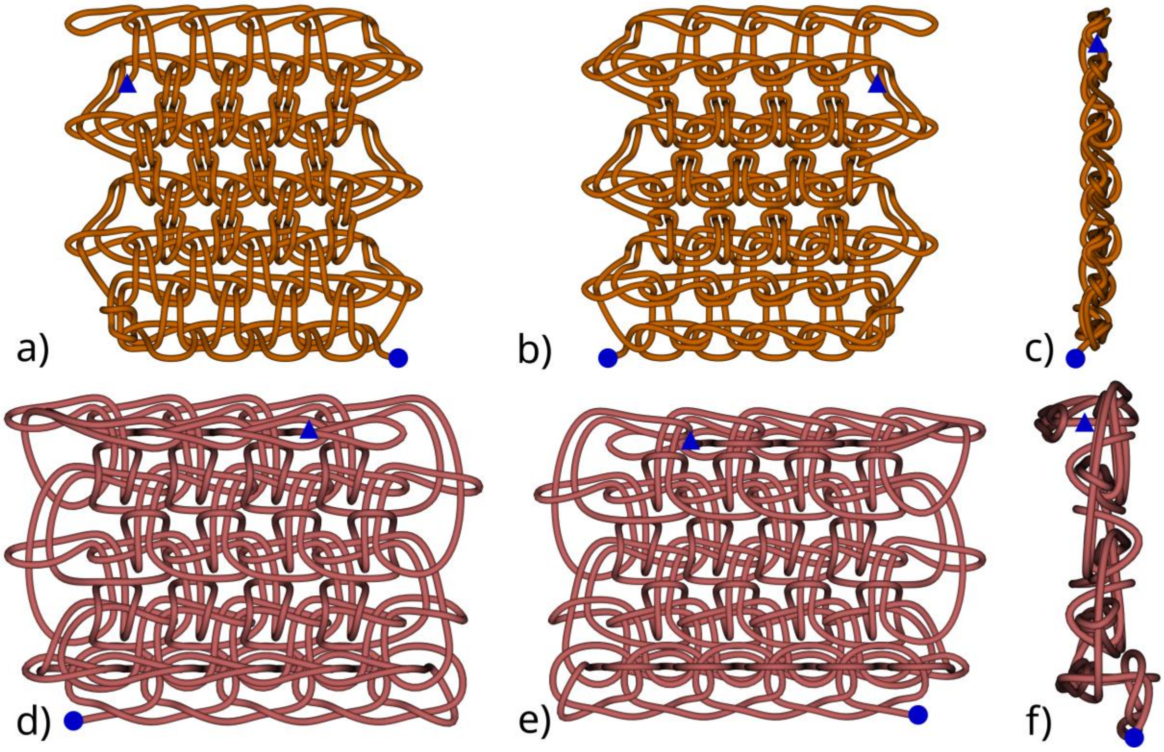

Figure 118. Comparison of the modeled structure of automatically (top) and manually (bottom) crocheted fabrics. The stitch structure of the fabric is depicted in Figure 98 in section 3.6.2. The starting point of the yarn path is indicated by a blue circle and the end point by a blue triangle. **a)** The technical face of the modeled machine-crocheted fabric. **b)** The technical back of it. **c)** Side view of the model. **d)** One side of the modeled manually crocheted fabric. **e)** The other side. **f)** Side view. Figure is under CC BY-NC-ND license taken without modification from reference A6 (Copyright © 2023, the Authors).

4.3.2 Modeling of INC and DEC

Details on the formation of INC and DEC are described in sections 3.3.7 and 3.3.8. Regarding the modeling it is relevant that one INC or one DEC consists of two elements or unit cells each. This is because, in contrast to normal stitches, these operations involve two ANPs and thus two stitch positions. A stitch position corresponds to an entry, defined by course and wale number, in the data array, which is used as output of the design tool and as input of the modeling. A wale number corresponds to a specific ANP. Figure 119 represents such an array and shows how INC and DEC are divided into a and b.

```
[['sc_dec_b', 'sc_dec_a', 'sl',       'hdc',  'sc',       't1',       'void'],       5
 ['t1',       'sl_inc_a', 'sl_inc_b', 'sl',   'sl',       'sl_dec_a', 'sl_dec_b'],   4
 ['void',     'sc',       'sc',       'sc',   'sc_inc_b', 'sc_inc_a', 't1'],         3
 ['void',     'flo',      'hdc',      'hdc',  'hdc',      'hdc',      'void'],       2
 ['void',     'void',     'ch',       'ch',   'ch',       'ch',       'void']]       1
Wale number 1        2           3           4       5           6           7    Course number
```

Figure 119. Data structure of an exemplary crocheted fabric with INC and DEC. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

As can be seen in Figure 119, the change in the width of the fabric results in "void" entries in the data array, which indicate that no stitch is set at the respective stitch position. The crochet structure resulting from this data array is shown by a crochet chart in Figure

120. The slanted orientations of the slightly modified symbols for INC and DEC illustrate the stitch connections [16,17]. These are additionally clarified by the small red arrows, while the normal stitch connections are indicated by blue arrows. A crochet stitch is connected to the element in the course beneath as well as to the previous element from the same course, which results from drawing loops during the stitch formation through two already existing stitches.

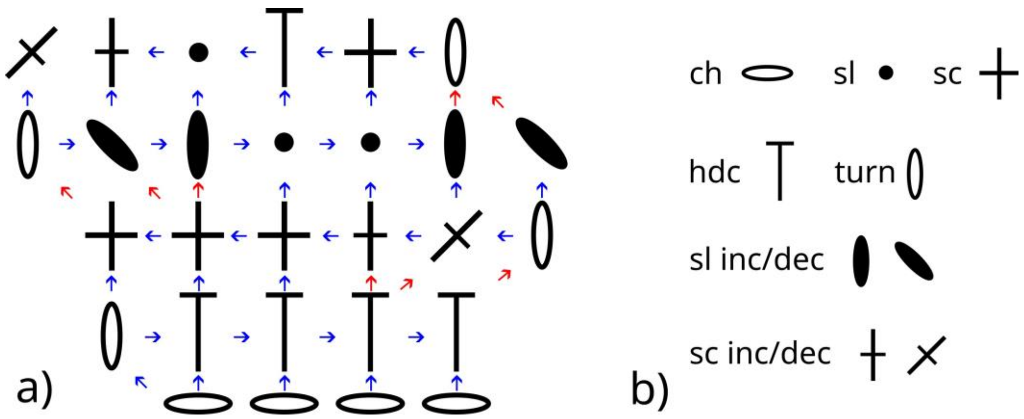

Figure 120. Symbolical representation of the crochet pattern shown in Figure 119. **a)** Crochet chart. **b)** Description of some symbols. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Next, the topology-based modeling of the respective crochet structure is shown in Figure 121. As can be seen, INC and DEC are also adjusted in height to the highest stitch in the course. As is evident from the illustrations regarding the other methods for changing the width of a textile in section 3.3.9, these can also be represented using the developed modeling. Beyond the modeling, the automatic generation of the G-code (cf. section 3.6.5) was also supplemented by these operations for changing the fabric's width. In the frameworks for modeling and generating the fabric's G-code, almost all crochet structures currently producible with the CroMat prototype are considered. In the future, the frameworks can be extended by adding further key point unit cells and G-code macros.

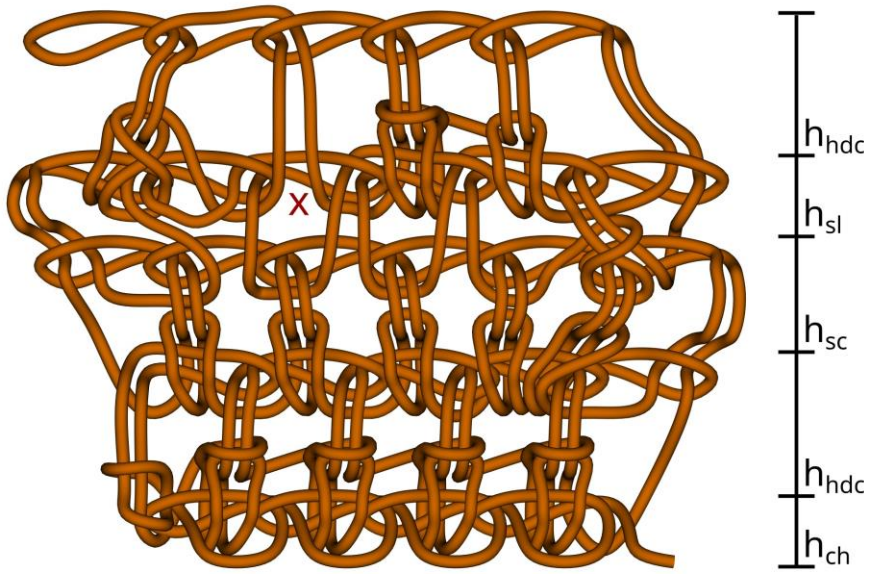

Figure 121. Model of the exemplary crocheted fabric (cf. Figures 119 and 120). The red "x" marks one possible crochet needle insertion point for drawing yarn through the working stitch. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

4.3.3 Simulative comparison of hand- and machine-crocheted fabrics

To compare machine-crocheted fabrics with manually crocheted ones, the FEM simulation described in section 4.1.3 was repeated with the model of the machine-crocheted fabric. In addition to the same fabric composition and similar meshing with 1 mm long beam elements, the identical material properties and boundary conditions were assigned in LS-PrePost (details in reference A1). Again, the explicit LS-DYNA solver was used.

The results of the displacement simulation in wale direction are shown in Figure 122 as a comparison between the models for machine and manually crocheted fabrics. It should be noted that the upper SL course of the manually crocheted fabric is positioned at a right angle to the fabric, while the machine-crocheted one is aligned in the fabric's plane. Also, the starting point of the yarn path is for the machine-crochet model at the bottom right corner while it is for the hand-crochet one at the bottom left corner.

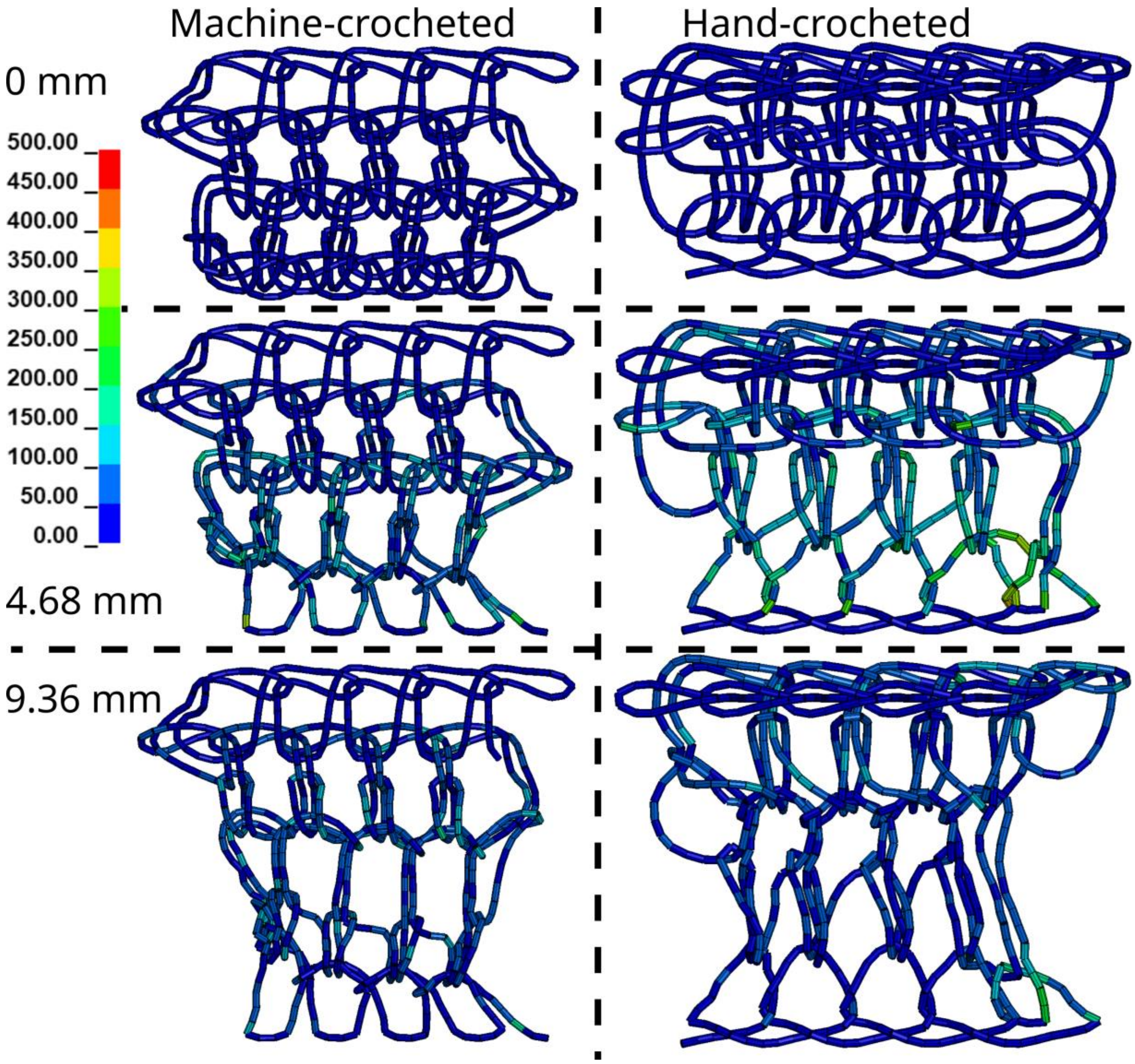

Figure 122. FEM simulation of displacement in wale direction comparing the modeled machine-crocheted fabric with the manually crocheted one. Both have the same structure with a CH course at the bottom, followed by two SC courses and a SL course on top. Yarn diameter is set to 0.5 mm and (*L*) to 5 mm. The displacements of the downward moving bottom nodes of the CH course are indicated at the left. By the fringe plot the von Mises stresses are indicated, the unit of the scale is Pa.

Generally, the deformation and the rapidly and evenly distribution of stresses in the fabric is similar for both variants (cf. Figure 122). In the beginning, the forces are higher at individual elements in the bottom parts of the fabrics, and then spread throughout the fabrics as the simulations progress, decreasing at individual elements. The much narrower CH of the first transition of the CH course to the SC course of the machine-crochet model deforms differently, as can be seen at 4.68 mm and 9.36 mm displacement. However, this is due to the alternative modeling rather than a structural difference. Also, the lower loops of the SCs of the machine-crochet model are tightened more during displacement than those of the hand-crochet one. Another difference, probably related to the differently set key point positions, is the transition between the two SC courses, which is clearly more pronounced in the hand-crochet model, even at a larger displacement.

Furthermore, the models of machine-crocheted fabrics and manually crocheted ones are compared by simulation regarding displacement in course direction. For this, the experiment shown in Figure 105 (from section 4.1.2) was recreated with the alternative model of the machine-crocheted textile. Due to the differently defined orientation of the first CH course, nodes at the left side of the machine-crochet model are virtually drawn to the left while nodes at the right side of the hand-crochet model are displaced to the right. Again, the resulting von Mises stresses of the beam elements are displayed as fringe plots at certain displacements in Figure 123.

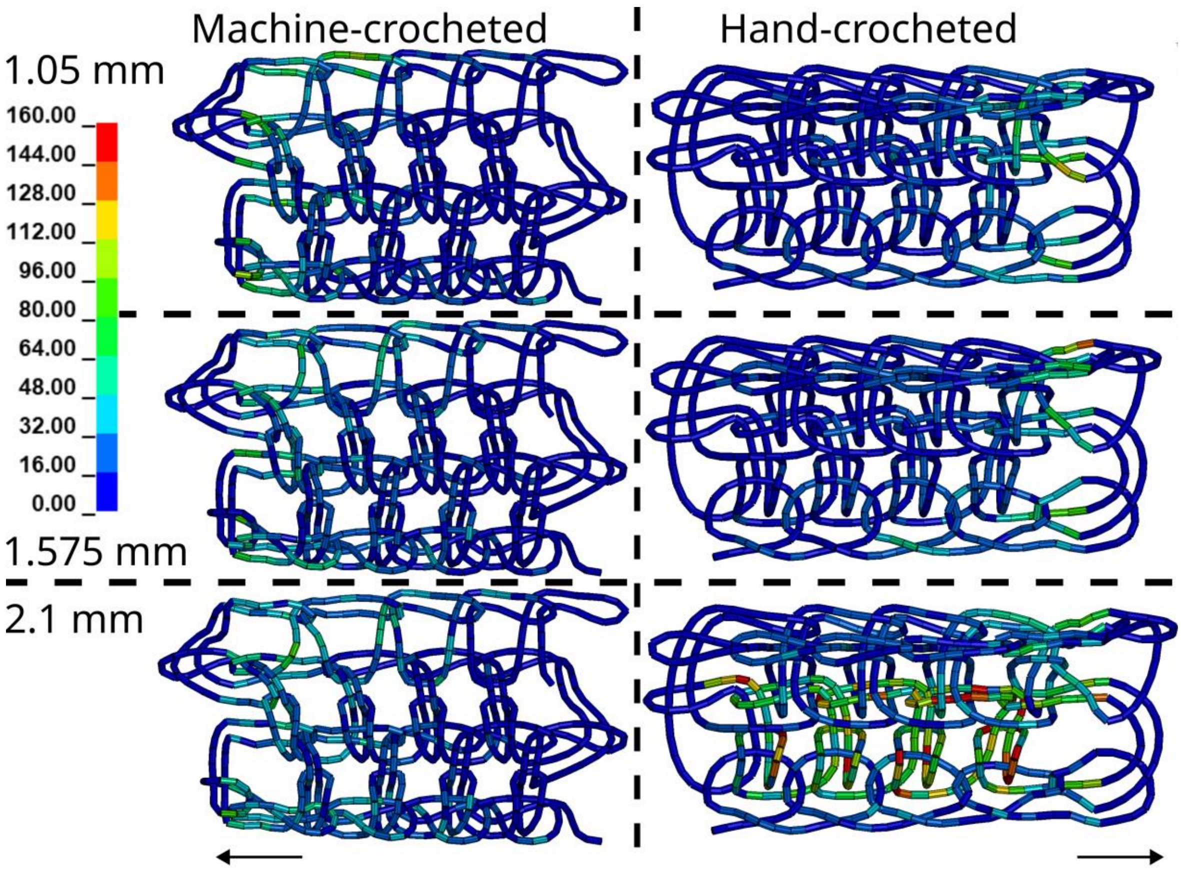

Figure 123. Comparison of the machine-crochet model and hand-crochet model by an explicitly solved FEM simulation of the displacement in course direction. The displacements of the moved nodes (at the left side for machine-crochet and at the right side for hand-crochet) is indicated to label the shown frames. Fringe plots denote the von Mises stresses of the beams referring to the scale at the left with the unit Pa.

As can be seen from Figure 123, the stress spreads comparatively fast in both models, although it is distributed slightly more evenly in the model of the machine-crocheted textile. This can be seen in particular at a displacement of 2.1 mm, where in the model of the manually crocheted textile the lower SC course is clearly more stressed than the others. Whether this difference is due to the slightly different structure of the machine-crocheted fabric compared to the manually crocheted one cannot be confirmed based on the simulations performed. Further investigations are necessary in the future.

However, the comparison shows a generally very similar behavior for tension in course and in wale direction despite the slightly different structure of the machine and manual crochet. The finding of anisotropy of the manually crocheted fabric can also be confirmed for the machine-crocheted fabric. This is because the stress in course direction spreads here faster, too. The overall lower stresses in course direction compared to wale can be explained by the lower displacement.

It was demonstrated that the models from the developed frameworks can be used as a basis for mechanical investigations with FEM simulations. The presented simulations are suitable for a rapid initial comparison of the stresses on the machine-crocheted and manually crocheted fabrics during tension but cannot provide any deeper insights at the present stage. The reason for this is the complicated structure of the fabrics, the frequent intrinsic contact of different segments of the same yarn, and the inaccuracies of the simple beam elements used. In the future, the models for FEM can be refined, and the simulation can be improved to obtain more valuable results.

4.4 Generating machine producible crochet patterns in shapes of 2D polygons

In this section, an approach that continues the automation of crochet in terms of the design of crochet structures is presented. The crochet structures of machine-producible flat crocheted fabrics are generated automatically according to the shapes of 2D polygons given as input. This extension of the CroMat design tool (cf. section 3.6) was published with the name *Numerical optimization of polygon tessellation for generating machine-producible crochet patterns* in the open access journal *Tekstilec* under a CC BY license (Copyright © 2023, the Authors) [A7].

The shaping is predominantly based on INC and DEC as the fundamental shaping methods in crocheting to change the number of stitches in one course (fabric row) with regard to flat crocheting or in one round regarding circular crocheting [14-17]. The approach is based on the CroMat prototype and thus the crochetability with this machine of the generated crochet patterns is ensured. It is intended, that this method can be used in the future in an industrial context for the rapid design of crocheted textiles without requiring knowledge of crochet.

This chapter is structured as follows. Section 4.4.1 provides a brief introduction. The developed algorithm for the subdivision of 2D polygons is described in section 4.4.2, while the numerical optimization of its quality is discussed in section 4.4.3. Section 4.4.4 shows the application of the method to exemplary polygons. Finally, the results and the algorithm are discussed in section 4.4.5.

4.4.1 Background

Regarding the control of the versatile V-bed knitting machines, there is a trend in research towards high-level programming with shape primitives or 3D objects and automated transfer to knitting patterns [250,251] as well as translation to machine commands for production [93,94,113,252]. For manually crocheted textiles, similar tools have been presented for automated generation of textual crochet instructions based on 2D sketches, which are transferred into 3D shape primitives [20], or based on 3D objects [19,92]. These breakdowns of geometries into individual stitches in a crochetable sequence refer to the technology of circular crocheting based on a magic ring, which can be used to create 3D structures.

In addition, there are some dedicated software tools for the design of manually crocheted textiles. These are based on the graphical arrangement of crochet symbols in charts to store the patterns and with these no automatic generation of instructions for production is provided [16,17]. Further information on the existing tools for designing manually crocheted fabrics is given in sections 2.1.4 and 3.6.1.

Here, in contrast to these fabric design approaches and in the context of high-level programming, the shapes of 2D geometries are transferred to machine-producible flat crochet patterns based on a chain line. From the output crochet patterns, the machine instructions for crocheting with the CroMat can be automatically generated. The focus on the producibility by the CroMat crochet machine distinguishes the here presented design approach from related ones concerning manual crocheting. Also, the structure of flat crocheted textiles is different compared to circular crocheted textiles, especially in terms of stitch sequence, so that it is necessary to develop new logic for dividing the geometry into stitches. Thus, an algorithm for subdividing the 2D polygon according to the rules and restrictions of machine-crocheting with the CroMat is proposed and the possibilities of shaping the fabric are discussed by considering the automatically generated crochet models.

4.4.2 Developed polygon subdivision algorithm

Fundamentally, the breakdown of a 2D polygon into a crochet pattern is a tessellation problem, since the polygon can be seen as a space which is to be partitioned into smaller stitch cells as well as not covered areas [253]. To ensure the machine manufacturability, the pattern generation must follow the constraints of the automated crochet process. Due to the various rules to be considered, no well-known area tessellation algorithms, like for example centroidal Voronoi tessellation [254], can be applied. Therefore, a new algorithm is developed that traverses a 2D polygon according to the CroMat's crochet process and decides stitch by stitch whether it may be set according to the rules.

As a simplification, stitches are represented by rectangles with the width as *L* and with the height corresponding to *H*. The stitch dimensions refer to the values used for modeling (cf. section 4.3). These rectangles for modeled SLs and SCs are shown in Figure 124. It should be noted that the stitches overlap with the surrounding ones to a large extent, while the stitch rectangles are defined without these overlaps for simplicity. It is also noteworthy, that courses are positioned staggered to each other which is due to the fashion of the wale-wise connections of crocheted fabrics. This renders the structure of crocheted textiles different from the regular wales of knitted fabrics.

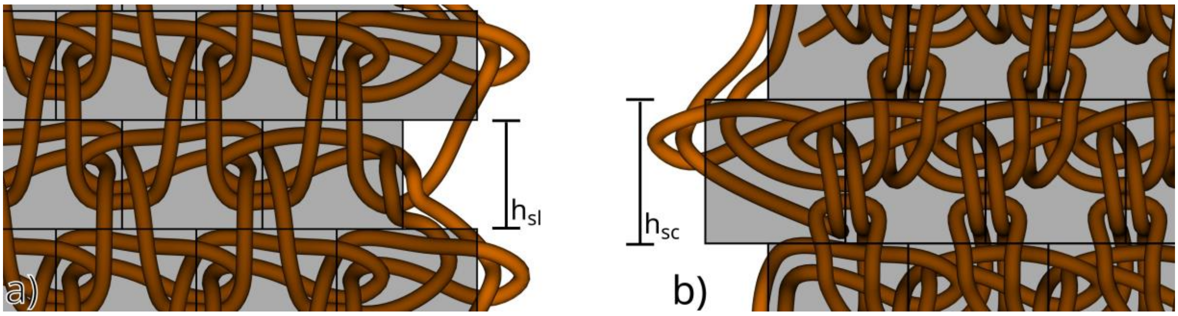

Figure 124. Examples of the arrangement of the stitch polygons with indicated *L* and stitch height (*H*). **a)** Part of rectangular fabric consisting of SLs. **b)** Respective SC fabric. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

According to the taxonomy of Lee et al. [253], such partitioning by polygons representing stitches refers to vector or feature-primary tessellation where the boundaries of features are described as polylines. In this regard, the shaping polygon is firstly divided into a course as a feature and then this sub polygon is further partitioned by the stitch rectangles. Afterwards the next course is partitioned. Stitches are placed in the polygon according to the sequence of crocheting, gradually filling the two-dimensional array with information on the resulting crochet pattern. The basic structure of the developed tessellation algorithm is illustrated with the main steps in Figure 125.

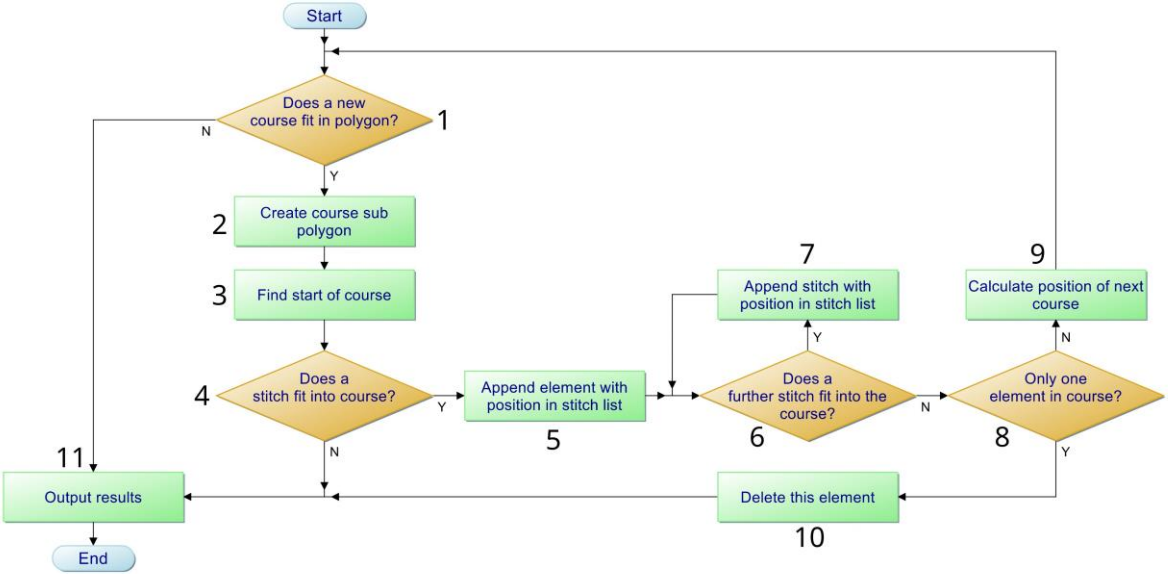

Figure 125. Flow chart of the crochet tessellation algorithm based on a convex input polygon. Y and N abbreviate yes and no. Created with the freeware PapDesigner from Friedrich Folkmann [255]. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

As depicted in Figure 125, the algorithm terminates and outputs the results, if no further course fits into the polygon, or no element can be inserted at the beginning of the course, or only one element was inserted in a course (which is then removed). A course with only one element, namely a turn, is not valid, because the turn aligns next to the last stitch of the previous course.

The stitch type and its width (default 5 mm) as well as a convex polygon with an arbitrary size and degree must be defined by the user. One polygon edge must be in line with the x-axis of a Cartesian coordinate system. It can also be decided whether the stitch rectangles are allowed to exceed the polygon within certain limits, per default 30% of the stitch area, or without this tolerance the polygon limits may not be exceeded.

Example subdivision

In Figure 126, the principle of the crochet tessellation is illustrated without tolerance (a) to c)) and with tolerance (d) to f)) for exceeding the polygon's boundaries. A stitch is indicated by two green vertical segments each consisting of two points, which are considered for deciding the stitch placement.

According to the flow chart's first step (cf. Figure 125), it is checked whether the corresponding sub polygon with a height of CHs fits into the shaping polygon. Then, the sub polygon is calculated (step 2) as well as the start of the course (step 3), which is the position of the outermost segment of the first stitch. This starting point, which can be shifted later to get better results (cf. section 4.4.3), is at the right end of the sub polygon (first course goes to the left). Stitches are then inserted in the sub polygon according to steps 6 and 7 (cf. Figure 125) until their segments would exceed the polygon boundaries or do no longer fulfill the tolerance condition.

At the end of the CH course, due to the machine's peculiarity, an exception occurs and the CH before the following special turn is removed. This is because the last CH is used as the FLO with which the machine production starts. The removed segment is indicated in Figure 126 b) by the dashed line in the area marked u_2.

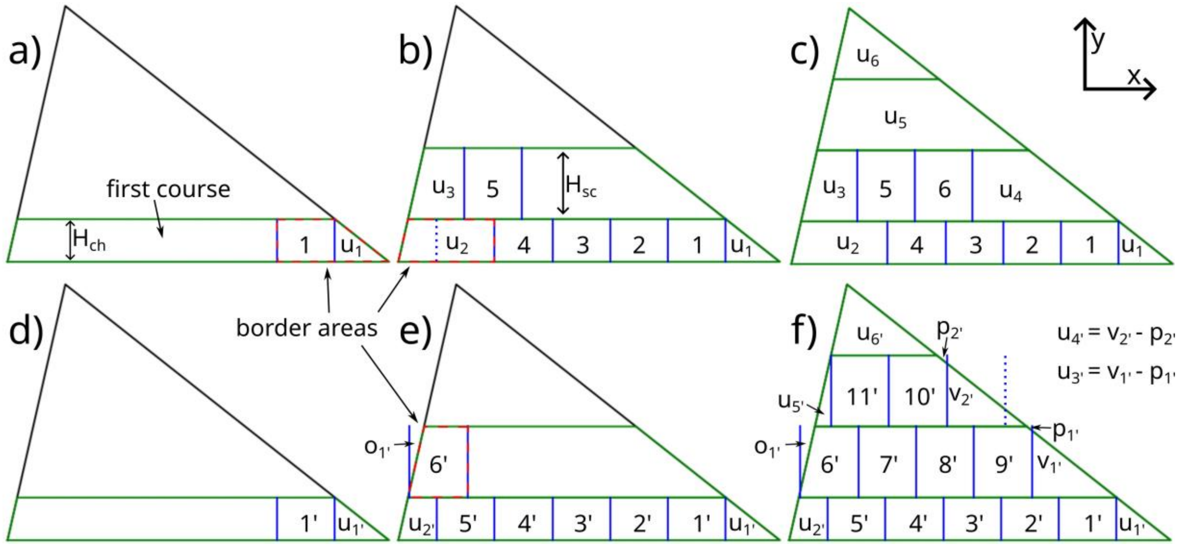

Figure 126. Crochet subdivision of a triangle without allowing the stitches to exceed the shaping polygon and with allowed crossing as long as 70% of a stitch area is inside the polygon. **a)** Placing the first CH in the first course. **b)** Start of second course. **c)** Result of the crochet subdivision without tolerance. **d)** Initial situation of the subdivision with permitted crossing of the borders by the stitches. **e)** Start of the second course. **f)** Result of the respective crochet subdivision. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Following the steps 8 and 9 of the flow chart (Figure 125), the next course is calculated with considering *H* and steps 1 to 4 are computed. As can be seen in Figure 126 b), the first element of the second course (5), being the FLO, is placed according to the alternating crochet direction and staggered stitch pattern. With the overlapping tolerance, four elements can be fitted in the second course as shown in Figure 126 f) instead of the two elements depicted in Figure 126 c).

In the third course of the partitioning without considered tolerance (Figure 126 c)), no element is placed. This is because the pattern and the polygon shape allow only placing one stitch, which is then removed due to the check of step 8 and step 10 of the flow chart (Figure 126).

Regarding the partitioning with considered tolerance, the program's termination also results from deleting a single element, which is here in the fourth course. Previously, the third course was filled with the turn 10' and the stitch 11'. To illustrate the logic about the decision of the x-position of the turn's first segment, an alternative position is indicated by the dashed line (near area $v_{2'}$).

Generally, only discrete stitch positions corresponding to the offset of the stitches from different courses (cf. Figure 124) are possible. For example, the dashed segment (near area $v_{2'}$) is an option but was considered unsuitable because the respective stitch would exceed the polygon boundaries by more than 30%.

For each turn, the algorithm checks first whether it is possible to add a stitch before it checks the possibilities to not change the number of stitches or to remove a stitch in the beginning of the course with RSTB (cf. section 3.3.9). If RSTB is not sufficient to fit the polygon's shape, a stitch is dropped at the end of the previous course to allow for placing the turn suitably.

4.4.3 Improving the subdivision's quality

Assessing the subdivision's quality

To assess the quality of the crochet subdivision, the resulting areas are considered. Only uncovered areas (u_i) are present in case of subdivision without crossing the polygon borders (cf. Figure 126 a) to c) in section 4.4.2). In the case of allowing the polygon boundaries to be exceeded, equations 30 are used to calculate the uncovered (u_i) and overlapping (o_j) areas based on the difference between the border area (BA) and the stitch area (SA). A BA refers to the area at the beginning or end of a course including the first or last stitch (cf. the red dashed lines in Figure 126 in section 4.4.2). In this regard, p_j is the area of a stitch extending the polygon while v_i is the part of the stitch inside the polygon (cf. Figure 126 f) in section 4.4.2).

$$u_i = v_i - p_i \; and \; o_j = 0 \quad if \; BA - SA > 0$$
$$u_i = 0 \; and \; o_j = p_j - v_j \quad if \; BA - SA < 0 \qquad (30)$$

If no stitches are set in a course, the resulting areas are also counted as uncovered areas u_i (cf. Figure 126 c) and f) in section 4.4.2). The absolute values of the areas u_i and o_j are added to a total area-error value (Z, see equation 31). The lower this value is, the better the shaping polygon was filled with crochet stitches, thus better mimicking the shape.

In the case of not exceeding the polygon's boundaries (cf. Figure 126 c) in section 4.4.2), the uncovered area is in total 173.61 mm^2. In relation to the area of the shaping polygon, the subdivision error is 58.45%, which means that most of the area was not covered. Contrastingly, the error with the considered tolerance (cf. Figure 126 f) in section 4.4.2) is only 30.00%, with 74.72 mm^2 non-covered area and 14.38 mm^2 overlapping the shaping polygon. That this approach yielded a better result, can also derived by comparing the models generated crochet patterns depicted in Figure 127.

a) ['void', 'void', 'void', 'void', 'void']
['flo', 'sc_dec_a', 'sc_dec_b', 'void', 'void']
['void', 'ch', 'ch', 'ch', 'ch']

b) ['sc_dec_b', 'sc_dec_a', 't1', 'void', 'void', 'void']
['flo', 'sc', 'sc', 'sc_dec_a', 'sc_dec_b', 'void']
['void', 'ch', 'ch', 'ch', 'ch', 'ch']

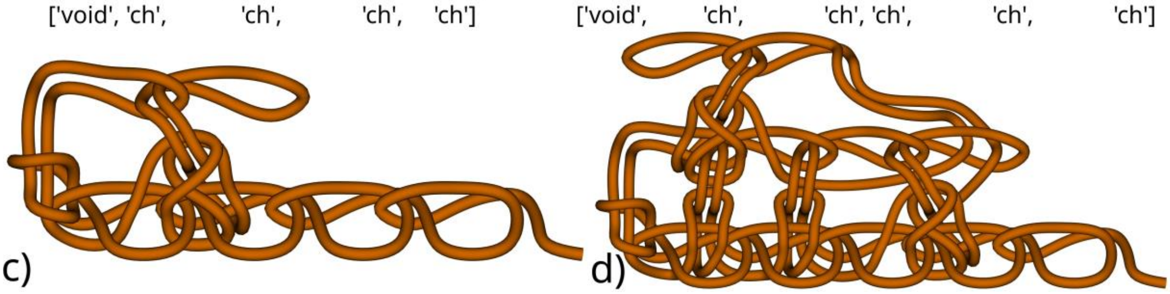

Figure 127. Resulting data arrays and crochet models. **a)** Output stitch array for the first partitioning approach without tolerance for stitches crossing the shaping polygon's border. **b)** Array of the second partitioning approach with considered tolerance. **c)** Computer-generated model of the first approach. **d)** Model of the second approach. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Regarding the crochet pattern of Figure 127 b), it is to note how two stitch positions are removed in the second course by combining DEC and removing a stitch in the end of a course with RSTE (cf. section 3.3.9). Generally, DEC is used for removing the first stitch at the end of a course, while potential further stitches are then removed with RSTE. At the beginning of the third course, the number of stitches is additionally reduced by one via RSTB. In the following, due to better results, only the subdivision with tolerance for crossing the polygon boundaries with the stitches will be considered.

Optimizing the subdivision

Fundamentally, the stitch pattern and the respective area-error result deterministically from the starting point, as the first point on the right segment of the first stitch set in the polygon. This first stitch is placed per default as far as possible to the right side of the first course without crossing the polygon borders. To improve the coverage of all possible polygon shapes, the subdivision can be optimized depending on the first stitch position.

The changing of the crochet pattern along the respective uncovered and overlapping areas depending on shifting the starting point in x-direction is illustrated in Figure 128. A section of the triangle from Figure 126 in section 4.4.2 is considered and the specific calculation of u_i (uncovered) and o_j (overlapping) depending on the *BA* according to equations (30) is demonstrated.

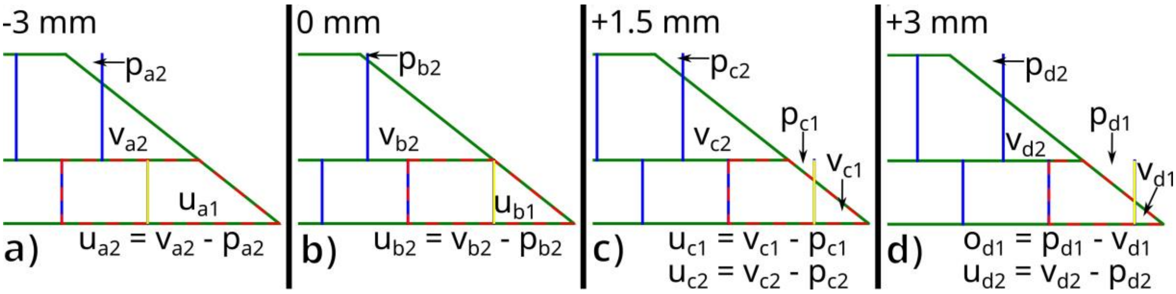

Figure 128. Effect of starting point shift in x-direction on the pattern and areas. The border area (*BA*) is marked with the red dashed line. The shifted right segment of the first stitch is displayed as a yellow line. **a)** First stitch shifted by −3 mm. **b)** Initial starting point. **c)** Starting point shift of 1.5 mm. **d)** x-shift of 3 mm. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

In principle, the problem of finding an optimal subdivision of a 2D polygon by stitch rectangles corresponds to the common initial situation of a bi-dimensional cutting stock problem or packing problem, where a set of smaller objects is placed on a set of larger objects under certain conditions [256,257]. Similar to minimizing waste, the uncovered and overlapping areas are to be minimized for an optimal subdivision.

The function *Z* is introduced to describe the total area-error (uncovered and overlapping) depending on the starting point shifts in x- and y-direction (equation 31). With equations 32 and 33, the boundaries of the x-shift and y-shift, as design variables, are defined with *L* as the stitch length and *H* as the height, respectively. A further shift than by one stitch width or height in positive or negative direction does not make sense, because the stitch pattern would be repeated with a greater error (cf. Figure 129 in section 4.4.4).

$$Z = f(x_{shift}, y_{shift}) = \sum_{i=1}^{m} u_i + \sum_{j=1}^{n} o_j \quad 31$$

$$-L \leq x_{shift} \leq L \quad 32$$

$$-H \leq y_{shift} \leq \mathrm{H} \quad 33$$

An analytical description of the functional relationship between the displacement of the starting point and the resulting area-error would exceed the scope of this work, because of the complexity of following the machine’s rules while subdividing countless possible polygon shapes. For this reason, common optimization algorithms known for example from cutting stock problems [258] cannot be applied here. Instead, a numerical approach is followed, where many data points are sampled and the best one is selected. Also, this is less computationally costly and error prone than approximating function Z for computing its minimum to find the optimal starting point.

The sampled data points consist of the starting point shifts in x- and y-direction with the associated area-error values. For the respective subdivisions, the step size and the number of steps for a shift are set by the user. The default value of the step size in x-direction is the L divided by the number of steps, while it is the H divided by the number of steps for the y-direction.

Regarding the algorithm's implementation, Python 3 and the SymPy library [259] are used for the geometric calculations. Also, the library NumPy [260] is utilized for handling the data. Additionally, the open-source Python library pytexlib [261] is applied for describing and saving the modeled textiles. Results are plotted with the Matplotlib library [262]. Parallel computing of the tessellation runs is implemented to speed up the algorithm via multiprocessing. The patterns are visualized by the developed modeling (cf. section 4.3).

4.4.4 Crochet subdivision results for exemplary polygons

First, the starting point of the triangle subdivision with SCs of Figure 126 in section 4.4.2 is shifted in negative and positive x-direction by 10 steps each with a step size of one tenth of the stitch width (L). The step size in y-direction was set to one tenth of the H. To avoid repetition of the crochet pattern and to save computation time, only the y-shifts smaller than the height of the CHs of the first course were performed. Therefore, fewer subdivision runs are calculated with respect to the y-direction. Generally, a crochet pattern repetition due to y-shifts would inevitably have a larger area-error, due to the missing coverage or overlap of the entire CH course.

Regarding the displacement in x-direction, a repetition of the crochet pattern can be observed with a starting point shift of one stitch width (5 mm). As shown in Figure 129, the repetitions (−2.5 mm and 2.5 mm, or 0 mm and 5 mm) differ in the first stitch being set at the polygons bottom right corner and therefore have deviating area-error values.

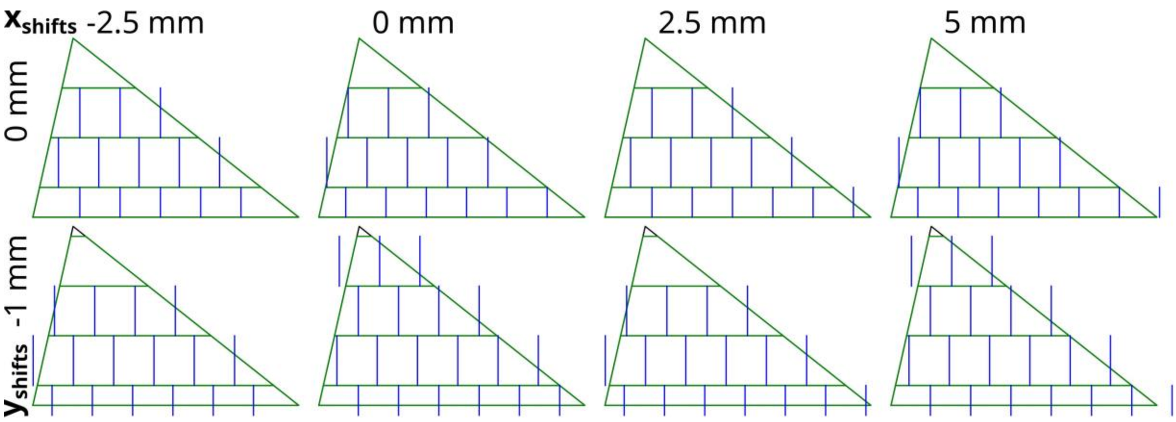

Figure 129. Crochet patterns resulting from exemplary starting point shifts, which were calculated during the numerical optimization of the triangle's crochet subdivision. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

In terms of the y-shift of −1 mm shown in Figure 129, the entire first course extends beyond the polygon, which significantly increases the o_j part of the area-error. However, such a shift can lead to another course being filled in the upper part of the polygon, which can be advantageous depending on the polygon's shape.

For visualizing the results of all performed crochet subdivisions for the numerical optimization of the triangle, the total area errors Z depending on the starting point shifts, are color coded and plotted in Figure 130. As can be seen, a shift in positive or negative y-direction influences the error values stronger than a shift in x-direction. This is because shifting in y-direction affects an error area in the width of the first or last course, while an x-shift only changes the area coverage of the courses' first and last stitches. It can also be seen that the areas around an x-shift by one stitch width are similar but not identical, because the area coverage differs by one stitch as illustrated in Figure 129.

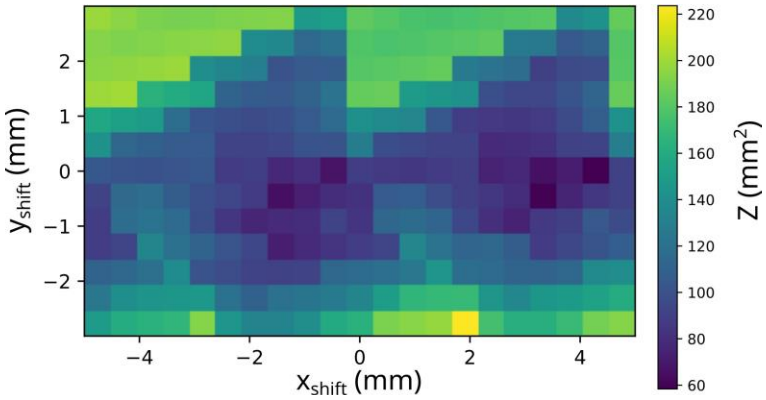

Figure 130. Area-error values depending on the starting point shifts of the triangle polygon of Figure 126 (in section 4.4.2) and 129 with color scale. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

The sufficiently optimal crochet subdivision with an area-error value of 19.65% was found with a displacement of the starting point by 4.5 mm in x-direction. Generally, smaller error values are at zero y-shift. By comparing Figures 131 and 127 (in section 4.4.3), it becomes clear that a better tessellation solution and crochet pattern was found due to the optimization.

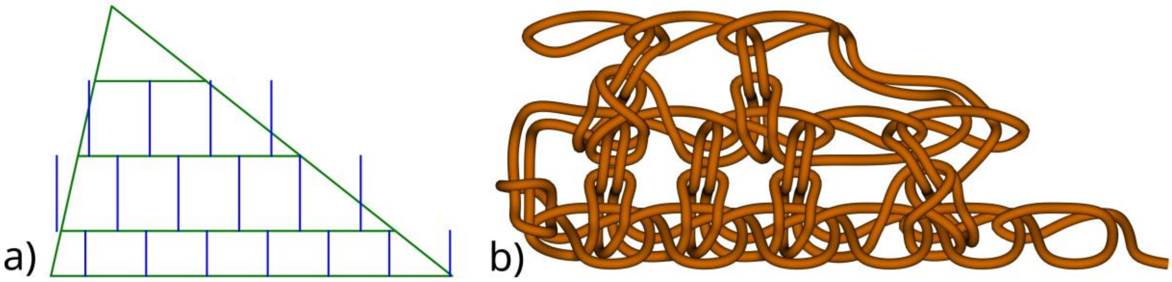

Figure 131. Result of the optimized crochet tessellation. **a)** Corresponding crochet subdivision. **b)** Respective model. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Scaled triangle and comparing subdivision with SCs and SLs

Next, the stitch types of SL and SC are compared regarding a crochet subdivision of a scaled variant of the triangle. The same starting point shifts were executed. Theoretically, more stitches can be placed in a larger polygon, which facilitates a better replication of the shape with the crocheted fabric. Accordingly, Figure 132 shows that the area-error values of the initial and optimized starting point are lower and that the shape is better reproduced compared to Figure 131. The lower *H* of the SLs allows for a subdivision with more stitches. However, the best SC subdivision resulted in a smaller area-error than the best SL subdivision. The shape replications are similar.

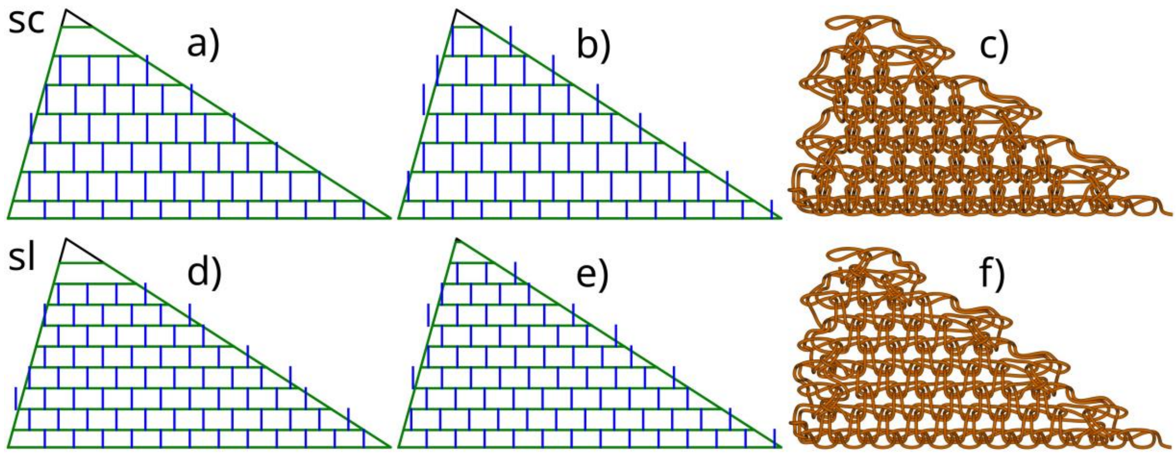

Figure 132. Comparison of crochet subdivision with SC and SL. **a)** Initial subdivision with SCs and no shifting (area-error value 18.88%). **b)** SC subdivision result with minimal area-error value of 5.64% and starting point shifted by 3 mm in x-direction. **c)** Corresponding model. **d)** Initial subdivision with SL and no shifting (area-error value 13.85%). **e)** SL subdivision with minimal area-error value of 9.12% and starting point shifted by 3.5 mm in x-direction. **f)** Corresponding model. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

For both SL and SC, the optimal tessellations show only a shift of the starting point in the x-direction. Accordingly, the area-error values shown in Figure 133 are similar to those of Figure 130 and indicate a larger influence of the error values by shifting in the y-direction. For the subsequent subdivisions, the more common SC stitch type is used.

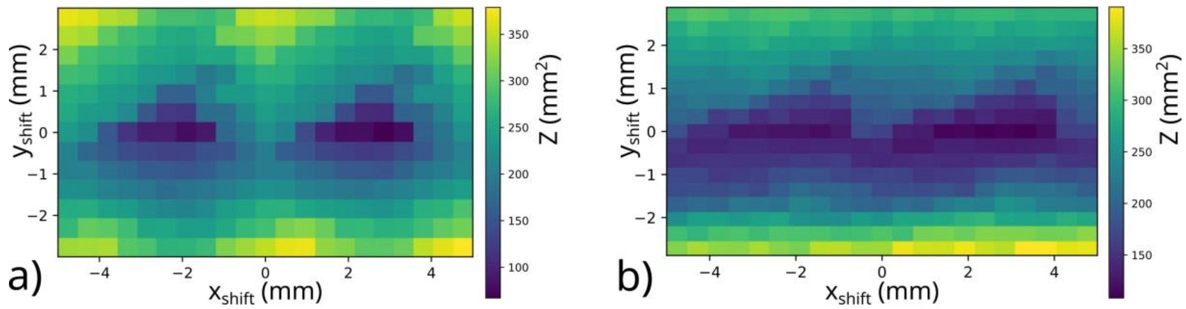

Figure 133. Color-coded area-error values of performed crochet subdivisions of the scaled triangle. **a)** SC as stitch type. **b)** Subdivision with SL. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Increasing the resolution

To investigate the crochet subdivision results in more detail, especially with regard to the repetitions of the minima regions visible in Figure 133, the resolution is increased. Accordingly, the starting point of the division of the scaled triangle is shifted with a step size of *L*/20 mm or *H*/20 mm, respectively. The higher resolution of the distribution of the error values of Figure 134 confirms the presence of two local minima repeating on the x-axis.

Again, the same starting point shift was chosen as optimal, despite the significantly higher number of data points (1024 instead of 272). However, this may be a coincidence. Depending on the application and the available computing resources, the shifts with step sizes of one tenth of the stitch size might probably be sufficient. Nevertheless, to further explore the possibilities of the developed shaping tool and the correlation between the starting point and the quality of the subdivision, the finer resolution with a step size of *L*/20 mm or *H*/20 mm is applied.

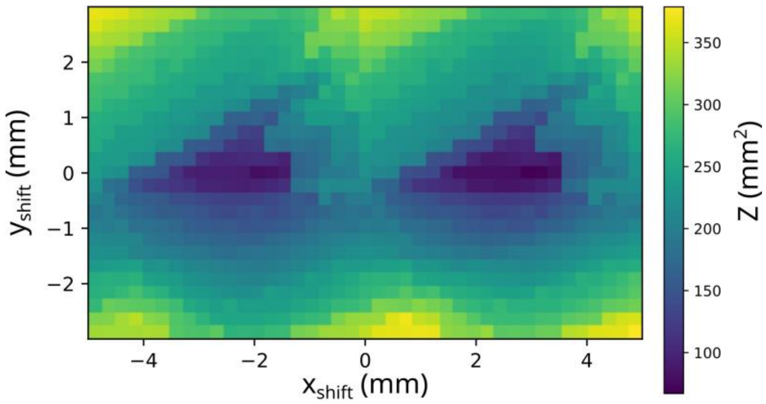

Figure 134. Area-error values with color scale as the crochet subdivision results with a higher resolution by using a step size of $L/20$ mm or $H/20$ mm for shifting the starting point. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Subdivision of a quadrilateral

To further investigate the shaping possibilities, polygons with higher orders are also tested. Figure 135 shows the initial and best crochet subdivisions of an exemplary quadrilateral. It is striking that the first stitch of the last course protrudes significantly more than the allowed 30% above the polygon boundaries. This is due to the difficulty of representing the slight slope of the upper edge (see also Figure 135 c)). In general, with a combination of DEC at the end of the previous course and RSTB at the beginning of the current course, the position of the first stitch of the corresponding course can be shifted by only two stitch positions. If more is required, the last stitch in the previous course is also removed and the beginning of the current course is set accordingly. Here it becomes apparent that the tool will have to be extended in the future to allow the removing of more stitches in the previous course to better fit the shape.

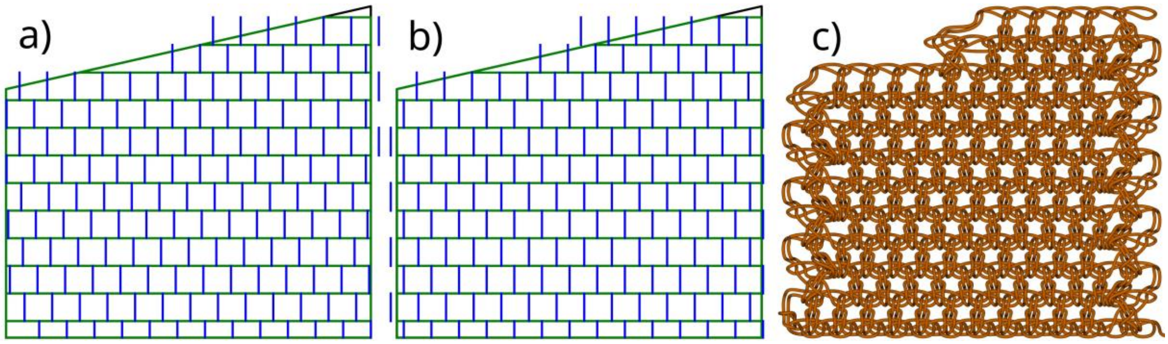

Figure 135. Crochet patterns as results from the subdivision optimization of the quadrilateral. **a)** Generated crochet pattern with initial starting point. **b)** Optimized crochet subdivision. **c)** Modeled pattern of the best run. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

The values of all subdivisions performed during the optimization are grouped in Figure 136. These illustrated area-error values are similar to the previous polygons in that strong y-displacements affect the area-error more than strong x-displacements. However, for x-shifts less distinct local minima of the area-error are seen. Here, with the relatively high computational effort, the area-error of the subdivision could be improved only slightly from 6.44% to 5.23% by shifting the first stitch by 0.25 mm in x-direction.

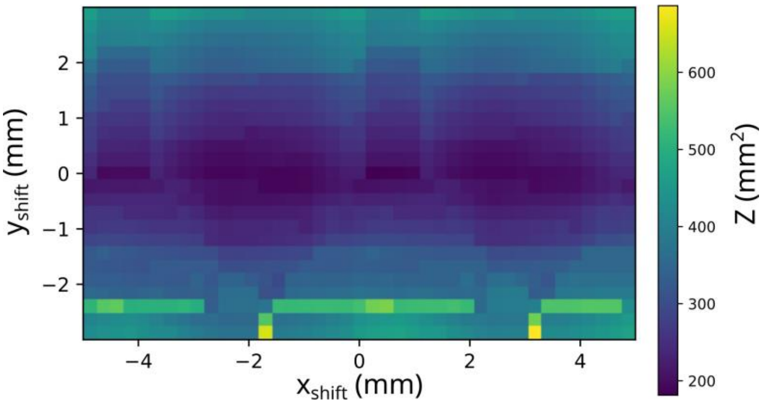

Figure 136. Area-error values with color scale regarding the crochet subdivisions of a quadrilateral polygon. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Subdivision of a pentagon

Next, Figure 137 depicts the results of the subdivision optimization with a pentagon as shaping polygon. Similar to the previous examples, the shape can be fundamentally recreated by the crocheted fabric, while the slopes of the edges and sharp peaks cannot be reproduced well, due to the limitations of the machine's shaping operations.

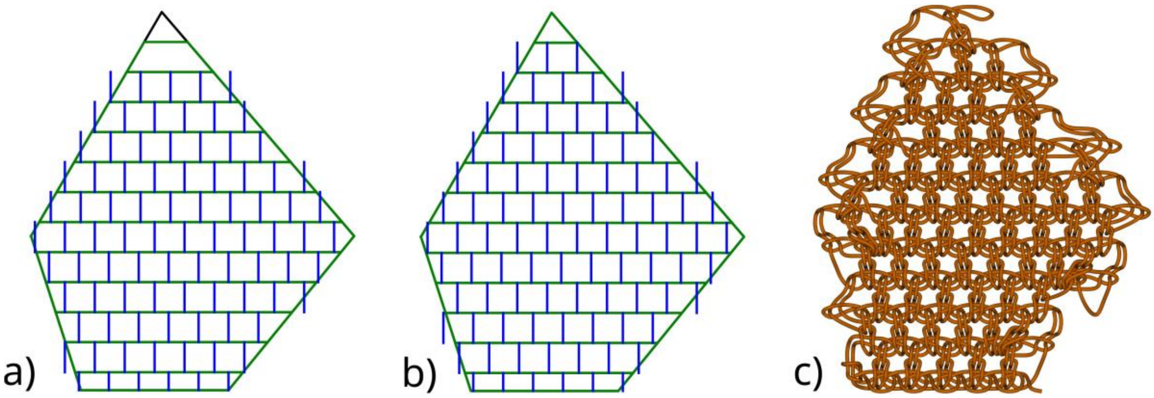

Figure 137. Crochet pattern generation with irregular pentagon. **a)** First crochet subdivision pattern with initial starting point and area-error of 10.10%. **b)** Optimal crochet pattern with start position shifted by 0.75 mm in x-direction and with an area-error of 7.47%. **c)** Respective model of the best run. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

As illustrated in Figure 138, the area-error value pattern exhibits like the previous results some kind of repetition along the x-axis with two local minima. Another similarity is that an additional course could be filled with stitches due to the starting point shift (cf. Figure 137).

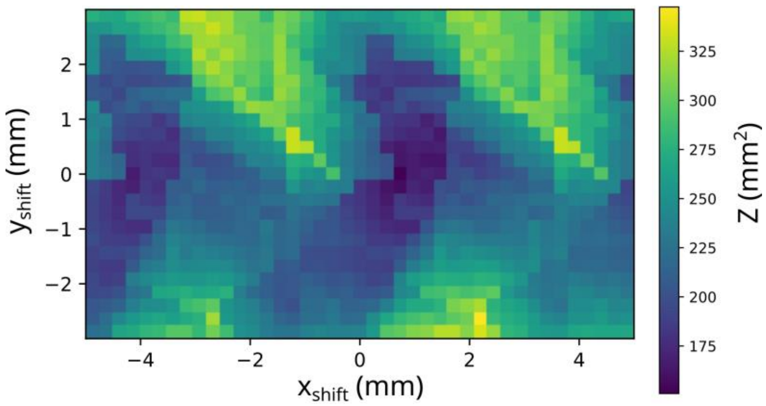

Figure 138. Area-error values with color scale regarding the optimization of the irregular pentagon. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Subdivision of a hexagon

Lastly, a crocheted fabric is exemplary shaped according to a regular hexagon. In Figure 139, the corresponding model shows that the shape is fundamentally reproduced, but the symmetry of the structure is not reached. By moving the starting point 1.25 mm in x-direction, the subdivision was improved from an area-error of 6.70% to an error of 4.68%.

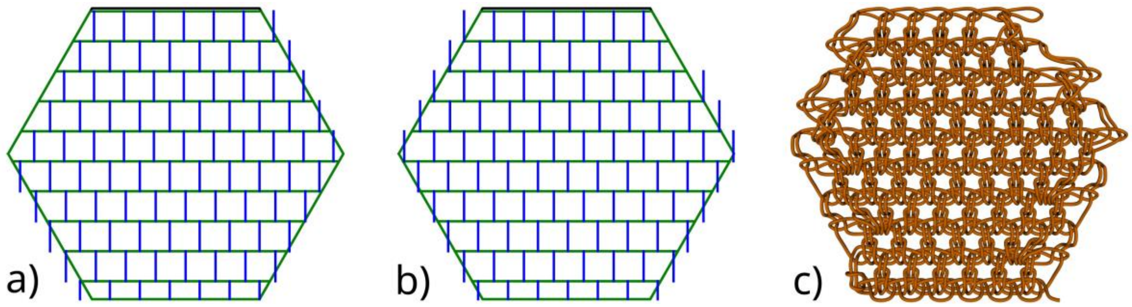

Figure 139. Resulting crochet patterns of the optimized shaping according to a hexagon. **a)** Initial crochet subdivision. **b)** Crochet pattern resulting from the optimization. **c)** Model of the optimal subdivision. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

Again, two distinct local minima with about zero y-shift are indicated by the pattern of the area-errors of Figure 140. At the right side, a further repetition of the error pattern emerges with another potentially local minimum. With a 1.25 mm x-direction shift, the ideal position of the starting point was placed in one local minimum. Large y-shifts result once again in large area-error values.

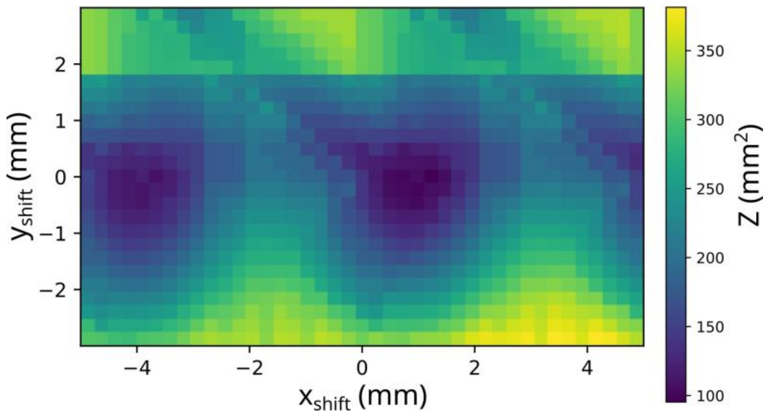

Figure 140. Results of the starting point optimization of the regular hexagon with area-error values in color scale. Figure is under CC BY license and taken without modification from reference A7 (Copyright © 2023, the Authors).

4.4.5 Discussing the results

Overall, the presented crochet subdivisions show that the developed algorithm allows shaping machine-producible crocheted fabrics according to diverse convex geometries. The generated data array of the crochet pattern (cf. Figure 127 in section 4.4.3) can be used as input for the developed G-code generation (cf. section 3.6.5). Thus, the developed approach of generating crochet patterns according to desired shapes can be utilized as a direct extension to the crochet design tool of section 3.6. The added automation in the design of machine-crochetable structures enables the CroMat crochet machine to be used in future without demanding any special knowledge of crochet technology.

The quality of shape matching, represented by the error of uncovered and overlapping areas, can be improved by increasing the computational effort and calculating multiple subdivisions with shifted starting points. This simple numerical optimization yielded better results in all cases, for which the starting points were shifted a few millimeters in the positive x-direction to a minimum of the error values. A step size of one tenth or one twentieth of the stitch width is suitable for the performed subdivisions. It can be adjusted depending on the requirements for the quality of the tessellation.

The observed repetitions of the area-error patterns with local minima along the x-axis emerge because the crochet pattern repeats itself when the starting point is shifted by one stitch width (5 mm) on the x-axis. As can be seen in Figure 129, the first stitch is an exception and is not repeated. The local minima further away from the initial starting point are associated with larger error values, since regarding a negative x-shifts, the first stitch position of the initial starting point is not covered, while large positive x-shifts cause the first stitch to extend far beyond the shaping polygon.

Besides the trend of the location of the minima, the tendency was observed that large y-shifts usually result in large area-error values. Based on these findings, computing time can be saved in future applications by scanning a smaller range in the y-direction with perhaps a coarser resolution.

The shaping possibilities of the developed CroMat prototype are much more limited compared to the almost unlimited possibilities of manual crocheting, and also compared to the technically mature V-bed knitting machines. This is mainly due to missing loop transfer capabilities, so that INC and DEC can only be performed at the beginning and end of a course, respectively. To expand the shaping possibilities of a future improved crochet machine, loop transfer should be integrated, for instance by means of fashioning points, as known from straight bar frames [106]. Another way to extend the shaping possibilities of the CroMat crochet machine is presented in section 4.5.2.

In the scientific literature, it is quite common to mesh a surface with rectangles representing stitches [19,92-94,250,251]. The approach presented here differs from this, because not the whole surface is meshed by rectangles. Instead, the rectangles are placed only at allowed positions in a fixed orientation one after the other, taking into account the rules for a valid textile and manufacturability. Especially the consideration of the manufacturability with a true crochet machine constitutes a new approach.

Also, the stitch structure is here modeled as slightly offset from course to course (cf. Figure 127 in section 4.4.3), which is a difference to the stitch pattern of manual crocheting modeled by Çapunaman et al. [92] and Guo et al. [19]. Çapunaman et al. assumed that the stitches will deform appropriately according to the desired shape of the fabric, while Guo et al. modeled the manually crocheted fabrics in various shapes without such offsets. This leads to a warped picture compared to the representation chosen here. The offset between courses modeled here is based on the observation of both manually (cf. Figure 6 in section 2.1.2) and machine-crocheted fabrics (cf. Figure 94 in section 3.5.1). However, the relaxed state of crocheted textiles remains unexplored, so it is not possible to judge which representation is more realistic.

4.5 Exemplary machine-crocheted fabrics

Here, crochet samples produced with the CroMat are presented and an overview of the structures that can be crocheted by machine is given. Section 4.5.1 illustrates typical crochet structures that can now be produced automatically. In section 4.5.2, the principle of manually repositioning the textiles in the machine is demonstrated. This enables the reproducible fabrication of complex 3D structures on the machine. Finally, in section 4.5.3 measurements of the Poisson's ratio of the textiles produced with the CroMat prototype are made.

4.5.1 Basic fabric structure

The structures of the machine-produced basic stitch types SL, SC and HDC are shown in Figure 141. In each case, the technical face of a slightly tensioned exemplary fabric is shown. With regard to SL fabrics, stretching is necessary to prevent the fabric from curling. SC and HDC fabrics do not curl, but with a slight stretch, the stitch structure can be presented more clearly.

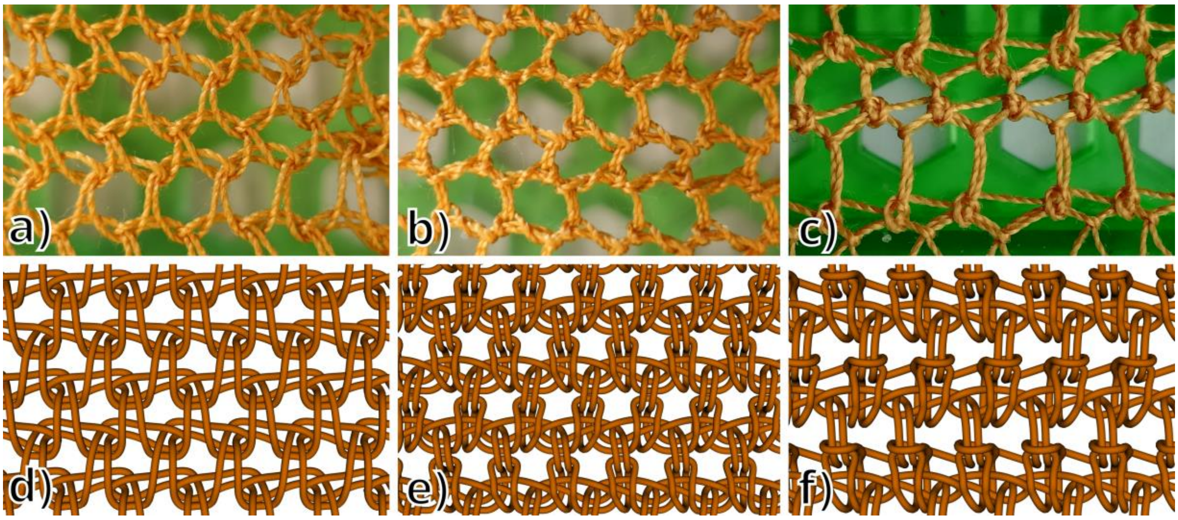

Figure 141. Comparison of fabrics produced with the CroMat prototype. **a)** Machine-crocheted SL fabric. **b)** Machine-crocheted SC fabric. **c)** Machine-crocheted HDC fabric. **d)** SL fabric model. **e)** SC fabric model. **f)** HDC fabric model.

Figure 141 reveals that the structure of SL is relatively loose, while the SC and HDC stitches are rather tightened and look similar to knots. In this respect, SC and HDC also differ more strongly from the topology-based models, in which especially the lower parts of the stitch are modeled distinctly more loosely. The latter is necessary to ensure intersection free structures for different combinations of stitch types. The topology, i.e., the relative orientation of yarn segments to each other (which yarn segment lies above which) is identical. Likewise, the offset of the courses to each other is reflected in the modeling. However, the exact geometry or deformation cannot be reproduced by the idealized topology-based model.

When comparing the machine-formed crocheted fabrics with the manually formed ones, e.g., shown in Figure 6 in section 2.1.2, it is noticeable that the ratio of stitch size to yarn diameter is significantly larger for the machine-formed stitches than for the manually formed stitches. This somewhat unfavorable ratio for the machine-formed stitches is due to the limited range of suitable compound needles as crochet needles (cf. section 3.4.3). The stitches must be large enough for the needle to be inserted into them and the yarn diameter must be small enough to allow three loops to be placed in the hook of the crochet needle without problems (see section 3.4.6). As there are not yet specific applications for machine-crocheted textiles, there are also no requirements for the ratio of yarn diameter to stitch size.

INC and DEC

Next, an automatically produced SL textile characterized by many INCs is shown in Figure 142. Following the possibility of CroMat, one stitch was added at the beginning of each course via an INC operation (cf. section 3.3.7). For simplicity, the lower courses are not shown. In a) the needles at the bottom pin the second course from the bottom of b). Again, the textile is stretched slightly over the green SLA printed device to better illustrate the shaping.

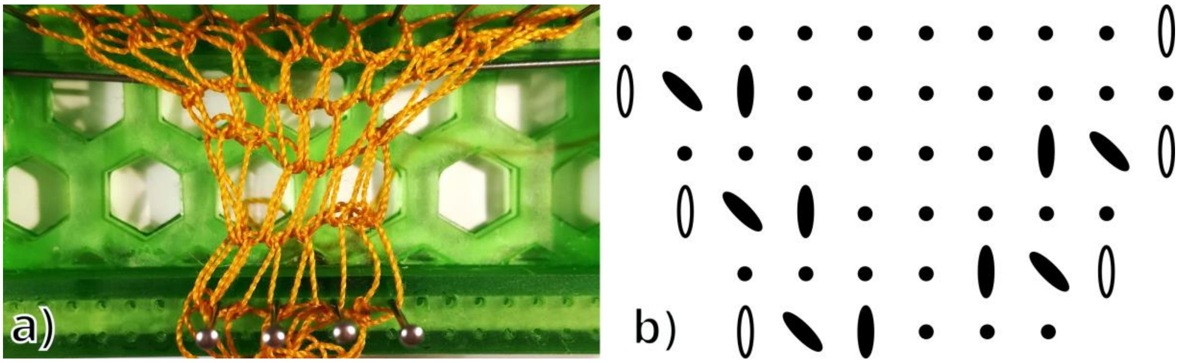

Figure 142. SL textile produced with the CroMat with multiple INCs. **a)** Photo of the stretched textile. **b)** Crochet chart showing the corresponding structure.

The structure of an SL textile with several DECs is shown in Figure 143. The shape is basically similar to the INC textile (cf. Figure 142), but the fabric goes from wide to narrow. This is slightly faster to produce with the CroMat, as the DEC operation is less complex to execute compared to INC (cf. section 3.3.8). As can be seen from the relatively irregular stitch structure in Figure 143 a), the DEC textile deforms considerably despite the stretching, which makes it difficult to recognize the stitch topology. As with INC, the structure of DEC can be better derived from the models in sections 3.3.7 and 3.3.8).

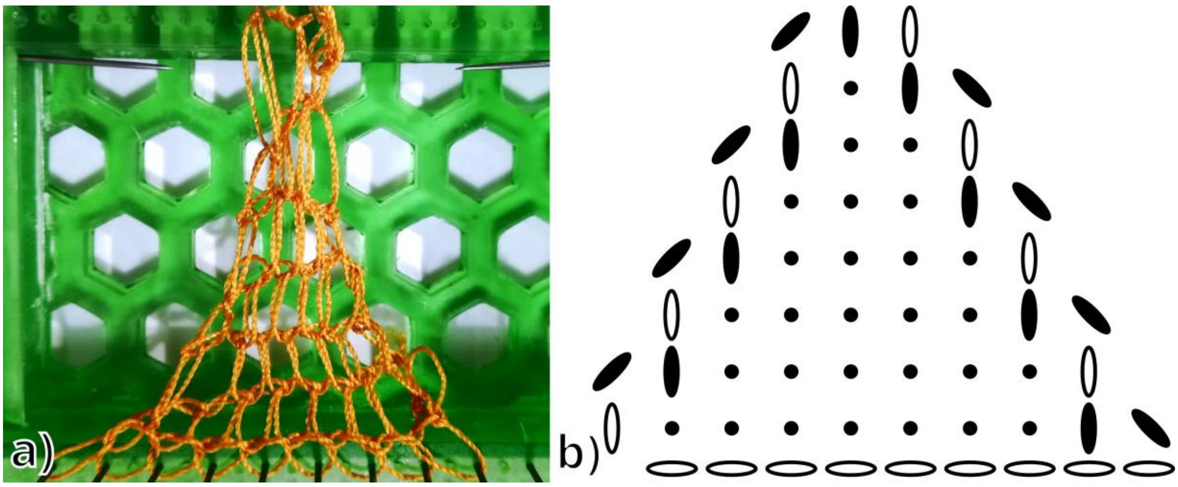

Figure 143. Automated DEC example textile with SL stitches. **a)** Photo. **b)** schematic structure.

Open work crochet

Open work crochet is defined by not stitching into every stitch of a course [11]. In principle, the CroMat machine offers two ways to achieve this, as described in section 3.3.6. In the first option, an ANP is skipped in that the stitch positioned is not used as a working stitch, but instead a CH is formed at the position.

An example textile consisting of SCs with plenty of CHs in the course (every second stitch) is shown in Figure 144 a). The fabric has a very loose structure with relatively large stitches, and it is difficult to see that only every second stitch of a course is used as a working stitch. The latter can be better derived from the model presented in b). With the produced fabric, the skipping of stitches becomes apparent at the bottom. Large holes, which are characteristic for open work crochet, are not visible, because only one stitch position was skipped here.

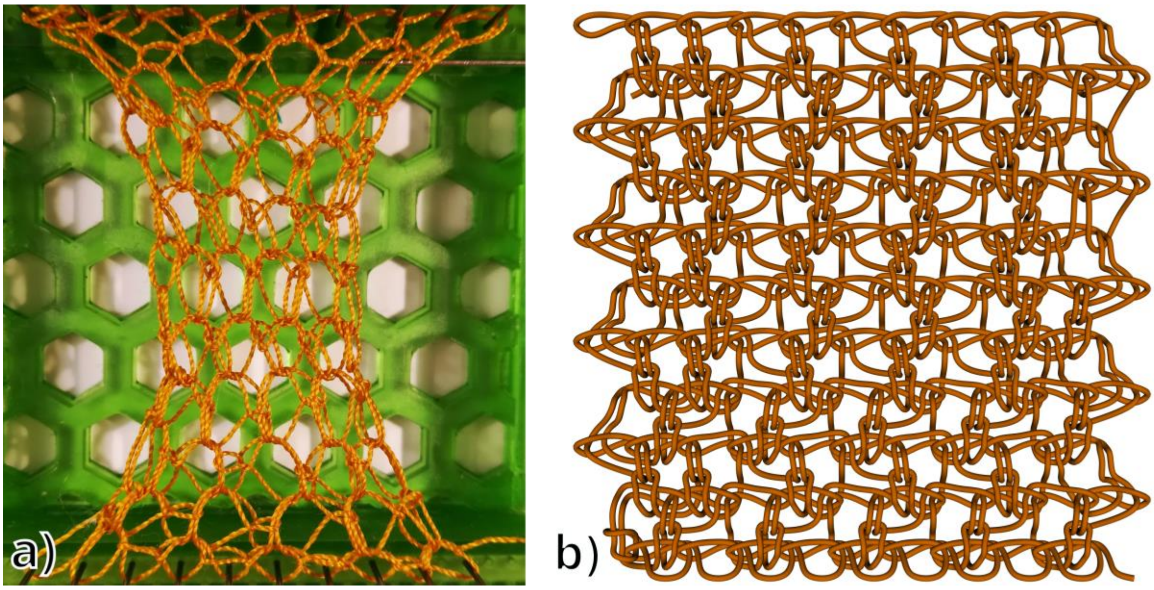

Figure 144. Exemplary open work crochet with SCs and CHs within a course. **a)** Photograph of produced fabric. **b)** Respective model.

Larger holes with correspondingly more CHs in a course, as it is characteristic of open work crochet, can also be created with the CroMat. However, it should be noted that it can be problematic to use the multiple CHs in a course as working stitches and to reliably insert the crochet needle or thread guide there. Due to the missing connection to the course beneath, the CHs are not pulled open directly through the fabric take-off.

With the option of skipping a stitch, the LL is drawn longer and placed over two ANPs (without forming a CH). A corresponding example fabric is illustrated in Figure 145. As can be seen at the bottom, only every second CH is used as a working stitch again. The structure resulting from skipping stitches is much looser compared to a normal SL fabric due to the larger stitches. Therefore, in Figure 145, the textile is strongly stretched in the wale direction and compressed in the course direction compared to the model. Regarding the model, a typical SL height was assumed.

Because in the example fabric (cf. Figure 145) the pattern is continued and each stitch extends over two stitch positions, the needle is inserted at every second stitch position, but this results in the use of each stitch as a working stitch. Thus, it is in a strict sense not a true open work crochet. In the end, a textile is produced with twice the machine pitch and therefore with double sized stitches. In principle, it is therefore possible to change the stitch size via this operation by virtually changing the machine pitch.

Furthermore, with an adjustment of the G-code programs of the stitch formation, it is possible to achieve an increase of the stitch width by 50% by placing each stitch over three auxiliary needles (including the first CH course). It is not possible to adapt only the operation of skipping a stitch by placing the LL over three auxiliary needles, because this would result in a working stitch being suspended on only one auxiliary needle. Therefore, all G-code programs would have to be adapted so that a stitch is held by three auxiliary needles.

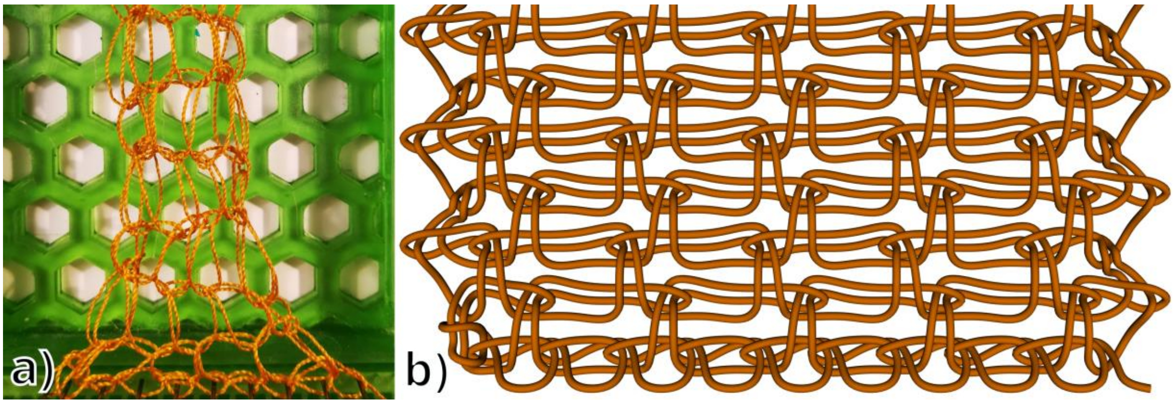

Figure 145. Machine-producible crochet structure of skipping stitches within a course. **a)** Photograph. **b)** Topology-based model of the respective structure.

Following this principle, it would also be conceivable to make an adjustment in that all stitches are placed over four auxiliary needles (two pairs) in order to obtain an alternative possibility to skipping a stitch and creating a fabric similar to the one shown Figure 145. Corresponding adjustments with stitches suspended on more than two auxiliary needles would result in a slower production speed because only two auxiliary needles can be moved at a time. However, this provides an opportunity to further increase the flexibility of the CroMat crochet machine through adjustments in the software, which is an advantage of a mechatronic system.

4.5.2 Advanced possible structures

In addition to the exemplary crochet structures shown in the previous section or the machine-producible patterns generated in section 4.4, the textiles can be removed and re-hooked during production in order to be able to produce complex 3D structures. Although this increases the production effort and requires manual intervention, it does in principle enable the reproducible production of a wide variety of textiles precisely adapted to the application. This makes it possible, for example, to crochet reinforcements for near net-shaped composites (cf. section 2.6.2) [6]. Although a manual step is necessary, most of the work is performed by the machine, so that corresponding production is also plausible in an industrial context.

Joining and tubular fabrics

With a single manual repositioning, tubular fabrics can be fabricated with the CroMat prototype. An example of this is presented in Figure 146. To produce such a fabric, first a rectangular textile is to be produced with the typical operation of the CroMat. Once the desired diameter of the tube is reached, the first CH course, with which the machine production starts, can be manually hung on the auxiliary needles besides the lastly formed course. After this transfer, the LLs of two stitches (from the first and from the last course) are suspended on each ANP. To connect both courses, stitches of a final course can be formed through their stitches at the same time. With this, the general feature of crochet of being suitable for connecting stitches of different fabrics (for example, regarding granny squares) can be utilized by the CroMat crochet machine.

Figure 146. Crocheting a tubular textile with the CroMat prototype. **a)** The first CH course hooked on the same needle as the current SL course before the final SL course is crocheted through both. **b)** Resulting product of a tubular textile. **c)** SLs of the joining course marked by black dots.

As shown in Figure 146 b) with an SL textile, a tubular, continuous textile can be crocheted with the CroMat. The joining of the two courses creates a small irregularity in the structure. This is manifested in the fact that the lower part of the stitches of the joining course (marked with black dots in c)) are connected to the lower part of one course, while the upper part is connected to the upper part of another course. In Figure 146 a), the textile is shown after the re-hanging step and before the final course is formed. It can be seen how both halves of the textile are arranged in front of each other.

Based on the possibility of joining two courses as illustrated in Figure 146, different fabrics can also be joined. Accordingly, the edges of the respective fabrics to be joined must be suspended on the ANPs in such a way that the loops of a new stitch can be drawn through between the yarn segments of both fabrics. The possibility of such a new type of joining technology extends the range of applications of the developed crochet machine and, in general, of automated crochet technology.

Also, the possibility of producing tubular textiles, which normally are crocheted in the round based on a magic ring, significantly increases the application range of the CroMat. For example, it is possible to produce similar textiles as with the Croche-Matic approach, which is presented in section 2.3.2 and which attempts to automate the circular crocheting based on the magic ring. Advantageously, the CroMat can benefit from a much less error-prone stitch formation method compared to that approach [14,15]. However, it should be mentioned that changing the diameter in the tubular textile would in principle be more difficult with the CroMat approach than with the Croche-Matic approach, which specializes in circular crochet.

T-beam shapes

Manual crocheting is characterized by the flexibility to form a new stitch at any point of the fabric by simply using the crochet hook to pull a new loop between arbitrary yarn segments of the fabric [6]. The CroMat crochet machine does not offer this freedom because it can only form new stitch based on a working stitch suspended on an ANP. The use of a working stitch not secured in this way would lead to severe limitations in the reproducibility and reliability of the stitch formation, similar to the Croche-Matic approach (cf. section 2.3.2). With a manual removing and re-hooking of the already produced textile, a workaround can be found in that the textile can be suspended with any row of stitches on the auxiliary needles, so that new stitches can be formed at these almost arbitrary points.

In general, the CroMat crochet machine is more suitable than knitting machines for removing the fabric and re-hanging it in a different orientation. Since in knitting, the entire last course is always open, so that a corresponding re-hanging would be much more complicated [6].

This principle is used in the second example of a producible advanced crochet structure to crochet a continuous fabric in the form of a T-beam or Y-shape. To do this, a rectangular textile consisting of SLs is again crocheted by machine at first. This is then turned 90° and hooked into the auxiliary needles with the former right edge as shown in Figure 147 a). In this configuration, SLs are formed up to half the wale length. Then the fabric is repositioned again so that the middle course, to which the half course was previously crocheted, is suspended on the auxiliary needles. As illustrated in Figure 147 b), both halves of the fabric hang down. Based on the middle course, further courses can then be crocheted.

As can be seen in Figure 147 c), the courses formed after the second reassembly are arranged at right angles to the original textile formed before the first repositioning. For better illustration, the third plane of the fabric is also stretched in Figure 147 d), so that the Y-shape becomes clear. Crocheting the half course between the first and second re-hanging is necessary to move across the fabric and to maintain the regular fabric structure. Otherwise, there would be very long and loose stitch, which bridges the large gap between the two different crocheted rows.

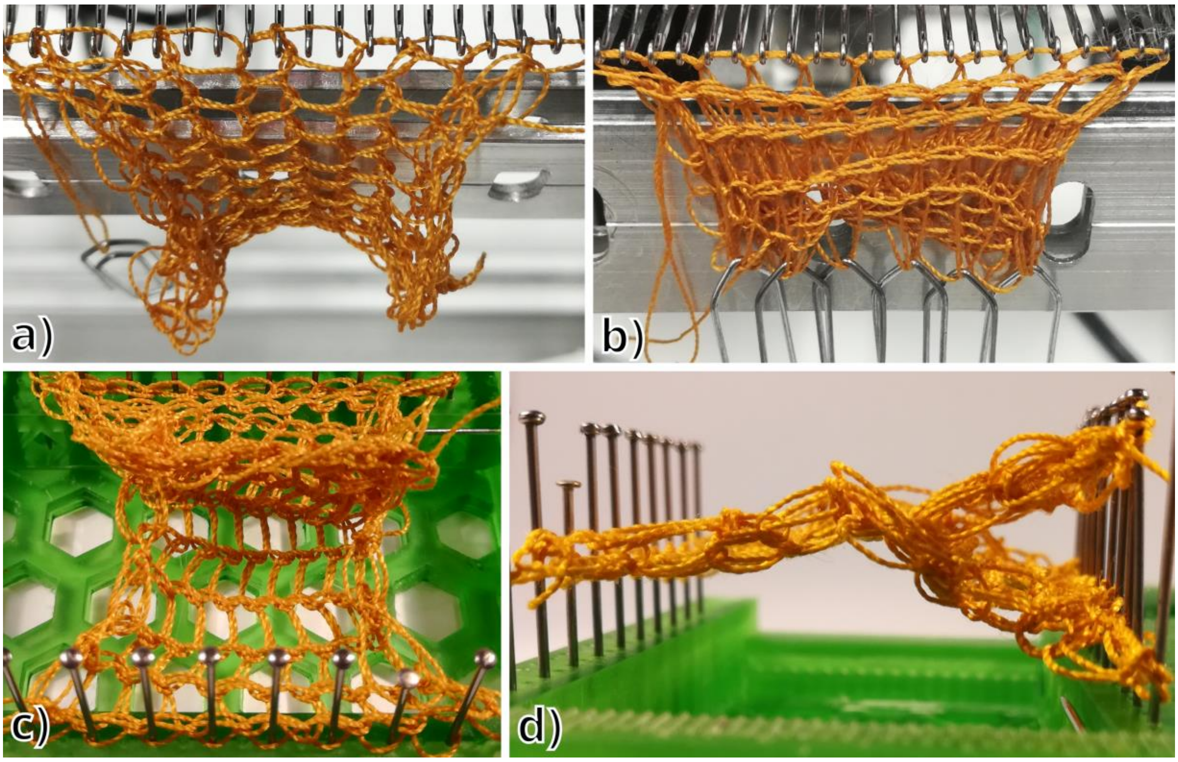

Figure 147. T-beam shaped example fabric produced with the CroMat prototype. **a)** Textile after the first repositioning. **b)** Textile after the second rearranging. **c)** Textile stretched in the original configuration with the additional plane in the center. **d)** The additional plane also pinned in the view from the side.

A machine-formed T-beam textile consisting of SC stitches is shown in Figure 148. This was produced according to the same principle as the corresponding SL fabric from Figure 147. The middle textile plane is also perpendicular here but is not affected by curling due to the SC stitch structure. In Figure 148 b), the bottom edge shows how a few SLs were crocheted from the last course (right edge) of the horizontal plane to the center to create a transition to the middle plane. These SLs were crocheted between the first and second re-hanging.

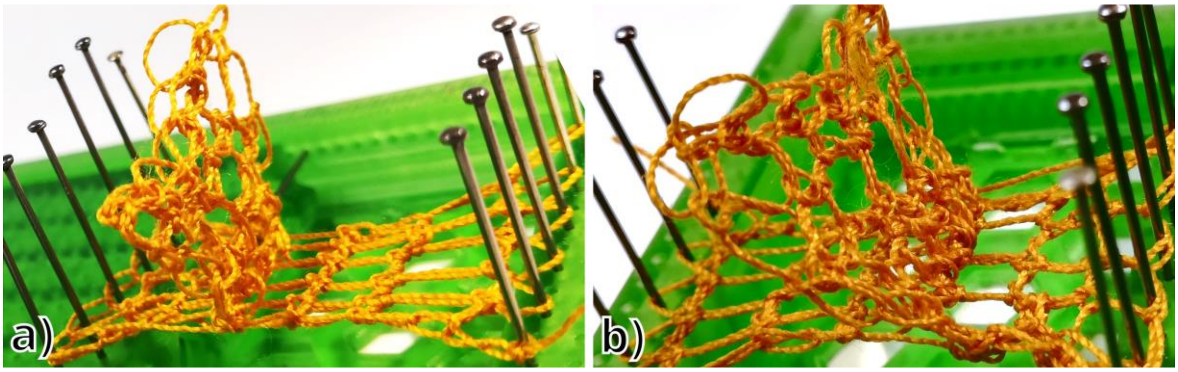

Figure 148. Photos of an SC textile in the shape of a T-beam made by repositioning within the CroMat prototype in the view from two sides (**a)** and **b)**).

Such T-shaped fabrics could be used as near net-shaped reinforcements for composites. Most composite T-beams are fabricated by draping 2D fabrics into the appropriate shape and laminating them therein [177]. However, such structures made from non-continuous reinforcements are prone to delamination at the junction between rib and panel [177]. The same labor-intensive principle is usually used to produce complex skin-stringer composites [176]. The production of such near net-shaped reinforcements with the CroMat crochet machine would preserve the continuity between panel and rib and is thus promising with respect to mechanical properties. Besides complex modifications of flat-bed weft knitting machines [176], the CroMat crochet machine also has the potential to produce corresponding complex near net-shaped reinforcements for skin-stringer composite and other applications in one piece.

Following the principle of re-hanging, more complex 3D textiles can also be produced waste-free with the CroMat. In this respect, Figure 149 shows a double T-beam (or I-beam) crocheted from SLs as a logical extension of the T-beam. As with one of these, a rectangular area is crocheted first, then turned 90° to crochet around the edge to its center. Additional, after rehanging, another rectangle is formed based on the middle course of stitches of the originally made rectangle.

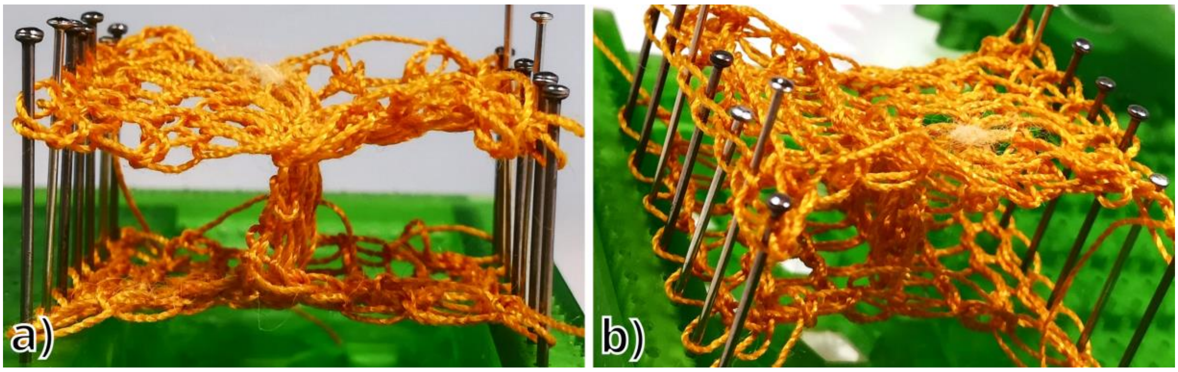

Figure 149. 3D textile made with CroMat and rearranging from SLs in the shape of a double-T-beam (**a)** and **b)** show different views).

Unlike a simple T-beam, additional courses of stitches are crocheted beyond the desired length of the middle rectangular plane. Specifically, a number of additional courses are crocheted up to half of the desired length of the upper plane of the T-beam. This is because the other half of the upper plane can then be formed after appropriate re-hanging steps starting from the center right-angled plane. Firstly, the textile must be re-hooked turned 90° to crochet on one edge of the lastly formed rectangular part to half the desired length of the upper plane. This, as described earlier, prevents a long, loose yarn segment.

Secondly, the course of stitches, up to which has been crocheted, is to hang in the auxiliary needles to crochet the second half of the upper plane of the double-T-beam.

This example illustrates the CroMat's possibilities to go beyond reinforcements shapes such as T-beams, which are already difficult to produce with current textile machinery, to produce even more complex shapes for potential near net-shape composites. The inherent advantage of crochet technology, that theoretically new stitches can be formed at any point of the fabric which enables the production of very complex 3D shapes, can be exploited with the CroMat. Thus, this novel textile machine has great potential to be used for the production of near net-shaped composites or other complex-shaped, technical fabrics in the future.

The data elaborated in section 4.2 regarding manually crocheted textiles have already shown the suitability of plain crocheted fabrics as composite reinforcements with partly even superior properties compared to knitted fabrics. This emphasizes the production of composites with crocheted reinforcements as a promising application of the CroMat crochet machine. Also, by focusing on special applications and producing small quantities, the comparatively slow production speed is compensated. The production speed is an inherent disadvantage of crochet compared to knitting. This is because the speed of crochet is always limited by the fact that the current stitch must first be completely formed before the next one can be started, whereas in knitting all stitches in a row can be formed simultaneously [17].

However, in order to be able to accurately evaluate the suitability of the application in the form of (net-shaped) composites of textiles automatically crocheted with a CroMat machine, numerous further scientific experiments are necessary on the one hand. On the other hand, a further development of the CroMat approach into an industrial machine is needed. Both aspects can be carried out based on the foundations laid here.

4.5.3 Poisson's ratio investigation

In order to collect data for evaluating the machine-crocheted fabrics, the Poisson's ratio is considered, which is a fundamental mechanical property of engineering materials such as textiles [263]. The Poisson's ratio describes the ratio of lateral to axial strain under axial stress. Most materials contract laterally when stretched axially, which is why the Poisson's ratio ν of $\varepsilon_{lateral}$ (lateral strain) to ε_{axial} (axial strain) shown in Equation 34 has a negative sign [263]. Equation 35 shows an example of the calculation of the lateral strain ($\varepsilon_{lateral}$).

$$\nu = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}} \quad (34)$$

$$\varepsilon_{lateral} = \frac{l - l_0}{l_0} \quad (35)$$

To calculate the Poisson's ratio, a textile can be subjected to uniaxial tensile stress to plot the resulting lateral contraction versus axial extension [263]. The slope of a corresponding linear fit is the Poisson's ratio [263]. This method of determining the Poisson's ratio was used here. To stretch the fabrics axially, the stitches of the top and bottom courses were attached with pins and stretched over an SLA printed device (which was already depicted in the images in section 4.5). This device was designed and printed by Fredric Meyer as part of a student project under the instruction of the author [264]. Photographs were taken at various elongations, which were then evaluated using ImageJ to correlate the axial and lateral strain.

The crochet samples investigated are all rectangular and consist of 10 stitches plus one turn per course and 10 machine-crocheted courses plus the initial CH course. The Poisson's ratio measurement is less complex compared to the tensile tests performed in section 4.2 and was investigated here to give for the first time a brief insight into the properties of automatically crocheted fabrics (by the CroMat prototype).

Figure 150 shows an example of the deformation of a machine-crocheted SL fabric when elongated in wale direction. It can be seen how the width of the fabric decreases with an increase in length. In particular, the stitches in the center are elongated.

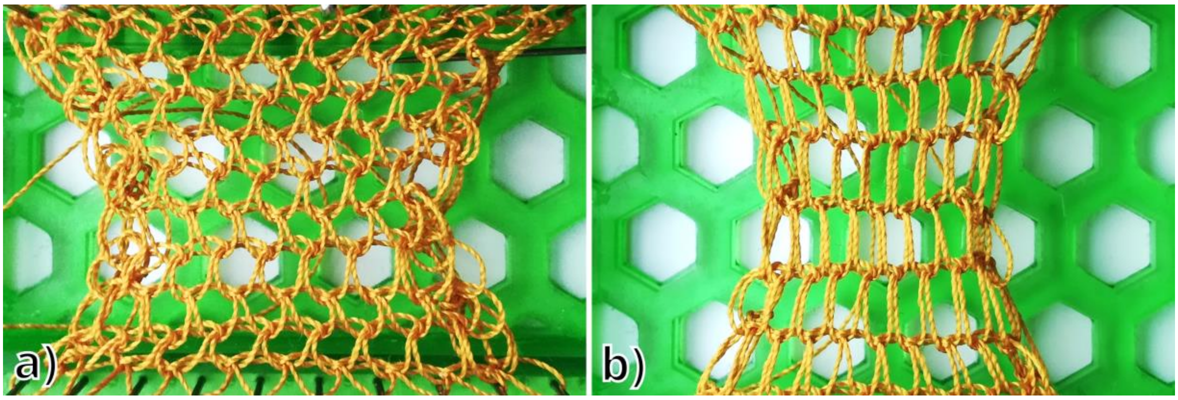

Figure 150. Elongation of a machine-crocheted SL textile in wale direction. **a)** Relatively small elongation. **b)** Greater elongation.

The deformation of the stitches and the whole fabric when stretched in wale direction of a SC textile produced with the CroMat prototype is shown in Figure 151. It is interesting to note that upon extension, the interlooped regions of the stitches contract more and yarn segments align parallel to the tensile direction. This was also observed when examining the manually crocheted fabrics (cf. Figure 106 in section 4.2.3). It can therefore be assumed that the machine-produced crocheted fabrics have comparable properties to the manually crocheted ones. The structural difference is mainly that in the machine-crocheted textile all loops were pulled through the fabric in the same direction, while in the manual one this alternates due to the turning of the textile at each turn (cf. section 4.3.3).

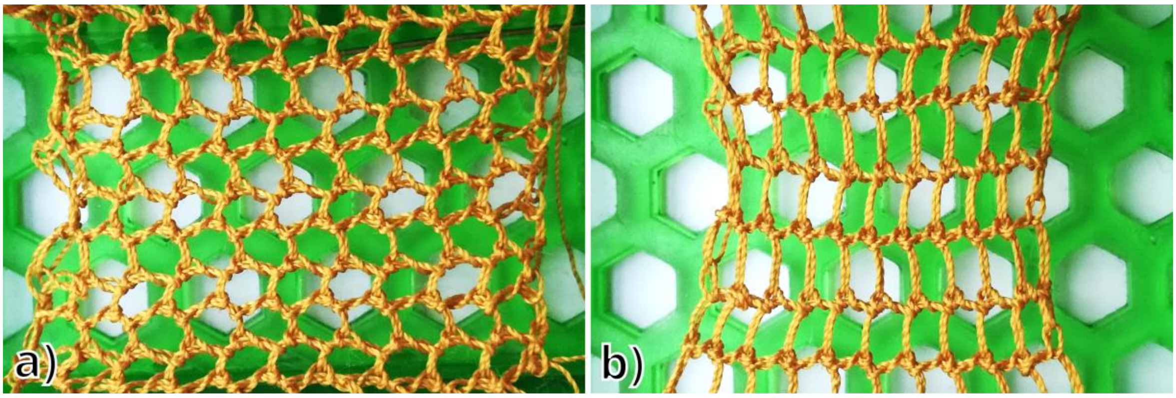

Figure 151. Elongation of a machine-crocheted SC textile. **a)** Low strain in wale direction. **b)** Greater strain in wale direction.

Due to the anisotropic properties of the crocheted textiles (cf. section 4.2.6), the stitch structure behaves differently when stretched in the course direction. This is shown with respect to the textile made from SLs in Figure 152. The stitch segments, which are arranged parallel in the direction of tension in Figure 150, form triangular structures there.

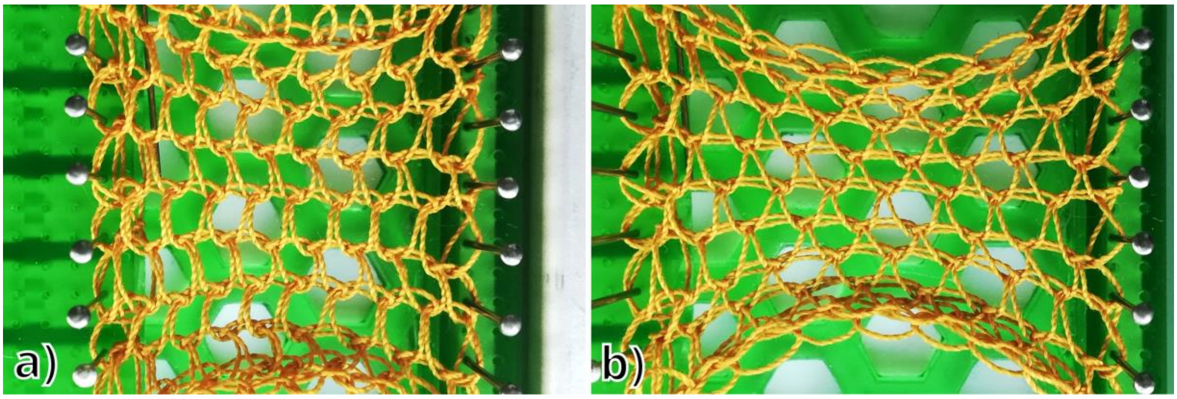

Figure 152. Elongation of a machine-crocheted SL fabric in course direction. **a)** Low strain. **b)** High strain.

The SC fabric also deforms in a fundamentally different way during the tension in course direction shown in Figure 153 compared to strain in wale direction. The interlooped regions deform much less and the stitch segments between them are not stretched. In general, the honeycomb structure of the fabric remains more present.

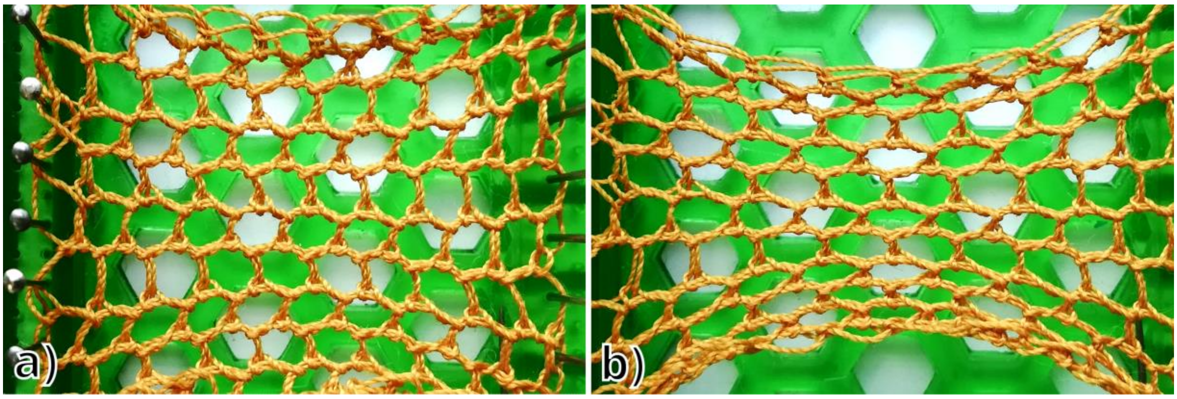

Figure 153. Elongation of a machine-crocheted SC fabric in course direction. **a)** Low strain. **b)** High strain.

Due to time constraints, the samples could not be produced as triplicates for the Poisson's ratio investigations, so that the measured values shown in Figure 154 are not statistically reliable. The specimens SL 6.3 a to c were crocheted identically with SLs and a thread tension of 6.3 cN, but the Poisson's ratio of one fabric was measured clearly higher than the other two. This indicates measurement inaccuracies.

In general, a problem with Poisson's ratio measurements is that curling can occur at the edges (cf. Figure 152), which affects the accuracy of the measurement [263]. Also, relatively short samples were used here, so compared to long samples, the clamping or fixing at the sides can have an effect on the deformation in the center [263]. Thus, the measurements performed here are rather to be understood as preliminary investigations showing tendencies about the material properties of machine-crocheted textiles. For a detailed quantitative investigation, more elaborated test series will be necessary in the future.

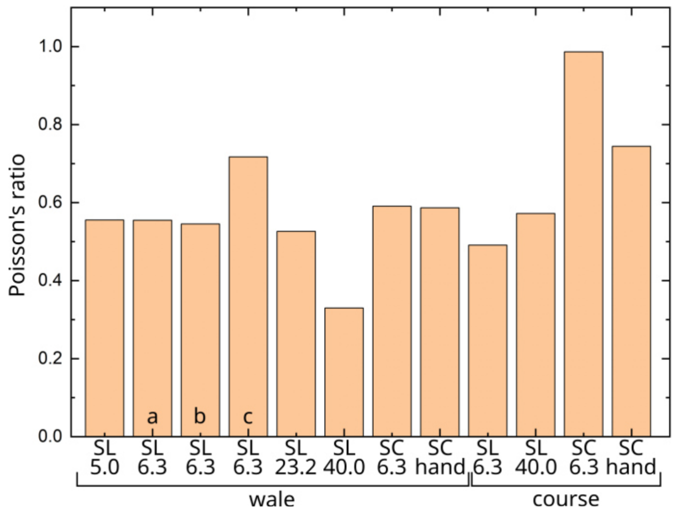

Figure 154. Measured Poisson's ratios in wale and course direction of a few machine-crocheted samples. The yarn tension during production is indicated in cN. Image created in Origin by Marius Dotter based on the data prepared by the author.

For SL fabrics and tension in wale direction, a trend of decreasing Poisson's ratio with increasing yarn tension during production could be assumed based on the data depicted in Figure 154. However, such a trend is not observed for the course direction. As expected, the SL fabrics produced with a higher thread tension have tighter stitches with a lower height in comparison.

In general, no differences in Poisson's ratio between wale and course direction were measured for SL fabrics. In contrast, for the machine-made SC fabric, the Poisson's ratio value in course direction is significantly larger than in wale direction, and also larger than for the other samples. The Poisson's ratio value of SC in wale direction is comparable to SL in wale direction.

The SC textile crocheted manually with a 5 mm crochet hook and the same yarn is very similar to the machine-made one in terms of elongation in wale direction. The value in course direction is slightly lower than that of the machine-made one, but slightly higher than the other samples. The measurements indicate a similarity between the properties of manually and machine-made SC textiles. Thus, the structural difference that with the machine all stitches are formed from one side only and the textile not being turned has probably little influence on the material properties.

For most materials, the Poisson's ratio ranges between 0 and 0.5 [265]. However, fabrics can also move outside this usual range. For example, for woven and warp knitted textiles, Poisson's ratios above 0.5 and sometimes even above 1 have been measured [266-268].

These results reveal promising material properties of machine-crocheted textiles. In the future, these are to be explored in more detail in order to make more reliable statements about the properties and to derive suitable applications. A corresponding exploration will be feasible after the construction of an improved CroMat crochet machine for industrial use. With such a machine, the creation of a sufficient number of samples in a reasonable time is possible. Nevertheless, the presentation here of samples produced with the current prototype is useful to provide an overview of the capabilities of the CroMat and the basic properties of the manufactured fabrics.

5 Conclusion

5.1 Summary

The presented work lays the foundations for a future development of crochet technology. The automated motion sequences of manual crocheting and the construction of the CroMat prototype form a template for an industrially applicable crochet machine. The benefits of such a machine, particularly for the production of complex textiles such as double-T-beams or joining of textiles, was demonstrated by the capabilities and properties of crocheted fabrics investigated in this work.

For the automation of flat crocheting based on a chain line, the necessary motion sequences of the fundamental machine elements consisting of crochet needle, auxiliary needle and yarn guide for the formation of CHs, SLs, SCs, HDCs, turns (T1 and T2), INC, DEC and other possible structures were defined on an abstracted level. This is largely independent of the developed CroMat prototype and can therefore also be used as a basis for alternatively constructed machines. For a secure stitch formation, the novel principle of placing the upper loop of a stitch over two auxiliary needles was invented. With a stitch secured in this way, the crochet needle can be inserted into this stitch reliably.

In addition to these patented motion sequences, an innovative yarn guide has been invented. It can be inserted into the working stitch through the technical back of the fabric in order to feed a yarn segment, which becomes a loop, to the crochet needle through the working stitch. This is particularly essential for producing SCs and HDCs.

For the machine implementation of these motion sequences and principles, a prototype was built which, at the end of the development phase of the innovation process, can implement all the features of the CroMat crochet machine for the first time. In terms of basic design, this CroMat prototype is based on the initial crochet machine approach for the production of rectangular SL fabrics ("the largest crochet machine in the world"). However, the range of functions and the mode of operation have been extended to such an extent that the CroMat is an independent, technically superior approach.

Furthermore, the CroMat prototype differs significantly from the Croche-Matic approach to automate circular crochet, which was developed in parallel to this work. The Croche-Matic approach was the first to demonstrate the machine formation of INCs and DECs using the principle of circular crochet based on the magic ring. The automation of SCs and HDCs was previously demonstrated for the first time by the CroMat patent. Despite the differences of flat crochet and circular crochet, the motion sequences for stitch formation are similar. Compared to the Croche-Matic, which has a very high stitch formation error rate, the CroMat is technically superior.

Thus, the CroMat prototype offers reproducible stitch formation and scalability over the two alternative crochet machine prototypes to an optimized, industrially deployable machine. The other approach of automatization with a crocheting device moved by a robotic arm (cf. section 2.3.3) does not yet have a prototype that can provide proof of concept. Therefore, compared to this approach, the CroMat prototype is also considered to be more technically advanced and more suitable as foundation of an industrially applicable crochet machine.

The CroMat prototype was developed according to RP and features a frame made of aluminum extrusion profiles, belt drives with V-slot pulleys and many FDM printed parts. With ten motion axes driven by stepper and servo motors, this mechatronic setup differs from conventional textile machines such as V-bed weft knitting machines. Not only can the prototype demonstrate the basic functions, but it can also produce machine-crocheted textiles, which were presented in this work for the first time. To this end, the motion sequences for machine stitch formation were defined in G-code macros for all producible crochet structures.

Compared to manually produced fabrics, the machine-crocheted fabrics have a technical front and technical back. This becomes particularly clear by considering the topology-based modeling, which was developed for both manual and machine-crocheting. With the modeling, the stitch structure was analyzed as well as replicated. Based on the models, FEM simulations can be performed, which indicate the anisotropic behavior of crocheted fabrics. The modeling framework can also be used for a visualization of the crochet structures.

A preview of the machine-crochet structures is particularly useful for the world's first tool for the design of machine-crochetable fabrics, which was developed in the context of this work. This tool offers a pixel-based programming interface with which fabrics can be constructed from individual stitches with standardized symbols, similar to a crochet chart. With an integrated error checking, the validity regarding crochetability with the CroMat prototype can be checked. The error checking reflects the definition of machine-crochetability with the CroMat. A G-code program for producing the designed textile can also be generated automatically. Thus, in addition to the construction of a suitable machine, the crochet technology was digitalized to provide a framework for future technical applications.

To further facilitate the design of machine-crocheted textiles with regard to future users who are not very familiar with crochet, an algorithm for the automatic generation of machine producible crochet patterns was developed. In particular, crocheted fabrics can be shaped according to the form of convex 2D polygons, taking into account INC and DEC as well as other shaping possibilities of the CroMat prototype. With a performed numerical optimization, the shapes can be well reproduced with valid crochet structures. This approach allows a higher-level programming of the crochet machine than with the manual setting of stitches and thus extends the possibilities of the design tool.

With regard to potential technical applications of crocheted textiles, the tensile properties of manually crocheted fabrics were systematically investigated for the first time in this work. In contrast to the properties of weft knitted textiles, the course direction of crocheted fabrics made of SCs or HDCs exhibits a tendency to resist higher forces compared to the wale direction. Also, the crocheted fabrics were able to resist higher forces at greater elongations compared to the reference knitted fabrics. This tendency of a more stable structure compared to knitted fabrics, with otherwise similar properties, was also observed in the world's first composites with crocheted reinforcement. These tend to have the potential to overcome the known weak in-plane properties of knitted composites.

Furthermore, the possibilities of automated crocheting with the CroMat were discussed and machine-crocheted samples were examined. Compared to manually crocheted fabrics, the stitches have an unusually large ratio to the yarn diameter, which is due to the limited sizes of available needles as appropriate machine elements. In principle, the CroMat enables automated production of crochet products that were previously made only manually. The machine can produce entire fabrics from SLs even beyond the possibilities of manual crochet.

However, the shaping possibilities with regard to changing the number of stitches in a course are limited in terms of INC and DEC, because the CroMat prototype does not allow stitch transfer. Also, a machine implementation of the flexibility of crochet to be able to insert the crochet hook at any point of the fabric and form a new stitch is only achieved to a limited extent. This is because with the CroMat prototype, a new stitch can only be formed based on a stitch suspended on an ANP. Therefore, manual removal of the fabric in production and mounting of a row with the desired working stitch is necessary for this formation of a new stitch at an arbitrary already formed stitch of the fabric.

This manual intervention in the automated crochet process slows down and complicates it, but, as with manual crochet, it enables the production of complex-shaped 3D textiles. This is demonstrated by the example fabrics produced in the form of a T- and double-T-beam. Thus, the intended goal of harnessing the possibilities of crochet technology for the production of complex-shaped textiles with the developed machine is fundamentally achieved. The CroMat crochet machine is in principle capable of producing near net-shaped composite reinforcements, which are difficult to produce with other textile technologies. The reproducibility is only limited by the manual re-hanging, which can be further automated in the future. As a result, the basis has been created for meeting the demand for future near net-shaped composites and machines that can produce them using crochet technology.

Moreover, the CroMat prototype enables the joining of textiles by manually suspending the rows to be joined on the same auxiliary needles and forming a new course in which the loops are pulled through both textiles. Thus, in accordance with the original intention, a novel technique for joining fabrics was also developed with the crochet machine.

To put it in a nutshell, in this work the first prototype for the automation of crochet, which is scalable to an industrially applicable crochet machine, was developed. The first tool for the design and automatic generation of patterns of machine crocheted textiles with a general framework for modeling crocheted fabrics was developed. Based on this, crocheted fabrics were studied with FEM for the first time. Also, for the first time, the tensile properties of crocheted textiles were systematically investigated, and new composites were created from them. Furthermore, machine-crocheted fabrics were examined for the first time and the possibilities of machine-crocheting of complex-shaped fabrics were demonstrated.

5.2 Outlook

The company partners in the *HaekelMasch* project are developing an improved industrial prototype of the CroMat crochet machine with the participation of the author at the time of completion of the present work. This revised machine can be placed between the elaboration and production phases of the innovation process according to Koltze and Souchkov [179]. In particular, the goal of this industrial prototype is to significantly increase the reliability and speed of the CroMat prototype's stitch formation process by upgrading to metal parts, linear guides, and motors according to industrial standards. The fundamental machine elements, axes and motion sequences remain identical in accordance with the provided industrial scalability of the CroMat prototype.

A specially designed motherboard and control system for the industrial CroMat machine, based directly on the current prototype, enable parallel operation of all motors and real-time communication with the EFS 920 yarn feeder. The dynamic change of yarn tension during stitch formation made possible by this allows in particular the reliable formation of HDCs to be significantly increased and generally allows the height to be adjusted. It also increases the range of yarns that can be used.

Due to the possibilities offered by parallel motor control, the sequence programs can be optimized in terms of speed. They can also be executed faster, as more powerful motors are going to be used in combination with improved linear guides (ball screw drives with higher positional accuracy at high accelerations than belt drives). A motorized fabric take-off is also to be added.

Based on the current state of the CroMat prototype, it is difficult to estimate the production speeds that can potentially be achieved. Nevertheless, it can be conservatively estimated that the stitch formation rates can be brought roughly into the range of the rates of manual crocheting. For an experienced crocheter, 2.9 s was measured for an SC [269]. Regarding the CroMat, this would be equivalent in more than a fourfold increase in speed and would result in the formation of an SL in under 2 s (cf. section 3.7). The maximum speeds of experienced crocheters are a good indication because the same motion sequences have been adapted for the machine without the advantage of being able to form a course at once as in knitting machines [17]. Therefore, the benefit of machine crocheting lies more in increasing reproducibility, which is essential for technical applications, and less in increasing the speed of production.

Presumably, the speed can be further increased by using specialized crochet machines. If only one type of stitch is to be formed, the speed can be increased compared to the general-purpose crochet machine by reducing the axes and moving masses. Future machine designs for other stitch sizes and yarn diameters are also imaginable. To adjust the stitch width, the distances between the auxiliary needles of a pair can be adjusted as long as reliable insertion of the crochet needle into the working stitch is possible. The distances between the ANPs can also be modified as long as the yarn guide fits through there. Beyond that, it may be necessary to develop needles in suitable sizes. In this context, the development of a special compound needle with two separately closable recesses arranged one behind the other would also be useful in order to enable the machine formation of double crochet stitches.

With regard to the expansion of the shaping capabilities of the CroMat crochet machine, fashioning points similar to those of straight bar frames can be added in the future, so that a stitch transfer to other ANPs is made possible, allowing INC and DEC to be used much more flexibly. In order to further increase the capabilities for the production of near net-shaped composite reinforcements, it would make sense to (partially) automate the re-hanging of a fabric with regard to a future CroMat crochet machine. Such re-hanging is necessary for complex shapes and the manual part should be reduced in view of a reproducible and cost-effective production.

In addition to machine improvements, it is necessary to further research machine-crocheted fabrics. In particular, the focus should be on near net-shaped composites, whose demand will increase in the context of the climate crisis and rising energy and raw material costs. Further research is a prerequisite for an actual, future application of machine-crocheted textiles in any technical field. Besides the application of crocheted textiles, the possibilities of joining based on crochet technology are to be further explored. The suitability of this novel joining technology in comparison to conventional processes needs to be investigated in the future.

The first major steps towards further exploration and harnessing of the great potential of crochet technology, especially with regard to complex-shaped textiles, have been taken by the CroMat crochet machine developed in this work. It is hoped that through this contribution more researchers and engineers will recognize the potential of this technology and will be motivated to continue this path.

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