Exploring expressive and functional capacities of knitted textiles exposed to wind influence

Citation for the original published paper (version of record):
Hörteborn, E., Zboinska, M. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3): 669-691.
http://dx.doi.org/10.1016/j.foar.2021.02.003

(article starts on next page)

ARTICLE IN PRESS
+ MODEL
Frontiers of Architectural Research xxx (xxxx) xxx

Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.keaipublishing.com/foar

Higher Education Press

SOUTHEAST UNIVERSITY

Research Article

Exploring expressive and functional capacities of knitted textiles exposed to wind influence

Erica Hörteborn*, **Malgorzata A. Zboinska**

Department of Architecture and Civil Engineering, Chalmers University of Technology, Göteborg, SE-412 96, Sweden

Received 26 October 2020; received in revised form 22 January 2021; accepted 14 February 2021

KEYWORDS
Textile architecture;
Knitted textiles;
Kinetic architecture;
Wind;
Aesthetic qualities;
Digital textile simulation

Abstract This study explores the design possibilities with knitted architectural textiles subjected to wind. The purpose is to investigate how such textiles could be applied to alter the usual static expression of exterior architectural and urban elements, such as facades and windbreaks. The design investigations were made on a manual knitting machine and on a CNC (computer numerically controlled) flat knitting machine. Four knitting techniques - tuck stitch, hanging stitches, false lace, and drop stitch - were explored based on their ability to create a three-dimensional effect on the surface level as well as on an architectural scale. Physical textile samples produced using those four techniques were subjected to controlled action of airflow. Digital experiments were also conducted, to probe the possibilities of digitally simulating textile behaviours in wind. The results indicate that especially the drop stitch technique exhibits interesting potentials. The variations in the drop stitch pattern generate both an aesthetic effect of volumetric expression of the textile architectural surface and seem beneficial in terms of wind speed reduction. Thus, these types of knitted textiles could be applied to design architecture that are efficient in terms of improving the aesthetic user experience and comfort in windy urban areas.

* Corresponding author.
E-mail addresses: erica.horteborn@chalmers.se (E. Hörteborn), malgorzata.zboinska@chalmers.se (M.A. Zboinska).
Peer review under responsibility of Southeast University.

https://doi.org/10.1016/j.foar.2021.02.003

Please cite this article as: E. Hörteborn and M.A. Zboinska, Exploring expressive and functional capacities of knitted textiles exposed to wind influence, Frontiers of Architectural Research, https://doi.org/10.1016/j.foar.2021.02.003

1. Introduction

Although textiles are not the most common building material, several good examples of textile architecture exist. An influential architect and theorist Gottfried Semper has claimed that the wall originates from woven structures, such as bast mats. In his seminal book "*The four elements of architecture*", he postulates that the true function of a wall is to serve as an enclosure instead of being merely a load-carrying structure (Semper, 2010). Textiles can, however, also be used to carry structural loads. Architect and engineer Frei Otto is perhaps the most well-known designer of tensioned, load-carrying architectural constructions. The work of Krüger (2009) demonstrates that the area of textile architecture shows great variation and richness of the design solutions, both for tensile and non-structural textiles.

Most examples of textiles in architecture use a woven textile, while the knitted structure is not as widely explored within this context. Compared to a knitted textile, in a woven structure the behaviour of the textile is more directly linked to the thread's strength and stiffness because the threads in the weave are almost straight. In a knit, the thread is forming linking loops. As a result, bigger deformations of the textile occur when forces are applied and the loops are stretched out.

Although scarce, examples of architectural designs and research work on knitted structures exist. For instance, the *myTread* and *Lumen* installations by Jenny Sabin (Sabin, 2013; Sabin et al., 2018), *Isoropia* and *The Tower* developed at the CITA - Centre for Information Technology and Architecture in Copenhagen (Deleuran et al., 2015; La Magna et al., 2018; Ramsgaard Thomsen et al., 2019), the *Knit Tensegrity Shell* project by Gupta et al. (2019) and Sean Ahlquist's sensory architecture (Ahlquist, 2015, 2016). These structures are, however, with some exceptions, mainly based on the principle of tensile textiles, in which the material is stretched until the structure is virtually stiff. They are designed to remain static and, in terms of geometric expression, are bound to an anticlastic surface typology only.

Another way to make use of the three-dimensional shaping possibilities with the knitted structure is to use it as a stay-in-place formwork for concrete or other composite structures. In this way, thin and material-efficient compression structures are produced. The *KnitCandela* is an example of such structures, cast in concrete (Popescu et al., 2020). The *Knitted composites tower* study, as well as other studies on a similar topic, provide further examples of composite shell structures, in which the knitted structure was hardened through applying resin (Liu et al, 2020a, 2020b). Similarly, different types of knits, sprayed with resin, were also explored to generate prototypes of façade panels (Tan and Lee, 2019). In initial tests, studies have also shown potential for knitted tubes to be used as formworks for concrete struts in a grid-shell structure (Pal et al., 2020). In explorations with more focus on the aesthetical appearance of a three-dimensional surface Scherer uses smocking techniques (i.e., gathering fabric in folds or wrinkles through a pattern of stitches) to create formwork for concrete structures (Scherer, 2019).

In contrast to the work mentioned above, this study aims to explore more loosely fitted and dynamic knits that are allowed to move, expand, and dynamically react to the action of wind, and through this change their geometric expression. For this research, the large-scale sculptures of Janet Echelman are an inspiration, but also the work from the fashion industry, such as Iris Van Herpen's new forms of textile movement in relation to the structure of the human body (Jordahn, 2020).

2. Existing work — wind-induced movement as a design variable

In architecture, examples of exterior textiles that are free to move in the wind are rare. One example is the fabric façade of a studio house in Almere, the Netherlands by CC-Studio, Studio TX, and architect Rob Veening. The façade is made from PTFE-coated fiberglass fabric, cut and placed as overlapping shingles that can move in the wind. The *Book House Pavilion* by Olga Sanina and Marcelo Dantas architects, as well as the *COS Space* by Snarkitecture are also examples of architectural structures that employ freely-moving textiles. Parts of the previously mentioned knitted installation *Lumen* by Jenny Sabine are also free to move. Common for these examples is that the motion of textiles is not orchestrated but rather spontaneous.

The flexible nature of the textile causes it to adapt to any force applied to it. Joïe Fuller was an artist that took the performance of textiles in dance to a new level. In her dance choreographies, she perceived her body as a structure that the textile is attached to and that guides the movement and shape of the textile piece. 'She became the moving vortex of billowing luminous silk. Movement of the body served only to set the silk in motion, and all movement activated the draperies' (Sommer, 1975, p. 3). More recently, Jody Sperling, Joïe Fuller, in a similar way uses voluminous, delicate textiles to enhance her performances. Taking this one step further, artist Daniel Wurtzel creates much the same effects, without the dancer, with his art installations, such as the *Magic Carpet*, *Pas de Deux*, and *Air Fountain*, in which it is the moving air that becomes the "body" directing the textile movement. The phenomenon of a textile set in motion by wind is also explored in fashion, where Yoshiki Hishinuma's *Kite Clothes* and *Air Clothes* from the 1980s are known precedents. The above examples can all be regarded as variations of loosely fitted textiles held up by a structure or body. Similarly, the building could also be regarded as a structural body that holds and directs the textile movement in combination with the action of wind.

There are also other instances of movement and shape change, which could be implemented in the design of architectural textiles. Jane Scott, for example, is achieving shape change through thoughtful patterning of single-bed knitted structures, making use of the fact that the geometry of the stitches in a single bed knit make the textile curl, and combining this effect with natural fibre yarns which absorb moisture, thus making the fibres in the yarns swell and therefore influence the shape of the textile piece (Scott, 2012, 2016). Obviously, such shifting of shape is represented by a slower change in appearance than the one achieved by using wind as a movement driver.

Outside the field of textile design, artists like Antony Howe and Ned Kahn are producing intriguing effects by including wind-induced motion into their structures. Howe's sculptures are balanced so that the slightest gust will generate a force strong enough to set the structures in motion, just like a light textile would be put in motion with the force of the wind. Kahn's *Wind Veil* is made from hinged aluminium plates free to move in the wind, creating an impression of textile-like ripples. It could also be noted that the works by these artists intersect conceptually and aesthetically with the field of textile architecture design. Antony Howe has collaborated with fashion designer Iris Van Herpen in her Hypnosis collection and Ned Kahn has created several kinetic structures involving textiles, as well as structures that give a textile impression.

3. Methods

3.1. Knitting techniques

There are two types of main bindings of kitted textiles - weft knitting, in which the yarns run horizontally, and warp knitting, in which the yarn runs vertically with respect to the direction of fabric formation (Ray, 2012) (Fig. 1). Thus, a weft-knitted textile could be produced out of one continuous yarn, while a warp knit requires several yarns. Common for all knitted structures is that they are built through intermeshing loops, also referred to as stitches. Loops forming a horizontal row are called a course, and a vertical row of loops is called a wale. This study focuses on weft knitting and the variations of this structure, because this knit can be produced on a hand-knitting machine as well as on automated machines. Weft-knitted textiles also have greater potential to form three-dimensional volumes compared to a warp-knitted textile that is knitted with a constant continuous width and is typically flatter (Elmogahzy, 2020). Hence, in this study, the term "knit" refers to the weft knit.

The knit's structure of loops is kept in place through friction between the treads, but the yarn can still move in the structure resulting in changed loop sizes. This entails that knitted textiles are generally more elastic compared to woven textiles. It also means that the yarns typically will not be stretched until the point of breakage, unlike in a woven structure (Francis and Sparkes, 2011). However, both the dimensional stability of the knitted textile (i.e., how well it keeps and retains its original shape and size during and after stretch) as well as the elasticity (i.e., stretch with recovery) depends on the type of the knit. As an example, a full rib structure will stretch more than a single-bed jacquard knit, which has to do with the number of yarns in the structure and how the loops and treads are interacting. The loop structure also enables a large variation in expression through alterations of stitches/loops. The possibility to decrease or increase the width of the knit, i.e., the number of stitches in a row (Fig. 2), combined with a partial knit, i.e., knitting one or several sections with more rows, enables three-dimensional shaping of large textile surfaces without cutting and sewing.

3.2. Machine knitting

Knitting machines can be circular or flatbed, with single or double bed, manual or automatic (Peterson, 2018). Furthermore, in a circular knitting machine the yarn carrier moves around needles placed in a circle, producing a fabric tube, whereas on a flat knitting machine the yarn carrier moves back and forth across the needles. The gauge number of the machine is a measure of the number of knitting needles per inch, which affects the appearance of the knitted structure and determines which yarns that can be used. The majority of samples presented in this study were knitted on a flatbed, manual, 8-gauge ("E8") knitting machine (Silver reed SK-840). The two of the pieces described in Section 4.4 were produced on a CNC flat knitting machine (STOLL CMS 330 TC).

The needle on a knitting machine could be set to either: "knit", "no-knit" (i.e., hold a stitch and do not add a new stitch), or "tuck" (i.e., keep the stitch from previous course on the needle and add a new stitch), see Fig. 3. Combining knitted loops with a held stitch ("knit" + "no-knit") will result in a float, seen as a straight line in the second course (row) from the top in Fig. 4 a, with the held stitch being the longer loop. Such a knitted structure with floats can have increased dimensional stability (Francis and Sparkes, 2011). A tuck stitch

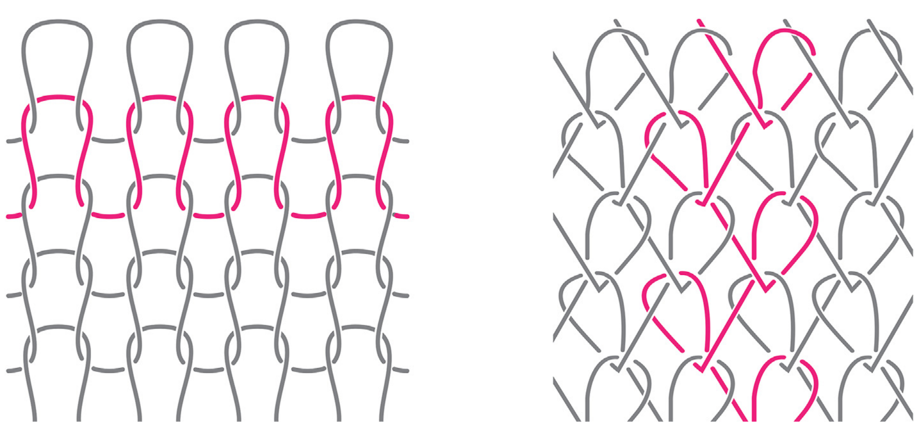

Fig. 1 The two main bindings of knitted structures (seen from the right side), left: weft knitting, right: warp knitting.

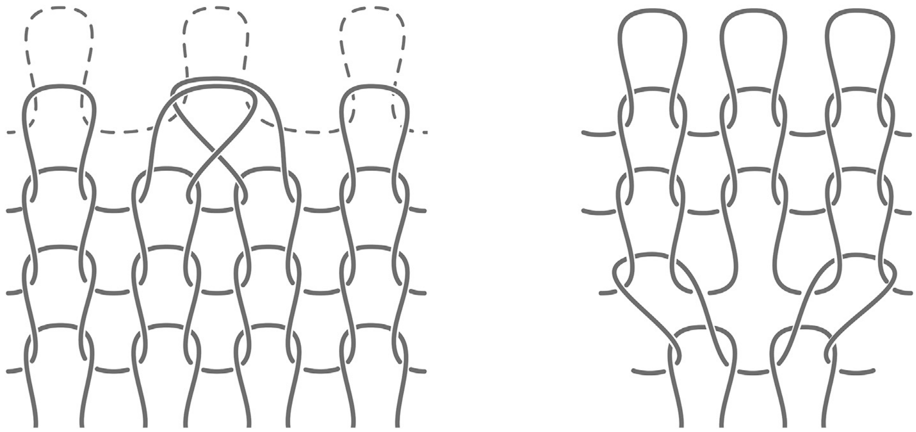

Fig. 2 Decrease (left) and increase (right) of a knit structure.

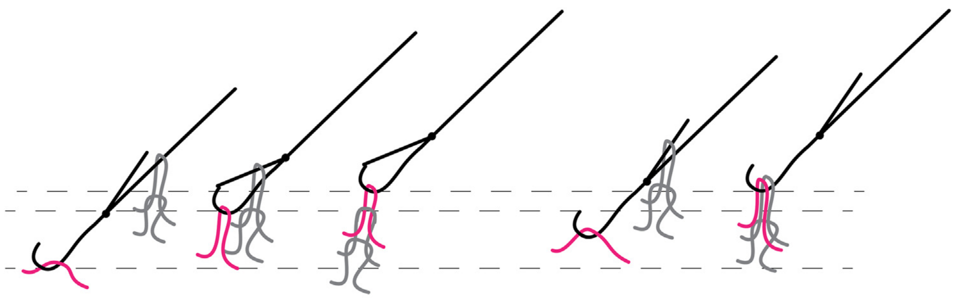

Fig. 3 Illustrating knitting needle and positions for knit and tuck-stitch.

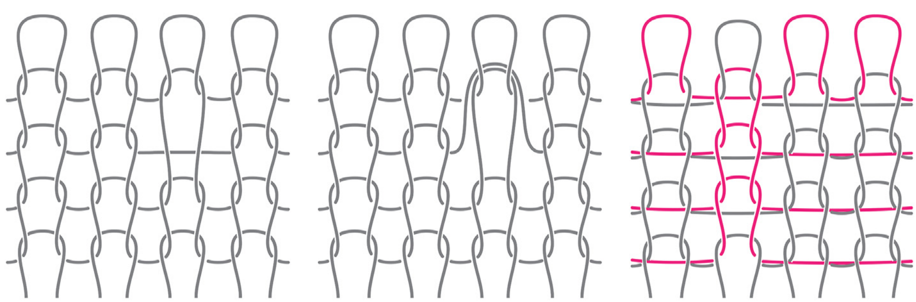

Fig. 4 Illustration of a) Slip stitch, b) tuck, c) jacquard.

is formed when a needle already holding a loop receives another loop and these are then knitted together (Fig. 4 b). Tuck-stitches could be placed above each other, resulting in multiple loops knitted together, limited only by the number of loops that the needle can hold and knit. To further add to the possibilities to vary a knitted textile, stitches can be transferred from one knitting needle to another, either manually on hand-knitting machines or mechanically on automated machines. The purpose of transferring the stitches could be to achieve aesthetic effects or to shape the textile's three-dimensionality. Some needles could also be put out of action and thus not used on a course (row), a section or a complete knit. For the knit in Fig. 5, all needles in the front bed are in action while in the back bed only every fourth needle is in action, thus generating different expressions on the back and front of the produced textile. Needles can also be in action only for a specific yarn, generating a jacquard, as in Fig. 4 c.

The left image in Fig. 1 is illustrating a single jersey plain fabric, which is knitted on one needle bed. The pattern for this structure can be drawn as in the top diagram in Fig. 6. Here, all needles in the "front bed" are set to "knit" and all needles in the "back bed" are set to "no-knit". This could be compared to the basic knit on a double bed, the full rib (Fig. 6, bottom image), where all needles are set to "knit". As mentioned before, this type of knit will stretch more than the single jersey, which can be deduced from the diagram of the yarn and the number of loops per width unit. In the diagrams/patterns in Fig. 6, it is also evident that a

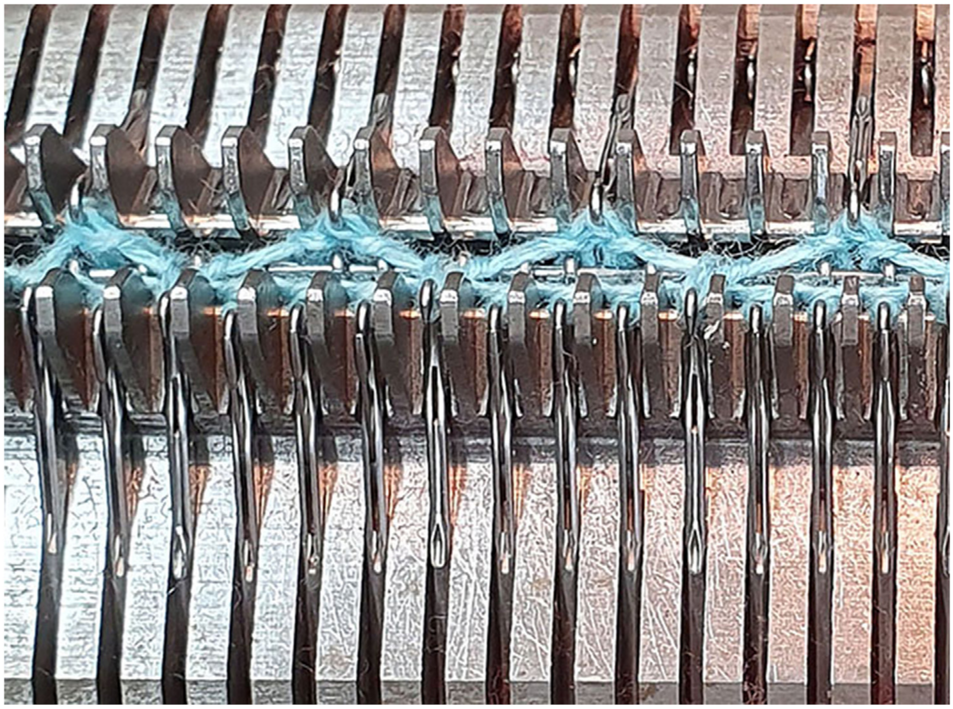

Fig. 5 Set-up in knitting machine, with all needles in action on the front bed and only every fourth needle in action in the back bed.

single bed knit will have a different expression on its right side and its purl side.

3.3. Physical setups for experiments with airflow

All samples, except for the bigger one described in Section 4.4, were mounted in Plexiglas frames, which made it possible to fix the entire edges of the samples instead of just clamping them at a set of points. The samples were attached to the frames at either two or all four edges, depending on the sample structure. The largest textile piece was mounted on a 1.7 m × 3 m wooden frame (Fig. 7 and Fig. 23). Same as with the Plexiglas frames, the textile was continuously clamped along the edge(s).

After mounting, all samples were exposed to the action of airflow. The airflow was generated using a Trotec R TTW 45000 Wind Machine, with an airflow rate of 12 650 l/s (45 600 m^3/h) and maximum air pressure of 70 Pa. For the smaller samples described in Sections 4.1-4.3, the fan was placed close to the textiles producing a direct airflow acting on the textile perpendicularly. This setup was used because it generated a stronger airflow, which was needed for some of the samples to change their appearance. The biggest textile piece presented Fig. 7, mounted on a wooden frame described in Section 4.4, was positioned at

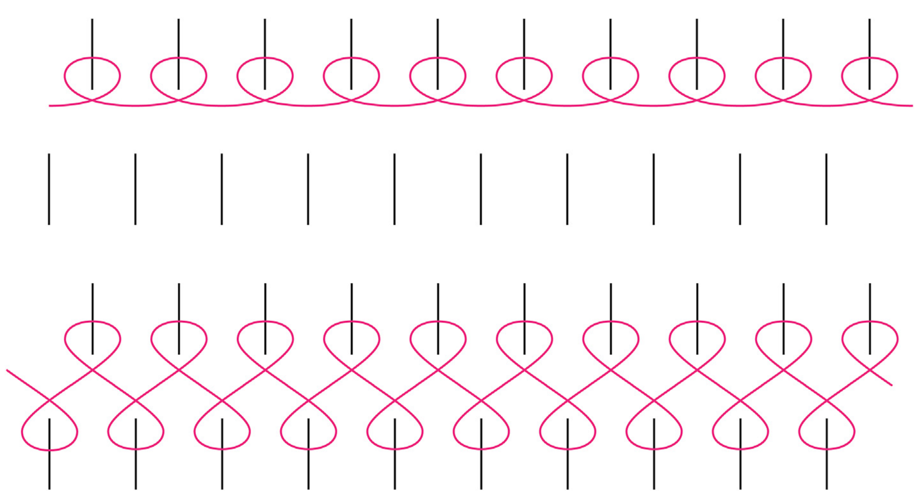

Fig. 6 A diagram of knitting needles, seen from above, with the yarn shown in red. Top: needle bed with single jersey. Bottom: needle bed with full rib.

Fig. 7 Wind-machine set-up for the larger drop-stitch sample described in Section 4.4.

an angle to the wind-machine, to generate more challenging conditions in terms of generating a three-dimensional volume, as well as to create a realistic scenario resembling the natural wind conditions outdoors.

4. Investigations of knitting techniques, resultant textile expressions and affordances

There is a three-level hierarchy of analysing and working with the design of the knitted textile: the fibre level (material of composition), the yarn level (twist and treads in the yarn), and the knitted structure/the textile level (stitch-composition). To shape certain properties of the produced textile piece, one, two, or all three of those levels could be altered (Scott, 2013). The variations of stitches and patterns, combined with a spectrum of yarns and materials, make the design possibilities seemingly endless. In the experiments for this study, the aim was to create three-dimensionality in the knitted textile, both on the scale of the surface structure and in the shape and volume of the finished textile/piece, and to explore the potentials of combining them with wind action. For this, variations of stitches and loop sizes were used, in some cases also in combination with different types of yarns having various roughness and thickness that all enhance the impression of three-dimensionality.

This section presents four different knitting techniques that could be interesting for creating three-dimensional shapes on architectural facades and windbreaks, both static and kinetic. The outcomes are investigated from an architectural design perspective. Thus, when discussing the structure of the surface, the changes in geometric expression are considered from the perspective of application at a scale much larger than that used for garments.

4.1. Tuck pattern

An effective and simple way to create a three-dimensional surface structure is to use the tuck stitch. The piece in Fig. 8 is knitted with three treads of wool yarn, stitch length 6, and a pattern of 5 tucks in a row, with altering positions (Fig. 9). The result is a zigzag billowing of the knit on the right side of the piece.

4.1.1. Behaviour of the model subjected to airflow

When strong airflow is applied, a global bulging of the entire piece is observed (Fig. 10). Yet, the knitting structure itself has little effect on the shape of the piece. The textile takes on a uniform sail shape. An interesting property is that the sample is form-stable - it does not fluctuate much in turbulent airflow. After the fan is turned off, it maintains the airflow-deformed shape. This behaviour is linked to the stiffness of yarns and stitch-length more than to the knitting structure itself. The wool yarns have high surface friction, which, in combination with tight stitch length, makes the yarn less prone to slide in the loop structure. Thus, the surface structure is maintained even under strong airflow, as can be seen in Fig. 10, and in the close-up in Fig. 11.

4.1.2. Potentials for architecture

This technique can be useful for generating sail-like architectural textiles with a textured, tactile, corrugated surface expression. The fact that the textile can maintain its shape after the force is gone could be used as a design element, allowing users to directly interact with the structure. However, it is likely that the form stability is difficult to achieve when the structure is scaled-up to architectural dimensions. Further research is needed to investigate which yarns and knitting parameters would have the best effect when combined with wind action and user intervention on a larger scale.

4.2. Hanging stitches

A three-dimensional draping effect can be created through hanging up stitches from previously knitted courses, in a similar manner as with the tuck stitch. However, here the

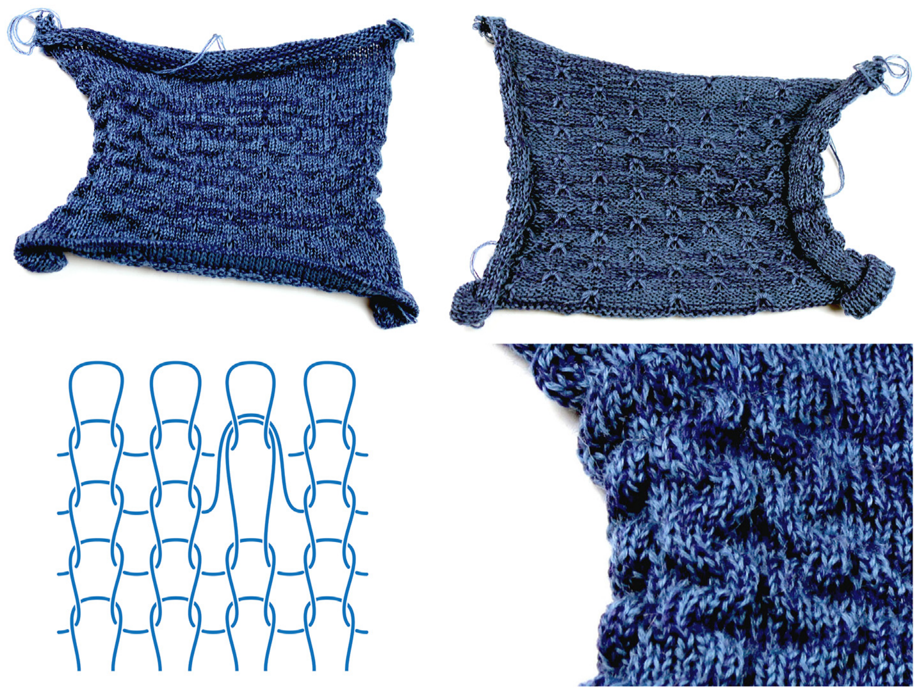

Fig. 8 Top: textile knitted with a tuck pattern, right side, and purl side. Yarns: wool 28/2 × 3 in two shades of blue, knitted with stitch-length 5, on 72 needles. Bottom: illustration of a single tuck-stitch and a close-up of knit.

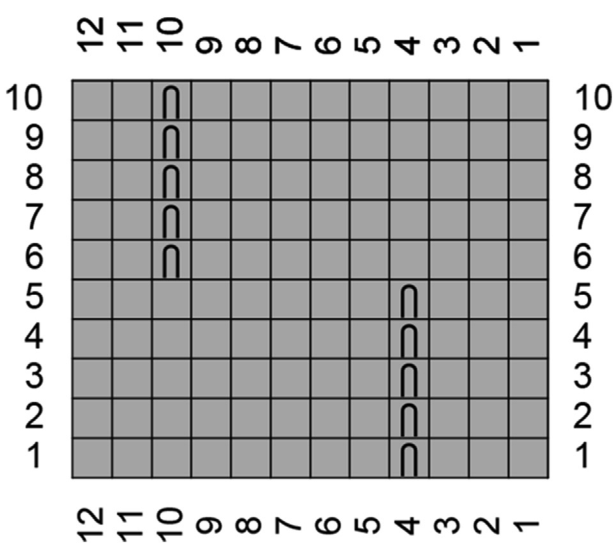

Fig. 9 Pattern for knit in Fig. 8. Where every cell represents a stitch in the structure and the loop-symbols represents tuck stitches (the pattern is repeated 6 times along the width of the sample).

courses in-between are left unaltered. Fig. 12 shows a sample, knitted with a combination of soft wool yarns (pink parts) and a stiff linen yarn (beige parts), in which this technique was used in combination with knitted stripes and variations in stitch length. A random number of rows was left in-between the hung stitches. Stitches were hung either to the left or to the right of their original wale (i.e., the vertical row of stitches). Additionally, in the top wool section of the sample, the stitches were hung in an altering repeated pattern to the left and right, to create a braided effect.

The thicker and heavier wool yarns are accentuated by a tighter spacing of the folds through hung stitches, and a shorter stitch length. In the linen sections, the stitches are picked up with a longer spacing in-between, creating bigger and looser folds. Due to its stiffness, the linen yarn holds its shape well and its folds are billowing out.

4.2.1. Behaviour of the model subjected to airflow

Same as with the tuck-sample, described in Section 4.1, the hanging-stitches sample picks up movement from the applied airflow, generating a uniform sail-like shape. Yet, the folds and bulges in the structure are only partially affected (Fig. 13). As can be seen in the close-up in Fig. 14, the linen sections are marginally bulging out with airflow applied, while the stitches, as well as the vertical fold in the wool section, are to some degree stretched. There could be several reasons for this. Firstly, as with the tuck-sample, the friction of the yarns and the stitch length, in the wool sections, decrease the possibility for shape deformation. Secondly, the linen yarn has a high bending stiffness (compared to most yarns) which keeps the loop-structure in place. These sections are also wind-permeable, due to the single yarn and long stitch length, causing a larger portion of the air to pass through these sections, instead of pushing against them. In addition to this, the folds of the hanging-stitches-structure block part of the force from the airflow. Finally, the sides of the textile piece curl inward (a natural effect of the single-bed knitting structure's stitch geometry, as mentioned in Section 2), which makes the wind-affected area smaller than the textile's actual size. To increase the proneness of the textile geometry to be affected by wind, a lighter, more

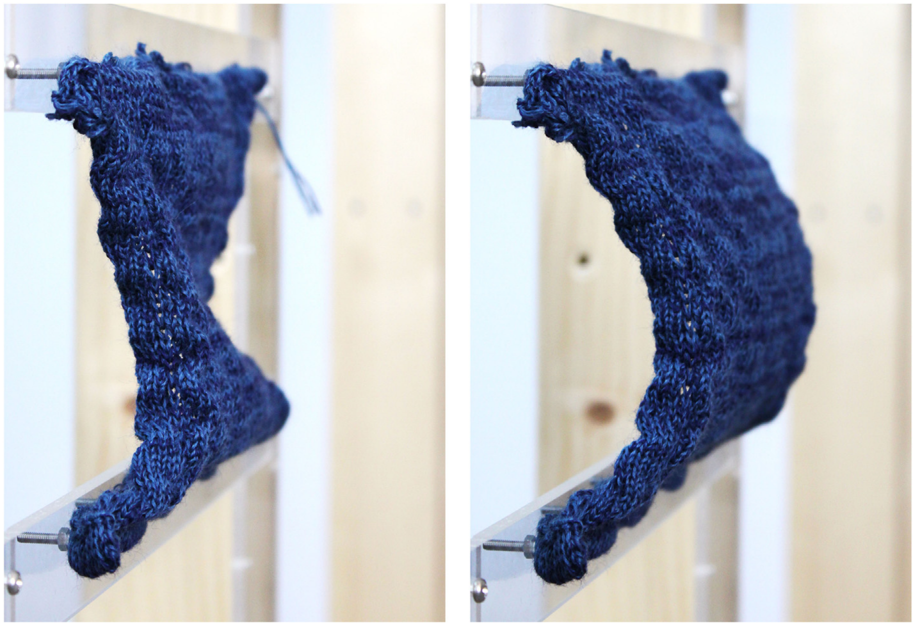

Fig. 10 Tuck-knit. Left: before airflow was applied. Right: exposed to airflow.

flexible yarn could be chosen, at the expense of a less pronounced tree-dimensional effect in the structure without airflow applied. Further explorations of the knitting pattern could be made to diminish the curling effect of the piece, for example by designing a form-stable edge of the knit while maintaining the folds in its inner parts.

4.2.2. Potentials for architecture

This technique shows potential for creating three-dimensional draping effects. The stiffer yarns chosen for this sample generate large, bulky folds, which keep their shape well even when exposed to airflow. This could be an interesting effect, featuring a global volume that changes with the wind and a local geometry that remains constant. A different, more dynamic expression for local folds would be achieved by using a lighter yarn. Resulting in a non-homogenous architectural textile which, depending on wind direction and structure of the knit, would feature a variation of stiff, unaffected zones, and more loose ones that take various shapes.

4.3. False lace

The sample produced using the false lace knit in Fig. 15 was knitted with wool yarns (green) combined with a linen yarn (yellow). Since it is a false lace jacquard, the linen and wool are knitted together in the green sections (light grey sections in the pattern in Fig. 16, left), while only the linen yarn is knitted elsewhere (dark grey sections in the pattern in Fig. 16 left), with the wool yarn as floats (yarns hanging loose) on the purl side. The single bed knit's tendency to curl, in combination with the denser knit, cause the wool patches to deform inwards and, as a result, the looser linen knit deforms outwards, generating a pronounced textured, tactile, surface.

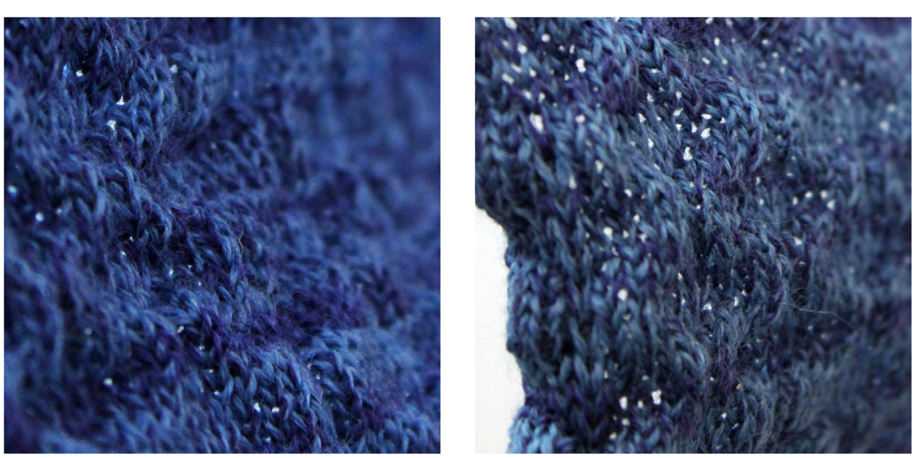

Fig. 11 Tuck-knit, close-up. Left: in relaxed state. Right: exposed to airflow.

Fig. 12 Top: sample produced using the hanging stitches technique, seen from the right, and purl side. Yarns: wool 28/2 × 3 in two shades of pink, stitch length 5, and uncoloured linen, stitch length 7. Knitted on 80 needles. Bottom: illustration of the knitting technique and a close-up. Note, this sample was fixed at a set of points to keep edges from curling in.

Fig. 13 Hanging-stitches knit. Left: in relaxed state. Right: exposed to airflow (Note: mounted with the knitting direction from left to right).

Fig. 14 Hanging-stitches knit, close-up. Left: in relaxed state. Right: exposed to airflow.

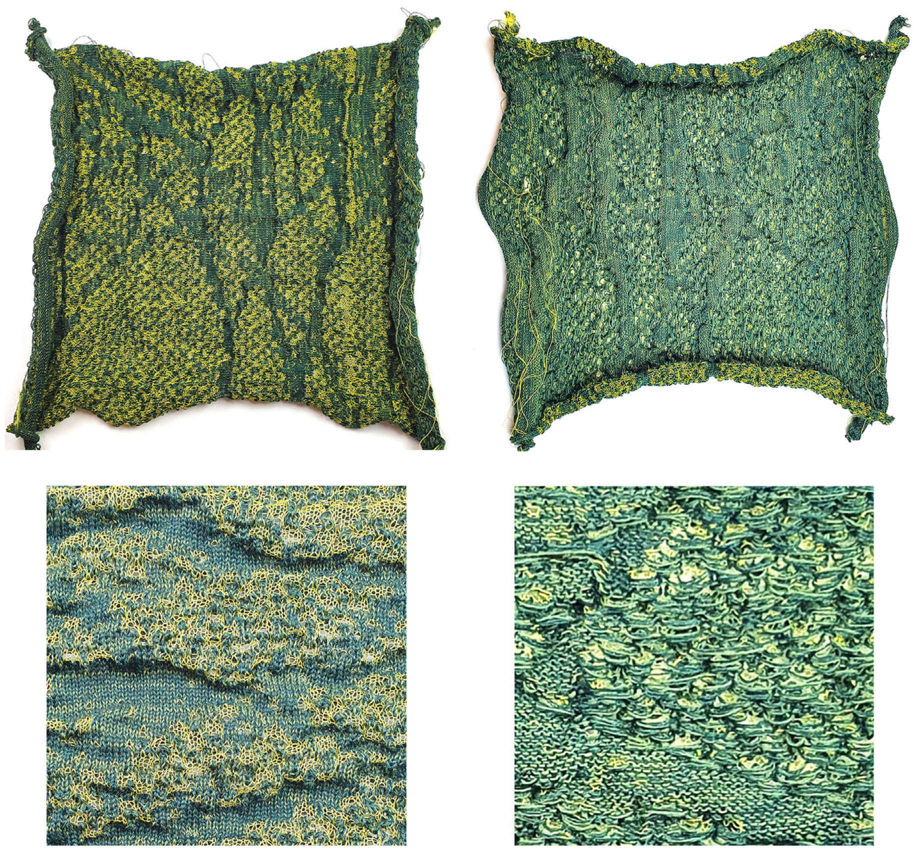

Fig. 15 Top: false lace pattern, based on fractals, right side, and purl side. Yarns: wool 28/2 × 3 in two shades of green, and a linen yarn in bright yellow. Knitted with stitch-length 5, on 162 needles (note sample is knitted from left to right in the image). Bottom: Close-up of right side and purl side. (Note: On top images the knitting direction is from left to right, while the bottom images are rotated so that the knitting direction is from top to bottom.)

4.3.1. Behaviour of the model subjected to airflow

The elasticity of the knitted structure becomes evident as the sample is stretched out into a doubly curved, saddle-like shape, when the airflow is applied, while having a flat shape when no force is applied (Fig. 17). The anticlastic geometry of the wind-deformed piece is the result of the mounting topology, i.e., the fixing only at two edges, as well as the single-bed knit's inherent tendency to curl. Thus, the knitted textile piece captures more air along the top and bottom edge, due to higher pressure in these areas. The global stretching effects are also observed at a surface texture level, as the examined piece becomes porous and permeable when airflow is applied (Fig. 18).

4.3.2. Potentials for architecture

Three elements in this technique have architectural relevance: its allowance to combine yarns with varying properties, its capability of varying the density of the knit, and

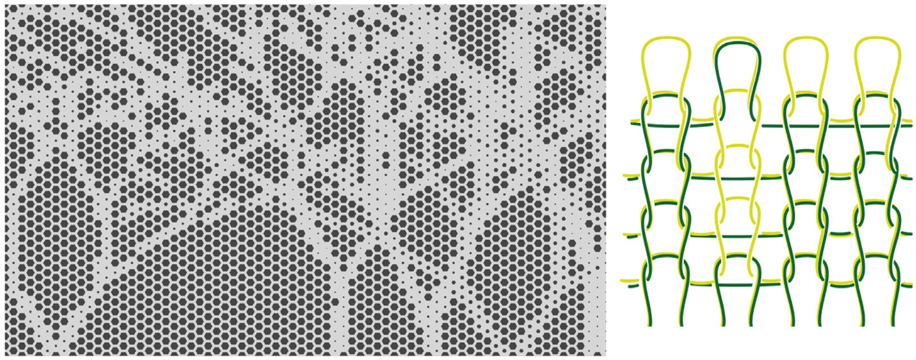

Fig. 16 Left: pattern for sample above. Right: illustration of a false lace knit-structure.

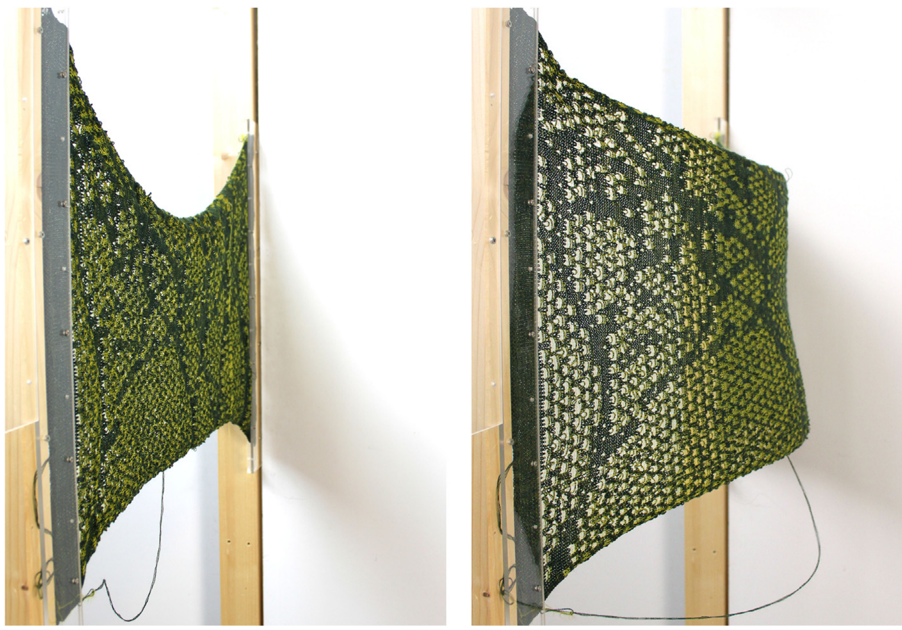

Fig. 17 False lace knit. Left: in relaxed state. Right: exposed to airflow (Note that the piece was mounted horizontally with respect to the knit direction).

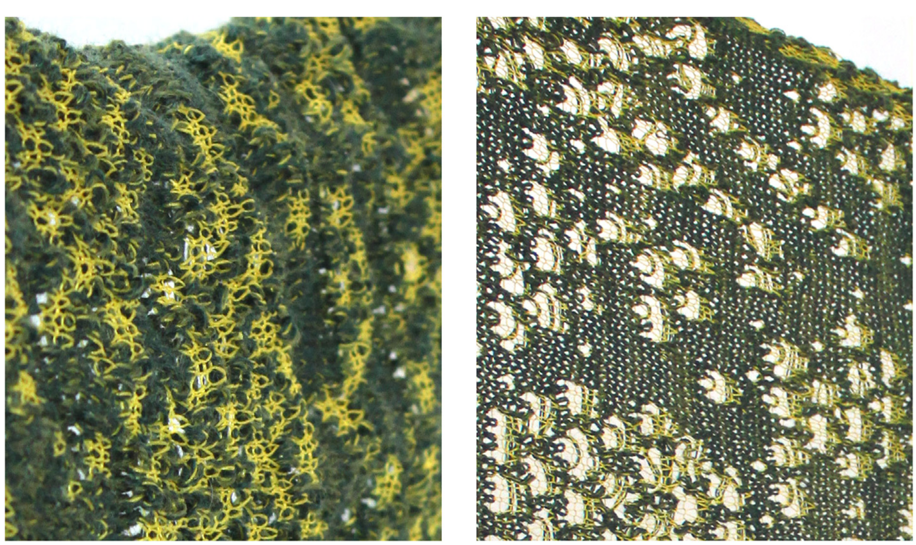

Fig. 18 False lace knit, close-up. Left: knit in relaxed state. Right: exposed to airflow.

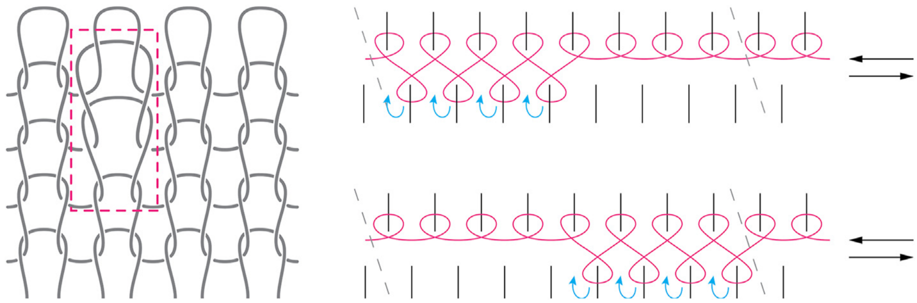

Fig. 19 Drop stitch. Left: illustration of knit with 2 dropped stitches. Right: "needle bed pattern" for 4 dropped stitches.

the elasticity that it introduces to the textile piece. Thus, it could be varied in endless textile patterns and yarn combinations. With elasticity in the structure, it adds the possibility to create voluminous shapes in the wind that are flat when no force is applied. The gradation in textile surface thickness and density can also be used as a strategy for wind force damping but also have additional architectural functions, such as solar shading.

4.4. Drop stitch

The drop-stitch technique allows for large variation in loop size, and thus large variation in the density of the textile. Set up as a single bed knit, the bigger loops are produced by putting the needles in the front bed into action for one or several knitting courses, to, later on, drop these stitches and therewith give the loops that lie opposite to the dropped needles more yarn (Fig. 19).

The sample in Fig. 20 is knitted with a repeat of 8 needles in action and 8 out of action on the front bed, dropping the stitches after 8 rows, and then racking the bed by 8 steps, which switches the position of the in- and out-of-action needles. The change of the location of the dropped stitches makes the 8 $\times$ 8 stitches with the bigger loop size appear hexagonal. Through the variation in loop size, a variation in the density of the textile is created, as well as a three-dimensional effect. Here, the cotton yarns are combined with a thin polyester effect yarn.

Fig. 20 Top: Drop stitch knit, right side and purl side. Yarns: cotton 20/2 $\times$ 2 in grey together with a gold coloured effect yarn. Knitted with stitch-length 6 on 80 needles. Bottom: Close-up of right side and purl side.

This technique and pattern were iterated into a bigger pattern based on an image depicting a set of mathematical fractal trees (see Appendix A). This allowed for several options of tensioned paths when mounting the structure as well as when airflow was applied. The resulting piece (Fig. 23) was produced on a CNC flat knitting machine (STOLL CMS 330 TC), using cotton yarns with plating. With its big patches of dropped stitches, there was a need to manually pull out the stitches (Fig. 24).

A section of the same pattern was also tested in combination with a three-colour, birds-eye jacquard (Fig. 25), using the same type of cotton yarn and the same machine (STOLL CMS 330 TC). Here, there is a significant difference in the appearance between the right side of the textile and the purl side. While the right side is three-dimensional, the purl side is flat, combining the bird's eye-pattern with floats.

4.4.1. Behaviour of the model subjected to airflow

The variation in loop size causes variation in the textile surface density and in flat versus three-dimensional zones, which becomes apparent when airflow is applied (see Figs. 21, 23, and 25 and, in the online version of this paper, Video 1 and Video 2, Supplementary video related to this article can be found at https://doi.org/10.1016/j.foar.2021.02.003). The sample in the first iteration with this technique takes on a global sail-like shape when airflow is applied. The "bubbles" on its surface, resulting from the longer stitch length, are stretched out when airflow is applied (Figs. 21 and 22) while hanging loosely otherwise.

The bigger piece in Fig. 23 shows the greatest variations in shape when subjected to airflow. The large textile pockets effectively catch the wind and form voluminous, billowing shapes and soft ripples travelling along with them. The stiffer, two-dimensional patches in-between the pockets keep the overall structure in place. These effects are most apparent when the textile is fixed along both the top and the bottom edge. The sparse structure in the pockets allows for a large portion of the air to pass through, preventing the structure from getting heavily strained.

Initial tests show a reduction of average wind speed from 5 m/s, measured 4.5 m from the wind machine (position 1 in Fig. 26), to approximately 0.5 m/s on the other side of the textile (position 3). Similar values were measured for both mounting options. In these tests, the frame was positioned 7.5 m from the wind machine. The windspeed was also reduced by approximately 1.5 m/s just in front of the frame (position 2). Point 2 and 3 is roughly 20 cm from the frame or textile.

The floats in the drop-stitch pattern combined with birds-eye jacquard (Figs. 25 and 27) enable to have a flat, tensioned global surface whose pockets can change shape in the wind, generating an aesthetic effect that departs from the sail-like or saddle-like effects observed in the other samples.

4.4.2. Potentials for architecture

From an architectural design perspective, the drop stitch technique, with its possibilities for varying the loop size and the density of the textile, creates opportunities in several aspects. Firstly, the parts with a smaller loop size are stiffer, which offers structural design possibilities for the mounting as well as for applying other loads parallel to the surface. Secondly, the variations in the porosity of the textile surface add the possibility to regulate the amount of wind and light that will be let through, making the textile act as a filtering device for the environmental factors. Finally, as the number of loops does not change, the longer loops generate a larger area within the billows, contributing to a fluctuating three-dimensional surface effect, that continuously changes its geometric and aesthetic appearance. Therefore, the variation in stiffness of the textile piece achieved through the single jersey knit and the presence of sections with dropped stitches can help to

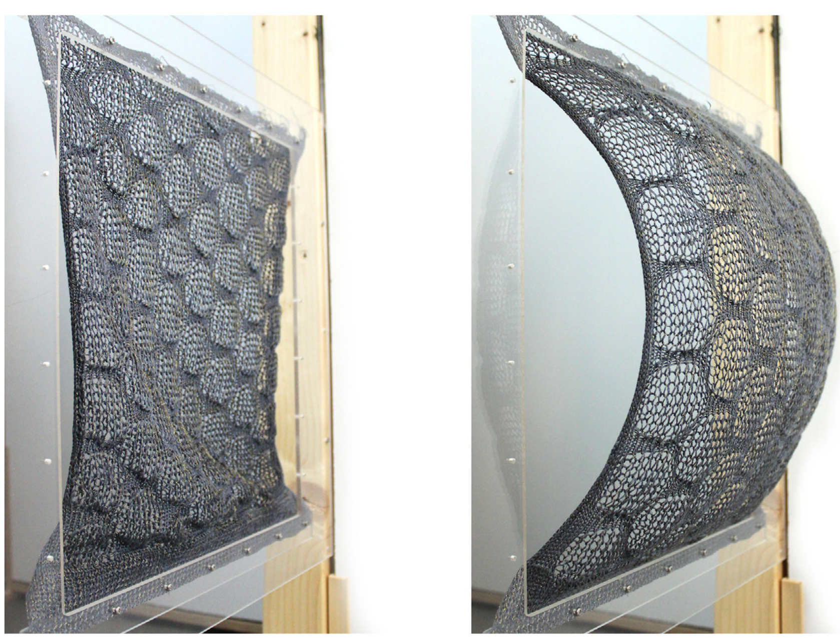

Fig. 21 Drop stitch knit. Left: in relaxed state. Right: Exposed to airflow.

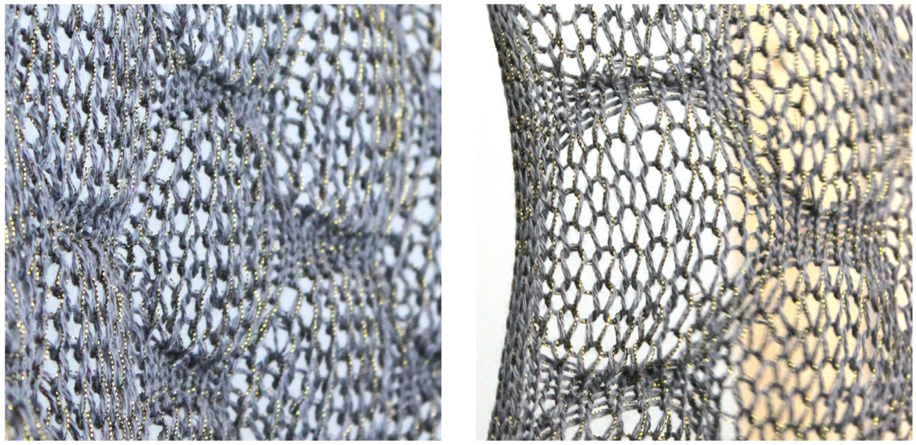

Fig. 22 Drop stitch knit close-up. Left: in relaxed state. Right: Exposed to airflow.

Fig. 23 Wind studies of the drop-stitch textile mounted on a wooden frame. Top: textile only fixed at the top. Bottom: textile attached to both top and bottom of the frame.

combine load carrying with loose and soft aesthetics. With the combination of dropped stitches and jacquard, the two-dimensional sections have high dimensional stability and the floats on the purl side restrict the textile from being stretched sideways, thus adding more control of the global geometry. This is also adding a load-carrying potential to this type of architectural textile and can result in a hybrid structure that has stiffer pre-tensioned zones combined with loose zones allowed to deform.

5. Digitally simulating textile behaviour in wind

For the knitted structures presented in this article, physical prototypes and explorations of their behaviour are essential in a design process. Nevertheless, it is interesting to investigate the potential of digital simulations of textile behaviour, and if these could be used as an early-stage design tool, guiding the design of knitted patterns. In a previous study, the authors worked with a combination of physical and digital simulations, to design kinetic structures from smart textiles (Hörteborn et al., 2019). That study concluded that while it is difficult to make accurate digital simulations of textile in wind, less accurate models are still useful in a conceptual design phase, as a complement to physical prototypes.

5.1. Challenges in simulating dynamic behaviours of loose textiles subjected to airflow

Digital simulation of large deflections of a textile moving in the wind is a so-called fluid-structure interaction (FSI) problem. It is a challenging area of study within computational fluid dynamics (CFD), as the movement of both the wind and the textile need to be tracked, but also the forces that the two exert on each other. It also requires substantial computational power, and accurate simulations can take many days to carry out. A broader discussion of these challenges can be found in the previous study by the authors (Hörteborn et al., 2019).

In general, for wind analysis, mesh-based methods are favoured, but creating a mesh that represents the environment around a studied object becomes problematic when large deflections of the textile occur. Textile structures could be simulated with this type of method, using a portioned, Eulerian-Lagrangian approach, as shown by two of the few studies that investigated the dynamic behaviour of textiles moving in the wind (Michalski et al, 2009, 2011). However, the studied textile structures were tensile umbrella structures, which have a relatively controlled movement, in contrast to the loose structures in this study. For conceptual design of loosely fitted textile structures, it seems more reasonable to look at mesh-free methods, such as smoothed particle hydrodynamics (SPH), which is used within computer animation (Hörteborn, 2020). This type of simulation has the potential to be close to real-time (depending on available computation power) and does not run into problems when large deformations occur. Common tools used by architects for wind simulations such as Maya

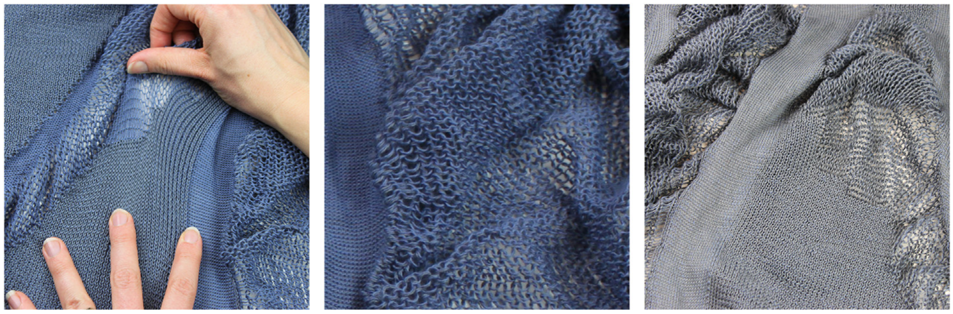

Fig. 24 Left: dropping stitches on the purl side. Middle: Close up of the purl side stitches dropped. Right: Close up of the right side stitches partially dropped.

Fig. 25 The drop-stitch pattern combined with three-colour jacquard. Left: the right side of the piece. Right: the purl side of the piece in detail.

nCloth and Grasshopper in combination with the add-ins Kangaroo 2 or Flexhopper use a particle-based method (Cuvilliers, 2020; Felbrich, 2020; Piker, 2017; Wang, 2015). These simulations are all based on position-based dynamics (PBD) (Bender et al., 2013; Müller et al., 2007) or variations of this method.

In the case of knitted structures, there is also an additional complexity, represented by the loop structure of the textile, which is kept in place through friction forces, as described in Section 3.1. For simulations at the loop level, a hexagonal grid representation, approximating the physical arrangement of the loops, is useful, with grid nodes placed at intersections between the yarn/loops, as shown in Fig. 28. Ideally, these nodes should be able to slide along some of the links, when the applied forces are higher than the friction forces. This method has been used for artistic purposes in computer graphics and animation (Cirio et al., 2017). For larger models with architectural dimensions, this level of detail is not possible due to the computational cost. Schmeck and Gengnagel (2016) are, however, using a courser hexagonal grid for structural analysis of a knitted textile hybrid pavilion. When generating a knitting pattern based on a three-dimensional surface model a quad mesh is usually used (Liu et al, 2020a, 2020b; Narayanan et al., 2019; Popescu et al, 2018, 2020).

The short description above, concerning the complexity of digitally simulating large deformations of soft materials like textiles subjected to airflow, is not a full overview of the subject. Rather, it aims to indicate that such simulations are very complex. In fact, for several reasons, physical wind-tunnel tests are still widely used for wind analysis (Hörteborn et al., 2019; Kraft, 2010). The computational cost, as well as the time to set up a digital model for wind simulations, are some of the key factors in this. However, also the physical scale model becomes problematic for physical wind analysis. One of the reasons is that a small irregularity in the model's structure can have a large impact on the result.

This may become a problem when building components are represented as scaled-down models, with a lower level of detail than the 1:1 scale. Additionally, it is difficult to scale the Reynold's number, *Re* which is the ratio between the inertia forces and the viscous forces at a point in a fluid flow:

$$Re = \frac{\rho v D}{\mu},$$

where ρ is the density of the fluid (1.2 kg/m^3 for air), v is the velocity of the fluid, D is the characteristic linear dimension (for a rectangular body, it is the width (m) normal to the flow), and μ is the dynamic viscosity of the fluid (18×10^6 Pa $\times$ s is typical for air). Thus, it is a dimensionless number. It gives information about whether or not airflow is turbulent. A low Reynold's number means a steady, parallel flow while turbulent flows have Reynolds numbers greater than 3000 (Aynsley, 1999). As the characteristic linear dimension, D, varies greatly between a 1:1 building component and its scaled model representation, also the Reynold's number will be significantly different.

Finally, for architectural textile structures, the representation of the textile material, with its low thickness and high flexibility, in a scaled-down model of a building is difficult (Hörteborn et al., 2019). Looking at this the other way around, it also becomes difficult to represent the imperfections and material textures naturally occurring in the real world in a computer simulation. For wind simulations, it is not only the building model itself but also the surroundings of the building that are of importance for the results.

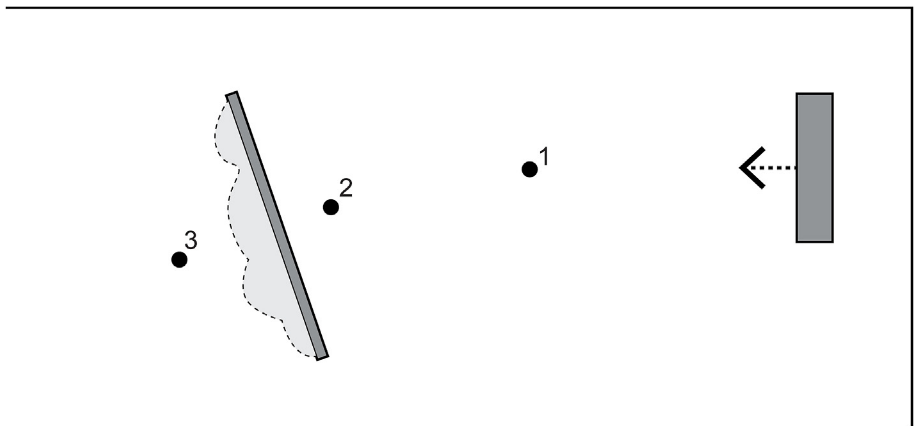

Fig. 26 Diagrammatical representation of the setup for wind speed measurements, in top view. All measurement points were located at a height of 1.1 m above the floor.

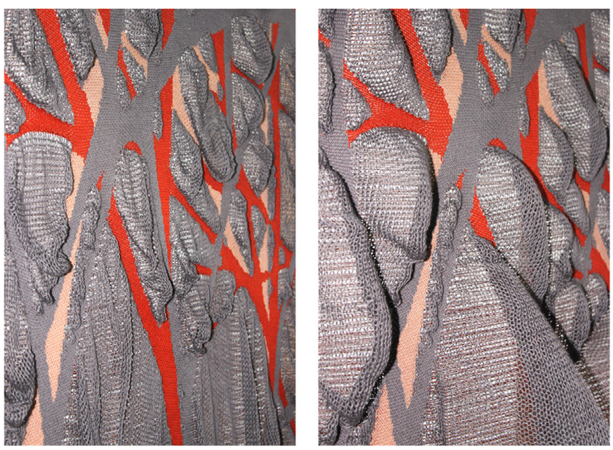

Fig. 27 The drop-stitch pattern combined with three-colour jacquard, close-up. Left: relaxed state. Right: with airflow applied.

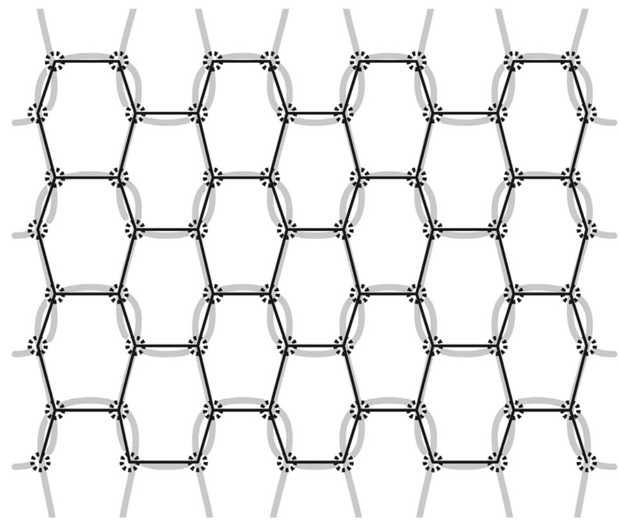

Fig. 28 Representation of a knitted structure as a hexagonal grid, based on the friction nodes in the structure.

5.2. Basic simulations of textile behaviours using programs for architectural designers

For the simulations of the prototypes presented in this article, a 3D modelling environment Rhinoceros 3D, version 6, was used, supported with a visual programming interface for parametric design - Grasshopper. Within that environment, two add-ins for parametric wind simulations were employed - Kangaroo 2 (included in Rhinoceros 3D version 6) and Flexhopper (Felbrich, 2018, 2020). They were chosen as they give real-time visual feedback of the simulation, allow for quick changes of the simulation parameters, and enable high customisation of the tested models. Finally, they are accessible and often used by architects.

Based on the structure of the knitted textile and on how kitting patterns are generally represented, a quadrangular (quad) mesh was chosen for the simulations. Alternative meshes were also investigated, as shown in Fig. 34.

The simulations of the four knitting techniques fall into two categories. The first category concerns the tuck and hanged stitches and is represented by introducing springs in the model. For the second category, concerning the false lace and the drop stitch, the mesh representing the textile is divided into sections with different parameters numerically describing two main textile properties, i.e., the stitch length and permeability.

5.2.1. Simulation with added springs

For the tuck pattern and the hanging stitches technique, the springs could be given varying lengths, in this way representing the loops hung or grouped together on the purl-side of the knit. This principle resembles smocking, i.e., using a stitching technique to gather fabric. The Flexhopper add-in was chosen here as the simulation tool, as it provides good user control and an overview of several parameters that affect the behaviour of the textile material. It also has components that integrate springs into the system of mesh face nodes and edges. The node indices are associated with a simulated spring, at the start- and endpoints of lines in a given pattern. For the tuck simulation, the bitmap pattern, used earlier on for the knitting machine, was employed here to generate these lines. For the hanging stitches technique, on the other hand, which was a manually generated

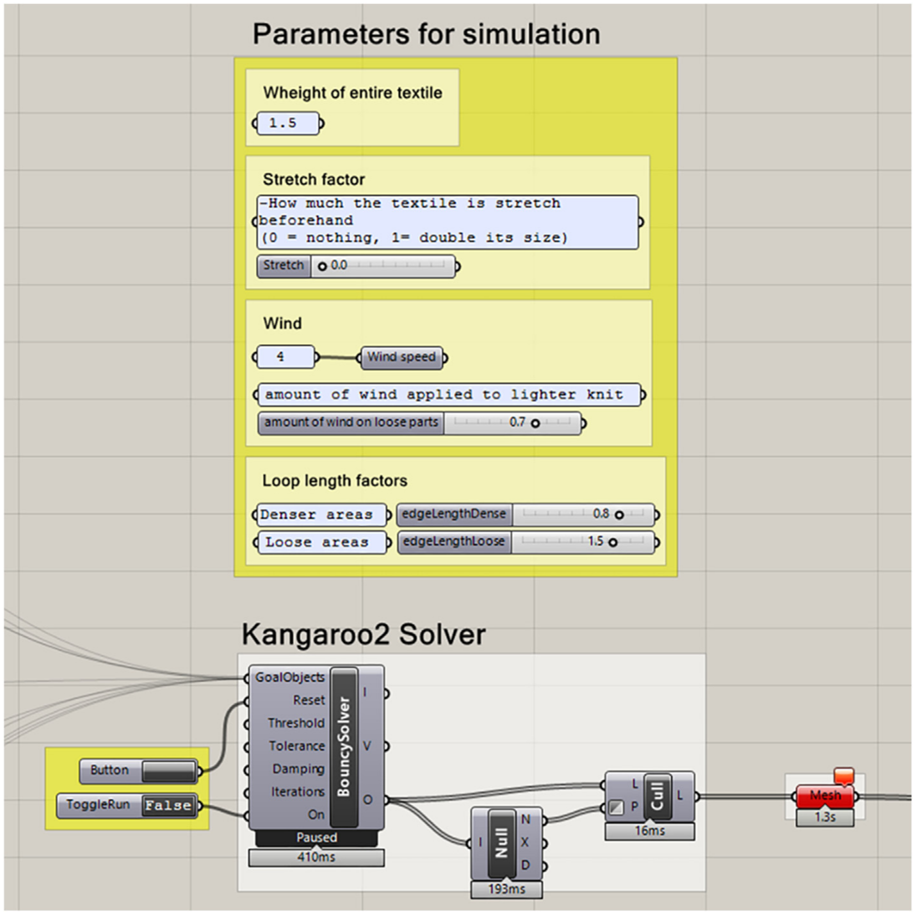

Fig. 29 The main parameters and the computational solver used for the simulation of the drop stitch sample.

pattern, the lines were drawn in a Rhinoceros 3D model and then parameterized in the visual programming environment of Grasshopper, within which Flexhopper was installed.

5.2.2. Simulation using mesh patches with varying properties

The samples knitted with the false lace and drop-stitch technique have patches that were given different properties in the digital simulation. In the false lace sample, the biggest difference between the patches of the pattern was the permeability. In the drop stitch samples, it was permeability but, even more importantly, the stitch length. For these samples, Kangaroo 2 was chosen as the simulation tool. The starting mesh was divided into two sets of patches based on the pattern image (the same as used for the knitting machine). The sets of patches were given different goals. The first goal, which differed between the two, was represented by different stitch lengths, achieved by assigning a new length for the edges in the mesh. The second goal represented the textile structure's permeability and was simulated by applying less wind force on areas with higher permeability (Fig. 29).

5.3. Simulation results

For models having a high number of mesh faces, it is not possible to achieve real-time simulations on a personal computer with a high-end graphics card and processor, with either plugin. Flexhopper simulations generally have higher speed because the add-in employs the graphics processing unit (GPU) for calculations. In general, for the produced simulations none of the models gives an accurate representation of the physical behaviour. At this stage, the drop stitch simulation was the closest to representing its physical counterpart. Simulations like these are, however, to some extent useful in the early stages of the design process, as a rough sketching tool. It is possible to generate and save image frames of the simulation and use them to compare various design options for the textile patterns. If more computing power were available, it would also be possible to test variations of the simulation parameters with real-time visual feedback.

5.3.1. Tuck pattern simulation

The prototype digitally simulated in Flexhopper does not exhibit the same s-shaped bulging as in the physical piece (Fig. 30). However, although not identical, the similarities in the bulging of the textile make the simulation useful as an early-stage design sketch. In Flexhopper, it is easy to adjust the bending stiffness in the textile, and simulated bending stiffness is essential in the representation of a stiffer knit like this one, made from wool yarns.

A simulation of the tuck pattern was also done using the Kangaroo 2 add-in. Here, the knit pattern was

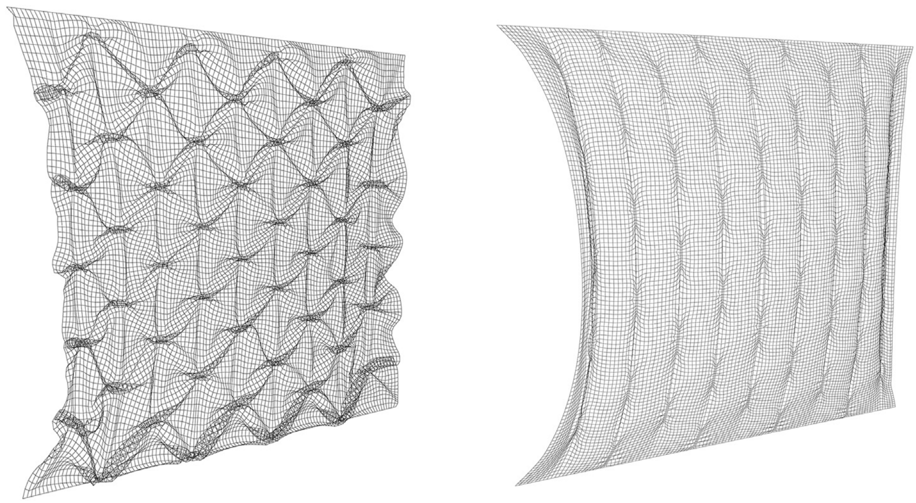

Fig. 30 Right: simulation of tuck pattern, using springs to represent the tuck-stitches. Left: simulation of the tuck stitch, using patches with shortened mesh edges.

approximated by shortening the mesh face edges around the tuck stitches. As can be seen in Fig. 30, the simulation was not as successful in displaying the bulging of the tuck stitches. In both of the tuck pattern simulations, the same sail-like homogenous bulging on a global level was observed, just as in the physical test.

5.3.2. Hanging stitches simulation

This simulation in Flexhopper was not able to fully capture the pronounced draping effect from the physical prototype, even if similarities between the physical and the digital model are evident (Fig. 31). The smoothening of the draped folds in the textile, when airflow was applied, was more pronounced in the digital model, compared to the physical. It is likely that the digital prototype could more accurately mimic the physical prototype by exploring combinations of parameters describing the line pattern, the bending stiffness and the amount of mesh length that needs to be added to allow for large folds and draping. Further experiments are needed to explore if such a parameter set could be derived.

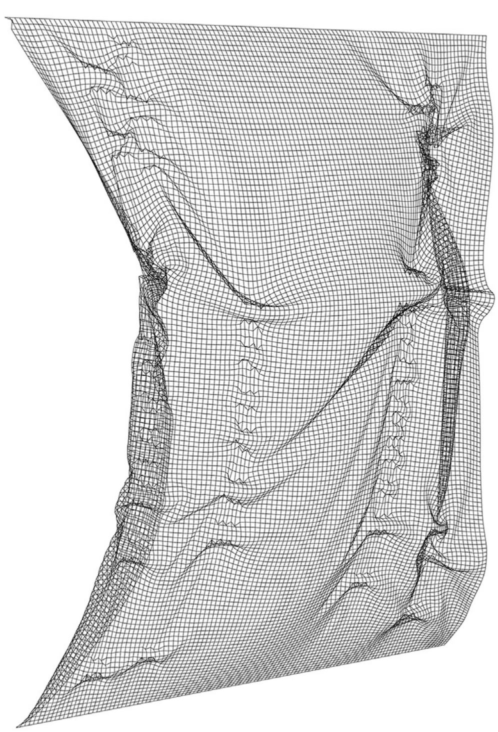

Fig. 31 Simulation of the hanging stitches knit, using springs to represent the hung stitches.

5.3.3. False lace simulation

The digital representation of the false lace pattern in Kangaroo 2, using mesh patches with a higher and lower amount of wind applied, did not have much impact on the global shape of the simulated textile, as shown in Fig. 32. This was also the case for the physical prototype. Examined from up close, a slight variation in the mesh occurs, but it is hardly noticeable. With the simulation techniques explored in this study, it was not possible to simulate the bulging and curvature in the physical piece that results from the geometry of the loop structure in a single bed knit. Nor was the variation and change in transparency and density of the knit possible to simulate at this stage.

5.3.4. Drop stitch simulation

The simulation of the drop-stitch technique, with its large and pronounced variation of the geometry, works well using Kangaroo 2. At a global level, bulging occurs just as in the physical piece (Fig. 33). At a local level, the loose textile pockets are shaped into bulbous volumes, mirroring the behaviour of the physical model.

Different mesh types and densities were explored for this simulation, some of which can be seen in Fig. 34. In principle, the triangle mesh exhibited a more faceted appearance and added diagonal stiffness, which is negligible in the physical knit.

Additionally, to get a hint of the structural effects that the wind is causing on the knit, a visualisation of the

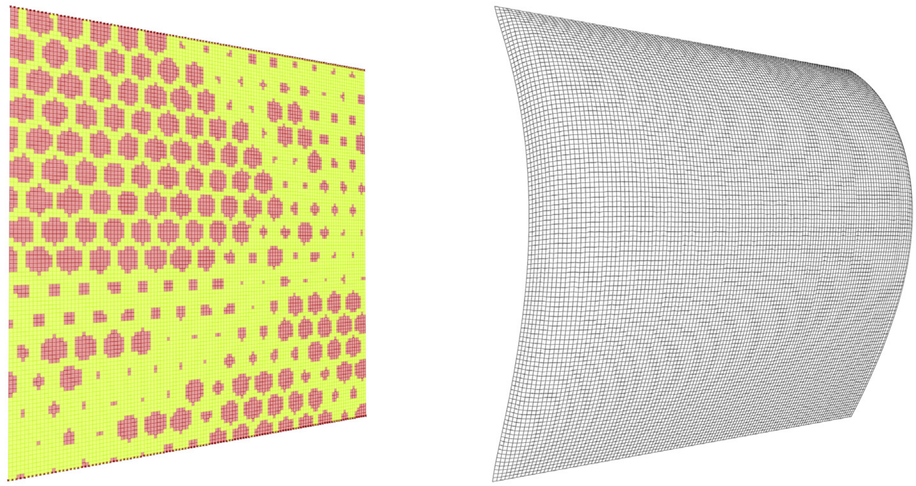

Fig. 32 Left: mesh patches representing the varying properties of the false lace pattern. Right: wind simulation of the false lace knit.

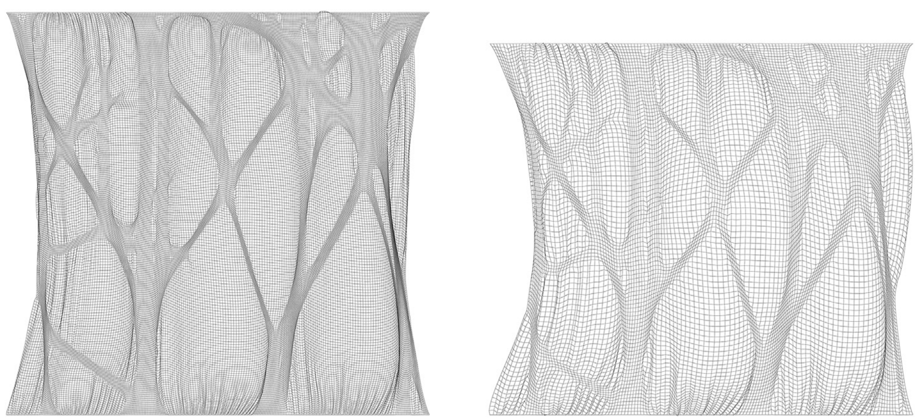

Fig. 33 Simulation of the drop-stitch technique, with quad-meshes of varying resolutions, produced with Kangaroo 2. The mesh to the left is also stretched slightly in the simulation to closer represent how the physical piece was mounted on the frame.

changes in length of the edges in the mesh was done, as an attempt to visualize the most strained areas (Fig. 35). As all values in the model, as well as the simulation method itself, are approximations and little physical data is added to the model, these results are difficult to verify from a structural engineering standpoint. The strain variation is, however, visually compliant with the distribution of strains observed in the physical model.

5.4. Concluding remarks regarding the simulation results

To accurately simulate the behaviour of these types of knitted structures is difficult, if not impossible, with the current techniques and computational power. It is, however, possible to simulate parts of the behaviour at a level acceptable for a conceptual design stage, also as a tool to use in a dialogue with a textile designer or a knitting machine technician to express the design intentions prior to producing the physical pieces. Due to the limitations of the digital method, it is important to compare the simulation results with physical tests.

A downside of the simulations carried out in this study is that, due to the computational cost, they are restricted in terms of the mesh resolution as well as the size and detail in the textile pattern. The heavy computations also restrict the possibilities of real-time feedback, which makes it more difficult to detect smaller wind-induced movements and other details affecting the aesthetic appearance of the textile surface. It should also be noted that the simulation algorithms developed in the two add-ins used in the experiments are still at a development stage and could likely be improved through further research.

6. Conclusion and discussion

The presented study aimed to examine and identify the potentials of four knitting techniques for shaping aesthetic architectural textile elements subjected to the action of wind. The main limitation of the study was that it embraced investigations of textile samples produced mainly as the first design iteration. The study could be developed further by iterating the knitting parameters of those initial textile designs towards a greater number of textile pieces and

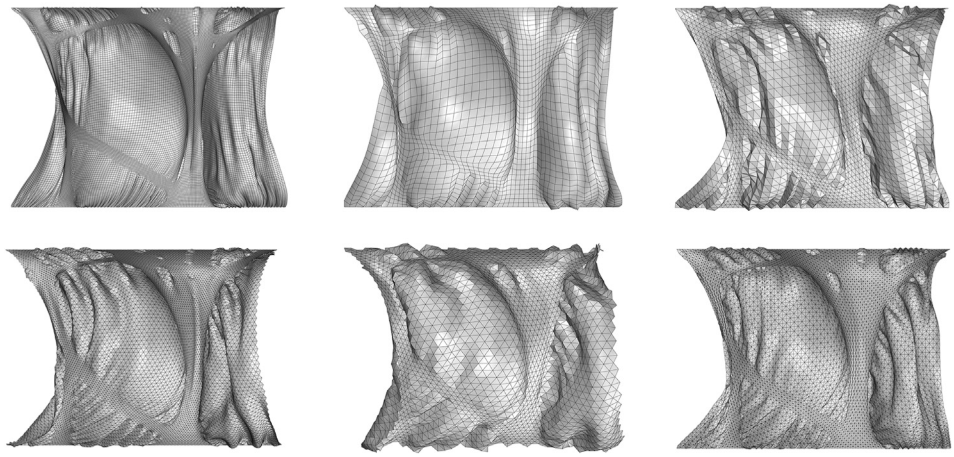

Fig. 34 A selection of the tested mesh types. Textile knits are represented by a mesh surface right.

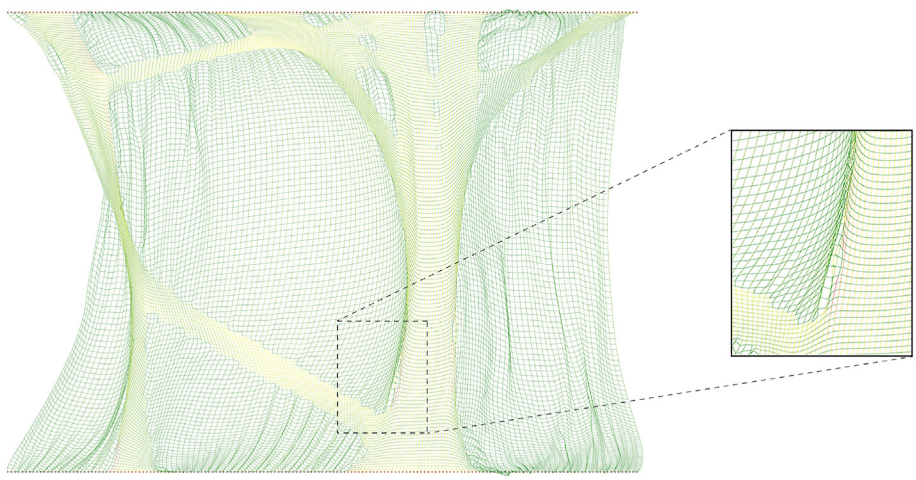

Fig. 35 Visualisation of strain in the knit, where red represents the most strained links in the mesh and green the least strained ones.

simulations that exhibit even more pronounced and varied reactions to airflow and wind. Digital simulation methods and systematic ways of translating the yarn structure of the knitting techniques into simplified mesh representations could also be further studied and developed.

6.1. Potential architectural functionalities and applications

Results from the study indicate that the drop stitch knit shows strong potential in terms of producing a highly pronounced, expressive textile surface with proneness to observably change its shape under the influence of airflow. Thus, it seems suitable for designing various types of structures, e.g., freestanding windbreaks in urban waterfronts, load-carrying facades and roofing, as well as lightweight shelters against wind and dust in dry, arid and windy climates.

The drop stitch knit allows for creating heterogeneous textile pieces with performance zones varying across the surface of the material. In this way, a part of the energy from the wind will be absorbed as motion in the textile as well as filtered by the textile. The relatively open structure should make the textile better cope with stronger winds at the same time as it becomes sufficiently lightweight to pick up movement also from light winds. The movements and structure are resembling the already proven positive effects seen in natural windbreaks, such as trees and bushes. Such textile windbreaks could be an interesting alternative in local situations where greenery cannot be used. Also in more extreme climates, such as those where sandstorms occur, it could be used to prevent access of dust and sand into the interior lightweight shelters clad with these textiles. Hence, there is a reason to believe that it may well be designed as both an aesthetically attractive as well as an efficient structure.

The sections with higher density and increased dimensional stability have great potential to be engaged in structural load carrying within the building skin. This is especially applicable for textiles that include the jacquard pattern, in which the denser patches exhibit high dimensional stability. Hence, it becomes relevant to include the design of the load paths in the overall design of the textile knits, which, due to the robustness of the knitting technique, can be well aligned with the desired structural load carrying role that accompanies the aesthetic effects.

The hanged-stitches technique shows similar capacities as the drop-stitch technique with a highly pronounced and expressive surface-structure that could, potentially, change its appearance under the influence of airflow, in combination with load-carrying possibilities. Further iterations are, however, needed to explore this alternative. There are also difficulties with scaling up the textile piece, produced using this technique, as the stitches need to be hung manually. Thus, a larger version of this piece cannot be produced on a CNC-knitting machine, using the exact same technique. Nevertheless, similar effects could be achieved for example through manipulation, like smocking, of a finished single jersey knitted textile, possibly combined with partial knitting. It could also be interesting to look further at smart textiles whose structures can be changed using heat, to further enhance the draping effect, structural stability and load-carrying potentials. In this case, the chesterfield and line sample presented in another study done by the authors could be used as inspiration (Hörteborn et al., 2019).

In terms of absorbing wind energy, elastic yarns could also be explored, achieving stronger elasticity than in the knit-structure itself and creating a piece that remains flat in calm weather while stretching and altering its shape in strong wind. In addition, textile techniques that employ partial knitting as well as three-dimensional shaping through decreased and increased number of stitches are also interesting to explore further in this context.

6.2. Potentials with enhancing the user experience and interaction

We all have a sensory relationship to textile materials, for example through the clothes we wear and the furniture we use. It is a material that invites to be gotten close to, touched, and interacted with (Hörteborn, 2020). As discussed earlier, the type of knitted structures presented in this study has big potential to be developed into efficient, urban windbreak structures that define the space and create comfortable wind environments. However, the intention is also that such textiles invite to be interacted with directly by people, rather than being merely admired from a distance. If form-stable knits, like the presented tuck-sample, were developed into such interactive structures, the city inhabitants could form and reconfigure them on days when wind is not present, taking an active part in the shaping of the aesthetic expression of their immediate built environment. Dumitrescu (2013) is pointing out that it is important to plan how the physical design will be related to and interacted with regarding its relationship to the human scale. The design explorations presented in this study are all intended to address both scales, i.e., an architectural scale of a building or an urban landscape element, and the scale of the human body and the human hand. Thus, the loop structures of the presented knits are designed to provide an enhanced tactile experience of the fabric when in contact with the human hand, while also enabling experiencing the structure as part of the architectural and urban environment that intricately reacts through its shape to the changes in natural wind conditions.

The tactility and touch friendliness are something that Ahlquist (2016, 2015) makes use of in his knitted hybrid structure *StretchPLAY*, where he also adds sensory effects to the structure, such as sound and light. That structure was developed as a response to a challenge for children with Autism Spectrum Disorder in filtering multiple sensory inputs, but its design makes it intriguing for most people. Another example of enhancing the sensory user experience of space is the *Lumen* installation by Jenny Sabin et al. (2018), in which yarns that change colour in sunlight and integrated interactive systems were used to create spaces that engage users. *Breathing Room* and *Slow Furl*, by Thomsen and Bech (2011), also use electronic devices and shape change of a textile installation to encourage users to manipulate the position of the textile and therefore have their personal influence on the nearest surroundings. In the *Knitted Heat* project, Dumitrescu and Persson (2011) investigated heat as means to induce surface transformations of knitted textiles, with an aim to broaden the influence of users on the aesthetic appearance of textile patterns.

Digital sensing and reacting systems like the ones mentioned above could be integrated also into the structures presented in this study. Alongside the physical action of wind, electro-mechatronic devices could be embedded within them to enrich the multisensory interaction experience of users if wind is not present, but also as a means to amplify the visual and tactile experience of form and expression change induced by the wind.

6.3. Hinders and opportunities for knitted textile applications in architecture

There are several thresholds that might hinder the design of loosely fitted knitted structures in an architectural context. The first one is the lack of possibilities for architects to create sketches for knitted structures. The textile design software and machines for producing knitted structures are not affordable and easily accessible. Their use requires an extensive understanding of the knitting technique, the software itself, and the knitting machine setups. It is also not a straightforward task to translate the three-dimensional geometry representations, typical for the standard 3D modelling tools used by architects, to the representation conventions used in the knitting design software (Liu et al., 2020b). Gives an overview of the state of the art in this aspect. Although some authors (McCann et al., 2016; Narayanan et al., 2018; Popescu et al., 2018) presented methods of transforming three-dimensional meshes, representing architectural surfaces, to knitting patterns. These tools could never replace the knowledge of a textile designer. Therefore, it seems that the best solution for a successful application of knitted textiles on an architectural scale would be a cross-disciplinary collaboration, in which the abovementioned methods of translation from 3D models to textile design patterns could be very helpful in communication and design iteration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was financed by the Chalmers University of Technology Foundation. The knitted pieces in this paper were produced within the course 'Knitting Technology, advanced level' (AX2TA1), led by prof. Delia Dumitrescu at the Swedish School of Textiles, University of Borås. Prof. Dumitrescu also gave valuable inputs on the knitting designs presented in this article.

Appendix A. Pattern for drop-stitch knits

The image in Fig. A1 was the base for the drop-stitch pattern of knits in Figs. 23 and 25. For the first sample, the light grey patches are knitted with drop-stitch and all other colours as single-bed knit (single jersey). For the sample that combined drop stitch with three-colour birds-eye jacquard, only a section of the pattern was knitted. For this piece, the light grey patches were knitted with drop-stitch and the rest knitted in birds-eye jacquard, with colours corresponding to the ones in the pattern. Thus, the dark grey and light grey colour in the pattern were knitted with the same colour, but different knitting structure.

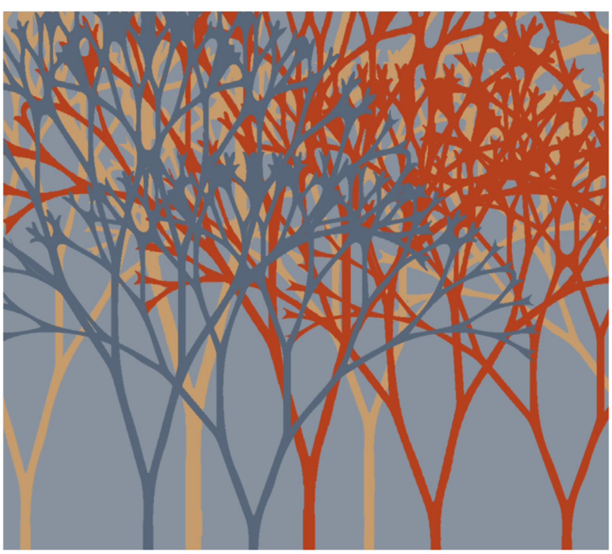

Fig. A1 Image for drop-stitch patterns.

References

Ahlquist, S., 2016. Sensory material architectures: concepts and methodologies for spatial tectonics and tactile responsivity in knitted textile hybrid structures. Int. J. Architect. Comput. 14, 63–82.

Ahlquist, S., 2015. Social sensory architectures: articulating textile hybrid structures for multi-sensory responsiveness and collaborative play. In: Computational Ecologies: Design in the Anthropocene: Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture. ACADIA, Ohio, USA, pp. 263–273.

Aynsley, R.M., 1999. Shape and flow: the essence of architectural aerodynamics. Architect. Sci. Rev. 42, 69–74.

Bender, J., Müller, M., Otaduy, M.A., Teschner, M., 2013. Position-based methods for the simulation of solid objects in computer graphics. In: Eurographics (STARs), pp. 1–22.

Cirio, G., Lopez-Moreno, J., Otaduy, M.A., 2017. Yarn-level cloth simulation with sliding persistent contacts. IEEE Trans. Visual. Comput. Graph. 23, 1152–1162.

Cuvilliers, P., 2020. The Constrained Geometry of Structures : Optimization Methods for Inverse Form-Finding Design. Thesis. Massachusetts Institute of Technology.

Deleuran, A.H., Schmeck, M., Quinn, G., Gengnagel, C., Tamke, M., Thomsen, M.R., 2015. The tower: modelling, analysis and construction of bending active tensile membrane hybrid structures. In: Proceedings of IASS Annual Symposia 2015, pp. 1–13.

Dumitrescu, D., 2013. Relational Textiles: Surface Expressions in Space Design (PhD Thesis). University of Borås.

Dumitrescu, D., Persson, A., 2011. Exploring heat as interactive expressions for knitted structures. Nordes (4).

Elmogahzy, Y.E., 2020. 10 - textile fabrics. The Textile Institute Book Series. In: Elmogahzy, Y.E. (Ed.), Engineering Textiles, second ed. Woodhead Publishing, pp. 249–274.

Felbrich, B., 2020. Flexhopper. WWW Document. GitHub: FlexCLI. Available online at: https://github.com/HeinzBenjamin/FlexCLI. (Accessed 24 February 2020).

Felbrich, B., 2018. FlexHopper. WWW Document. Food4Rhino. Available online at: https://www.food4rhino.com/app/flexhopper. (Accessed 20 January 2021).

Francis, N., Sparkes, B., 2011. 3 - knitted textile design. In: Briggs-Goode, A., Townsend, K. (Eds.), Textile Design, Woodhead Publishing Series in Textiles. Woodhead Publishing, pp. 55–87e.

Gupta, S.S., Tan, Y.Y., Chia, P.Z., Pambudi, C.P., Yogiaman, C., Tracy, K.J., 2019. Knit tensegrity shell. In: Proceedings of IASS Annual Symposia, pp. 1–9. Barcelona.

Hörteborn, E., 2020. Textile Architecture Informed by Wind. Chalmers University of Technology, Gothenburg.

Hörteborn, E., Zboinska, M.A., Dumitrescu, D., Williams, C., Felbrich, B., 2019. Architecture from textiles in motion. In: Proceedings of IASS Annual Symposia, pp. 1–8.

Jordahn, S., 2020. "There Is So Much in Fashion that Is Unexplored" Says Iris Van Herpen. Dezeen. WWW Document. Available online at: www.dezeen.com.

Kraft, E.M., 2010. After 40 Years Why Hasn't the Computer Replaced the Wind Tunnel? ARNOLD ENGINEERING DEVELOPMENT CENTER ARNOLD AFS TN.

Krüger, S., 2009. Textile Architecture (Textile Architektur). Jovis, Berlin.

La Magna, R., Fragkia, V., Längst, P., Lienhard, J., Noël, R., Šinke Baranovskaya, Y., Tamke, M., Ramsgaard Thomsen, M., 2018. Isoropia: an encompassing approach for the design, analysis and form-finding of bending-active textile hybrids. In: Proceedings of IASS Annual Symposia. IASS, pp. 1–8.

Liu, Y., Chai, H., Yuan, P.F., 2020. Knitted composites tower — design research for knitted fabric reinforced composites based on advanced knitting technology. In: Design in the Age of Humans — Proceedings of the 25th CAADRIA Conference, pp. 55–64. Bangkok, Thailand.

Liu, Y., Li, L., Yuan, P.F., 2019. A computational approach for knitting 3D composites preforms. In: The International Conference on Computational Design and Robotic Fabrication. Springer, Singapore, pp. 232–246.

McCann, J., Albaugh, L., Narayanan, V., Grow, A., Matusik, W., Mankoff, J., Hodgins, J., 2016. A compiler for 3D machine knitting. ACM Trans. Graph. 35, 1–11.

Michalski, A., Haug, E., Bradatsch, J., Bletzinger, K.-U., 2009. Virtual design methodology for lightweight structures — aerodynamic response of membrane structures. Int. J. Space Struct. 24, 211—221.

Michalski, A., Kermel, P., Haug, E., Löhner, R., Wüchner, R., Bletzinger, K.-U., 2011. Validation of the computational fluid—structure interaction simulation at real-scale tests of a flexible 29 m umbrella in natural wind flow. J. Wind Eng. Ind. Aerod. 99, 400—413.

Müller, M., Heidelberger, B., Hennix, M., Ratcliff, J., 2007. Position based dynamics. J. Vis. Commun. Image Represent. 18, 109—118.

Narayanan, V., Albaugh, L., Hodgins, J., Coros, S., Mccann, J., 2018. Automatic machine knitting of 3D meshes. ACM Trans. Graph. 37 (3), 1—15.

Narayanan, V., Wu, K., Yuksel, C., McCann, J., 2019. Visual knitting machine programming. ACM Trans. Graph. 38 (4), 1—13.

Pal, A., Chan, W.L., Yi, Ying, Chia, P.Z., 2020. Knit concrete formwork, design in the age of humans. In: Proceedings of the 25th CAADRIA Conference. CUMINCAD, Bangkok, Thailand, pp. 213—222.

Peterson, J., 2018. Knitting Technology, Products & Production. Textile support Scandinavia HB.

Piker, D., 2017. Kangaroo Solver [WWW Document]. Kangaroo Group on Grasshopper Forums. Available online at: https://www.grasshopper3d.com/. (Accessed 14 January 2021).

Popescu, M., Rippmann, M., Van Mele, T., Block, P., 2018. Automated generation of knit patterns for non-developable surfaces. In: Humanizing Digital Reality. Springer, Singapore, pp. 271—284.

Popescu, M., Rippmann, M., Liew, A., Reiter, L., Flatt, R.J., Van Mele, T., Block, P., 2020. Structural Design, Digital Fabrication and Construction of the Cable-Net and Knitted Formwork of the KnitCandela Concrete Shell. Structures.

Ramsgaard Thomsen, M., Sinke Baranovskaya, Y., Monteiro, F., Lienhard, J., La Magna, R., Tamke, M., 2019. Systems for transformative textile structures in CNC knitted fabrics — Isoropia. In: Softening the Habitats - Tensinet Symposium 2019, pp. 95—110.

Ray, S.C., 2012. 2 - classification of knitting. In: Ray, S.C. (Ed.), Fundamentals and Advances in Knitting Technology. Woodhead Publishing India, pp. 12—18.

Sabin, J.E., 2013. myThread pavilion: generative fabrication in knitting processes. In: Adaptive Architecture: Proceedings of the 33th Annual Conference of the Association for Computer Aided Design in Architecture. ACADIA, Cambridge, Ontario, Canada, pp. 347—354.

Sabin, J.E., Pranger, Dillon, Binkley, Clayton, Strobel, Kristen, Leo Liu, Jingyang, 2018. Lumen. In: Recalibration, on Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture. CUMINCAD, Mexico City, Mexico, pp. 444—455.

Scherer, A.L., 2019. Concrete form[ing] work: designing and simulating parametrically-patterned fabric formwork for cast concrete. In: Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th ECAADe and 23rd SIGraDi Conference. CUMINCAD, Porto, Portugal, pp. 759—768.

Schmeck, M., Gengnagel, C., 2016. Calibrated modeling of knitted fabric as a means of simulating textile hybrid structures. Procedia Eng. 155, 297—305.

Scott, J., 2016. Programmable knitting. In: Posthuman Frontiers: Data, Designers, and Cognitive Machines: Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture. ACADIA, Michigan, USA, pp. 276—281.

Scott, J., 2013. Hierarchy in knitted forms: environmentally responsive textiles for architecture. In: Adaptive Architecture [Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). ACADIA, CUMINCAD, pp. 361—366.

Scott, J., 2012. Knitting moves: bio-inspired transformable textiles for knitted architecture. In: Proceedings 2011 Borås Sweden Editors: Lars Hallnäs, Annika Hellström, Hanna Landin, p. 151.

Semper, G., 2010. The four elements of architecture and other writings. In: RES Monographs in Anthropology and Aesthetics, First paperback edition. Cambridge University Press, Melbourne Sydney (Original work published 1989), Cambridge New York New Rochelle.

Sommer, S.R., 1975. Loie fuller. Drama Rev.: TDR 19, 53.

Tan, Y.Y., Lee, T.L., 2019. Knit preform shaping — design of textile preform and edge-shaping mechanism for curved composite panel formation, intelligent & informed. In: Proceedings of the 24th CAADRIA Conference. CUMINCAD, Wellington, New Zealand, pp. 43—52.

Thomsen, M.R., Bech, K., 2011. FCJ-130 Embedding response: self production as a model for an actuated architecture. Fibreculture J. 31—46.

Wang, H., 2015. A Chebyshev semi-iterative approach for accelerating projective and position-based dynamics. ACM Transactions on Graphics (TOG) 34 (6), 1—9.