Weaving Ontology. Patterns of Textile Structures from the Knot to the Digital Lace

Giorgio Buratti, Sara Conte, Valentina Marchetti, Michela Rossi

Abstract

One of the main design issues concerns the connection of components in artifacts. The ancient art of weaving presents interesting and relevant aspects, which apply to the field of design and architecture and emphasize the truth of Gottfried Semper's statements about the classification of materials and construction techniques.
The combination of digital technology and textile patterns derived from the development of the connective structure of the knot/button in the weaving and then in the lace, creates textile structures adaptable in many fields, in which the properties of the formal archetypes of weaving are found. In its development, weaving has always benefited from technological innovation, for example the invention of the Jacquard loom in the 17th century introduced the mechanical control of patterns with recursive algorithms.
Starting from the 16th-century tradition of Milanese bobbin lace, passing through the 20th-century interpretations within the schools linked to the Modern Movement up to the most recent interpretations, the research develops the application of structures generated by digital algorithms for the production of innovative artifacts through the revitalization of a heritage of ancient knowledge.
Once basic elements are defined, i.e. the weaving movements and the complete cycle to be repeated, it is possible to recreate the formal structure of the lace through the control of geometric parameters of shape and movement.

Keywords: node, algorithm, linking, weaving, visual modeling.

Introduction. Theoretical premises

Gottfried Semper, who demonstrated the relationship between *artificial forms* and the *specific working techniques* of the four categories into which the natural materials used in the arts are framed [Semper 1860, vol. I, pp. 9-12], argued that architecture learned the rules of style from the forms of used objects. Today we can add that, when industry replaced craftsmanship and the figure of the creator became disjointed from that of the maker, the same principles passed from Architecture to Design. The two arts were then reunited with the industrialization of architecture, until the digitalization led to the nullification of the differences of scale between different design categories, focusing again on the founding principles of basic Design [1].

The primary concepts of symmetry, proportion and movement, which reinterpret in construction the elementary laws of balance, are reflected in the three essential forms (knot, weave, fabric) that characterize the formal archetypes of weaving. This, considered as the first fundamental technique for the definition of the formal principles of style, regulates the artifacts' articulation according to a strict functional and performance reference. Unlike objects of use and manufactured products, architecture has always tended to develop hybrid models between the four constructive principles formulated by Semper: weaving, modeling, tectonics and carpentry. As underlined by the common root of the Germanic words '*Wand*' and '*Gewand*' ('wall' and 'garment' respectively), the

principle of re-wearing unites textile art with construction. Both are associated with the constructive principle of creating spatial structures by linking pieces of small dimensions. The connection of pieces or parts, in fact, is among the main problems of the project, which must balance technology and functionality, conditioning the aesthetics according to the terms of the Vitruvian triad of *firmitas*, *utilitas*, *venustas*.
Today, digital technologies offer control tools applicable in the design and construction phase, capable of renewing interest in the adoption of hybrid technological solutions. Starting from the fundamental construction archetypes, they allow the improvement of mechanical and hygrothermal performance of evolved products and construction components.
In particular, generative modeling methodologies allow the development of algorithms capable of transforming textile processes into advanced construction systems, applicable at different scales in multiple product sectors. The need to rigorously define the pattern parameters that govern textile algorithms in order to adapt them to the final form, renews interest in the principles expressed by Semper over a century ago. Digitization has reunified the process of design/representation/construction, but the possibility/need to optimize it requires its preliminary setting according to pre-established procedures, especially when these can be traced back to recursive operations. From this point of view, the weaving technique is particularly interesting both for the peculiarity of its structures and for their replicability in the fields of architecture and manufacturing industry. The reason can be traced back to some crucial factors articulated by the art of weaving since its archaic beginnings:
- the generalized importance of the connection of pieces in all construction processes;
- the structural characters of the fabric and its mechanical prerogatives;
- the aesthetic aspect and visual quality produced by the repetitiveness of textile structures;
- the great adaptability to different materials and systems.

Therefore, it becomes natural to start from textile structures for the definition of an operative methodology based on recursive algorithms applied to variable parameters. The first experimentation concerns the digital reconstruction of the structure acting on the metric dimensional parameters to simulate the adaptation to different formal situations. This matches with the design contents of the Drawing in its design nature, but the prerogatives of the parametric modeling allow today the simulated representation of other properties that allow to verify also performances independent of the geometry.
The primitive elements of weaving, the knot and the weave, which allow two or more filaments to be connected together, create elongated linear structures [Semper 1860, vol. I, pp. 18-87] from which arise respectively:
- the button and the sewing, the two anchoring structures that lock the relative position of two independent elements by making them integral;
- knitting, a fabric created from a single thread, and weaving, which extends the process in the two dimensions of the surface to a warping of yarns in multiple directions;
- embroidery and lace, in which the decorative vocation derives from the same constructive aspects of the weaving of the net.

The weaving and lace rework the three-dimensional binding of the knot [Semper 1860, vol. I, pp. 177-201], born from a movement of the rope in space to make two stumps solid with windings or overlapping, which is presented as the primitive structure that allowed the development of others. It is no coincidence that the art of knots, which is not only of interest to seafarers, includes a series of structures that can be classified according to the number of loops and their use (fastening, lengthening or attaching). Moreover, it is the mathematical study of a branch of topology that has generated the Theory of Knots, which studies closed curves intertwined in space, which finds application in biology, subatomic physics and molecular chemistry.
The knot fixes the beginning of elongated structures (braids) which in turn can generate mats and fabrics in which recursive regularity constitutes the main element of order and resistance, allowing the creation of characteristic patterns. The articulation of the signs of the interlacing/knotting of refoli in different directions determines on the surface a design that springs from the material and becomes form, combining the principles of construction and ornamentation (fig. 1).
From the 16th-century tradition of Milanese lace, of which traces remain in Cantù's lace and in Gio Ponti's publications, begins research that intends to experiment the applicability of structures generated by digital algorithms in the realization of innovative and sustainable materials and artifacts, reinterpreting an ancient art through digital tools and technologies.

Tradition and 20th-century reinterpretation

According to a Venetian legend, the first lace was made of sea foam and donated by sirens to a fisherman from the Burano island as a reward for his loyalty to his fiancée. The story reveals the origin of the lace, which evolves from fishing nets to become a decorative object: women in fact refine the plot by studying figures and refined geometries. Between the end of the Fifteenth and the beginning of the 16th century the needle lace of Burano spread in stately homes. Moreover, in the documents of property division between the sisters Angela and Ippolita Sforza Visconti (1493), the term '*tarnete*' is used to indicate braids, lace and trimmings, testifying their presence also in the Milanese area and since 1584 lace is among the teachings of the University of Embroiderers of Milan. In the second half of the 17th century the lace technique found wide diffusion thanks to the establishment, in the monastery of Santa Maria in Cantù, of teaching the use of bobbin lace to girls' groups. Then, this practice and the canturina technique spread to various schools including La Regia scuola d'arte applicata all'industria locale, founded in 1882. A few years earlier, in 1872, the School of Burano was opened in the lagoon area under the patronage of Queen Margherita, and in 1898 the Aemilia Ars was founded in Bologna, called the 'Society for the Protection of Decorative Arts and Industries of the Emilia Region', reflecting a growing interest in lace and needlework.
After the setback caused by the First World War and in opposition to the spread of machine-made lace, craft and industrial activities were relaunched by ENAPI (Ente Nazionale per l'Artigianato e la Piccola Industria, a National Organization for Crafts and Small Industry) and soon textile works became part of the Biennale di Monza and then of the Triennale, attracting the attention of various architects including Gio Ponti. Moreover, columns of a practical nature were born, alternating with writings about the art of embroidery and photographs of artifacts, demonstrating a growing interest in the phenomenon and an attempt to link it to the concrete needs of a less abstract public. *Domus*, *Stile* and *Fili*, a magazine founded in 1934 by Emilia Kuster Rosselli, contributed significantly to the diffusion and modernization of lace. *Domus* provided accurate reviews of the section dedicated to lace and embroidery at the Triennale of 1933, promoting the preparation of the Triennale of 1940, born "with the precise aim of realizing […] the most exhaustive and highest modern exhibition of embroidery

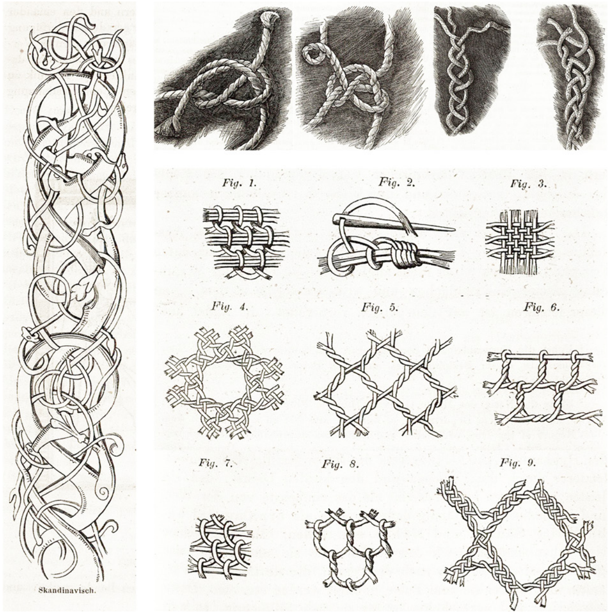


Fig. 1. Ornamental pattern. Textile structures. Abacus of knots, braids and nets. Images from Semper 1860, pp. 83, 180, 181, 184, 186, 187]

ever seen in Italy" [Ponti 1939, pp. 65, 66]. Starting from 1928, various examples of 'modern' lace were published, including those designed by the architect Giorgio Wenter Marini, who in 1931 took over the direction of the Scuola Canturina del mobile e del merletto (School of furniture and lace) with the intention of relaunching it. According to Ponti, the VII Triennale was an opportunity "to make the sense of a tradition shine again among us, a tradition that is not a limitation –that is, copy and imitation– but the living continuity of that prodigious Italian inventive spirit that has always amazed the world" [Ponti 1939, pp. 65, 66].
The researches of the 1930s focused on the abstraction and the geometrization of the drawing, without significant modifications in terms of materials; only from the end of the 1950s, after the new setback of the war, we witness on one hand the diffusion of lace and doilies made of plastic, where the innovation consists only in the application of the new material, and on the other hand diversified experiments that reinterpret the traditional practical technique moving away from it (fig. 2).

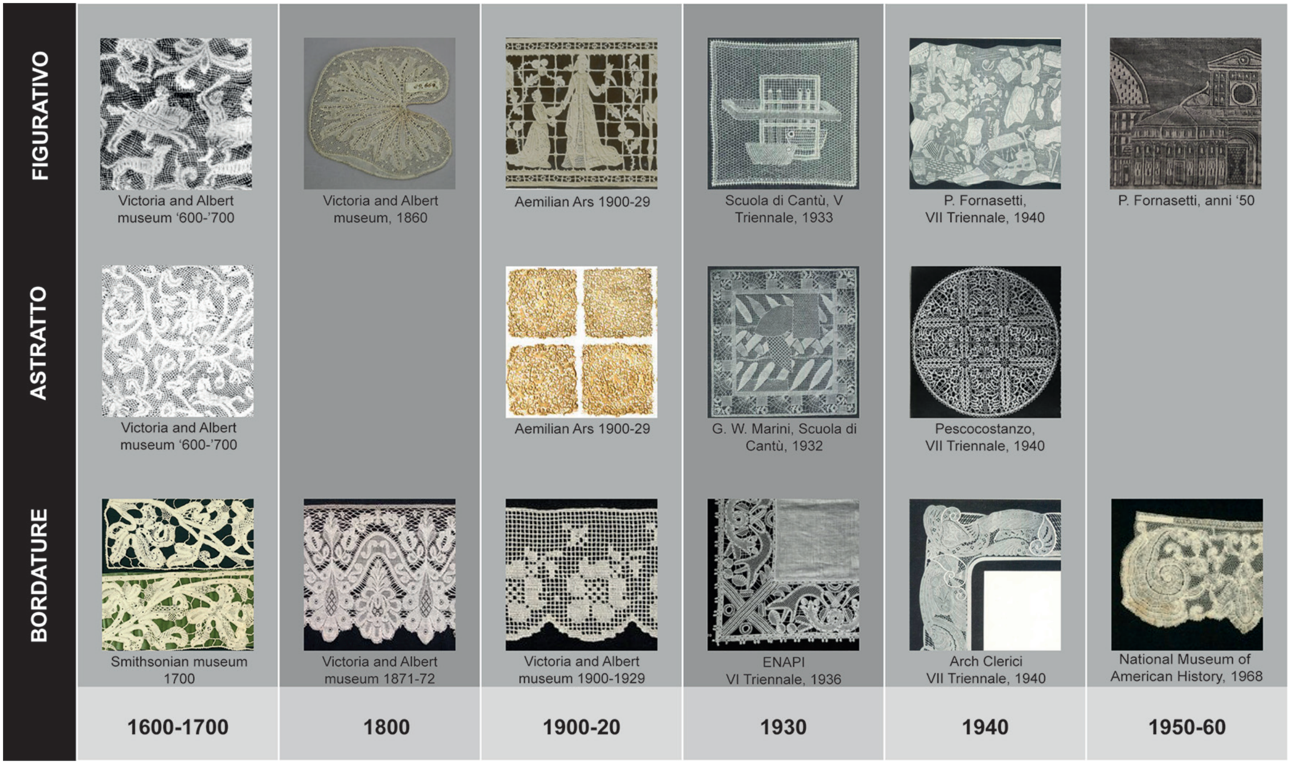


Fig. 2. Scheme of bobbin lace types (edited by V. Marchetti).

Carla Accardi's Tenda, in 1965, overcomes the two-dimensional limit of the canvas by creating a 3D environment in 'sicofoil', enriched by a dense weave of graphic signs. This refers to the traditional weaving technique reinterpreted through graphics and color. Other interesting works are developed by Franca Sonnino starting from the second half of the '70s. Here the weaves of iron wire and cotton thread recreate three-dimensional books, construction elements such as bricks, mosaics or abstract three-dimensional representations of architecture, countries or landscapes.
Since the early 90s, initiatives for the preservation of the lace tradition have proliferated, such as the Internazionale del merletto di Cantù and the related Merletti e Design. These initiatives see the collaboration between artists, architects, designers and lace makers to create innovative projects that enhance the craftsmanship, inserting it in the research of contemporary design [Guglielmetti 2015], culminating with the candidacy of the same for inclusion in the list of Intangible Cultural Heritage of UNESCO. In the last 10 years, the revival of traditional techniques and of the aesthetics of lace combines with new technologies. Serena Confalonieri presents in 2014 two lamps that exploit 3D technologies
reinterpreting the typical weaves of traditional Italian lace and goldsmith in sintered polyamide. The tradition, the universal language of geometry and the preordained and repeated patterns typical of lace are also the basis of the architectural elements of The Flying Mosque macro-installation in 2018 by Choi+Shine Architects. Finally, lace be-

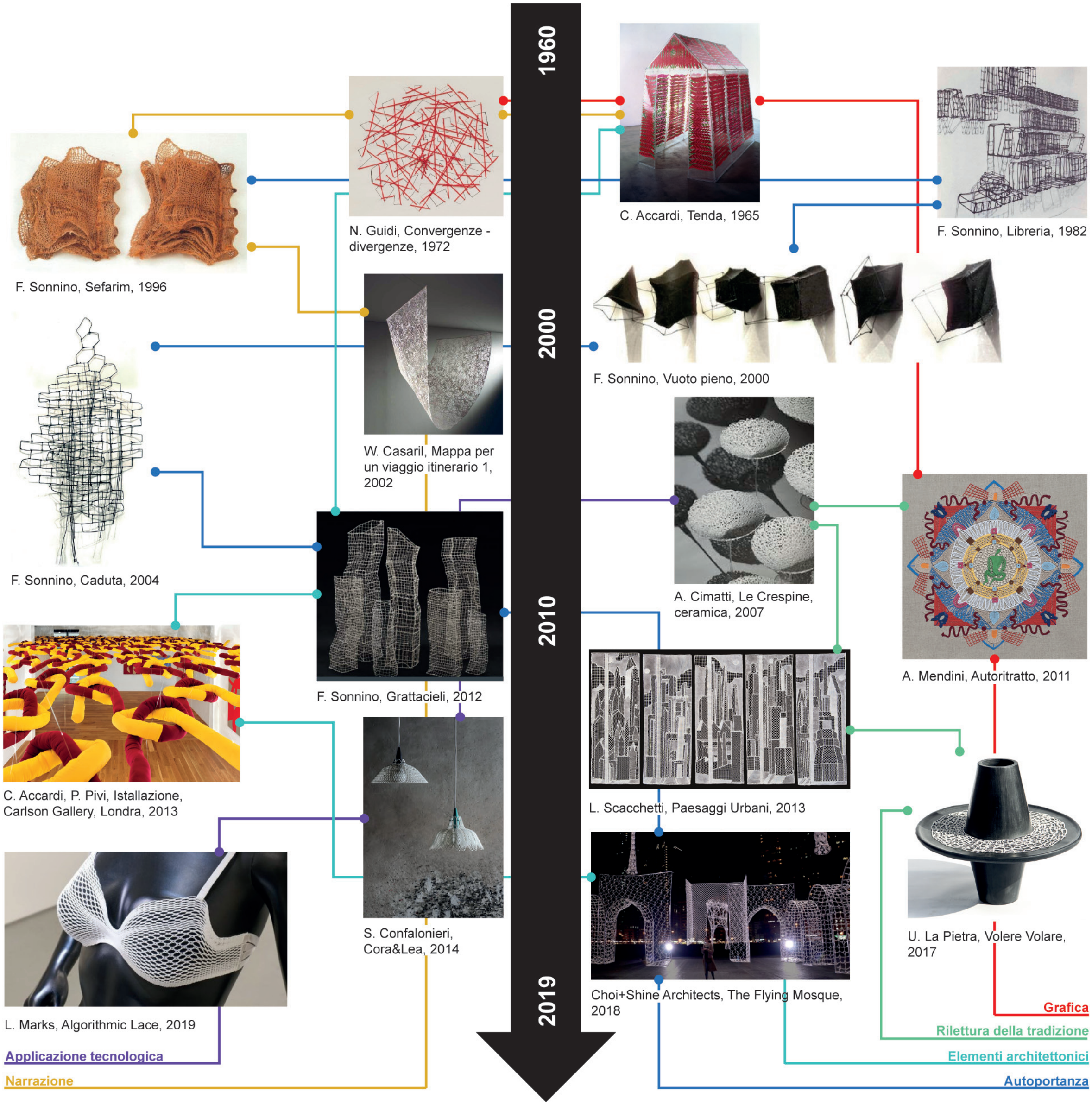
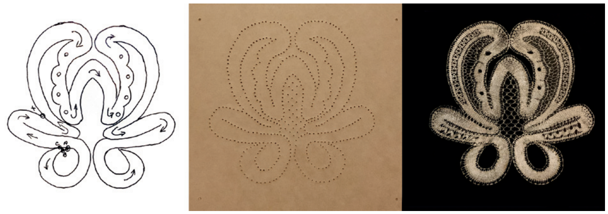


Fig. 3. Timeline of development and application: selection of case studies (edited by V. Marchetti).

comes a technical structure in Lisa Marks' project for a bra for mastectomies' women, in which algorithmic modeling generates a true three-dimensional lace, able to adapt to any anatomical shape: lace becomes structure (fig. 3).

The bobbing lace and the Lombard technique of Cantù lace

The bobbing lace is a hand-made textile artwork, realized weaving a pair of few single threads partially wound on bobbins at the ends, commonly called '*fuselli*'.
The weaving is worked on a cylindrical pillow padded with horsehair from which it takes its Italian name, '*tombolo*', and to which it is fixed with pins. The pins also block the several passages during the work progress. The threads traditionally used are linen, silk, cotton, or more particular metallic threads, while in modern creations materials of all kinds are used.
The bobbing lace can be subdivided according to the technique used to make it into straight laces, continuous braid laces and part braid laces or discontinuous laces. In the first case, the fabric is entirely executed simultaneously in both full and empty parts, called 'fillings', starting from a constant and sometimes very large number of bobbins. The continuous braid bobbing laces is executed with a limited and constant number of bobbins where the braid, following the drawing of a series of more or less elaborate patterns, constitutes the full part of the work; when different parts approach each other they are joined by thread passages with the crochet hook or bobbins, called 'seewings' or 'bars' and with more complex filling patterns.
Lastly, the part braid bobbing laces or discontinuous bobbing laces used a variable number of bobbins, increasing or decreasing during the work following the drawing; the full parts, called 'braids', can be made by more than one single person, and then they are joined with crochet hook and filled in the empty parts by fillings, bars or nets.
Since its origins in the 15th century, the main feature of the bobbing laces in the Lombard area, the Milanese lace or Milano stitch, was the continuous braid lace or '*bisetta continua*' technique. This last tchnique is an antique one, which can be defined as the lace of the origins, illustrated by numerous drawings already in *Le Pompe*, one of the first and most popular books concerning lace patterns printed in Venice in 1557. The



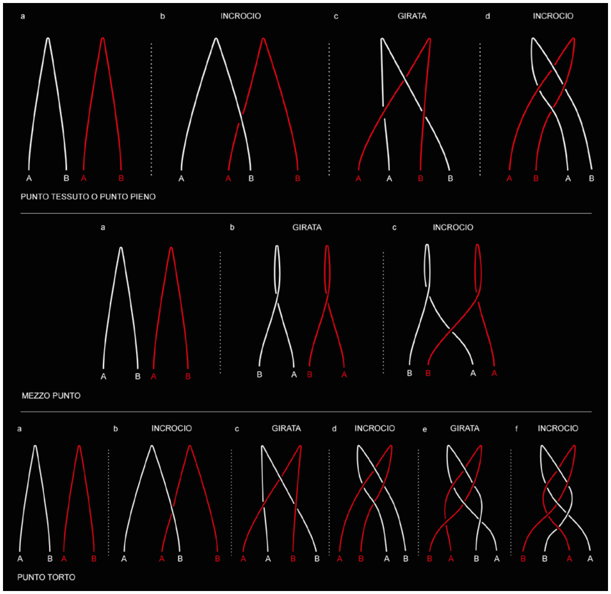
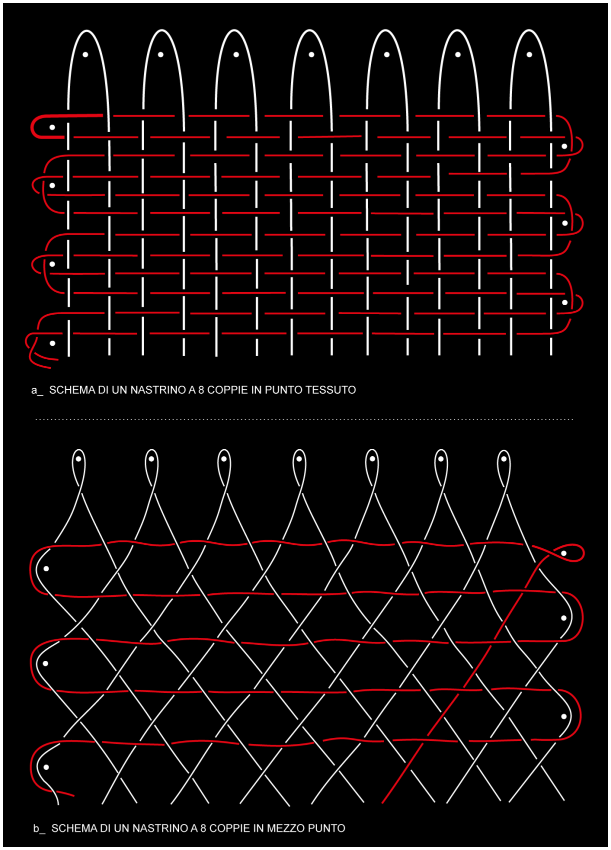


Fig. 4. Schematic drawing, trimmed cardboard, the realized motif (edited by S. Conte).

Fig. 5. Sequence of movements for the execution of basic stitches: cloth stitch or whole stitch, half stitch and turning stitch (edited by S. Conte).

weaving was compact and solid, fairly fast to execute, a characteristic determining, together with "the miracle of lightness" [Il girovago 1943, p. 3], its success over time. In the oldest Cantù laces that have come down to us, unlike Flemish needlace of that time, the braid was continuous and worked with cloth stitch, drew flowers and foliage with traditional ornamental patterns. Unlike needle lace, the Milanese did not require a bottom net to support the work and the different parts were joined together by bars during the work [Jourdain 1905, pp. 384, 385].
From the middle of the 17th century, the bottom net appeared in the processing and not applied afterwards, with the same base points to fill the spaces with cobwebs, fish, jealousy or Valenciennes patterns.
This specific type of lace is made following a graphic design on medium-weight cardboard by a designer using a defined code, in which the cross bars indicate the number of turns of the thread, the dots indicate the pins that hold the work in place and the circles indicate a specific basic stitch, the turning stitch. Then the trimmer perforates the cardboard, organizing the course and direction of the weaving, which will serve as a path for the lacemaker to create the weave (fig. 4).
At the beginning of the drawing some pairs of bobbins, usually in odd numbers and called passives, are hanged in line with pins, while the weavers pair, also called workers or leaders positioned lower than the vertical ones, will be worked alternately from side to side creating the braid [Read, Kindcaid 1988].
All the basic stitches originate from the use of two pairs of bobbins, a worker and a passive, working with *turn movement*, exchanging position of the threads in the same pair, and *cross movement*, exchanging position between the side by side threads of two different pairs.
The lacemaker thanks to the combination of these movement gives life to a weave that can be:
- compact with *cloth stitch* (or *whole stitch*), obtained by reproducing the sequence of *cross*, *turn* and *cross* movements;
- more sparse with *half stitch*, thanks to the scheme of *turn* and *cross* movements;
- open-worked with *turning stitch*, which is formed by a sequence of five movements between the bobbin threads (*cross*, *turn*, *cross*, *turn*, *cross*). This stitch is also used where the project requires the endorsement of work or the division of a braid (figs. 5, 6).



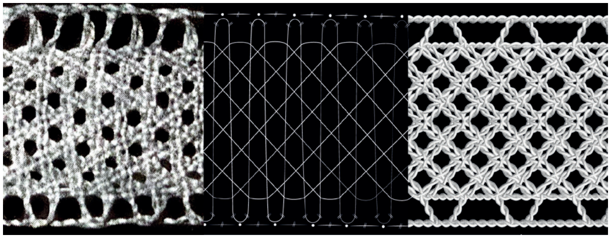


Fig. 6. Schemes of whole and half stitch braid. In red the workers and in white the passives; at the end of the row a double or single twist of the workers and the placing of the pin allows to start again with the work (edited by S. Conte).

Fig. 7. A traditional basketweave braid, drawn diagram and the digital algorithmic construction (edited by S. Conte).

In traditional Cantù lace, the succession of these simple codified sequences alternating with empty spaces has given rise to a great variety of braids, about 80 in number, which, combined according to consolidated ornamental patterns or new designs created by the creativity of the lace-makers, generate a practically infinite series of decorative motifs or patterns. Over time, the designs of the bezels have become much simpler, even abandoning their absolute continuity, but keeping the basic idea of decorative structure unchanged. This idea is reborn today in the re-elaboration of new languages, the result of design collaboration between ancient knowledge and contemporary design, capable of infusing the technology of mechanized production with the uniqueness of the workmanship.
Among the traditional geometric type of workmanship, the basketweave pattern [Read, Kindcaid 1994] presents some prerogatives, such as the self-supporting characteristics, the fabric robustness and its permeability, of great interest for application in various fields of design. The variety of stitches used in the construction also favored its choice to experiment with the automated generation of a braid through algorithmic modeling (fig. 7).

Digital Laces

The binomial combination of computational processes and textile production has attracted the interest of the industrial and academic world since the invention (17th century) of the Jacquard loom, which allowed the automatic handling of single warp threads starting from perforated cartons to set more complex weaves than those that could be obtained by hand. The technology has given a considerable boost to the textile sector: computational textile [Yi et al. 2007] has allowed solutions capable of improving the properties of washability and elasticity by promoting new functions. The result is the current variety of advanced textiles whose properties derive from the synergy between innovative materials and the study of the geometries that characterize the weave.
Representing textile morphologies through algorithms means understanding the combinations and sequences of characteristic knots, to translate the constituent and constructive elements into entities that computer can recognize and manage. The process involves the parameterization of the basic elements that determine the final result, making the digital modification of shape and size possible and facilitating the study of properties, functionality and manufacturability of the object. Through *Grasshopper*, visual algorithm editor associated with *Rhinoceros* (McNeel), the parameters that control elements, movements and recursiveness of simple lace, then assembled into articulated elements, have been defined:
- the basic braiding of 2 or more wires is obtained by dividing an *L* series of circumferences into 6 known points. These become the control points of an interpolation spline curve, defined by a 3rd degree polynomial function capable of maintaining, for each pair of points, the position and tangent continuity that characterizes the physical behavior of the textile fiber, simulating the helical trend of the braided yarns and controlling the parameters that determine the different types of braiding: thickness, turns and pitch of the helix (fig. 8);
- logical Boolean denial operators, linked to points *A*, *B*, *C*, *D*, *E*, *F* guarantee the non interpenetration of the surfaces and limit the variation of the thread thickness up to the tangent point, regardless of the number of threads. By modifying in cartesian space the curve on which the generating circles lie perpendicularly, it is therefore possible to obtain any type of geometry while maintaining and controlling the characteristics of the weave;
- the weft thus obtained defines the basic components of Cantù lace: by overlapping three or more threads it is possible to create finished products, but it is also possible to create load-bearing lattice structures, where ornamental finishes characterized by different geometry complete the composition.
The algorithm describing this interweaving exploits the previously told properties of the interpolation spline curve, bound at the extremes of the curve *AB* and at point *V*, projection of point *M* in the *xz* plane, which lies on segment *AB* belonging to *xy*. By making *M* a variable between the values of the length *AB* and *MV* a variable in a range between 0 and infinite it is possible to modify the morphological characteristics of the curve. By modifying the curve on which the generating circumferences lie, it is possible to obtain the desired geometries. The rototranslation with respect to point A creates a sinusoid whose waves are bound to the variable points *M* and *V* and to the symmetry itself. With two other translations by symmetry, it is possible

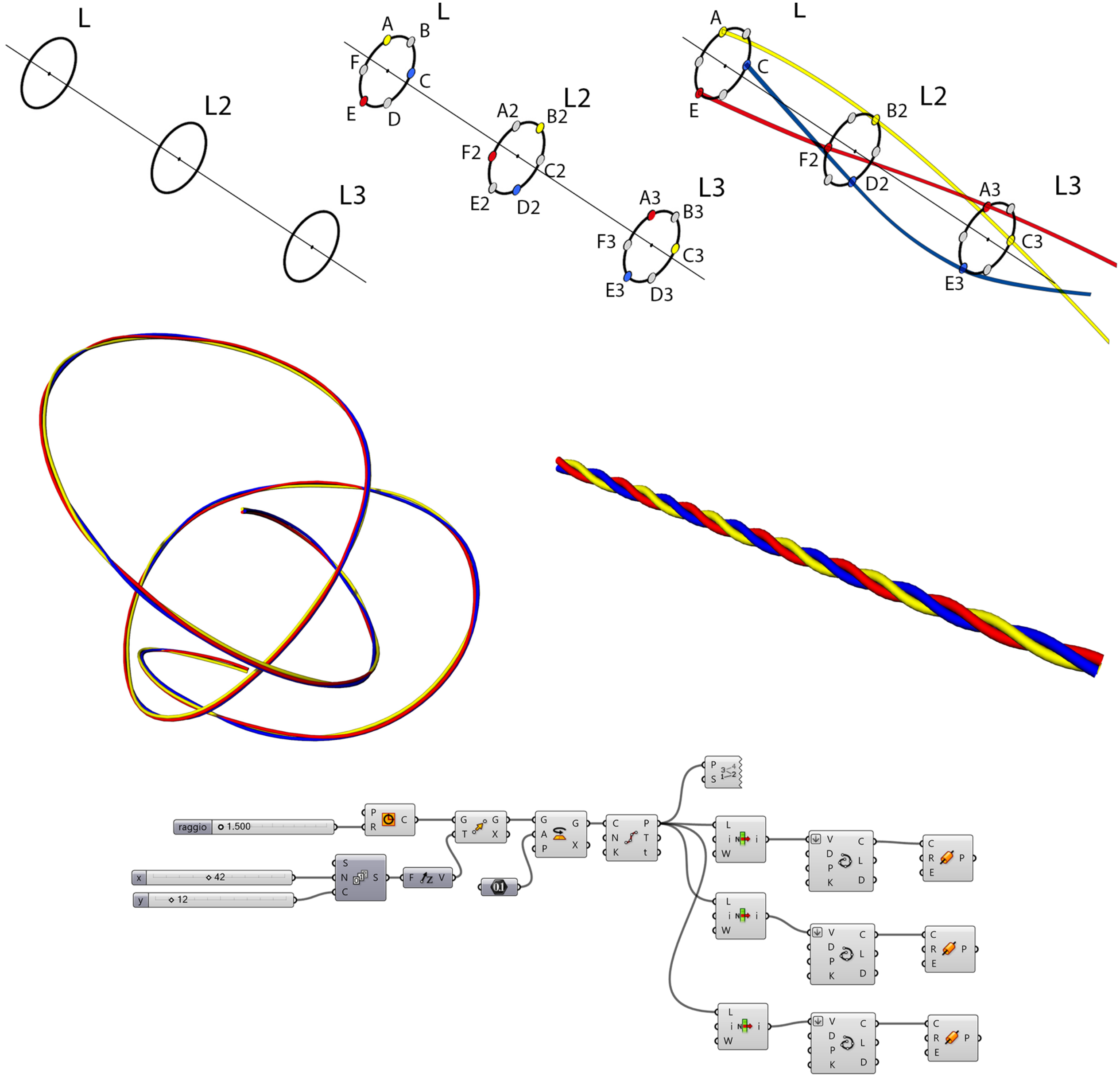


Fig. 8. Algorithmic construction of the braid (edited by G. Buratti).

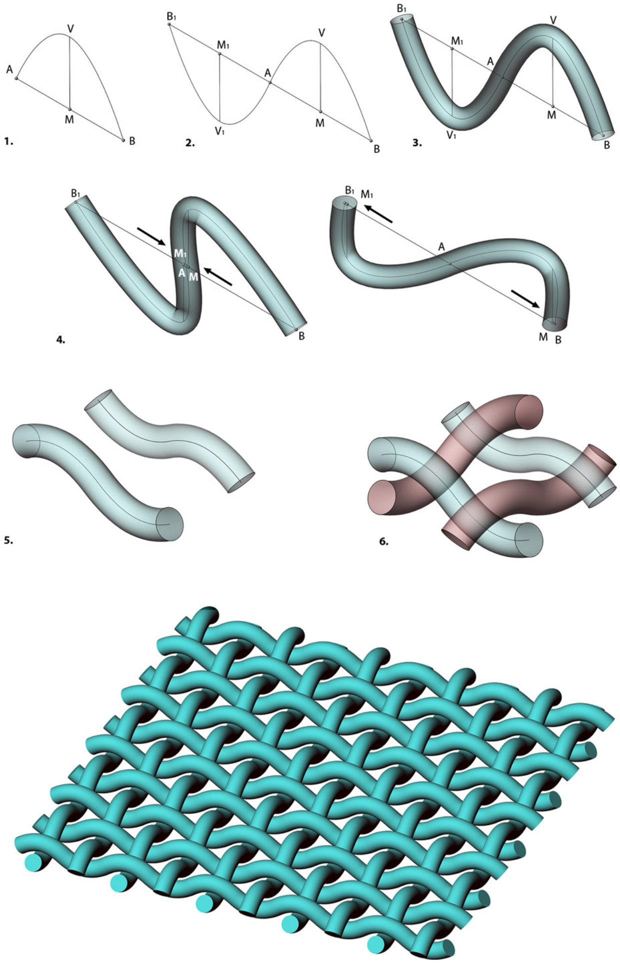


Fig. 9. Armor definition algorithm. Algorithm for defining the weave. The parameterization of M and M1 allows the modification of the morphology by simulating the textile reaction (edited by G. Buratti).

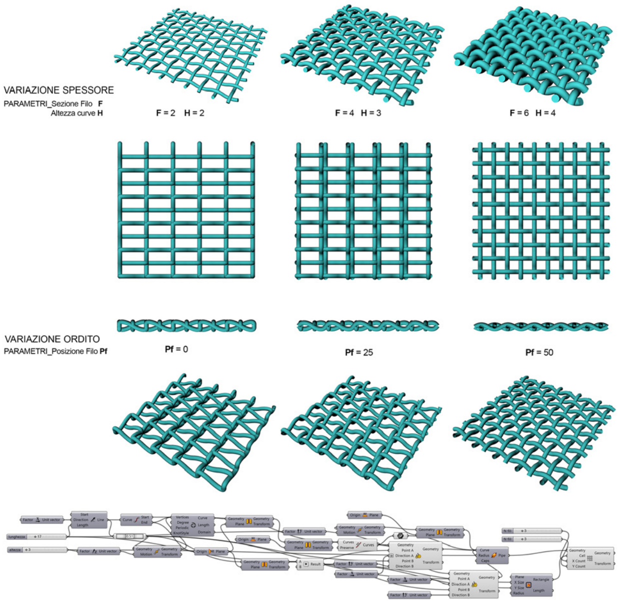


Fig. 10. By modifying the different parameters, it is possible to obtain morphological variations and texture density (edited by G. Buratti)

to obtain the basic unit of the armature, i.e. the sinusoidal braiding between the weft (fig. 9) and the warp of the Cantù lace.

By changing the parameters and extending the common characters, the algorithmic writing generalizes the totality of possible cases. It is possible to create weft, chain (fig. 10) or three-dimensional structures and the latter, so far little investigated for the productive and morphological complexity, present interesting structural properties also for sectors other than textiles (fig. 11). The structural elasticity of the weaves, which does not depend only on the material, allows them to act as springs and for this reason the stresses are absorbed at a structural level affecting the material to a lesser extent.

The possibility to control with the computational design the yarn configuration, in synergy with highly automated production processes that can give materials new performances of lightness and resistance, offers interesting application perspectives for architecture and design, but also in aerospace or medical field.

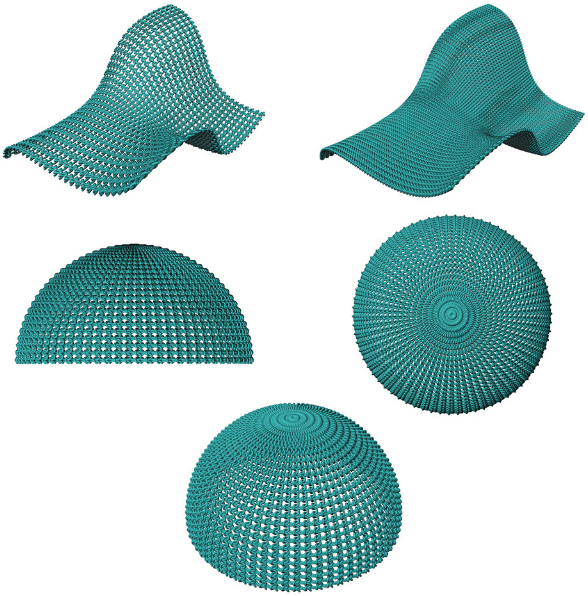


Fig. 11. Three-dimensional studies for the geometric adaptation of the weft for a strange surface and a spherical cap (edited by G. Buratti).

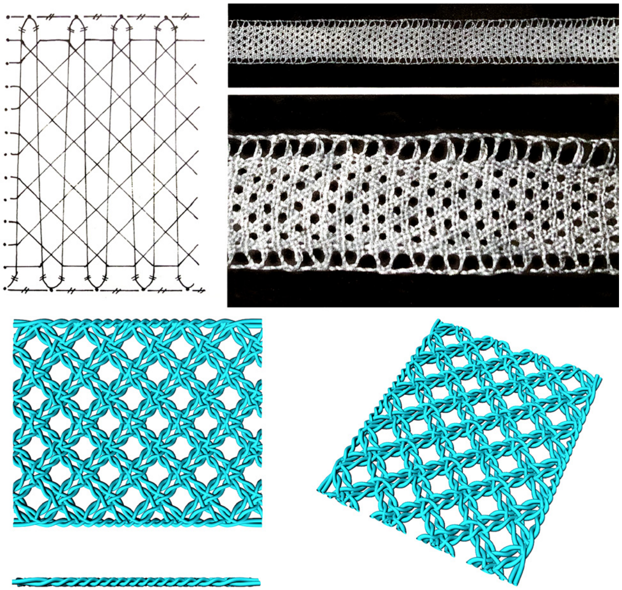


Fig. 12. Partial reconstruction of a basketweave braid (edited by G. Buratti).

Conclusions. Old lace and new materials

The work here presented is the first result of a research in progress that aims to introduce parametric tools for industrial innovation starting from the valorization of ancient arts and manufacturing. This is intended not only as a preservation of past models, but as a contemporary reinterpretation of patterns that are still current. In order to overcome the crisis triggered by the exhaustion of economic mechanisms based on increased consumption and the delocalization of production, it is necessary to enhance the value of tradition aimed at the application of processes capable of providing more effective solutions in terms of performance, use of materials and ecological and economic sustainability.
The knot, the interlacing and the weaving develop the modular approach and the geometric rules of the surface and, together with the symmetries of space, constitute a theme of theoretical (mathematical) and project (design) research. The geometric structures used in the laces refer to the investigations of Maurits Cornelis Escher, Richard Buckminster Fuller e Roger Penrose on modular grids, on the symmetries of the lattices at the basis of spatial constructions and on the rules of plane and three-dimensional tessellation.
This also allows to underline the close link between weaving, architecture and applied arts, considering the importance of the textile principle applied to the project. The various scales of application of the formal principles of knot, weave and fabric and their reworking for application in multiple fields represent a valuable source of references for the transposition of traditional lace techniques to different scales. The contemporary diffusion of digital tools don't deny but does reaffirm the importance of the primary constructive principles, and it underlines the value of the introduction of new digital applications to the basic elements of weaving.
The deepening of the constructive processes of the Milanese lace and the investigation of the properties of lightness and complexity of the structures realized

according to this tradition constitute the cultural substrate of departure for the application of computational processes. The digital control of geometry favors the diffusion of a past cultural heritage both as a model for the creation of new materials, structures or products, and for the valorization of traditional techniques and intangible cultural heritage.
Ancient techniques together with modern tools allow to reinterpret the lace through applications not only aesthetic but also structural, since –as Semper teaches– there is an indissoluble link between material and processing technique. The characteristics of lightness, permeability and resistance, typical of the Milanese lace, can be translated under new guises in the study of moldable, flexible, elastic and responsive materials. The manipulation through the new tools of design and production of formal parameters, such as the variation of the section of the 'thread' or of the size of the 'binding', allows the realization of innovative structures on a small or large scale previously impossible. Architecture can take advantage of this by imagining flexible elements, mass-producible and endowed with peculiar characteristics that are not only formal and aesthetic, but also structural and economic.

Note

[1] Although the contribution was conceived jointly, Michela Rossi is the author of the paragraph *The theoretical premises*; Valentina Marchetti is the author the paragraph *Tradition and twentieth-century reinterpretation and the related images*; Sara Conte is the author of the paragraph *The bobbing lace and the Lombard technique of Milanese lace* and the related images; Giorgio Buratti is the author of the paragraph *Digital Lace* and the related images. The conclusions were drawn jointly.

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