

DESIGNING MOVABLE CHAIN LIKE STRUCTURE WITH 3D MODELED ELEMENTS

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Abstract: *The field of 3D printing has developed greatly to date, and it is expected that this development will continue. 3D printing is already being used in the fashion industry, where it was first used for rigid, architectural shapes and later for a variety of movable structures. However, the area of mobility, comfort and softness is still under development in this field. The exploration of the above properties was also the reason for the present research work, the aim of which was to study the process of creating a textile-like 3D structure by assembling individual elements into a mesh. Various factors in both the design and technical areas had to be investigated and considered. The design process included the technical and visual part, i.e., the design of the individual elements, as well as the creation of different repeating patterns, as the shape and colour of the elements influence the final appearance. Different approaches were tested when modelling the individual elements. Through the research, other design approaches were also used, such as the use of geometry nodes or animation nodes, which are available as plug-ins in the Blender software. We combined different elements to create meshes or textile-like structures that were simple at first, but later resulted in more interesting designs by varying the size and shape of the elements, their arrangement, and colours. There are still many possibilities to develop the patterns further, for example, the elements could be arranged in different ways, or more emphasis could be placed on the shape and colour of the elements.*

Finally, we experimentally printed part of the chain-like structure and compared it with other structures designed in a 3D program and checked the size and density of the mesh by virtually simulating the fall of the mesh onto the body.

Key words: 3D printing, 3D textile-like structure, fashion, SLA technology

1. INTRODUCTION

3D printing is still considered a futuristic technology, although the first concepts of 3D printing appeared in a science fiction story "Things Pass By" by Murray Leinster in 1945. However, it was put into practice in the early 1980s when Chuck Hull invented the process of stereolithography (SLA) (Turney, 2021). Nowadays, 3D printing is used in various industries such as medicine, aerospace, culinary, fashion and others. In the textile field, 3D printing is used in three forms: 3D printing directly on textiles, 3D printing of flexible structures, and 3D printing with elastic materials. Different printing technologies are used for all three forms. For direct printing on textiles, the most commonly used technology is FDM (Fused Deposition Modelling), in which the extruded polymer is deposited layer by layer through the nozzle of the 3D printer onto the surface of the textile. SLS (Selective Laser Sintering) technology is the most used for printing solid but flexible structures, and SLA technology is usually used for printing with elastic materials. Due to the high precision of both SLS and SLA technologies, SLA technology can also be used to fabricate flexible structures, but printing would require supporting structures (Sitotaw et al., 2020).

The goal of our research and design process was to create various chain-like structures that mimic a textile structure. They should be movable and able to adapt to the object of collision for different purposes, such as making a dress, a fashion piece, or an accessory for interior decoration. During the design process, we used the 3D program Blender to model various chain elements derived from Celtic knots, which were virtually assembled into a chain-like structure to create interesting mesh patterns. We also simulated the fall and collision of the material with various collision objects, such as cylinders, cubes, and also with a 3D human avatar. The simplest structure, consisting of a torus, was also 3D printed using SLA technology so that we could test the mobility of the textile-like structure.

1.1 3D printing of flexible structures

Flexible 3D-printed structures that simulate textiles can be produced using three different methods (Sitotaw et al., 2020). In the first method, called "mesostructure," the individual elements of thin layers or

sheets are aligned perpendicular to the base surface, which allows them flexibility in different directions. In this way, materials such as metal can be made flexible without changing their physical properties (3DPrint, 2014). This discovery was made by Andreas Bastian, who developed his new material, which can be seen in Figure 1.

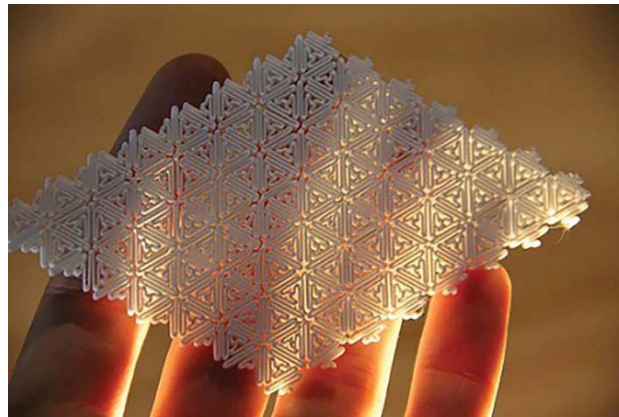


Figure 1: Andreas Bastian - "mesostructure" (3DPrint, 2014)

The second method is based on a patterned structure of many precisely designed and modelled triangular panels connected by hinges. They are all 3D printed as a single piece. While each element is rigid, when they form an entire dress, they behave like a continuous fabric that conforms well to the body. Unlike traditional fabrics, this fabric-like structure is not uniform, but varies in drape, flexibility, and pattern in space. No cutting is required to make such a structure, and much less material is needed. An example of the mentioned method is the Kinematic dress developed by the Nervous System company (Nervous System, 2014), shown in Figure 2.



Figure 2: a) Kinematic dress, b) Detail (Nervous System, 2014)

Finally, the third method is based on connecting rings (Bingham and Hague, 2013) or other closed elements (of different shapes and sizes) and mimics the structure of medieval protective clothing, which consists of tightly connected metal rings. Each ring has enough space to move freely, which allows good draping around the body. When printing such a material, for example, with FDM or SLA technology, we need to use support structures, because the empty spaces between the rings do not provide a stable surface for printing.

Jiri Evenhuis and Janne Kytanen were the first to start designing material using the third method mentioned above (Janne Kytanen, 2000). The first project using 3D printing of textiles was carried out in 2000. The project included a fully 3D printed dress ("Black drape dress"), which can be seen in Figure 3.



Figure 3: Jiri Evenhuis and Janne Kytanen drape dress (Janne Kytanen, 2000)

2. METHODS

The research began with the design of the individual elements in the 3D computer program Blender. In the further course, the individual elements were connected to form a mesh. First, we modelled the simplest torus shape and started with the determination of the design method, where we learned the process and method of modelling and assembling the elements into a mesh. The elements assembled into a mesh represented a textile-like structure, part of which was also 3D printed using SLA technology with the FormLabs Form 2 printer.

After the testing part of the design process was completed, the design of the individual elements inspired by Celtic knots began. The design process was the same as for the torus, where the individual elements were first modelled and then assembled into a mesh.

As mentioned above, the 3D computer program Blender was used for the design process, and all the elements were modelled based on Bezier curves (Bezier Curve, Bezier Circle) or using the Curve plug-in: Curve - Knots - Torus Knot Plus and Braid Knot.

2.1 Determination of the design method

The first step was to become familiar with the process and methods of modelling a single element and assembling it into a mesh that would mimic textiles. Therefore, the first element was a simple torus shape as shown in Figure 4.

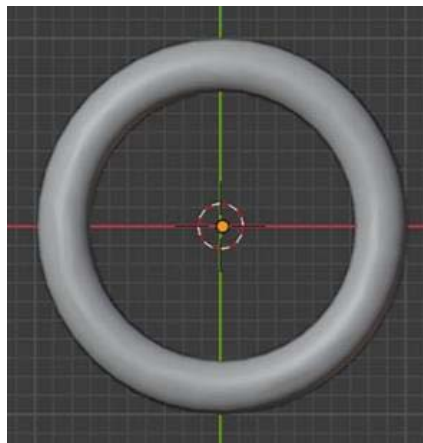


Figure 4: Initial torus shape

Once the single element was modelled, it was assembled into a grid, considering the slope of the elements and the distance between them. The slope ensures that the elements fit together, and the distance between them allows the structure to move. Initially, the tori were assembled into a single chain and then duplicated until a larger surface was created (Figure 5).

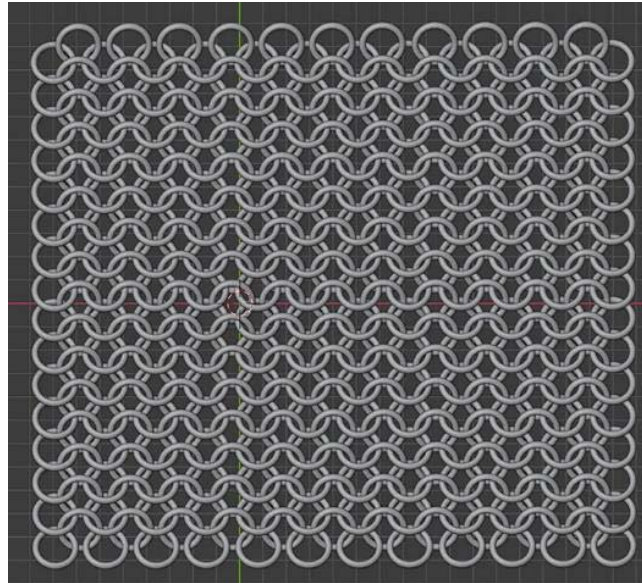


Figure 5: Textile-like structure from torus shape

Further on, the mesh imitating textiles was simulated on the collision object, observing the movement of the structure and its visual appearance. The Rigid Body command was used to calculate the physical forces involved. The physics of Rigid Body is discussed in Section 2.3. and the resulting simulation is shown in Figure 6.

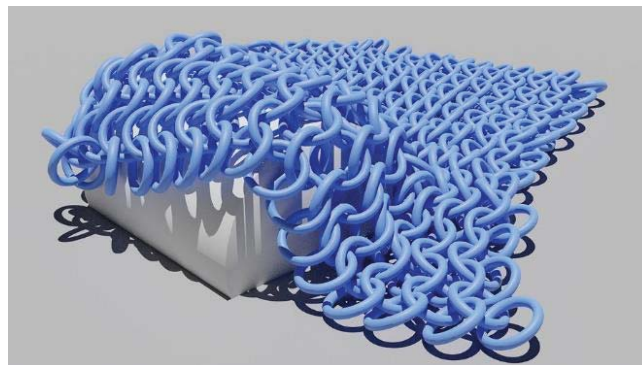


Figure 6: Simulation of textile-like structure on the collision object

2.2 Method verification process

In the test part, we established the method, which was verified during further development and design. This was followed by the design of individual elements inspired by Celtic knots, although the starting point for each design of the element was different. The initial geometry of the chain link was obtained from the Curve plug-in, such as the Torus knot, the Braid knot, and the Bezier Circle template. The shape of the Dara knot was based on a curve - Braid knot (Figure 7a), with the number of sides reduced and the thickness of the basic shape increased (Figure 7b). Figure 7c shows the solid model of the individual chain link. For the process of 3D printing and simulation, the final shape of the knot had to be changed from a curve to a mesh.

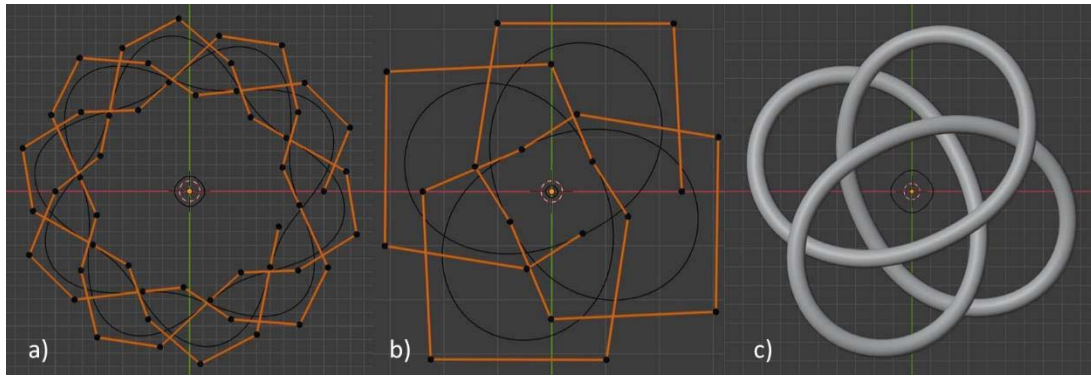


Figure 7: a) Initial geometry of Dara knot, b) Remodelled geometry, c) 3D model of the knot

The shape of the Endless Knot looks like interconnected squares; therefore, the individual element was square-shaped. The starting point of the element was the Bezier Circle template (Figure 8a), for which the number of points on the curve was increased with the Subdivide command, which then facilitated the transformation of the circular shape into a square, as shown in Figures 8b and 8c.

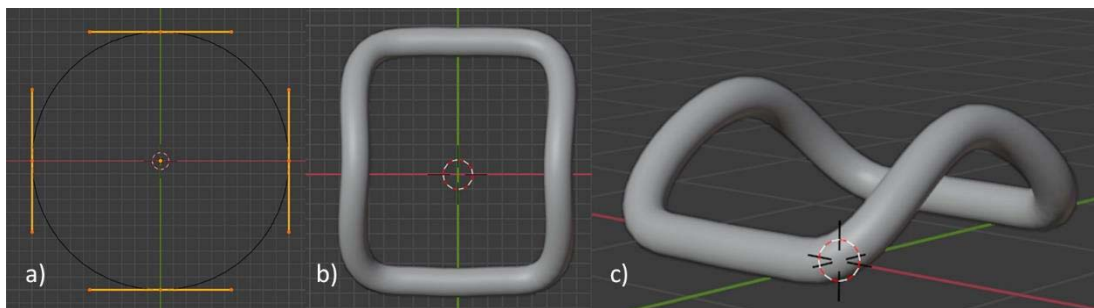


Figure 8: a) Initial geometry, b) Final shape of the element, c) Side view of the final shape

The element inspired by Solomon's knot was modelled using a curve - Torus Knot Plus (Figure 9a), increasing the number of spins (Figure 9b) and reducing the inner circumference, and therefore the shape of the curves shifted towards the centre, which can be seen in Figure 9c.

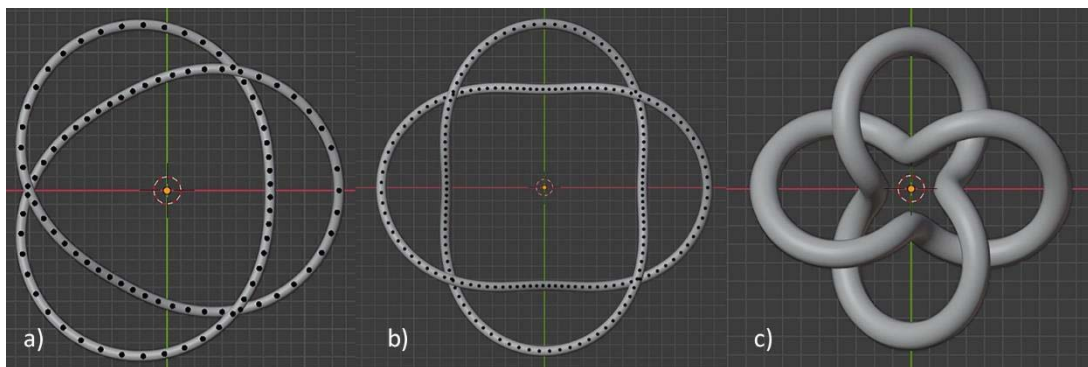


Figure 9: a) Initial geometry, b) Remodelled initial geometry, c) Final shape of the element

2.3 Assembly of elements and simulations of textile-like structures

All the resulting textile-like structures were assembled in the manner already described in the test section. First, the elements were assembled into one chain, which was then multiplied to the desired size. Figure 10 shows meshes made of identical elements.

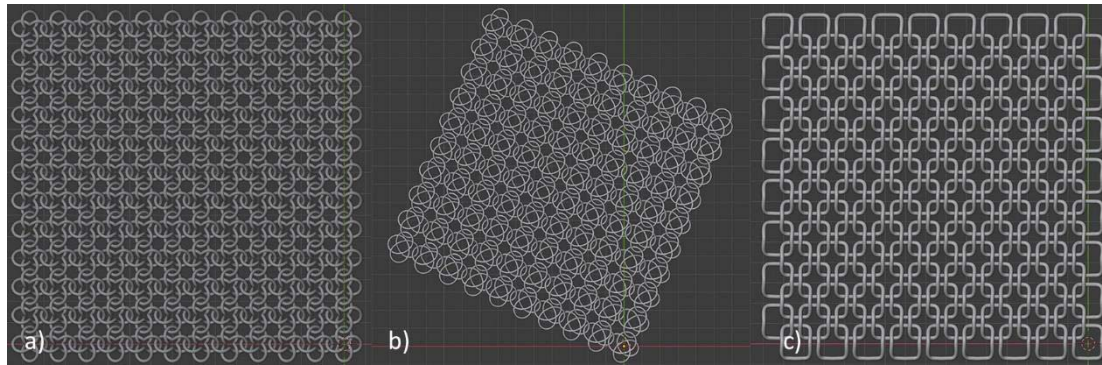


Figure 10: Textile-like structures of a) Dara knot, b) Salomon's knot, c) Endless knot

By simulating the fall of a rigid object onto a collision object, we learned about the use of physics in Blender on the Physics Properties - Rigid Body tab. The Rigid Body command is used to simulate the motion of solid objects, defining active and passive bodies. Active bodies are simulated dynamically, while passive bodies remain static (Blender, n.d.). The purpose of creating simulations was to observe the behaviour and movement of the designed textile-like structures on various collision objects, including the body. An example of a rendered simulation is shown in Figure 11.

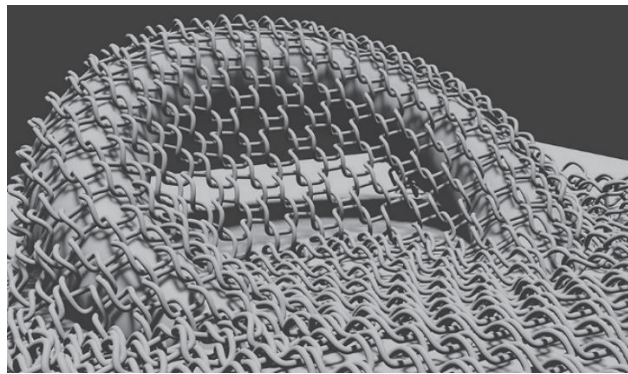


Figure 11: Simulation of textile-like structure designed from Endless knot elements

2.4 Designing patterns

Different shapes, colours and sizes of the elements were used to achieve different patterns in textile-like structures. Two different forms of elements were created from one knot, one of which was a Celtic knot, the other a variation of it. After designing an interesting pattern of similar elements, a contrasting colour was added to some of them. A colour combination of white and blue was used, and a monochrome pattern was created for comparison. Figure 12 shows an example of patterns in textile-like structures using colours and the Solomon knot in two variations.

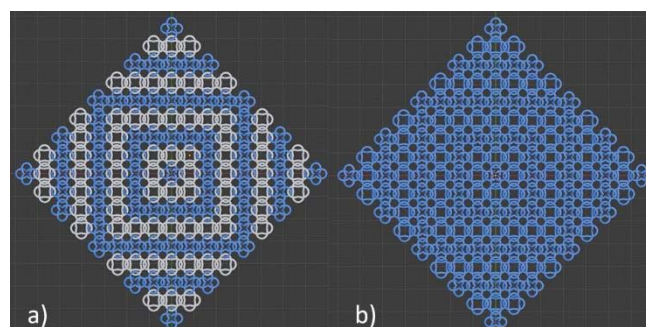


Figure 12: a) Blue-white pattern, b) Monochromatic pattern

2.5 3D printing of textile-like structure

The 3D printing attempt refers to the test part, where a part of the torus mesh was printed with printer FormLabs Form 2. Printer supports SLA technology and allows high precision and quality print as well as easy preparation and maintenance. The purpose of 3D printing was to check the flexibility and the strength of the textile-like structure and to find out the appropriate size of each element.

Firstly, the 3D model was checked for possible errors in computer program Blender using the 3D print suitability checker plug-in, and then imported into the PreForm application, where it was prepared for printing (determining the layout and slope, creating support structures). The printer took 7 hours and 5 minutes to print a part of the textile simulation with dimensions of 6.5×6.5 cm, producing 1331 layers of 0.05 mm thickness.

After 3D printing, further processing was required. The object was washed with isopropyl alcohol (IPA), moving, and soaking the individual parts in the solvent for optimal cleaning. After printing with SLA, the polymerization reaction may not be fully complete, which means that the printed object has not yet reached its final material properties and may not have the expected properties, especially for heavily stressed parts. Exposing the object to UV light helps to solidify the material properties (Formlabs, n. d). The support structure was then removed. Figures 13 and 14 show the printed test part with the support structures still visible and the printed part after removal of the support structures.

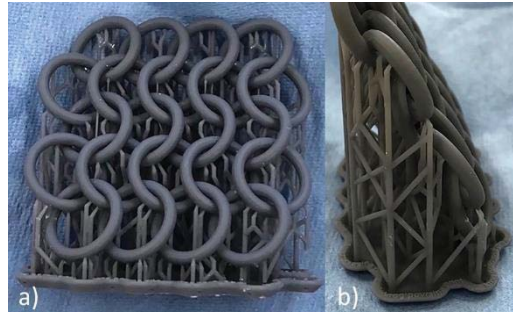


Figure 13: a) 3D printed part with visible support structures b) Side view

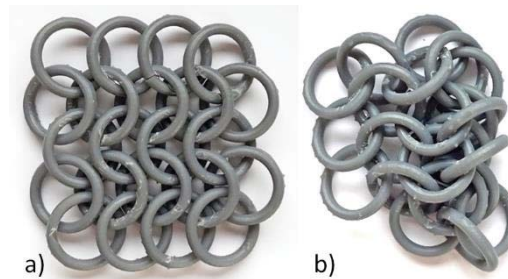


Figure 14: Printed part after removing support structures

3. RESULTS AND DISCUSSION

The 3D printing process has shown that the textile-like structure can be movable, even if it consists of rigid elements. The spacing between the elements is very important because it allows the chain-like object to be flexible. In our 3D-printed piece, the distance or slope was a bit too small, so the elements stuck together in some places. Nevertheless, the elements could be separated, but the surface was damaged, which can also be seen in Figure 14.

In our case, the diameter of each element was 21 mm, but they could be larger or even slightly smaller, depending on the purpose for which the structure is used. For making lampshades, bags or decorative curtains, the elements could be even larger, but for making clothes, the elements should be closer together and smaller.

3.1 Final textile-like structures

When designing patterns in textile-like structures, it was also necessary to pay attention to the spacing between elements, as mentioned earlier, because spacing allows for movement. Visually interesting patterns were created when we put together different shapes and sizes of elements. In addition, even more interesting patterns were created when colour was added.

Colour emphasizes the difference between elements and highlights the pattern on the surface. In monochromatic patterns, the different shapes of the elements are somewhat lost, although they still form an interesting structure because of the empty areas of the elements that make up the patterns. Looking at the multi-coloured patterns from a distance, one colour would most likely dominate the other and the overall structure would look the same, however every step closer to the textile-like structure, the pattern becomes more visible. Patterns also appear when light shines through the structure because the empty spaces between the individual elements create shadows, as seen in Figure 22. This paper presents some approaches, but the possibilities for pattern design are endless.

Example 1:

Figures 15 and 16 show examples of the Dara knot pattern. The pattern was created by combining original elements into squares, separating the squares with lines of Dara knot variations. Figure 15b also shows a monochrome pattern that focuses on the empty spaces between the elements and their shapes.

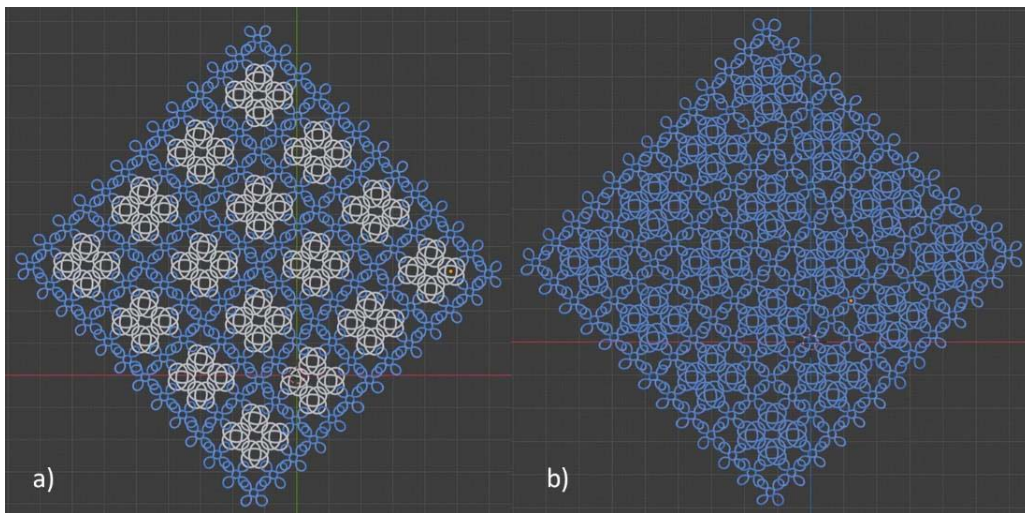


Figure 15: a) Blue-white pattern, b) Monochromatic pattern

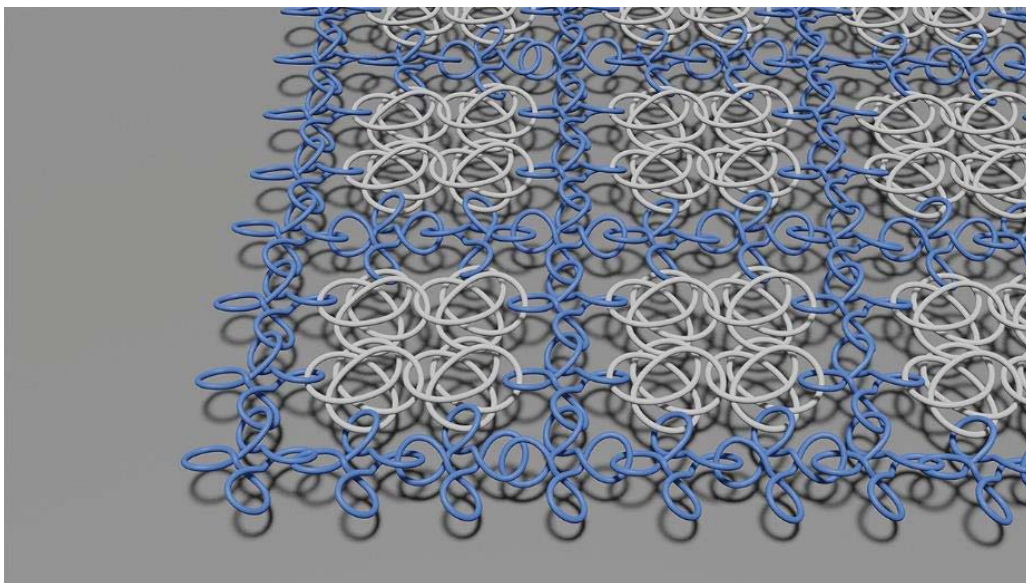


Figure 16: Blue-white pattern render

Example 2:

Figures 17 and 18 show a Dara knot pattern in different sizes, in the combination of blue and white, monochrome and in a combination of light and dark blue tones. We can see that all colour combinations offer new patterns, although the base is the same in all of them. To create interesting patterns, we must not forget about the colour in addition to the shape, size and arrangement of the elements.

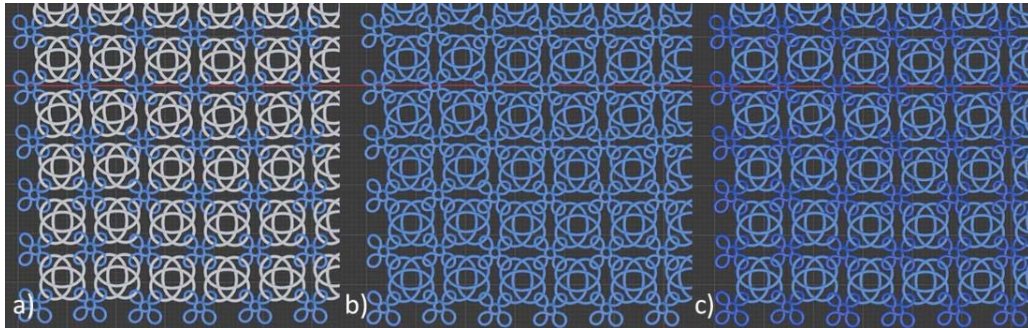


Figure 17: a) Blue-white pattern, b) Monochromatic pattern, c) Light-dark pattern

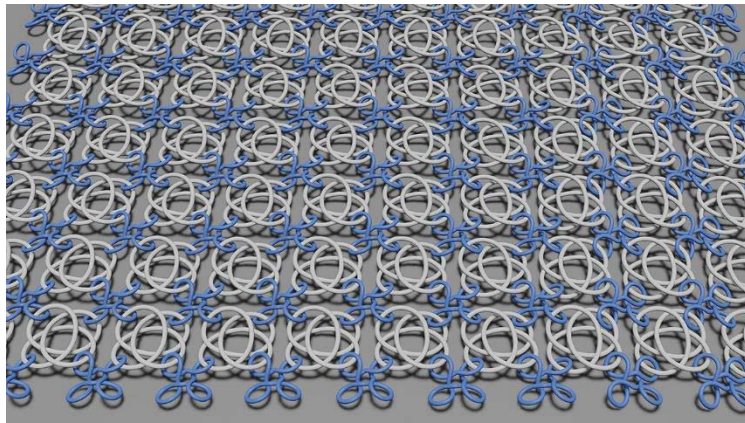


Figure 18: Blue-white colour pattern render

Example 3:

A pattern in combination with the Endless Knot and the Torus shape element, where the torus connects the Endless Knot elements in vertical and horizontal lines, is shown in Figures 19 and 20.

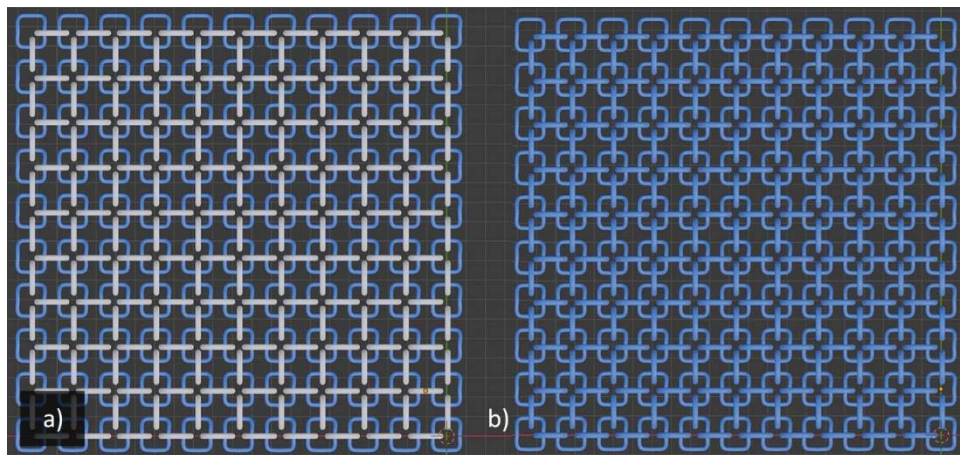


Figure 19: a) Blue-white pattern, b) Monochromatic pattern

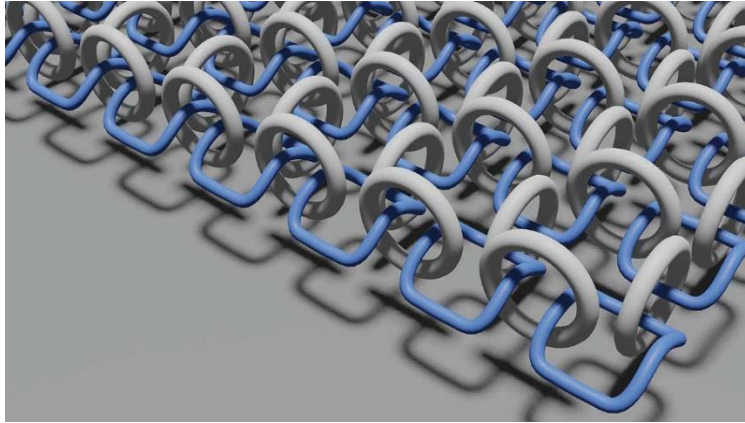


Figure 20: Blue-white colour pattern render

Example 4:

Example 4 shows the Solomon's Knot pattern and its variation in a different size, with the elements arranged in lines, as shown in Figure 21. The monochromatic pattern shows the pattern generated by the elements themselves with their unique shape. The present example also shows the pattern of the shadow created by the light shining through the structure (see Figure 22).

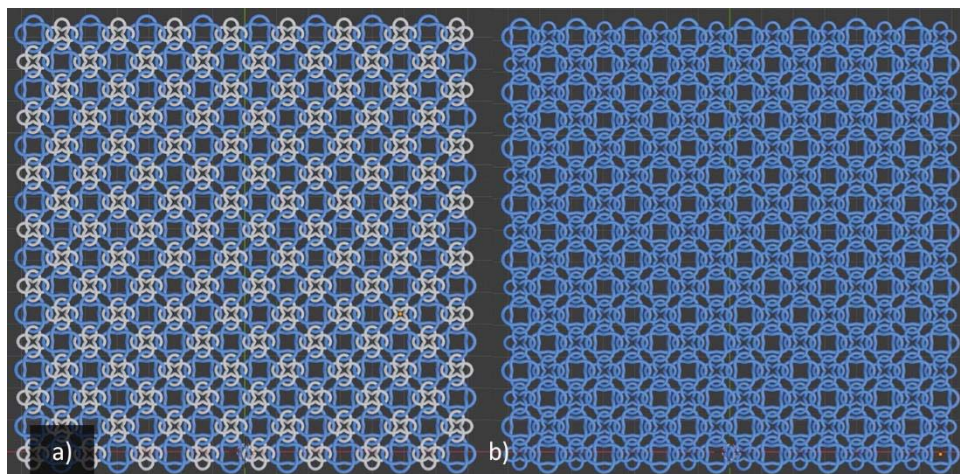


Figure 21: a) Blue-white pattern, b) Monochromatic pattern

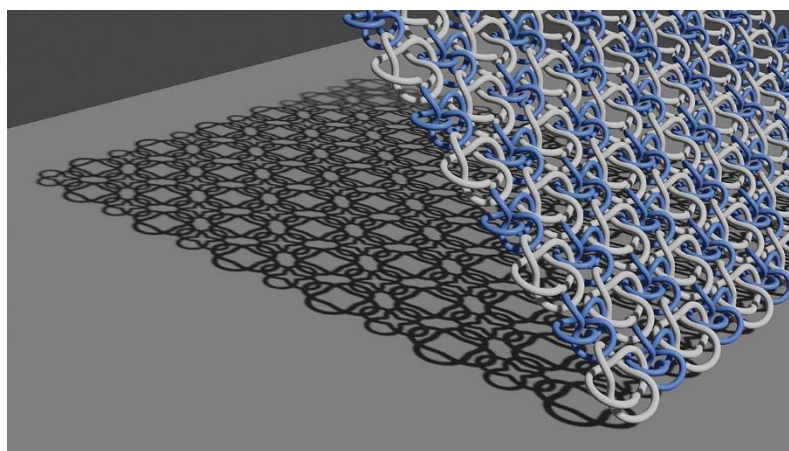


Figure 22: Interesting shadow of the pattern

3.2 Final simulations of textile-like structures

The simulations of textile-like structures have shown us that the size of the elements also affects the wrinkling - smaller elements provide a better fit. Therefore, a larger number of smaller elements allows for a better fit of the mesh to the object and consequently a better mobility of the structure. Figures 23 and 24 are examples of rendered simulations on different objects, showing the behaviour of each mesh-textile simulation.

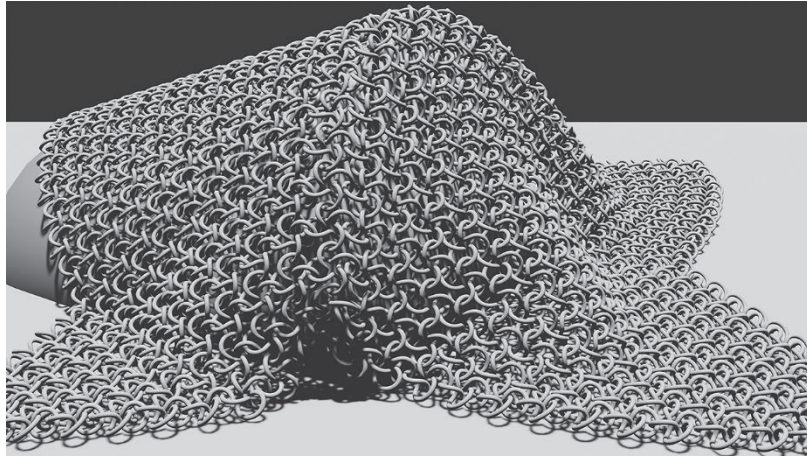


Figure 23: Simulation of Salomon's knot textile-like structure on an object

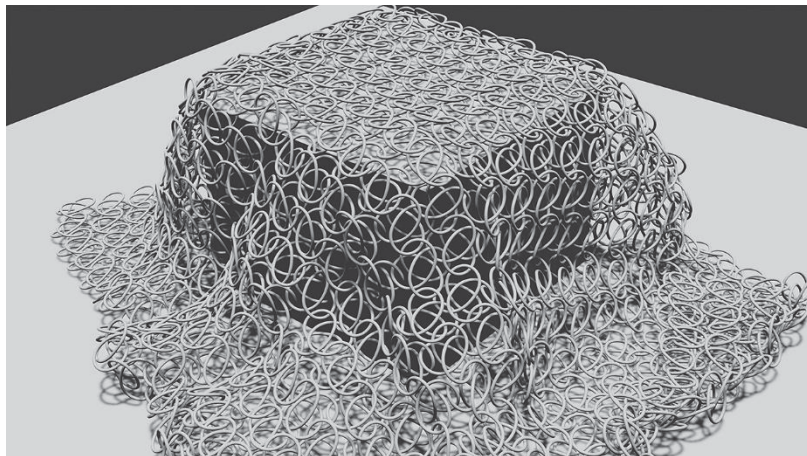


Figure 24: Simulation of Dara knot textile-like structure on a cube

The use of 3D textile-like structure simulations on a human body as a garment is shown in Figure 25. However, the use of "plastic" materials in direct contact with the skin as everyday clothing is still an open area of research, as the materials do not yet allow such comfortable and breathable clothing to be produced. Alternatively, the textile-like structure created could be used to make handbags, lampshades, and perhaps decorative curtains. With further research, 3D textile simulations could also be used to make the back and seat of chairs and deckchairs.

4. CONCLUSION

3D printing is becoming a widespread technology that already allows us to print many different objects, so in the future it may become one of the leading technologies for mass production.

This paper presents the process of designing a textile-like structure from modelling the 3D elements to assembling them into a mesh. During the modelling process, different approaches were used to create a single 3D element, which are presented in this paper. However, other methods can also be used, for example Geometry Nodes or Animation Nodes, both of which are used as add-ons in the 3D computer program Blender.

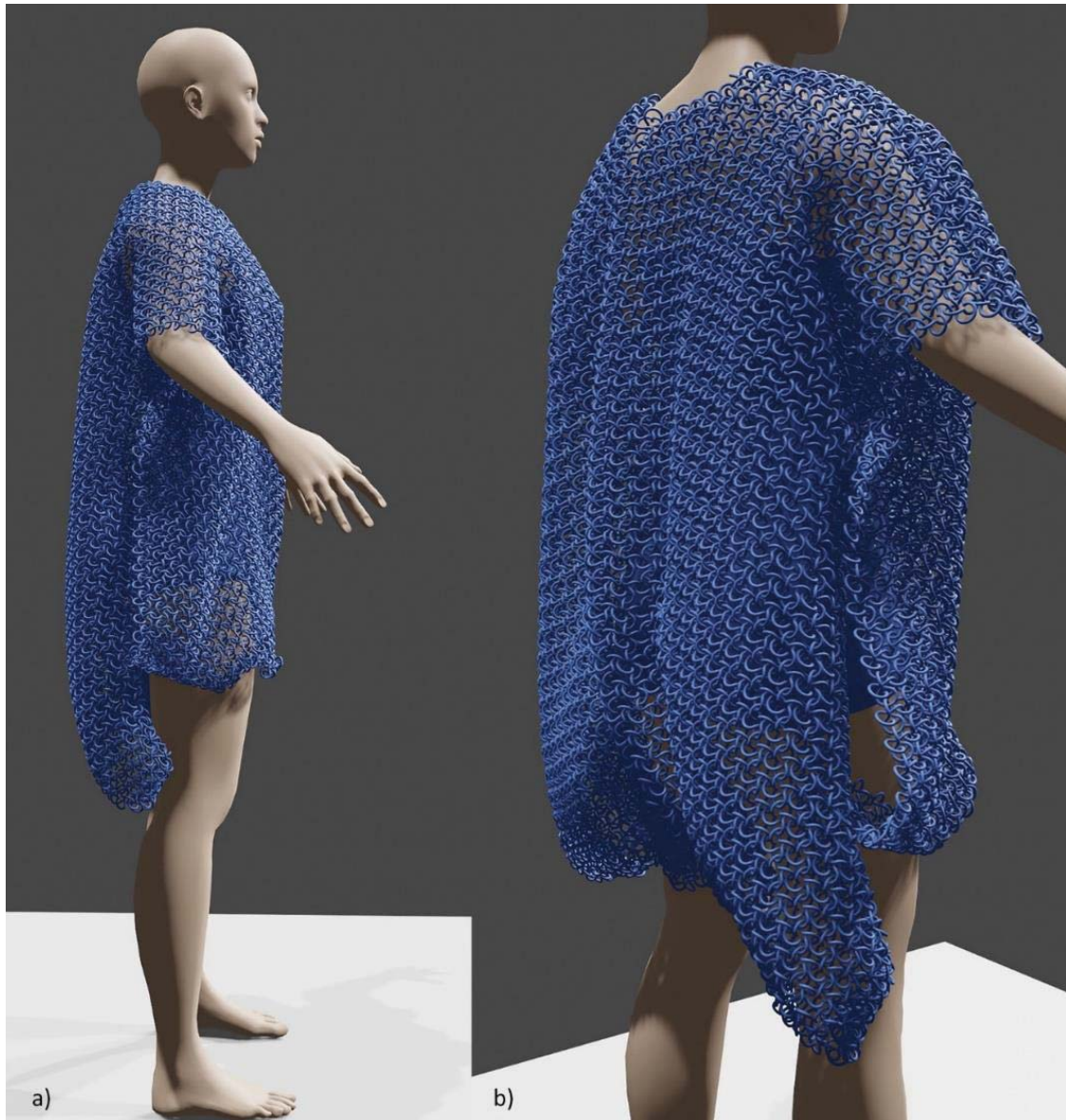


Figure 25: Final render of textile-like structure on human body a) Side profile, b) Back

Throughout the process of modelling, animating, and realistically rendering the textile-like structures, we learned that the individual elements of the textile-like structures must be considerably small and dense to create the chain-like material that is movable and drapes similarly to a textile. More interesting structures were also created by putting elements of different shapes and sizes together and then adding them colours to create patterns. However, there are many other ways to design patterns, and this can be whole other research. Further research related to colour can also be done in the field of 3D colour printing, where, for example, colour patterns can be printed using the HP Multi Jet Fusion colour 3D printer. Finally, further experiments can be conducted on the materials and physical properties of the elements, such as what happens when an elastic material or a different printing technique is used. Nevertheless, developments in various areas of creating textile-like 3D structures are possible, whether in terms of structure, materials, or colour.

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