Formal descriptions of material manipulations: an exploration with cuts and shadows

Book Section

Formal Descriptions of Material Manipulations:

An Exploration with Cuts and Shadows

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Abstract. Shape computation in design is never purely limited to visual aspects and ideally includes material aspects as well. The physicality of designing introduces a wide range of variables for designers to tackle within the design process. We present a simple design exercise realised in four stages where we physically manipulate perforated cardboard sheets as a case to make material variables explicit in the computation. The emphasis is on representing sensory aspects rather than easily quantifiable properties more suitable for simulations. Our explorations demonstrate the use of visual rules to represent actions, variables and form as well as how to control the variables to create new results, both desired and surprising, in materially informed ways.

Keywords: material computing · shape rules · making.

1 Introduction

Seeing is very personal and perceptual with a ubiquitous role in design. Most prominent studies on design feature its visual aspects and highlight the ambiguities in seeing as the key factor for design creativity and productivity. These studies approach design as a way of visual thinking and reasoning, often indicating an immaterial and cognitive process either separate from or prior to materialization. The "see-move-see" model of design advocated by Schön and Wiggins [1] upholds the "reflective conversation with the situation" through visual reasoning [2]. Similarly Goldschmidt [3] refers to a dialogue between "seeing that" and "seeing as" in the course of design sketching, where "seeing that is reflective criticism" and "seeing as is the analogical reasoning and reinterpretation of shapes that provokes creativity".

Pioneering studies within the new material computing research area challenge the long existing understanding of design as an immaterial and cognitive process with visual thinking in the spotlight. This research area has emerged through the extensive use of digital fabrication tools and technologies in design. Material practices commonly reappear at the centre of design activity, seeking potential effects of material information on design while aiming to define a framework where "material has the capacity to compute" [4]. The link between physical materialization and computing finds strength mostly in "advanced machine capabilities" [5]. Material-based design now is "a computational informing process that enhances the integration between structure, material, and form within the logic of fabrication technologies" [6]. This integration of "computational design, advanced simulation and robotic fabrication" considerably opens up our design spaces [7]. Moreover, form comes together with forces and material in a "new generative logic of form-finding" [8] and scholars now report on experimental design research with cutting-edge fabrication tools to show "how material information could become a generative driver rather than an afterthought in design computation" [9].

In parallel, there is a growing interest in revisiting the relation between the analogue and the digital how-tos. Thomsen & Tamke [10] discuss the "narratives of making" through the ways in which "new digital design practice introduces computational thinking into making" and "the means by which architectural practice changes as new digital tools become ubiquitous in architectural making." The knowledge embodied in crafts regarding material and process as a means of design results in new means of making with computer controlled toolsets [11]. Nevertheless, the existing literature summarized above is limited firstly in its approach to computation as the use of computational tools and technologies whereas computation encompasses reasoning in general. Secondly, although rigorous and imposed formalisms exist due to the technical interfaces with digital tools, there is a lack of computational formalism to represent the sensory aspects of working with materials. In one of the few studies that focus on filling this void, Knight & Stiny [12] propose making grammars to extend the shape grammar formalism from computations with shapes to computations with material things. They consider designing as a kind of making itself where the designer perceptually and bodily engages with materials. Suitably, shape grammar computations are a "highly sensory, action-oriented" kind of computational making where "shapes are the materials that one works with by hand and by eye" [12].

In this paper, we consider making as a personal and perceptual act of material manipulation in design with visual and haptic means rather than with numbers. We make use of shape grammars to represent the visual thinking in design and to establish sharable grounds to talk about it as a visual calculation process [13]. The distinctiveness of shape grammars over other approaches to recording and reporting visual thinking lies in its ability to handle uncertainties of seeing. In return, its rule-based approach enables the creative exploration of design spaces and generation of novel alternatives. Visual rules in shape grammars are not determinate and support embedding. In the course of a shape computation, it is possible to see new shapes that emerge from the application of shape rules. The user can decide what shapes to see and which rules to apply. This is what makes visual calculating both "perceptual and improvisational" [12].

Along similar lines, we report in this paper ongoing research on exploring how shape grammars can extend beyond the abstract shapes that compose sketches, drawings and digital design models in CAD systems, to incorporate material shapes that have a physical and tangible existence. Theory suggests that material manipulation in design can relate and translate to shape computing, but the physicality of material introduces a range of properties beyond visual form. A key challenge lies in deciphering the causal links between interventions on the material and our shape making, so that both can be integrally represented in shape rules that support formal computation. Our main objective has been to clarify and handle the creative outcomes of the translation of material manipulations to shape computing. We postulate that we can apply shape rules creatively, as is possible when shapes are viewed as abstract visual objects, without the physical character of material forcing us to conform to highly determinate rules.

We present our arguments with reference to a particular experimentation in which sheet materials with systematically varied cuts are manipulated in specific ways. The process is short and simplistic but embodies controlled action that can be traced easily and, most importantly, emerging shapes that are characteristic of design processes. In the end, we are interested in formalising the emerging shapes and the material manipulations that bring them about. We aim at formally modelling the material properties of the sheets by relying on visual rules and weight definitions according to the theory of shape grammars.

2 Formalising Material Aspects of Design

Being able to express a process in a formal way, e.g. as an algorithm, shows a deep understanding of the process [14] and the resulting formal description is useful in communicating this understanding to others. For design processes where visual thinking dominates, shape computations have been shown to provide appropriate formal descriptions that give insight on processes of shape transformations. For example, Prats et al. [15] describe how explorative sketching in a design process can be formalised according to shape rules, and Paterson [16] presents a series of studies where shape rules formalise explorative prototyping, including physical model-making. In both these works shape computations give formal descriptions of creative design processes, with a focus on the transformation of representations, and this description is then used to analyse the processes, giving insight based on objective external evidence, rather than designers' recollections of their internal thought processes. Both works exemplify practical applications of Stiny’s schemas of shape computation [13], which generalise shape transformations according to a small set of possibilities. Whilst basic, schemas are powerful, giving a high-level visual language to describe transformations of design representations.

Visual rules and schemas are well suited to design explorations involving sketches or digital models. However, they are not yet explored as modes of representations that have a physical and tangible existence. Designers’ interactions with physical models, either through craft-like process of making, or via interaction with digital fabrication tools, cannot be fully described as visual interactions. The materiality of such representations introduces physical considerations imposed by the material world: the fact that orientation is not homogenous, because of gravity; the need for support material, to resist gravity; the occlusion of internal shapes by external surfaces; etc. Even though the materiality results in decisions of form, visual representations do not capture the full range of interactions that designers employ as they explore and discover the properties of material form. Instead designers use other senses to augment their visual interaction, mostly importantly the tactile exploration that arises from touching, lifting, and manipulating objects in space. In our exploration, we create rules with labels and weights to capture some of these aspects.

3 Case Study

We conducted a three day workshop in Istanbul Technical University with the participation of graduate level computational design students. The aim was to guide the participants to explore material manipulation in design with a computational perspective. The participants worked on two simple design tasks. The first group of students worked with a knitting machine and systematically explored the machine knitting process. The second group of students were asked to cut slivers into sheet materials (cardboards of different thicknesses) to play with surface flexibility. Both groups were introduced to shape computing after a half day hands-on exploration working with the design task. They were guided towards defining visual rules and weight definitions, using shape grammars to represent their shape making process of generating the cutting and knitting patterns. Afterwards, they were asked to physically explore their material samples and define a formal way to relate their shape making and interactions with the material.

All generated sets of material samples from the cutting experiments are shown in Fig.1. In the examples shown in Fig.1-a and Fig.1-b the participants explored the variable bending capacity of cardboard by cutting repetitive patterns on planar sheets. Fig.1-c shows an exploration where the flexibility of the planar surfaces under twisting motion is controlled by cutting concentric radial slits of varying density. In Fig.1-d, discrete lines cut the planar surfaces and the sequential change in the angle of the lines alters the final forms of the samples when pulled from both ends.

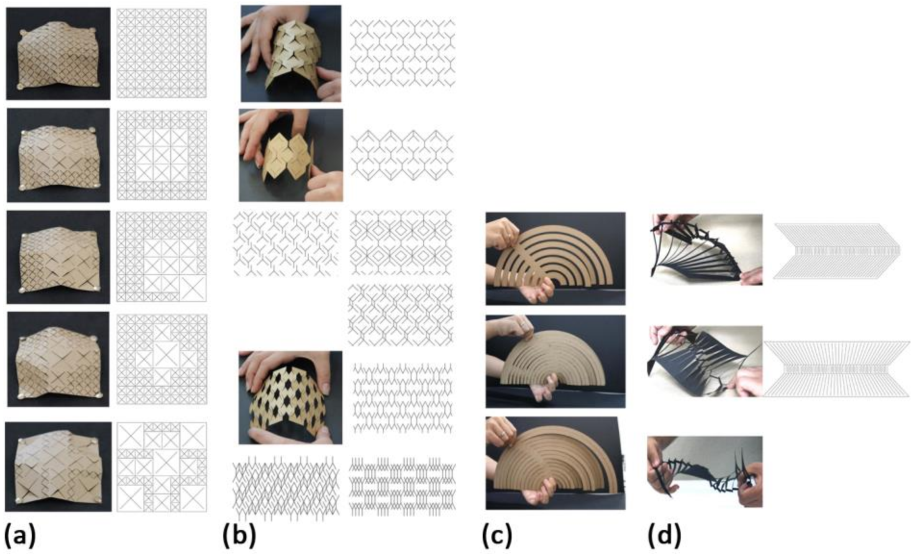

Fig. 1. Student work from workshop. Details of the material experiments from the knitting and cutting groups' works can be examined at http://materialcomputing.wix.com/knittingcutting.

We have since extended the exploration in Figure 1-a to develop our approach to material computing. First, we generated our own set of cut samples for a more systematic inquiry into the variables affecting the material outcome. Our aim has been to put forth the relations between our shape computations which alternate the cut patterns and our material manipulations, and to find a formal way to correlate the two. Following the starting set of schemas for the cuts and the manipulative action (bending), we did not have a clear design goal at first but engaged with the material in an exploratory manner. In the process, we observed that while the cuts have an effect on the overall flexibility of the surface, as previously explored by the participants of the workshop, they are also differentiated in light transmittance as well. Considering light as a design variable, we concentrated mainly on manipulating it with our cut sheets. We saw that variations on the cut patterns generated different shadow-light configurations. When the cut sheets are held towards a light source, different patterns emerge as light and shadow on projected surfaces. While the emergent light patterns simultaneously change with their relative position to the cut sheets, they also change with reference to the form of the surface of the cut sheets. Bending a cut sheet correspondingly changes the light-pattern. Since bending capacity depends also on the changes in material specifications (i.e. thickness of the material), same patterns cut from cardboards of different thicknesses do not bend to the same form, causing different light patterns to emerge. We systematically explored and documented these various material outcomes and formally represented our explorations with shape rules.

3.1 Shape Manipulation: Generating the Cut Patterns

In exploring the links between our shape making and our material manipulations, we designed a systematic process with a simple set of material samples. The simplicity of the set mostly lies in the symmetry of the square shaped cut sheets with 4 fold rotation axes and 4 mirror planes. The sheets are cut with repeating symmetrical patterns which contain symmetrical shapes. The meticulous use of symmetry is to create homogeneous surfaces of which the material properties are shaped by the cut slivers. We change the variables of the cut patterns consistently. The samples obtained at the end can be explored in relation with each other, in a systematic way, according to the changes in the variables. Below, we present the shape rules and computations which generate our samples. This first set of rules also serves as a reference point for all other rules in our explorations.

Rule 1 and Rule 2 each describes the division of a square shaped whole into identical parts (Fig.2-a). We can thus obtain square grids of varying sizes from an initial square. We choose to derive three specific grids for our study (Fig. 2-b).

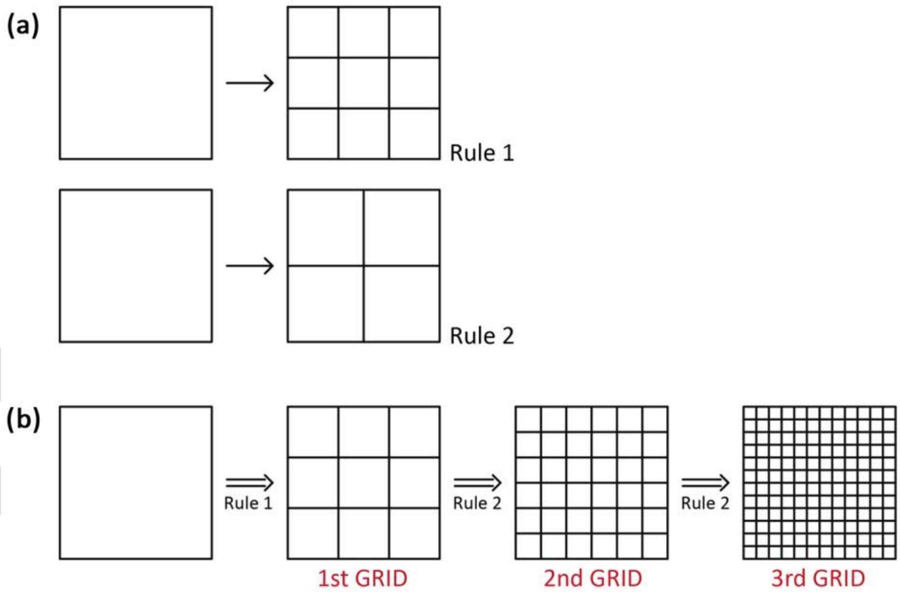

Fig. 2. (a) Rules and **(b)** the computation that transform the square to grids

Another rule, describes how squares transform into crossing lines (Fig.3-a). We can thus generate repetitive patterns of crossing lines based on the square grids. Rule 3 is altered with a label that changes the length of the crossing lines, and with a weight that affects the width of the crossing lines. (Fig. 3-c and Fig.3-d) These variations of Rule 3 describe our initial systematic manipulations on the material and serve as devices of control.

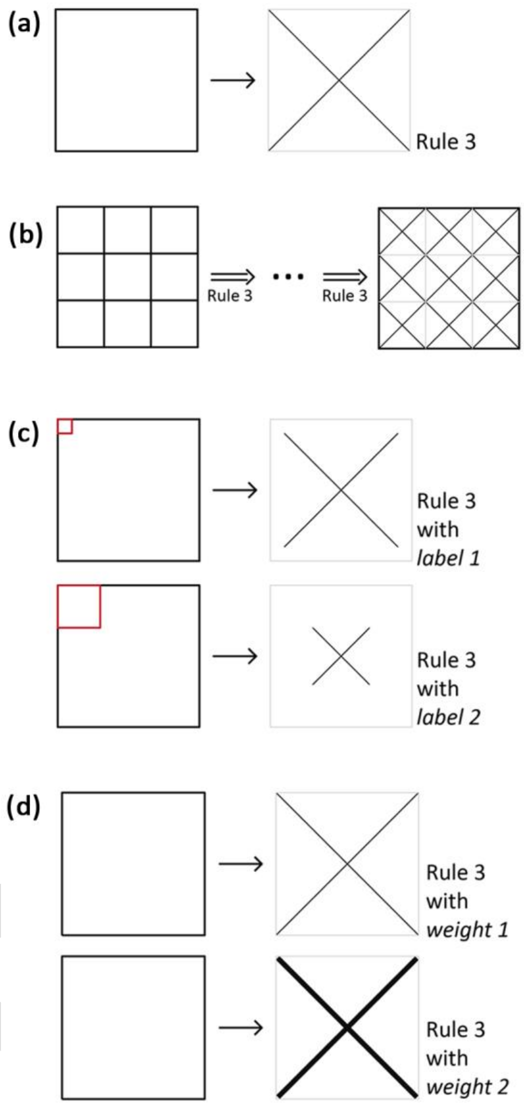

Fig. 3. (a) Rule 3 that transforms the square to a cross, **(b)** the computation that shows the transformation of the grid to the alternate grid of diagonal lines, and variations of Rule 3 **(c)** with labels and **(d)** with weights

By using the above four Rule 3 variations, we obtain 12 different cut patterns. We cut these samples from cardboards of three different thicknesses (0.2mm, 0.8mm, and 1.2mm). We refer to the cardboard thickness as *material weight* in the rules. All of the cut patterns we obtained are shown in Fig. 4 as a systematic exploration of the effects of the variables on the material outcome.

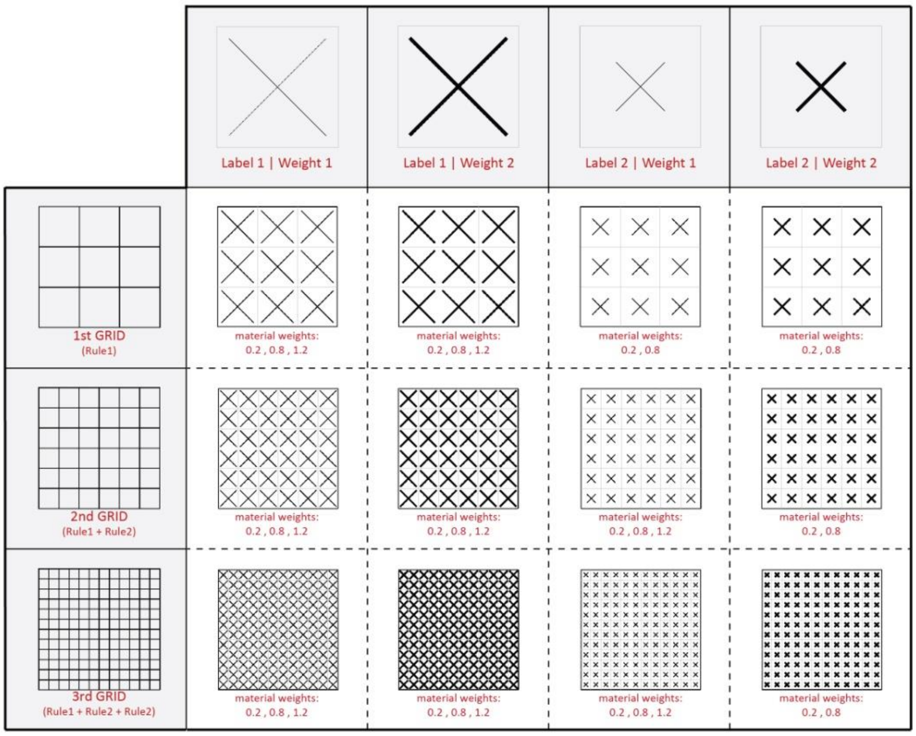

Fig. 4. The matrix that shows the set of cut patterns we use in our exploration

3.2 Material Manipulations

The exploration that corresponds to a simplified design process has been realised in four stages. We physically manipulate the cut sheets in four ways in each stage. In the first, where bending is applied to observe the altering degrees of perforations and smoothness in the material, the exploration led to observing the altering degrees of light intensity on the surface. We considered this as design emergence and established a setup to observe light systematically as it goes through the perforated surfaces (Fig. 5). The simple setup is inspired by traditional shadow plays where light transmitting through the perforations of the cut sheets generates light and shadow configurations on the screen. In the following three stages, we manipulated the distance between the screen in the set up and the cut sheets, rotated, and layered them. These manipulations result in patterns of light on the screen. We photograph these patterns and by recognising the emergent shapes, we trace new patterns in a different medium. In these experiments, we consider light almost as a material with which we generate new patterns.

Below we identify the actions and the variables for each exploration then represent these with visual rules.

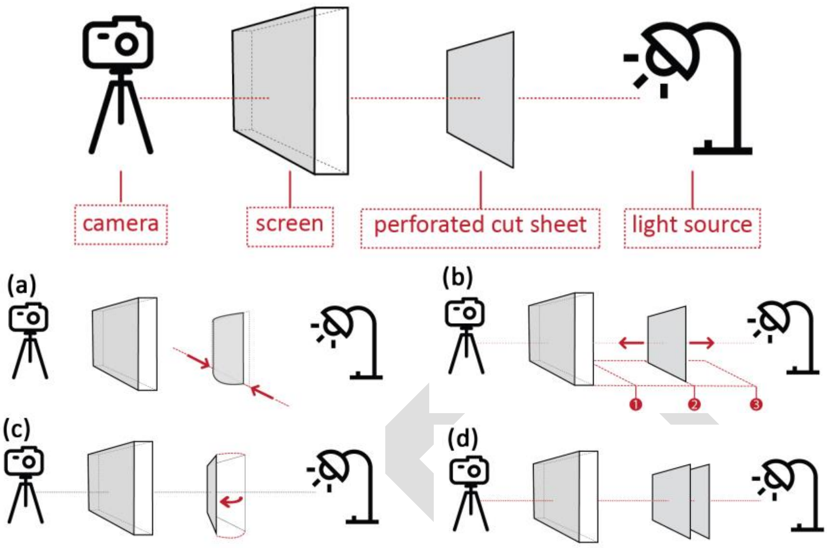

Fig. 5. The setup to observe light and the four variations of the setup in each of the four stages of the exploration: **(a)** by bending the cut sheets, **(b)** by changing the distance between the screen and the cut sheet, **(c)** by rotating the cut sheet, and **(d)** by layering.

Exploration #1

Actions: Bending.
Variables: 1. Cut patterns, 2. Material weights

For this exploration we have three rule sets: for materializing the cut patterns, for bending, and for light patterns. In the rules that materialize the cut patterns, a weight (mw) is introduced as an indicator of the thickness of the material samples (Fig. 6-a). In the rules that bend the cut samples, labels are used to denote the points where the samples are held to enable bending. A weight (w1) defines the intensity of the force applied for bending. We represent this weight with a point on a gradient scale bar. The lightest colour in the middle indicates flat position, darker left parts indicate bending forwards, and darker right parts indicate bending backwards. Different weights can be introduced for left hand thumbs and right hand thumbs. Here, to symmetrically bend the cut samples, we make use of a single weight, which controls both thumbs in the same way (Fig.6-b). Lastly, we evaluate light transmittance and the last set of rules generates the visual patterns on the screen (Fig. 6-c). We present in Fig.7 various computations in which the initial abstract shape is the same. We apply to this initial shape the rules that materialize this shape, the rules that bend the materialized shape and the rules that generate light patterns, in a sequential order. Applying the same *bending rule* with different labels and weights generates a considerable amount of variations in the materialized shapes, resulting in variations in the light patterns as well.

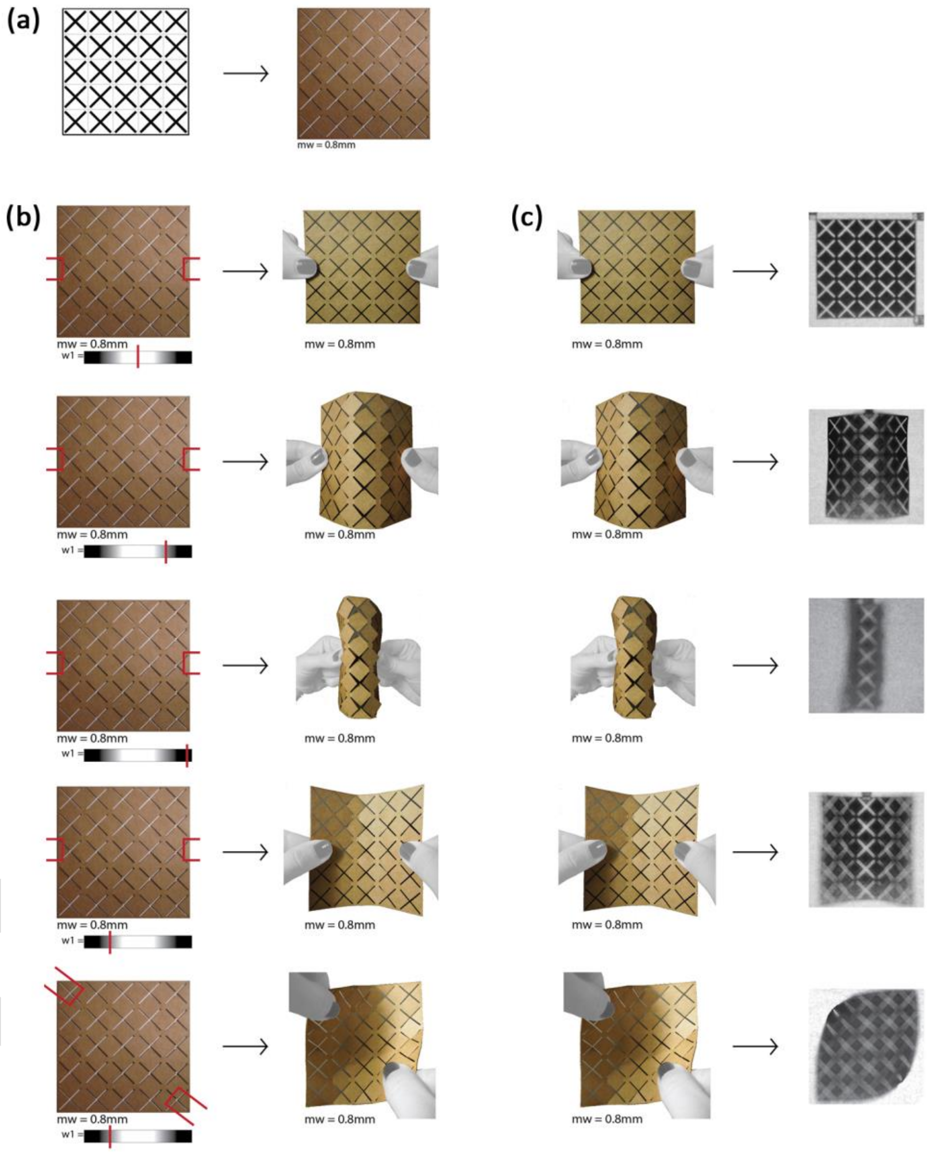

Fig. 6. Shape rules of the first exploration: **(a)** Rules to materialize the cut patterns. (mw) is a weight indicating the thickness of the material sample. **(b)** Variations of the rule that bend the material samples with labels and weights. Labels indicate the handling points for bending. (mw) and (w1) are weights. (mw) indicates the thickness of the material sample. (w1) controls the intensity of the force applied for bending. **(c)** Rules to generate the light patterns. Bent cut sheets generate distorted light patterns.

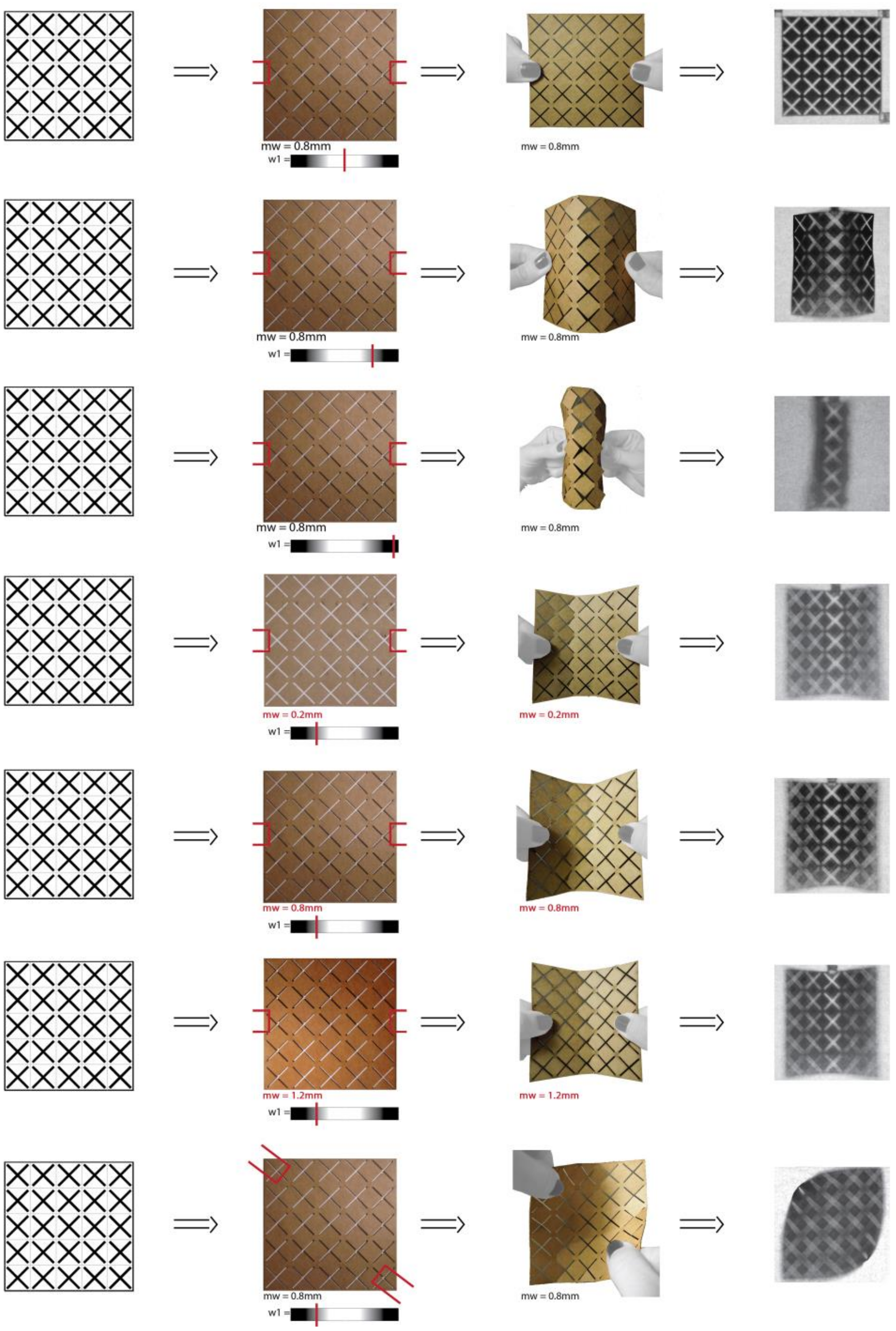

Fig. 7. The initial abstract shape common in the computations generates a considerable amount of variations of the materialized shapes (as both bent sheets and light patterns), when the labels and weights defined in the rules are changed.

Exploration #2

Actions: Moving the cut sheets on an axis perpendicular to the screen
Variables: 1. Cut patterns, 2. Distance between the screen and the cut sheet

The first exploration with bending the cut sheets shifted our design intent to manipulating the light effects. In the second exploration, without any physical intervention to the cut sheets, we explore the changes in the patterns emerging on the screen by gradually moving the cut sheets between three spots on an axis perpendicular to the screen. For this exploration we have three rule sets: for materializing the cut patterns, for generating the light patterns, and for translating the emerging light patterns to drawings. Rules for materializing the cut patterns do not require a weight to control the thickness of the material samples since the cut sheets are not physically manipulated (Fig.8-a). Labels in the set of rules that generate the light patterns denote the three spots where we place our material samples: the far left label indicating the closest distance to the screen and the far right, the farthest among the three (Fig. 8-b). This transition from abstract shapes to material shapes, back to abstract shapes can be observed as a generative process in the various computations we present, with a new rule that translates the light patterns to a new medium as drawings (Fig. 9).

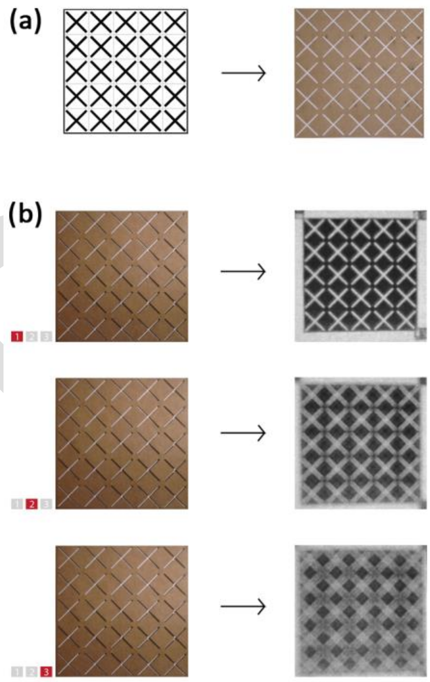

Fig. 8. Shape rules of the second exploration: **(a)** Rule to materialize the cut patterns. Thickness of the material is not a design variable. **(b)** Variations of the rule that generates the light patterns. Labels control the distance to the screen.

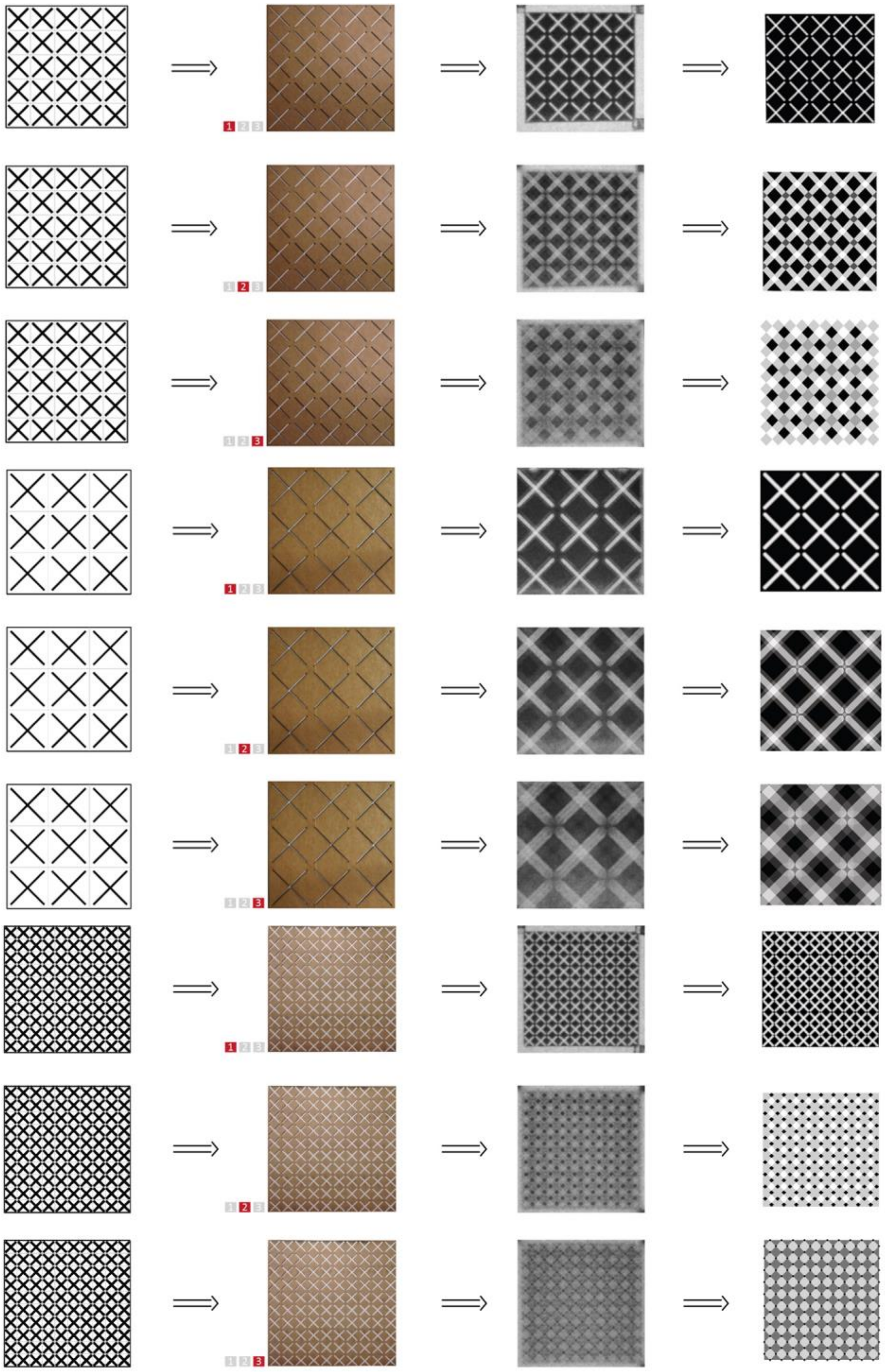

Fig. 9. The computations which showcase a transition from abstract shapes to material shapes, back to abstract shapes with a last rule translating the light patterns to drawings.

Exploration #3

Actions: Rotating.
Variables: 1. Cut patterns, 2. Rotation angle

In the third exploration, we rotate the cut samples by setting one of the sides as the rotation axis and then examine the light patterns on the screen. We keep the distance constant in each variation. Cut samples preserve their planarity, therefore material thickness does not have an effect on the outcome. A label defined with a line indicates the rotation axis of the cut samples. The rotation angle is defined with a weight (w2) represented with a point on a gradient scale bar. Within a range of 180 degrees, the left hand side of the scale bar adjusts the degree of clockwise rotation, and the right hand side, the degree of counter-clockwise rotation (Fig. 10-b). The computations which rotate the cut sheets, generate the light patterns and finally translate the light patterns to drawings are presented in Fig. 11. Even though the shapes on the cut sheets are the same, the shapes composing the light patterns are continuously and gradually changing when the cut sheets are rotated. Physical rotation of the cut sheets can therefore be considered as a *generative tool* within the setup we present.

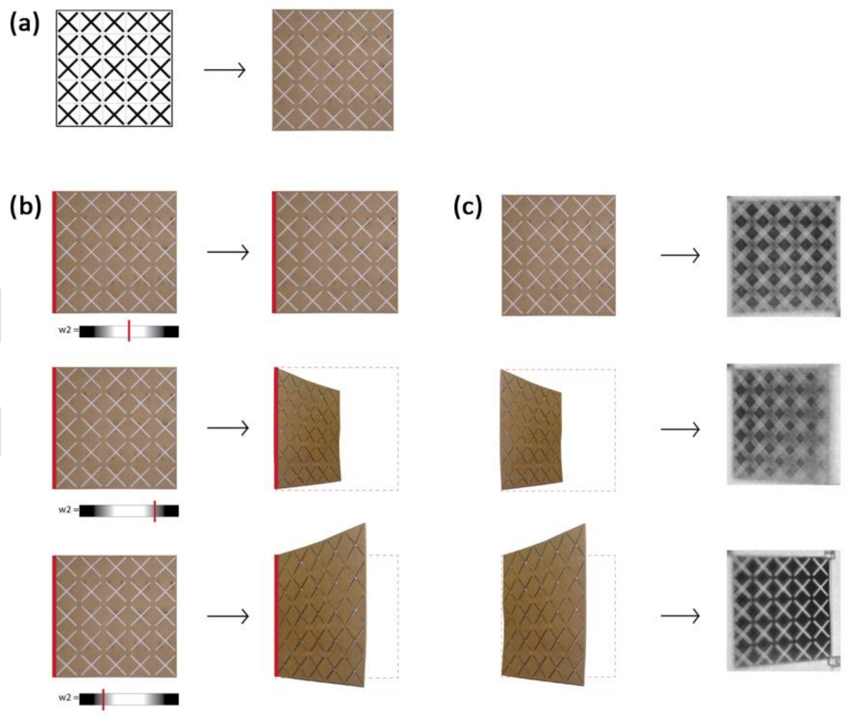

Fig. 10. Shape rules of the second exploration: **(a)** Rule to materialize the cut patterns. Thickness of the material is not a design variable. **(b)** Rules rotating the cut sheets on a rotation axis defined with a label indicating the rotation axis and a weight (w2) indicating the rotation angle. **(c)** Rules to generate the light patterns.

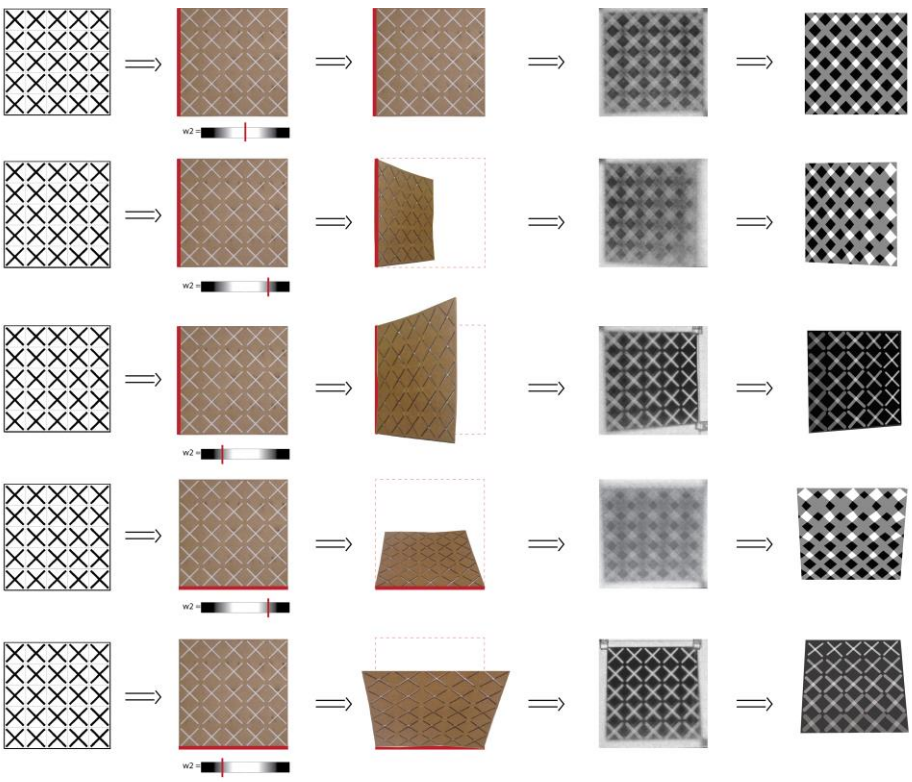

Fig. 11. Shape rules sequentially applied in computations with an additional last rule which translates the light patterns to drawings.

Exploration #4

Actions: Layering (Boolean Operations of cut shapes).
Variables: 1. Cut patterns, 2. Boolean operations

In the final round we physically overlay the cut sheets. The overlaid samples are then placed in a set up similar to the one in the second exploration, to explore the changes in the light patterns on the screen. Here, we choose to represent physical layering with Boolean union operations of at least two cut sheets, say **(A)** and **(B)**. These are generated with rules translating the two cut patterns into material samples in Fig.12-a. Materially, layering **(A)** and **(B)** corresponds to **(A) + t(B)** operation where the translation of **(B)** is with reference to **(A)** and controlled with a label. We represent this label with two perpendicularly intersecting lines, each aligned to **(A)** (Fig.12-b). Even slight changes in the position of the label of **(B)** create different configurations of perforations, resulting in new material samples (Fig. 12-c). The Boolean operations can be represented as shape rules with the material sample **(B)** as the left hand side of the rule and the layered samples of **(A)+t(B)** operation as the right hand side of the rule (Fig.13-a). These new material samples generated by layering the existing ones, result in a considerable effect on the light patterns on the screen (Fig. 13-b). The 4 fold rotational symmetry with 4 mirror planes of the cut patterns changes to a symmetry with a single mirror plane when layered. Also, while physically layering the cut sheets denotes a union operation, the resulting patterns on the screen correspond to a product operation where the shapes are the perforations on the cut sheets. If the same exploration was realised with translucent sheets instead of opaque cardboards, physically overlaying the sheets would correspond to a product operation, whereas the light patterns on the screen would be the result of a union operation. This shows how schematized representations can be misleading in describing the material manipulations in design.

The computations with the rules in Fig.13-a, Fig.13-b, and an additional rule to translate the light patterns to drawings are presented in Fig.13-c.

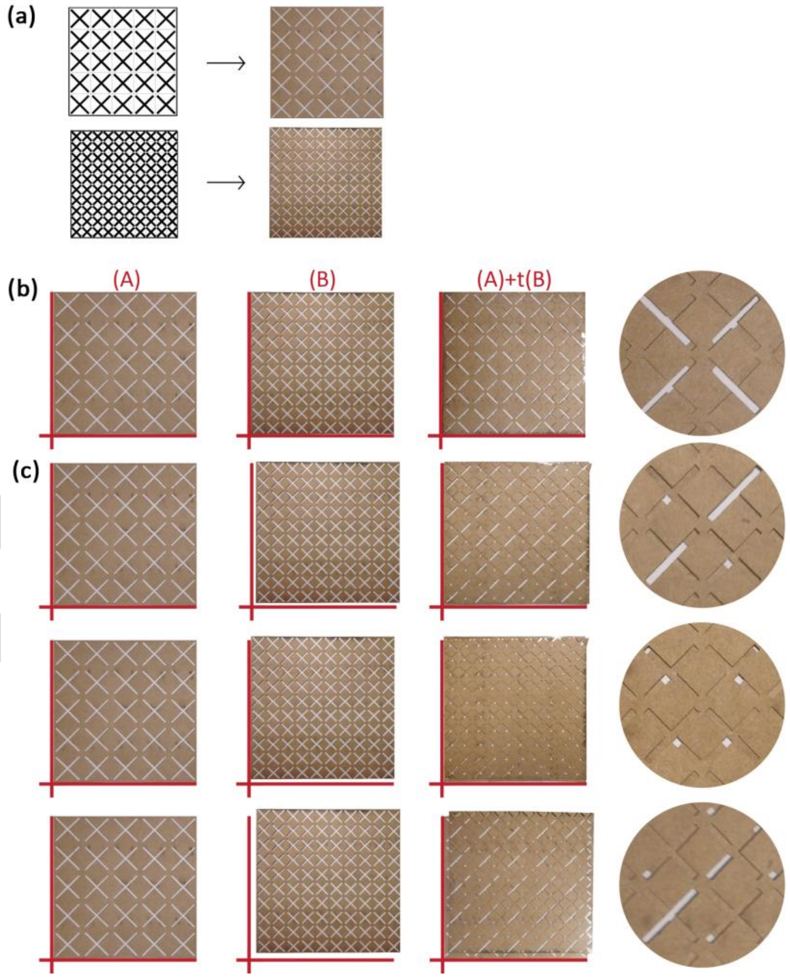

Fig. 12. Final exploration: **(a)**Rules that generate the material samples. **(b)** Labels control the translation of (B) with reference to (A) in a Boolean union operation. **(c)** Slight changes in the position of the label of (B) create different configurations in perforations.

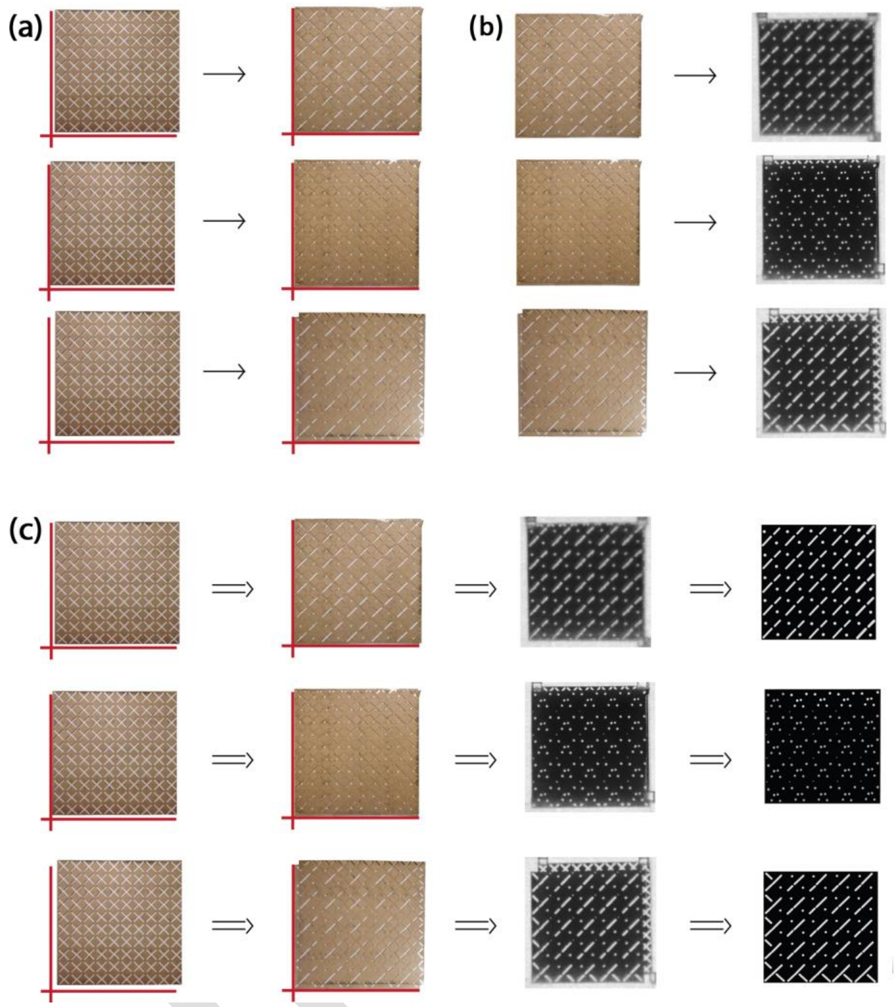

Fig. 13. Rules of the last exploration: **(a)** Boolean operations represented as shape rules **(b)** Rules generating the light patterns and **(c)** the computations which layer the material samples, generate the light patterns and translate the light patterns to drawings

4 Discussion

With open source sharing being a growing ethical practice, it is imperative more than ever that design process is traceable. Traceability is especially relevant in design studio environments where students are asked to communicate their acts and decisions with instructors and peers for the sake of learning how to reason in design. More than just for accountability to fellow humans, formalising reasoning as design computations, allows the individual designer to have control over the design process, to be able to determine how and why unexpected outcomes emerge and to turn them into design ideas. Yet, design computation is not widely inclusive of multisensory design processes. Due to their complex interfaces, digital fabrication tools already impose particular formalisms and require computation in design implementation. Nevertheless, there is still a need in the field to computationally represent the sensory aspects of working with materials in design.

The utilization of shape rules as analytical and creative tools have been demonstrated in the shape grammar literature. In addressing the need above, we attempt to extend this utilization by integrally representing the causal links between interventions on the material and our shape making in shape rules that support formal computation. The research we present is ongoing. We have selectively reported a set of explorations where we manipulate the three dimensional form of cut samples and light as a case study to show shape computation that is informed by material interventions. Our exploration has so far been limited only to a narrow scope of material and sensory aspects. These can be recapitulated as a texture composed of slits cut on a sheet material, manually applied physical force to bend the material, and light effects of perforations, as observed by the subjective eye. All three are very much in direct connection to form with the exception of bending, which involves tactile manipulation in addition to the visual effects of the resulting curve.

The four explorations demonstrate the use of visual rules to represent actions, variables and form. In the first, it is visible that bending axes impact the visual outcome. According to the axis, the slits allow the sheet material to behave differently. The causal link is partially represented in the tools. In addition to the changing effects of the surface texture when bent, from smooth to rugged, it was important to shift the design intent to light effects. This initiated the following explorations and hence the new set of rules.

In the second exploration, we describe a process of transition from abstract shapes to material shapes, back to abstract shapes. The slits transform to light patterns, which inspire new visual patterns that can be translated to yet another medium. Similar to the emergence in the first exploration, this supports our quest to formalise a materially informed design process. With a focus on the 2d shapes (of the cut patterns, on the cut sheets and on the screen) our attempts to correlate our shape making and material manipulations is communicated in a simple way.

In the third exploration, uniformly cut sheets are physically rotated resulting in different light patterns with gradual and continuous variations. We denote rotation as yet another generative physical action.

In the final exploration, the physical overlaying of the sheet materials has tremendous effect on the visual patterns on the screen. Here, we choose to represent the Boolean operations with the cut patterns rather than visual rules. Still, the representations of the operations can be considered as rules where the column to the far right is the right hand side of the rule. The result is unexpected new shadow patterns on the screen.

The rules that we have defined to show the physical cause and the visual effect are still mostly visual. The final exploration elevates rule representation to another level when material layering leads to the visual product suggesting a switch between making and seeing.

In each exploration, explicitly representing the cause and the effect allows for controlling the variables and for alternating them to create new results. Whereas the desired results assure the designer of the causal link, the surprising results indicate a materially informed emergence. The simplicity of this exercise is suitable for the studio context, but further research can extend the demonstration to more sophisticated processes of material manipulation and their causal links to form creation. Rather than quantifiable properties useful for exact simulations, our emphasis has been on representing sensory aspects in order to sustain a designer-centered formalism where the level of abstraction matches the sensory involvement. In the future, the formalism may be inclusive of inhabitants' experiences in designs at the urban scale.

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