Internship at Solliance: Shapes and Folding CIGS Modules

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Summary

My internship took place from the first of August to the end of December, working 40 hours a week. The company that employed me was Solliance, a solar panel research company which is part of the TNO conglomerate. The project given was explorative. The main objective was an exploration into how solar panels can be manipulated into three dimensional geometry. One of my goals as a designer is to integrate sustainable technology into everyday living; this project allowed me to begin to develop my vision of who I want to be as a designer, and the type of projects I want to work on in the future. There were two people to supervise this work, Bart van de Vorst, and Monique van den Nieuwenhof. With these supervisors, a meeting every week was held to communicate results and ensure that the direction of the research remained interesting.

The internship was centralized around the one objective, to find a way to manipulate solar panels into three dimensional geometric shapes, but consisted of many different projects to understand the design constraints. Additional projects included, documenting new machinery that the company procured, and starting an investigation into a future project that involved a small collaboration with another company.

For the main project, many activities were undertaken, such as a literature review to understand the mathematics behind origami and kirigami, this helped me develop my math, data and computing competency area. I also developed my technology and realization competency area in multiple ways, mostly by learning about solar cell technology, how to build samples, and building experimental prototypes. Within the internship I was also able to create a weekly meeting between many of the other interns working on applications of solar technology. This meeting allowed us to talk about our challenges and give each other ideas which helped us learn how to work within an interdisciplinary group. These meetings also gave us an opportunity to present our results to each other in a more formal way which helped us develop our business and entrepreneurship competency area. Another activity which aided the development of my business and entrepreneurship competency area was working with a partnering company. During Dutch Design Week, this other company had an internal exhibition where I presented my work to their clients.

There are a few final deliverables for this internship. The first being a collection of large prototypes showing the limitations of the materials. Some of the large samples are an exploration with just the protective layers for solar cells, and others have solar cells already integrated. There is also thorough documentation of how to build these prototypes for future exploration. This includes documentation of why specific materials were used.

Additional deliverables resulting from this internship was a binder which documents how to use the new die cutter and documentation of origami techniques which could be applicable to the materials. The die cutter binder includes troubleshooting, and samples of the specific materials that are cut within the lab at different pressures.

Company Description

Solliance is a solar panel research company. The majority of the company studies the manufacturing process of solar cells and the degradation of them in different conditions. There is also a small group of people working on the integration and application of solar technology. This group is where the research of the internship has taken place. The exploratory design research was done as an independent endeavor with guidance from two supervisors, Bart van de Vorst and Monique van den Nieuwenhof. The main supervisor, Bart van de Vorst, has a bachelors in industrial design and has worked in the field for the past eighteen years. With these two supervisors I have a weekly meeting where I present my findings and explain my plan going forward.

In addition to the weekly supervisor meeting I was also able to create a new weekly meeting among other interns who were part of the integration team. These five other interns worked on a wide variety of projects. Some of them were studying how to apply solar technology to different applications, and others were researching how circuitry, or the internal designs, could be optimized. This diversity of projects, as well as the diversity of the studies that we come from, me being the only industrial designer, created a fascinating environment where we could learn from each others' interdisciplinary perspective. Within this meeting there is both presentation of results from the various projects, to both each other and the occasional supervisor, as well as general discussion of challenges and plans for each project.

A large part of the internship has taken place in various labs. One of the labs has equipment for analyzing solar cells. Part of the work done was the analysis of cells after bending, or measuring how different connections impact the efficiency of the cells. Apart from occasionally analyzing samples, I spent a lot of time within the integration lab. Here, I learned how to build cells ready for integration and use equipment like the two laminators that are in the lab, and the newly installed die cutter. This lab allowed me to build samples and prototypes out of both the cells and the outside layers of the cells.

Overall, it was a fairly exciting environment as my time was split between doing a lot of lab work building physical prototypes, using machinery to analyze cells, and doing documentation and literature review in a more traditional office.

Introduction of Project

The main objective for this research is to understand how to develop complex shapes which have “double curvature”, such as spherical shapes or hyperbolic shapes out of thin film photovoltaic cells. These thin solar cells have flexibility due to how thin they are. There are multiple subsequent objectives to further divide this research as there are a lot of design constraints surrounding the CIGS solar panel technology. Such objectives include: understanding how to bend the materials, understanding how to arrange the cells, understanding the limitations of the materials and how to supplement this when necessary, and developing patterns which can create global curvature.

As solar panels become a more accessible technology, more efficient and more affordable, applying them to many applications is becoming of great importance. This means not just accommodating different types of roof tiles but small applications like bicycle helmets, and vehicles. Demand can be seen as companies like Lightyear, and Ford have already started to create electric cars with solar panel integration (Joti). All of these future applications have different challenges, as their global geometry is different. Another challenge for different applications is movement and durability. Some designs might need to incorporate movement such as putting solar panels on a collapsible or expandable designs.

Origami has been studied with relation to solar panel technology before. There are accounts of using these techniques to find flat folding devices both for space applications (Miura) and for collapsible designs (Kuribayashi). There are also accounts of kirigami being used to move the module to track sunlight (Lamoureux). This previous research makes it apparent that developing solar panels in ways that allows them to accommodate complex global geometry for a range of applications is becoming increasingly important. This research attempts to outline an understanding of the limitations of current solar technology in addition to cataloging prototypes.

CIGS

The solar panels that will be studied are known as CIGS panels. CIGS stands for copper, indium, gallium, selenium solar cells. To understand the design constraints a short explanation of the relevant layers on top and below of the CIGS panels will be discussed. The cells themselves will not be discussed, especially because commercial cells are used for prototyping. The main layers of a flexible CIGS panel ready for application are, from bottom to top, the backsheet, encapsulant, the solar cells, another layer of encapsulant, and then the frontsheet. This can be seen in Figure 1. The layers can be see in Figures 2, 3, and 4. When the panels are constructed these materials are stacked together and then put in a vacuum at a high temperature, around 135 degrees Celsius, to adhere everything all together, the encapsulant acting as the main adhesive. The laminator can be seen in Figure 6, page 7.

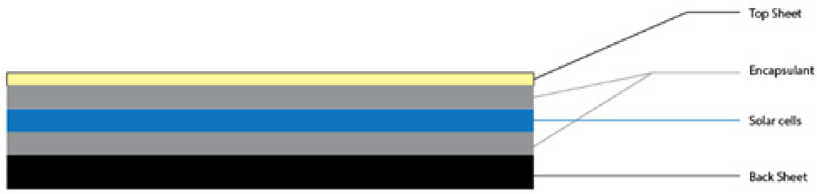
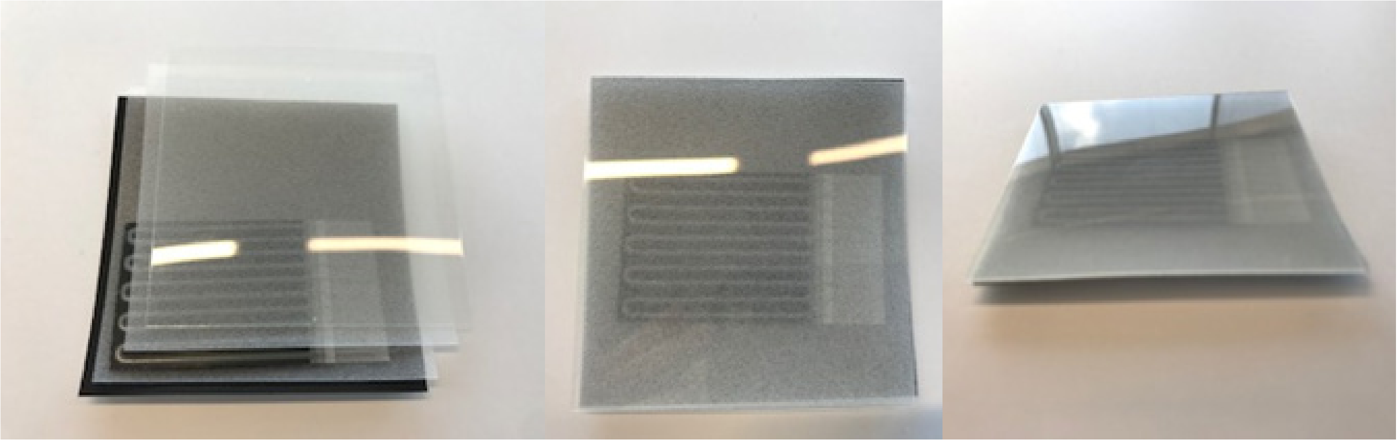


Figure 1: Diagram of the layers on top and below the CIGS cells.



Figures 2 and 3: Stack of materials before lamination

The backsheet, encapsulant, and frontsheet all help with weather proofing and durability of the cells. These materials also all composed of their own layers of different materials, mostly consisting of different polymers and metals. This means that with every layer there are different constraints on how they can be manipulated. There was a small exploration done to find the right backing material as well as the topsheet material for this specific application. Perimeters for these explorations included flexibility and creasability as well as durability. The materials themselves will not be discussed in this paper to preserve the confidentiality of the research Solliance is doing but a general description of their behaviour will be mentioned to understand the design constraints.

A general qualitative description of the materials used is helpful in understanding the limitations of the materials. The backsheet is flexible, just like paper, and can be folded, but cannot be manipulated out of plane. The encapsulant is also flexible and melts under the lamination temperature. This, once cooled, can easily be folded. The cells themselves have undergone a few different explorations to test how the cells can be bent. These explorations can be seen in the section “Bending the Cells”, page 9. The main finding from this exploration was that the cells can undergo curvatures but when folded, the cells become damaged. There are also limitations about the sizes and shapes that the cells can be arranged in, this is discussed in the section “Arranging the Cells”, page 9. The cells are connected and arranged with tabbing material which can be seen in Figure 4. The frontsheet also had similar issues with foldability, where bends do not cause any damage but the sharp folds would cause cracking in the material. Understanding how to manipulate these materials to fold and form into various shapes is explored in the section “Fold Exploration”, page 15.

Altogether, the complete stack of materials has the rigidity of a thin cardboard sheet. It is flexible but cannot be easily folded and cannot deform out of plane. More about these limitations are discussed in the section “Local Curvature Limitations”, page 8.

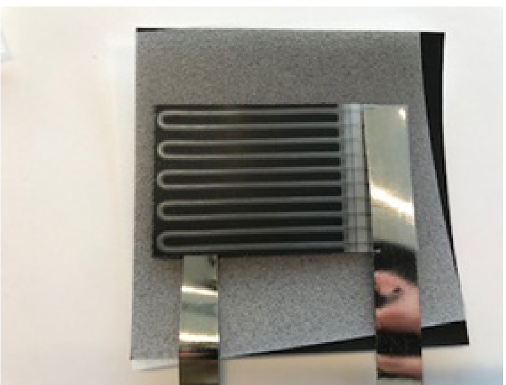


Figure 4: Tabbing materials on cell, showing how to connect the cell to other cells or to the outside world. One of the tabs is on the front contact (on top of the white wiring of the right hand side of the cell) and the other is connected to the back contact (the back of the cell).

Machines

Multiple machines are used within my internship. Some of the machines are used for the manufacturing of prototypes. These machines include the laminator (Figure 6), which adheres all of the layers of the modules together using heat and a vacuum press. The other machine used for creating prototypes is the die cutter (Figure 5). This machine is able to cut out materials into the sizes that are needed and I have also learned how to use the machine to preferate and cut designs into the layers to help aid in the folding process. The die cutter was a large part of the internship as part of the work that was done was cataloging the settings that should be used for the various materials.

The other machines used were for the analysis of the prototypes that were created. Many smaller iterations were done to analyze the impact of the bending techniques and different connections between cells. Two different machines were used for this analysis, one of which took IV (current voltage) measurements, the other was an imaging machine which took photoluminescence (PL) imaging.

Figure 5: Die cutter

Figure 6: Laminator used for combining layers together.

Design Constraints

Local Curvature Limitations

Currently the entire panels are flexible in one dimension, able to accommodate in-plane distortions. This is similar to a piece of paper so for lo-fi prototypes and discussion this will often be used as an analogy. The panels are also unable to shrink or expand within their plane, like paper, so traditional methods of forming complex curvatures, such as plastically stretching or using shearing deformations, used in forming sheet metal, plastics, or fibers cannot be done (Callens). At attempt to thermoform the backsheet can be see in Figure 7. While this is currently the case, stimulus responsive material, like shape memory polymers, might be able to help this development in the future (Manen).

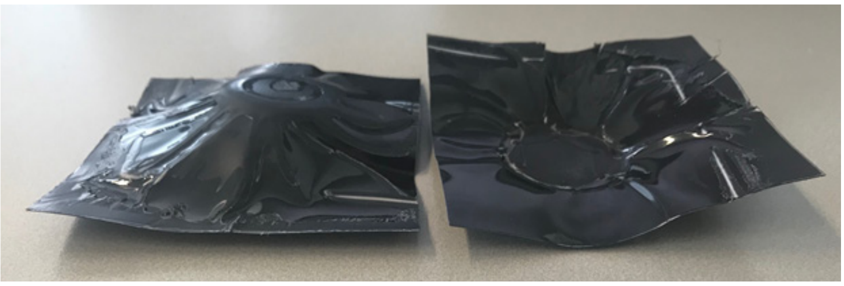


Figure 7: Attempt to thermoform the backsheet, resulting in the disruption of the layers.

Due to these constraints, the local curvature of the panels will always remain the same due to their inability to deform. This limits the global shapes that can be formed, see Figure 8. The objective for this research is to explore patterns that can be ingrained into the panels which can allow for more complex global curvature by allowing folding to occur. Such complex global curvature includes spherical shapes and hyperbolic shapes, see Figure 8. While this will not be able to fit curvatures smoothly, it will be able to approximate the shapes out of flat planes.

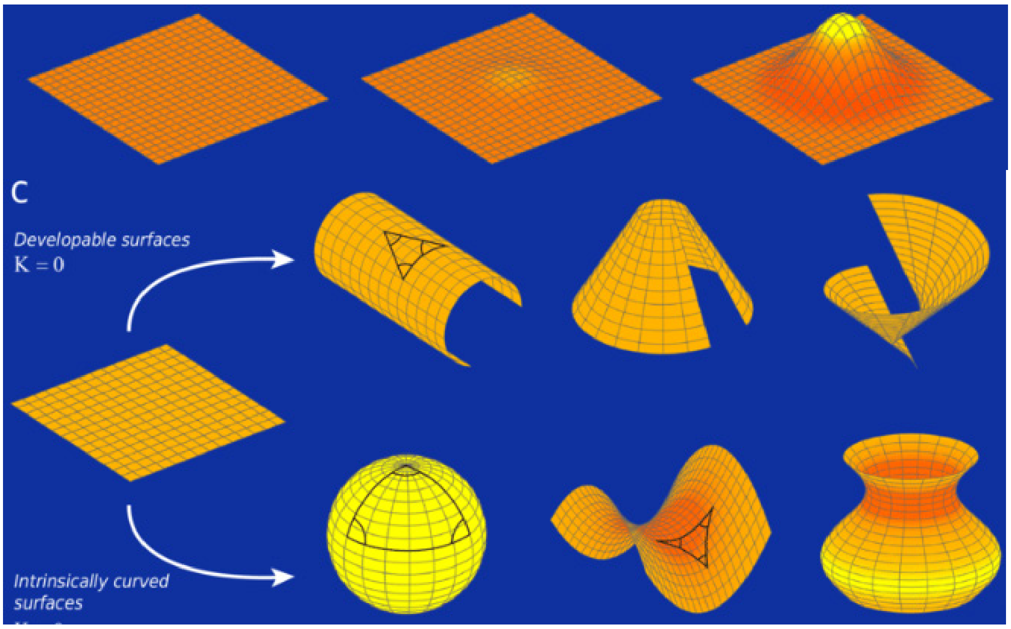


Figure 8: Figures on top show a plane being distorted. Solar cells are not able to accommodate this type of alteration. The next row of figures shows the shapes which can already be made by only bending the plane in one dimension. The last row of figures shows shapes which are too complex to be made without dimensional alterations. These are the type of shapes this research intends to focus on creating.

Citation: Measures of surface curvature. Adapted From 'flat sheets to curved geometries: Origami and kirigami approaches' by S. J. Callens and A. A. Zadpoor, 2018, Materials Today.

Bending the Cells

While the panels behave very similarly to paper, it has one major difference, it cannot form sharp bends without delaminating or shunting the cells. When forming sharp bends the cells themselves and the top sheet “buckle” when forming sharp folds or turns. To understand the limitations of the cells two experiments were run. The first experiment cells were folded to see the extent of the damage when this occurs. These cells were laminated within encapsulant before experimentation. The second experiment used cells without encapsulant or any protection and gradually bent them to gain insight into how extreme one dimensional distortions could be before causing damage. More can be seen about these two experiments in the “Bending Experiments”, page 13 and 14.

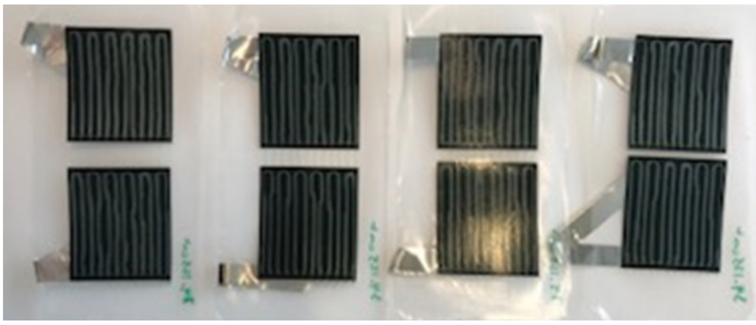
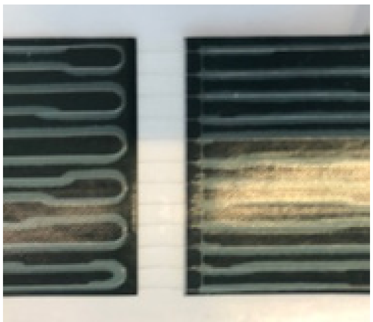
To circumvent the fragile nature of the cells, the prototypes made include many smaller cells that are all connected together. This allows for the designs to incorporate bends between the cells. There are still a lot of limitations using this method though, including the sizes and shapes that the cells can be. There is also the challenge of finding connections between cells that are able to survive through the bending process. Further information regarding the limitations of size, shape, and configuration of the cells can be found in the following section “Arranging the Cells”. Additional details relating to the exploration into the connection materials can be found in “Connection Exploration”, pages 20 and 21.

Arranging the Cells

For the prototypes created commercial cells are used. These cells have a grid on top of them, made by the front contact wires, which can be cut into pieces, so that the smallest cells are of the dimensions 4.375cm by 0.6cm (see Figure 9). While these are the smallest cells that can be created, the length can be adjusted into any multiple of 0.6 cm. The width is standardized but can be adjusted by adding cells in series, creating samples of any multiple of 4.375 cm wide (see Figure 10 and 11). When connecting cells which are directly adjacent in series the front contact needs to be completly overlapping the back contact. This was found in the experimentation seen in Figures 12 and 13. When arranging cells into an array within a module, the dimensions of the cells must be the same. Furthermore, when connecting cells in series the cells must be the same length. While these limitations often create rectangular grids of cells, extra connection materials can deform these arrays into more organic shapes. An example of this is shown in Figure 14, where the cells have been connected in a way to manipulate them into a rough parallelogram.

Figure 9: Smallest the cells can be cut into. To connect this to other cells or to the outside world tabbing materials are needed. These tabbing materials are connected to the back contact (the back of the cell) and to the front contact (right hand side white part of the cell).

Figure 10: Another size that the cells can be cut into.
Figure 11: Mia Sole cells connected in series to create larger cells. This is done by connecting the front contact to the back contact of the cells.

Figures 12 and 13: Cells connected in series by connecting the front contact to the back contact of the cells with different distances of overlap between the two cells. This was done to see if the extra spacing still provided an adequate connection between cells and if it enhanced the flexibility between cells. Unfortunately, the experiment drew the conclusion that the extra spacing created a connection that was not sufficient.

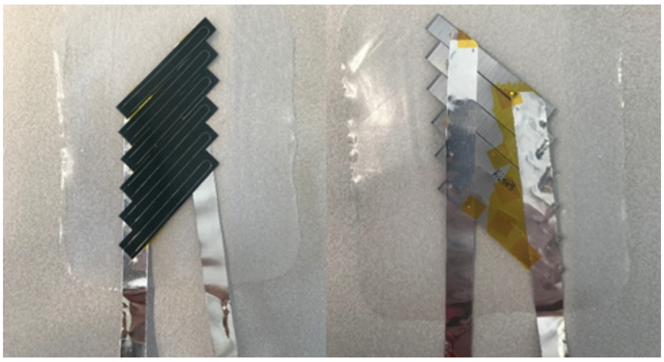


Figure 14: Parallelogram created by manipulating cells with connection material.

Cells which are not directly adjacent can be connected into arrays using additional tabbing material. Tabbing material can be used to extend the front contact of cells to be connected to the back contact of others to create series connections, see Figure 16. Extra tabbing material can also be used to connect back contacts of cells together and front contacts of cells together to create parallel connections, see Figure 15. More about how these connections can be integrated into prototypes can be seen in the section “Connection Methods”.

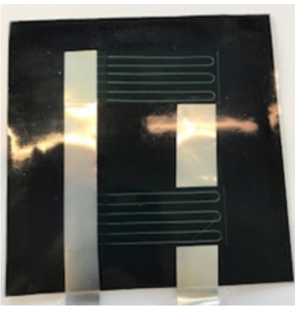



Figure 15: Parallel connections made with tabbing materials, with space between cells

Figure 16: Series connections made with tabbing materials, with space between cells

Further development into forming the cells into triangular shapes or more complex geometries is also being pursued. Such as cutting through the grid of wires to develop triangular shapes. While this can be done it has certain limitations such as not being able to cut off the front contact of the cell, since this is needed to provide connection to the outside world and other cells. Another challenge when trying to make different shapes from these methods is when cutting through the grid sometimes the wires that create the grid on top can shunt the cells during the cutting process. The triangle shape prototype can be seen in Figure 17.

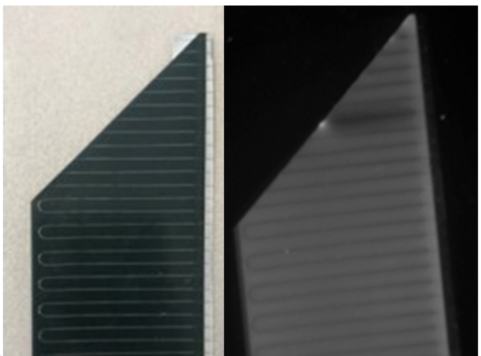


Figure 17: Triangular shape created by cutting through the grid in the Mia Sole cells. Small shunt occurred when wire was pressed into the cell during cutting.

Goals for Internship

Within my vision for myself as a designer I have always had ambitions to work in a large company. I felt that working at an internship gave me the best opportunity to understand how this environment might actually feel. This was one of my primary goals for this internship, to get work experience. While I feel like I have achieved this to some degree, I think that my internship experience did not accurately reflect how I would be working after graduation as within my internship I felt that I was given a individual project instead of being fully integrated into the work community. This was another valuable experience as I feel it has better prepared me for the challenges I will face in my final bachelor project.

I was drawn to work at Solliance because of their sustainable mission. Within my vision I have always stressed my desire to work for companies with are passionate about environmentally friendly development. Working at Solliance was a great opportunity for me to learn about solar technology and how to integrate this into everyday living. My prompt for the internship was all about finding the limitations of this technology and learning how to apply and integrate solar panels into products.

Within this internship I've been able to fulfill my first goal outlined in my personal development plan, learning new prototyping techniques. This has greatly expanded my technology and realization competency area. Throughout my work, I have learned both new prototyping techniques and new analysis techniques. Within my initial goal, outlined by my personal development plan at the beginning of my internship, I also planned on expanding my prototyping skills by doing extensive exploration with lo-fi prototypes. This aspiration was also fulfilled as my exploration of origami required a lot of paper prototyping.

My internship also gave me other opportunities to develop my technology and realization expertise area beyond what I had defined in my goals. I was able to learn a lot about what CIGS solar panels are, how to build them, analyze them, and find constraints for applications. Going forward, this has informed my sustainability design ambitions as it has given me a realistic understanding about how research in this field is done.

For one of my other goals for this internship, simulation and pattern development I was able to develop a greater understanding of the limitations of computer aided designs. Within my initial goals I planned on modeling CAD designs and using software to develop patterns. Once I began my research though, I was able to learn about how these programs which develop patterns work. Understanding the limitations of these software programs was a huge turning point in my personal development. It gave me insight into how a designer needs to bridge the gaps in the limitations of software. I found a new appreciation for the role of a designer, as I realized when I defined my original goal that I was searching for an answer to everything but instead found how every application needed to be designed by hand to accommodate cells and other complications.

Pattern Exploration

Different patterns have been explored since each one allows for different behavior and for cells to be placed differently. Many different papers also explore the behaviors of different folding patterns (Callens). Some look into depth about which patterns are ridged foldable (Tachi 2010). While others explore if patterns can be folded with thicker material (Tachi 2011). All of these patterns behave differently which is why such a thorough accounting needs to be taken of all of their advantages and disadvantages when being applied to solar modules. Most of these patterns were explored in paper first and then some of the promising ones were explored in the other materials. Some of them were even actualized by the complete prototype process described in the section “Manufactoring Method of Prototypes”, page 23. All of these different patterns are categorized into three categories. The first category being strips, the second being origami and the third being kirigami. Strips utilizes a long and thin piece of material to wind itself around an object. Origami often results in a textured surface which is flexible and can be applied in many different situations. Kirigami is a special type of origami which utilizes cuts. The entire pattern exploration which outlines all of the patterns which were researched and the advantages and disadvantages of each is in the appendix.

This exploration was a great way for me to expand my math, data, and computing expertise area. This is due to the extensive amount of mathematics that is within the origami field. Understanding some of these principles lead to a better evaluation of the patterns and awareness for the limitations. Furthermore, my computing skills were refined as I explored how different software worked and how this could be applied to the process. Although ultimately this approach was abandoned in favor of more consistent patterning as CAD modeling produced designs which were largely unviable for solar cell integration.

Bending Experiments

While the panels behave very similarly to paper, it has one major difference, it cannot form sharp bends without delaminating or shunting the cells. The cells and the top sheet “buckle” when forming sharp folds or turns. To understand the limitations of the cells, two experiments were run. In the first experiment cells were folded to see the extent of the damage when folding occurs. These cells were laminated within encapsulant before experimentation. The second experiment used cells without encapsulant, or any protection, and gradually bent them to gain insight into how extreme one dimensional distortions could be before causing damage.

These two experiments taught me how to use lab equipment for analyzing solar cells. Learning these procedures allowed me to expand my technology and realization area of expertise and helped me gain lab experience. Understanding how this practical research was done helped me gain an understanding of how I would like to conduct research in the future. The results described below gave me insight into the direction that the internship went into.

Experiment One

The first experiment cells were laminated within the encapsulant. The samples were then analyzed to find preexisting defects. After being examined, the cells were folded, one was scratched along the fold lines and folded and the other was just folded by hand. These were then tested again to see how the different folds impacted the cells. To ensure that the imaging process gathered relevant data, the samples were flattened and taped to the bed of the imaging machine so shading would have less of an impact on the images taken. The fold pattern designed for this first experiment tried to mix both having folds from the back, also known as valley folds (indicated by the blue lines in Figure 18), and folds from the front, mountain folds (red lines in Figure 18). The pattern also took into consideration having folds along an angle across the cells, or vertically or horizontally across the cells. The folded samples can be seen in Figure 19.

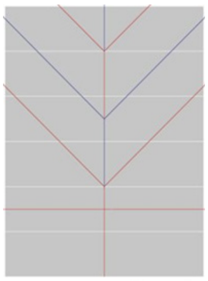


Figure 18: Folding pattern samples were subjected to. Blue lines indicate valley folds and red lines indicate mountain folds.

Figure 19 Samples after folding. Left folded by hand, right folded after lines were scored.

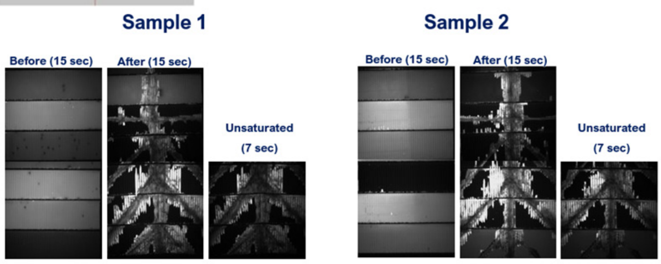


Figure 20: PL photos

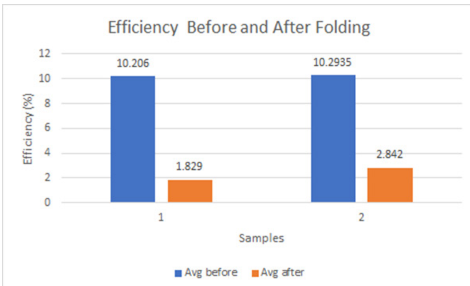


Figure 21: Chart showing the efficiency decrease after bending the cells.

As seen as the Figure 20 and 21 above significant damage was done to the cells when they were bent. There were a few challenges which need to be taken into account when considering these results. Some of the challenges were the fact that when doing imaging and IV measurements the bent cells did not lay completely flat despite being taped down. This most likely impacted the results as shading probably occurred in some sections and light was not distributed as evenly. Another complication was the process of folding. To incorporate such a diverse pattern the sample was manipulated and many folds were completed multiple times before scanning. In addition, the folding methods were experimental and often not done very precisely. This experiment does not draw many conclusions as the methods used could have been improved and the sample size was very small. Instead it lead to many more questions for future research, some of which are explored in the second experiment done in this section.

Experiment Two

Due to the knowledge acquired in the first experiment, that the sharp folding process shunted the cells, a second experiment was attempted to look into how the bending process might impact the cells. In this experiment there were 4 samples (see Figure 22), two were designed to be bent along the cells and two were designed to be bent across the cells. The samples were then sub divided again, having one of the across and one of the along samples being bent in a convex manner and the other two in a concave manner. The samples were labeled either “V” for vertical folding, across the grid of cells, or “H” for horizontal folding, along the grid of cells. The samples were also numbered either 1 or 2, 1 being a concave or valley fold, and 2 being a convex or mountain fold. The samples were analyzed flat after their manipulation to help limit the impact of shading but were also often analyzed bent to see the shading impact. After establishing how the cells performed without manipulation they were gently put into an adjustable tool (see Figure 23). This adjustable tool has walls which could be placed in closer and closer increments which would bend the sample. After a sample was bent in one of the settings it would be taken out of the tool and then analyzed again. This process repeated for each sample making the bends more extreme until the sample needed to be folded.

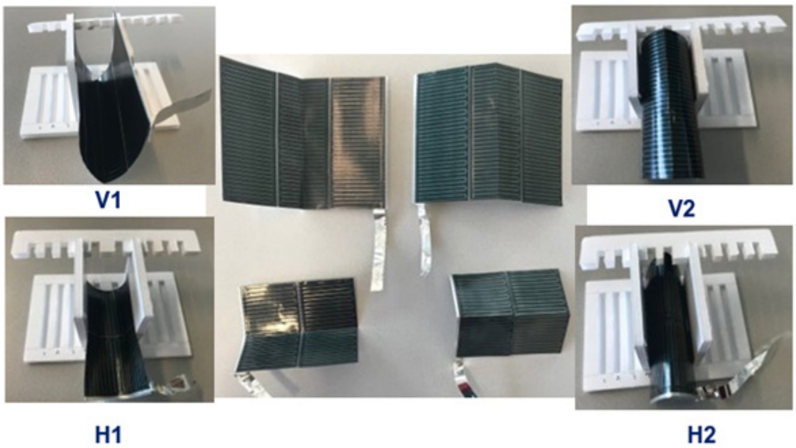


Figure 22: Photo of all four samples labeled and shown in the adjustable tool.

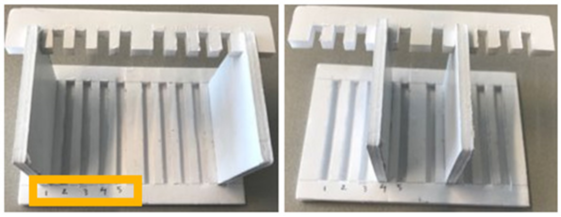


Figure 23: Close up of the adjustable tool and how the walls move. The numbers indicate how the steps were defined for this experiment.

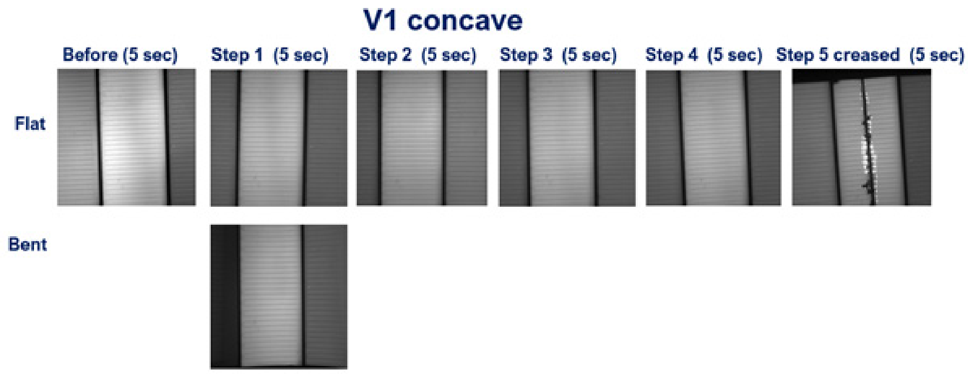


Figure 24: Vertical sample folded in a concave manner. As shown no permanent damage occurred until creased, where damage was contained to the fold with minimal shunting. Imaging occurring in the bent formation, while the sample was still in the adjustable tool, was inconclusive due to the tool impacting the images. The remaining images and IV data can be seen on the Sharepoint.

The results from this experiment, as seen in Figure 24, indicate that there is not much damage done from the folding process itself but rather from the creasing. While this is the case, further research needs to be done to understand the exact limitations as the radius curvatures were not standardized for this study. Also the folding method could be improved, as it was not always constant. Additionally, due to the method in which measurements are taken and how the adjustable tool holds the samples, light is not distributed evenly when samples are bent, impacting the measurements. Future research should be done into how the cells preform when they occupy curves. These findings have significance in how cells can be applied onto curved surfaces as well as how damaging roll to roll processing of cells is.

Fold Exploration

While the bending experiments, described above, allowed me to gain insight into how to analyze samples the hinge method exploration allowed me to expand my technology and realization expertise area in a different way, by having me create many prototypes. This rapid prototyping helped me understand how I prefer to design, by physical and rapid experimentation. The many samples created allowed me to better understand and explain the limitations and best methods of prototyping.

Due to the limitations of not being able to manipulate the cells, exploring how to bend the materials between the cells has been done. Being able to fold the materials will help in creating crease patterns that can be made to form specific shapes. There are currently two promising ways of getting the panels to bend. One of these methods uses spacing between the frontsheet and cells to create living hinges out of the backsheet materials and encapsulant. The other method uses the die cutter to cut dashed line patterns into the frontsheet or backsheet before they are laminated. Both of these methods, the spacing and the dashed lines, include spacing the cells out so that they are contained in the faces of the patterns, while the material around the faces folds to create a global geometry. Each method is explained in further detail in the sections below.

While these methods of circumventing the fragility of the top sheet and cells looks promising, to ensure weatherproofing and durability, the cells need to be surrounded by a border of at least 2 cm of encapsulant and frontsheet. This decreases the efficiency of the overall modules. Although, with edge tape this border distance can be decreased. Overall, it is beneficial to design patterns which have larger faces to ensure that the panels are efficient.

Another thing to consider when assessing folding methods is that many patterns require different types of folds. These types of folds fall into three main categories: mountain folds, valley folds, and living hinges. Living hinges have the ability to bend completely in both directions, while mountain folds can only bend upwards (the backsheet coming together), and valley folds only allow for the surface to be folded downwards (the frontsheet folding together).

Spacing

The hinge method plans out the crease pattern by cutting the frontsheet apart into pieces. Wherever there is a crease there should be a gap in the frontsheet. See Figures 25 and 26 for a photo of how these hinges work. This method results in a living hinge, a fold which can fold in both directions. This is due to the fact that the backsheet and encapsulant already have the ability to bend in both directions and this method removes all other materials from these fold lines. While the natural resting position remains flat for these living hinges, tension within the plane can cause them to develop into mountain or valley folds.

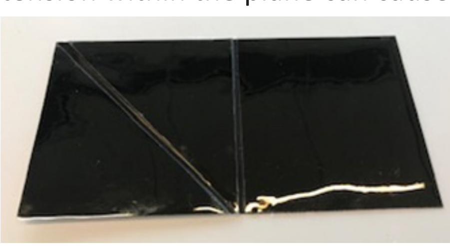


Figure 25: Sample of spacing hinge method lying flat.

Figure 26: Sample of spacing hinge method folded

Figure 27: Spacing exploration.

Several iterations of this method were done to best understand how to manufacture the hinges. These iterations explored the best distance between the frontsheets (see Figure 27) for the best bending as well how to prevent the frontsheet from peeling. See Figures 28 through 31 for an explaination of the different complications that the exploration found. The peeling exploration mainly investigated if rounding sharp corners helped to mitigate delamination in the corners. See Figures 32 and 33 for the rounded corner experiments samples. In conclusion, a spacing of 4 or 5mm was best for spacing between the frontsheet and rounding the corners to at 7mm radius was helpful to prevent peeling. Additionally, it was discovered that the encapsulant needed to be across the entire design because if misaligned the frontsheet would peel.




Figure 28: When the encapsulant is not lined up properly peeling can occur, especially in the corners

Figure 29: Material is still bendable when the encapsulant is extended beyond the frontsheet. Only corners still remain problematic. This can be solved by rounding them.

Figure 30: Full test pattern. 4 to 5 mm worked as the best distance between faces.

Figure 31: With less than 4mm between faces range of movement is lowered. As seen here the design does not fold flat naturally due to the spacing being too narrow.

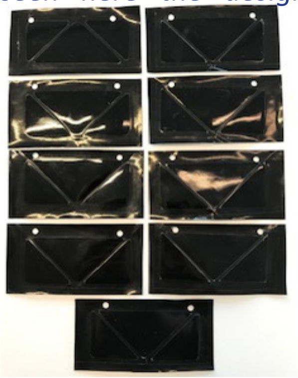



Figure 32: Exploration of different cornerradiusandtheimpactonpeeling

Figure 33: Sample with no rounding

The conclusions from these tests lead to a suggested process to design and manufacture prototypes that utilize this spacing method. First a pattern is developed, see Figure 34, this pattern is then expanded to create gaps of 4 or 5 mm between each of the faces, see Figure 35. The corners of the shapes that create the frontsheet are then rounded to have a radius of 6 or 7 mm see Figure 36. Once these are determined the entire pattern is cut into the frontsheet, To help with alignment and to limit the defects which occur a method of using application tape was developed. Once the entire pattern is cut, application tape, a sheet of adhesive foil that can withstand the lamination process, is put across the entire design. Then, the negative spacing is pulled off of the application tape, leaving all of the main faces behind. Once this is done the frontsheet can be placed on the stacked backsheet, encapsulant, connected array of cells, and another full sheet of encapsulant.

To help align and create the array of cells it is suggested to print out the final cut pattern on paper and align the cells on that with the tabbing materials, see Figure 37 and 38 to see the print out alignment method.

This method of creating hinges has many benefits and also many disadvantages. Some of the benefits include that the hinges are durable and that it is easier to connect the cells together as the tension in the hinges is not as high so the tabbing material survives these bends. Another advantage of this fold design is that every crease is designed to be able to bend in both directions with only the frontsheet needing to be cut. The disadvantages include that the extra spacing wastes a lot of useable area and expands the design to be larger than intended, so this needs to be taken into consideration when designing. Additionally, because the pattern needs to be expanded for spacing the folds are not always exactly in the intended place. Also because the

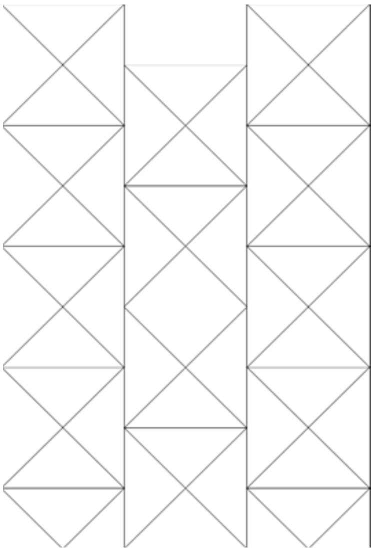


Figure 34: Crease pattern file example

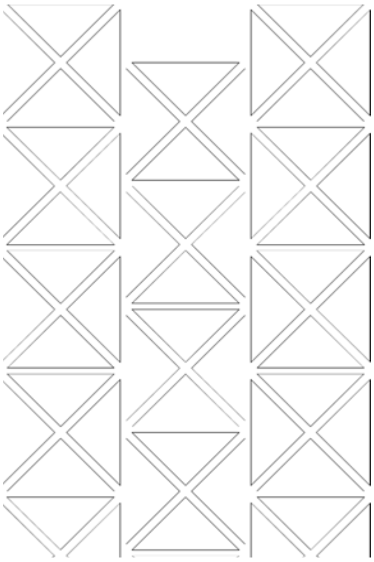


Figure 35: Crease pattern file expanded to create 5mm spaces between the faces.

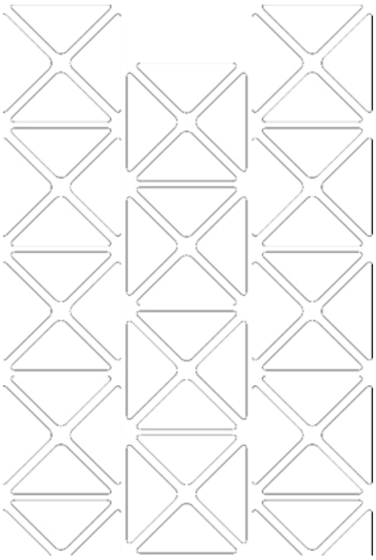
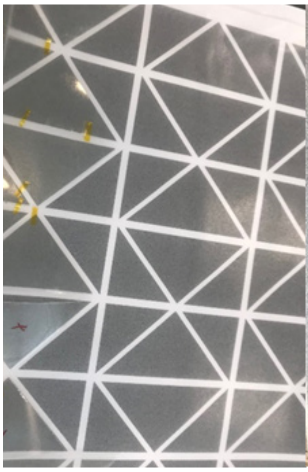


Figure 36: Crease pattern file with corners of faces rounded, ready to be cut into frontsheet.

frontsheet is cut apart entirely delamination can occasionally occur in places of high tension.

Future research needs to be done to refine this method, such research includes conducting durability tests. Understanding how these samples behave within a climate chamber and also how stress of manipulation over time should give better insight into the limits of the applications of this hinge method. Some exploration has already been done to see if applying edge tape would effect the flexibility of these designs. This initial exploration has concluded that both applying edge tape around the edges of each face or between each face, spanning the entire crease area do not hinder the designs (see Figure 39 and 40).

As a whole the method is promising and some full scale prototypes were created, see Figure 41.



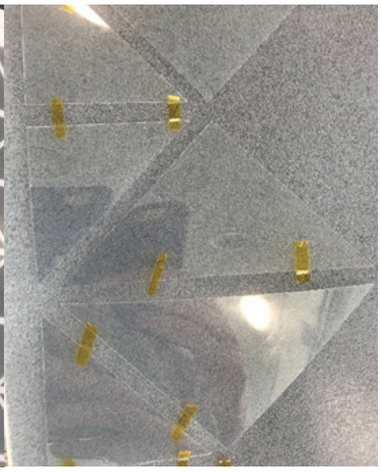


Figure 37: Template used to align frontsheet pieces.

Figure 38: Frontsheet pieces aligned on encapsulant, secured with pieces of tape.

Figure 39: Sample with edge tape (weather proofing) along each edge

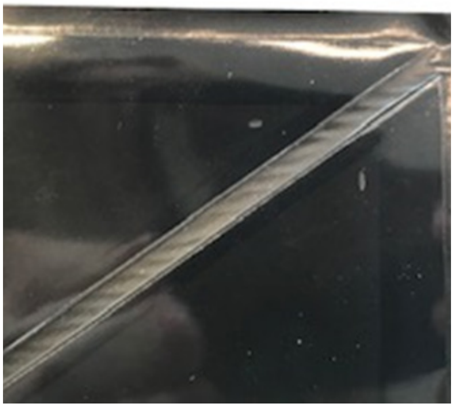


Figure 40: Sample with edge tape (weather proofing) split between edges.

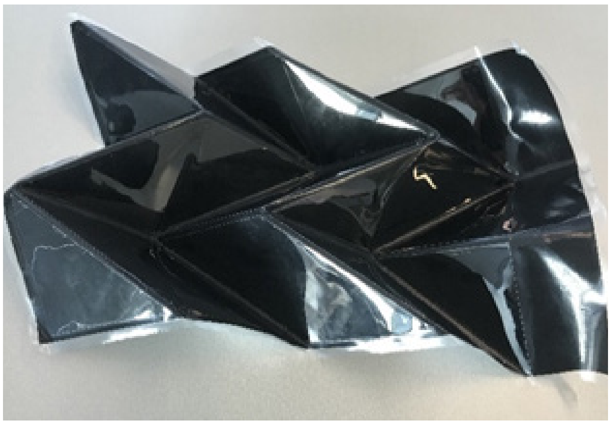


Figure 41: Full scale prototype using the spacing method to create folds.

Dashed Lines

Another method of being able to crease the materials surrounding the cells is to cut dashed lines into the materials. Explorations have been done to find the best methods (see Figure 42). This includes an exploration about the design of the dashed lines, an exploration of when in the manufacturing process is best to cut the dashed lines, before or after lamination, and also on which layers dashed lines should be cut. A sample was also made with edge tape to see if the added layer under the dashed lines impacted how the sample could fold.

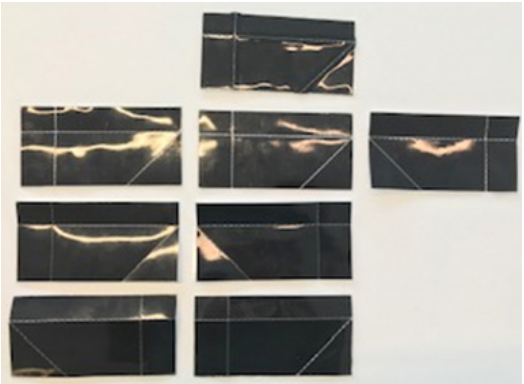


Figure 42: Samples with dashed lines testing how dashed lines should be created

Figure 43: series of small rectangles (top), string of line segments (bottom).

Dashed lines can be cut in many ways, one way it to create a series of small lines which can be cut into the material. Another way of creating a dashed lines is to create a series of small rectangles which can be cut out (see Figure 43). Both methods work well to bend the materials at a specific point. The preferred method for bending that was used in the prototypes was the series of small rectangles. This is because when bending the string of single lines would break the material completely, just like perforated paper (see Figure 44), while the series of small rectangles did not have as much tension so kept small connections between the faces.

Figure 44: String of line segments which has disconnected the faces

An exploration was also conducted to see when dashed lines should be cut into the samples. When lines are cut after lamination then it makes very little difference what side these lines are cut from as long as they are cut all the way through. When cutting lines after lamination these hinges are able to fold in both directions. This method is not recommended as aligning cells to be contained within the faces and cutting around them can be problematic. Instead frontsheet or backsheet or both can be cut, laminated, and folded after. See Figures 45 - 50 to see how materials can be cut and then layered. By cutting just the backsheet the sample can be folded forward also known as valley folds. Cutting just the frontsheet lets the sample fold backwards, also referred to as mountain folds. It is also possible to cut both the top and bottom sheet, these hinges are able to fold in both directions. There was also a small exploration of if there was a difference if the materials cut on the die cutter should be cut from one side of the sheet or the other, but there was no discernable difference between the impact of cutting from one side of the sheet or the other.

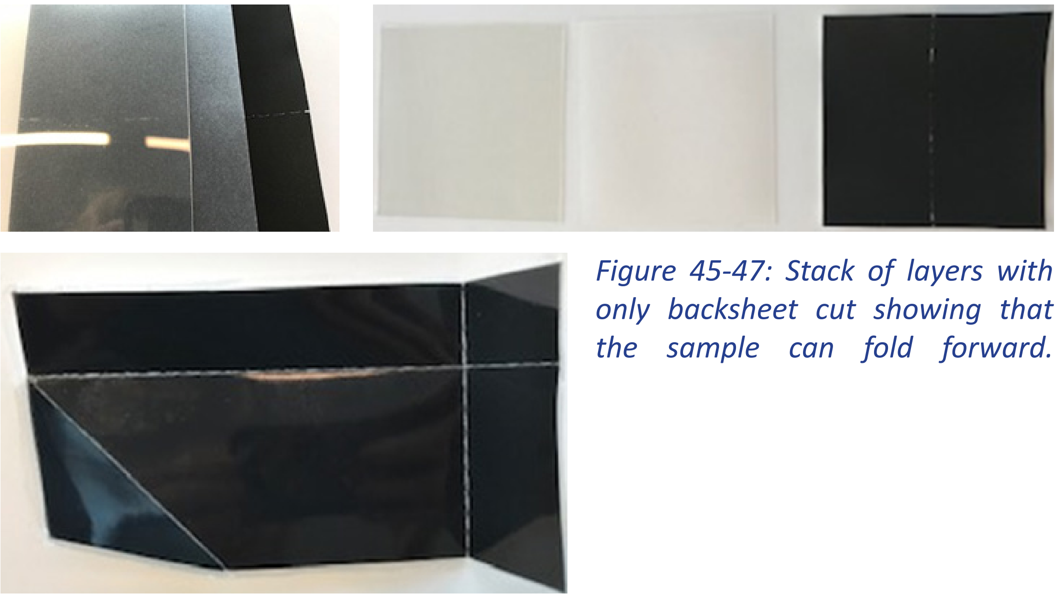


Figure 45-47: Stack of layers with only backsheet cut showing that the sample can fold forward.

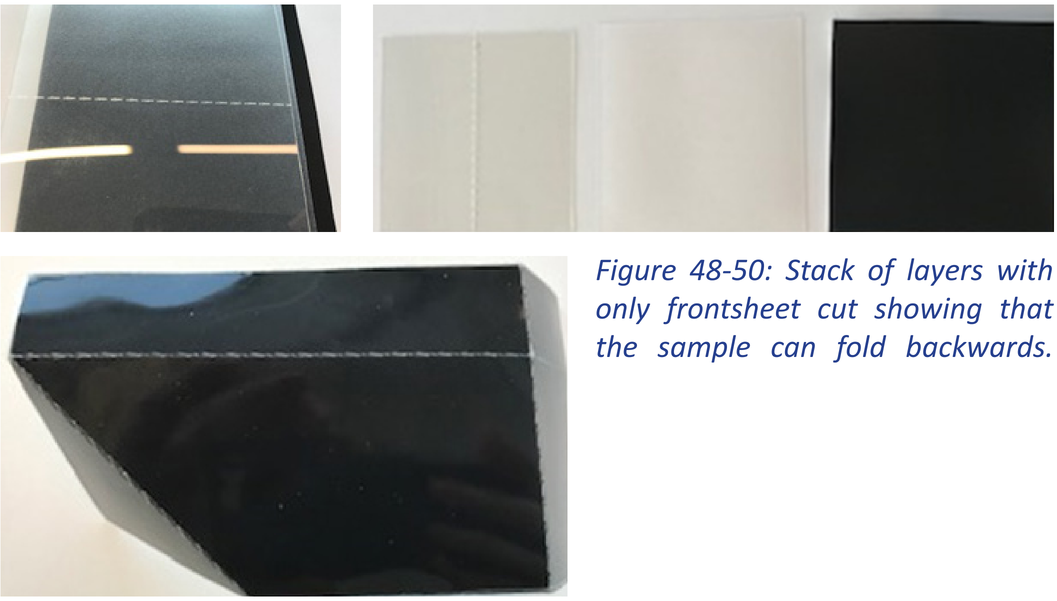


Figure 48-50: Stack of layers with only frontsheet cut showing that the sample can fold backwards.

This method has certain advantages and disadvantages. One of the advantages of this method is that being able to cut the top and bottom sheets without creating a lot of pieces is that alignment is much easier. If everything is connected then there is no more need for application tape to be placed on top. Additionally by cutting lines into just the top or the bottom folds can already be designed to fold one way or another. This is unlike the spacing method as each fold is made the same and can bend in both directions. The other benefit to keeping the top and bottom sheets all connected together is that there is less chance of delamination. Another advantage of this design is that there is no space added to the design. This increases the efficiency of the panels.

One of the disadvantages of this method is that there can be a lot of tension between the panels. This can cause tearing between the faces and connections between the cells can break. Because of this flaw an exploration in the connection methods between the cells was studied.

Connection Explorations

The connection exploration tested which types of connection materials can survive the folding process. This exploration used many different tools to analyze these materials. This helped me develop my technology and realization expertise area as I researched how to find a fitting material for this application through many different methods.

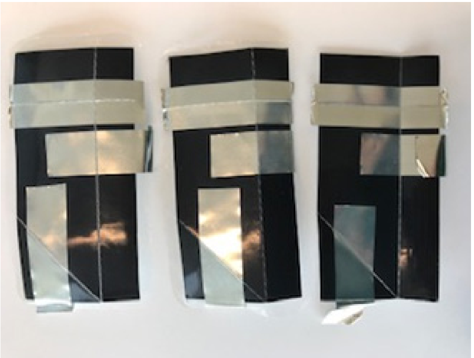
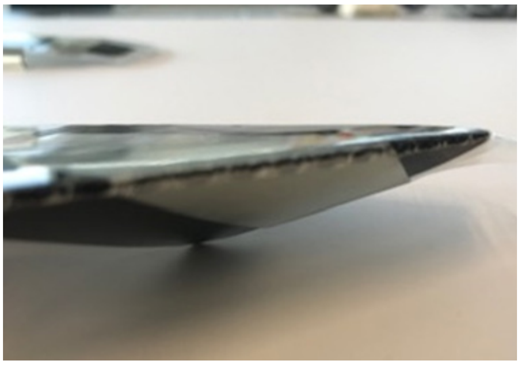



Figure 51 and 52: Normal tabbing materials explored. As seen on the right it broke after folded.

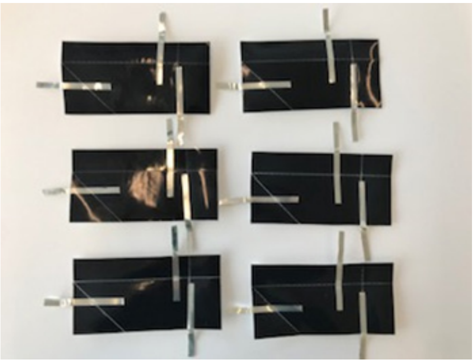
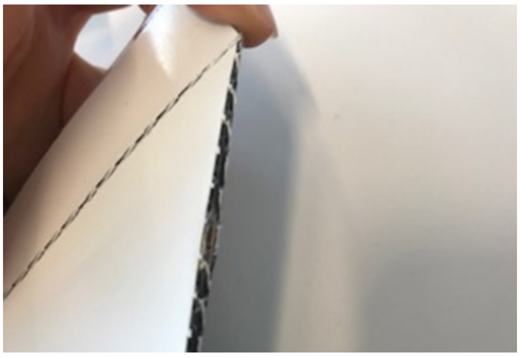



Figure 53 and 54: Thicker tabbing materials explored. As seen on the right it broke after folded.

Tabbing materials are often used to connect cells together into arrays and also to connect the arrays to the outside world. When folding patterns these connection materials need to withstand the stress of the folds. Multiple different connection materials were tested to find one which fit these requirements. There are two different tabbing materials which are already commonly used. Both of these materials are metal, so the tension that the bends exert onto the connections cause them to break. This can be seen in Figures 51 through 54.

Once it was established that the metal based tabbing materials were not sufficient through the folds, other materials were tested. These materials included a variety of conductive tapes, both woven and nonwoven, as well as a test of a braided wire. These materials were first tested to see if they were able to connect traditional tabbing material together (see Figure 55). Then two of the materials were tested to see if they could withstand folds. One of the two materials chosen was a woven conductive tape and the other was a non-woven variety. These two were chosen because they performed well within the initial tests. To insure that the material was durable enough and to find the limitations, each material was tested by folding it lengthwise, widthwise and also diagonally in addition to being folded in both directions for each of the orientations. Figure 56 shows the range of experimentation done. The conclusion from this test was that the woven tape preformed better but still had reliability issues when folded across it's width and also when forming "valley" folds, folds where the material is folded up.

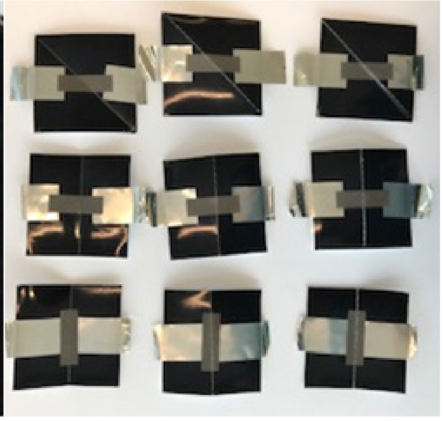
 

Figure 55 and 56: All alternative tapes tested to see if they can conduct traditional tabbing and further exploration.

While the woven conductive tape survived through most of the bends there was a concern that the material was not conductive enough for the application of connecting the solar cells. Therefore, another test was run which connected cells together using the conductive tape. This experiment was run twice to help validate the results. The experiment consisted of 10 samples (seen in Figures 57 and 58), these samples were split into two categories parallel connetions and series connections. Each set of 5 samples had control where the cells were connected with regular tabbing materials without any folding occuring. The remaining 4 samples from each category were split by material, one using just the woven conductive tape to connect the cells and the other using tabbing materials with tape overlayed ontop to renforce it. There were two samples with each material for each arrangement, one which was folded backwards (a “mountain” fold”) and the other which is folded forwards (a “valley” fold).

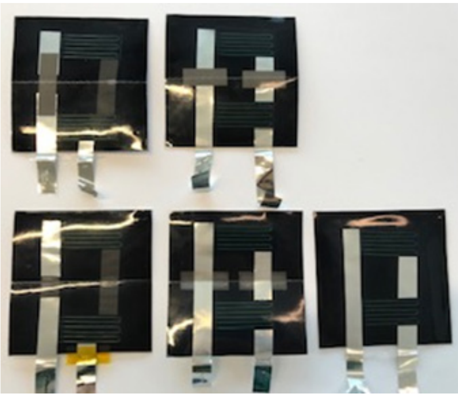
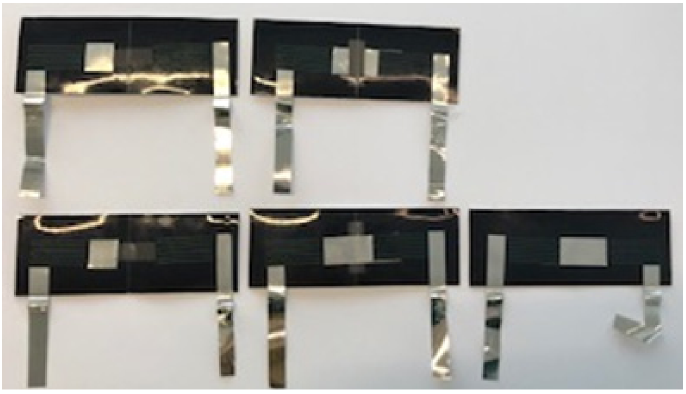
 

Figure 57 and 58: Parallel connection tests and series connection tests

The outcome of these experiments showed that when just using tape there was a significant difference in the perfomance of the cells. When using the tape to reinforce the tabbing material there was a small difference in performance. The samples were tested both before and after they were folded. Before being folded the cells generally performed a little bit better than after they were folded. There was not much difference after manipulation with the exception of one of the samples, the series sample with the reinforced tabbing folded from the back (“valley fold”). A potential explanation for this is that the tabbing material broke and was not saved by the tape so the tape was the only conductive connection left. This is hard to confirm with these samples as the tabbing cannot be seen though the tape.

Due to the relatively similar performace of the reinfoced tabbing method to the standard tabbing this method was the preferred one going forward.

Results & Outcome

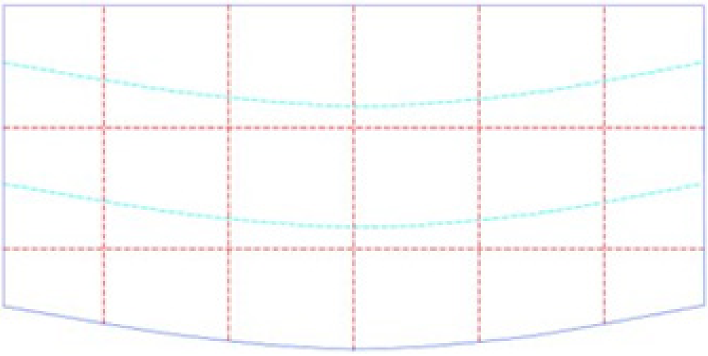
My work lead to a finalized method for producing large scale prototypes that could create three dimensional shapes. This method is outlined in the next section. Apart from the method that has been defined based on the research conducted there is also a number of full scale prototypes, and pattern documentation (which can be seen in the appendix) to accompany this method.

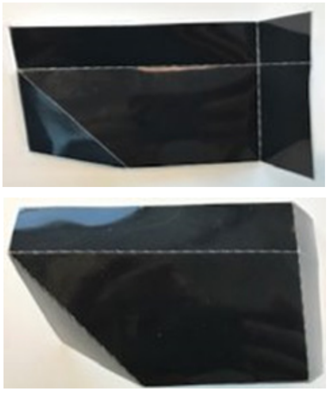
Apart from the documentation of the prototypes there was one other significant outcome from this internship, a manual for the die cutter. Due to this method involving a die cutter, during the work that was done a binder documenting how to use the die cutter as well as a step by step guide was also created. The die cutter was a new piece of equipment which was installed during the internship. Documenting how to use this machine and teaching others was a large part of the learning process of this internship. Learning how to use new machinery and new techniques for creating prototypes helped expand my technology and realization expertise area. Additionally, because I had the opportunity to visit the manufacturer of the die cutter I was able to see other machines and techniques that are currently in development. This experience was exciting as it inspired me to think about all of the different out of the box developments that could be utilized in manufacturing going forward.

Manufactoring Method of Prototypes

Based on the small prototypes created and the experiments done, a certain methodology has been defined to manufacture the larger prototypes.

First, the pattern is designed. Most of the time these can be prototyped in paper. The fold pattern is then put into Adobe Illustrator, Figure 59. The outline of the sample is defined with a solid line while the internal fold lines are defined as dashed lines. The dashed lines that have been determined to work best are the autogenerated series of small rectangles. This is done by changing the lines to dashed lines with the stroke function of Illustrator and then outlined by going to object in the top toolbar and then path, outline stroke. The folds which bend forwards and the lines which fold backwards are then colored different colors. The different colors allow for the lines to be cut into different layers more easily. Folds which bend forwards require dashed lines being cut into the backsheet, while the lines which fold backwards require cuts make into the frontsheet, Figure 60 and 61.





Figures 60-61: Only cut backsheet sample folding forward and sample with only cut frontsheet, folding backwards

Figure 59: Illustrator file

After the pattern is cut into the frontsheet and backsheet and the encapsulant is cut into the shape of the sample, arranging the cells is the next step. Faces that contain cells should be defined. In many patterns, not all of the faces are large enough to contain cells, or will be self-shaded so cells shouldn't be included. Once the location of the cells is defined, they should be all connected together with tabbing material. This is done similarly to conventional manufacturing of flat panels. Extra tabbing material is used to extend front contacts for series connections, Figure 62 shows how an array can be made. Conductive adhesive should be used to connect these extended front contacts to the back contact of the adjacent cell. Extra tabbing material and conductive adhesive can also be used to make parallel connections between cells.

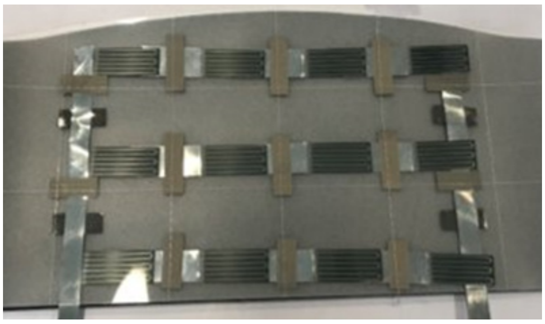


Figure 62: Array of cells within layers before lamination.

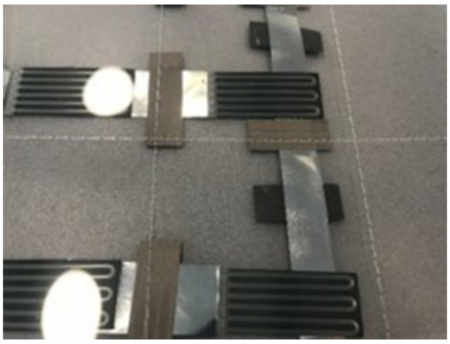


Figure 63: Close up of tape reinforcing the tabbing at the fold lines.

Once all of the cells are connected together, with the correct spacing between them, to center the cells into the correct faces then the tabbing material needs to be reinforced with conductive tape. The conductive tape should be placed on the tabbing wherever there is a fold in the design. Figure 63 shows how the conductive tape should be placed on the tabbing. The conductive tape should always be placed on the side of the tabbing closest to the perforated sheet. For example, if the frontsheet is cut to allow for a bend backwards then the conductive tape should be placed on top of the tabbing.

After cells are arranged and all the materials are stacked. Then the sample should be laminated. Figure 64 shows the stack right before lamination and Figure 65 shows it right after. The lamination process, temperatures and times are the same as the other samples made in the lab. Once lamination is over and the sample cools, then the prototype can be folded into the final form, the folding process can be seen in Figures 66 and 67.

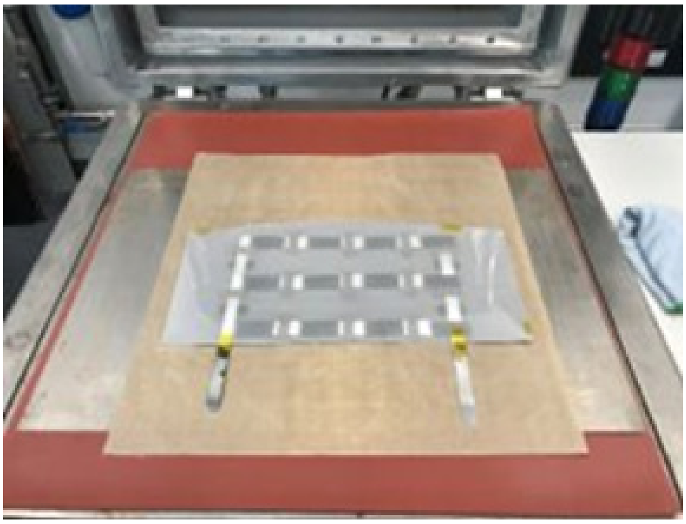


Figure 64: Stack of materials right before lamination.

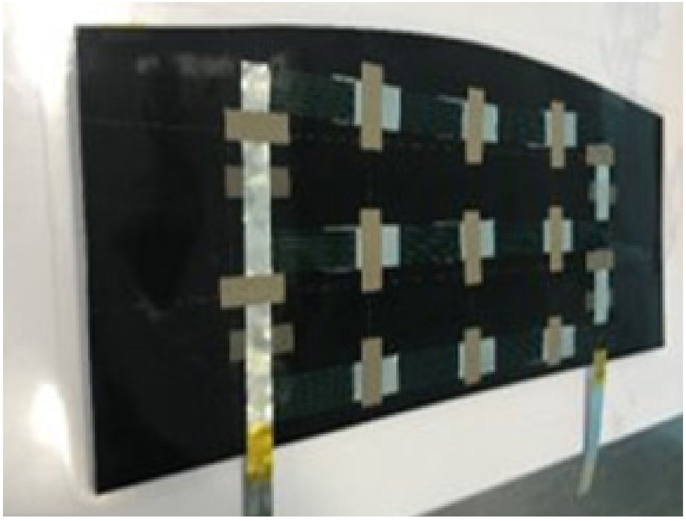


Figure 65: Sample after lamination, cooling down.

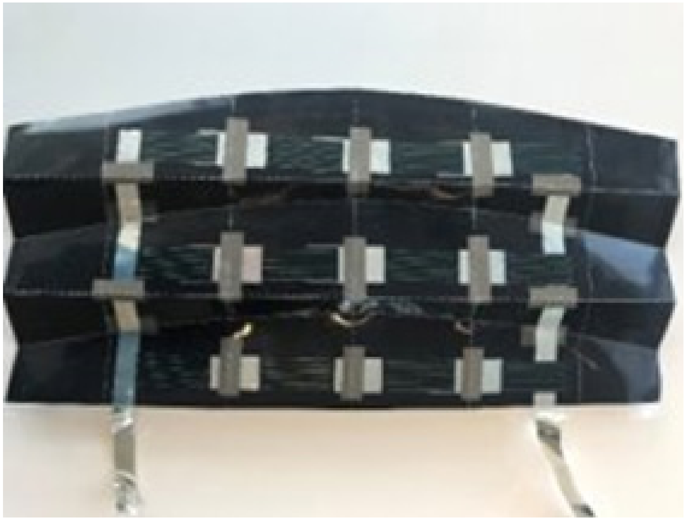


Figure 66: Sample in the process of being folded.

Figure 67: Sample in the final folded form.

Conclusions & Future Work

My internship at Solliance was a very fulfilling experience. I was able to expand my technology and realization expertise area extensively as I was able to learn new prototyping techniques and explored design through rapid prototyping. I also was able to expand this expertise area through learning how to use different machinery. Throughout this research many prototypes were made. These prototypes give a glimpse into the future of applications for solar panels if this research continues to be pursued.

I really loved being able to split my work between the hands on prototyping, analysis, and literature review. I was able to spend this time to expand my math, data, and computing expertise area. Delving deeper into the mathematics of origami and folding techniques has taught me a lot about how to integrate mathematics into design.

I left Solliance with how this research could be pursued in the future to develop this application method. Some of the future research that needs to happen before these designs are implemented is durability testing. Durability testing includes assessing weather proofing, and the lifespan of the folds. In addition to durability testing different applications and different patterns need to consider how shading impacts the designs. Further development that should also be considered to develop the design would be optimizing space, considering and exploring more material choices, experimenting with aesthetic changes, and manufacturability for the future. While I left with a lot of notes for future research I feel this reflects how much potential there is in the further development of this process. Communicating these points for future work, presenting, and documenting everything has allowed me to expand my business and entrepreneurship skills.

Acknowledgements

I would like to thank both of my supervisors at Solliance, Bart van de Vorst and Monique van den Nieuwenhof, for their guidance throughout my internship. I am very grateful for this great opportunity they have given me to explore this field.

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Appendice

Formally Approved Internship Plan

Formal approval

Internship

Student	Rachel Feldman	**Date**	02/07/2019
Teacher coach	Yaliang Chuang		
Period activity	☒ September - December	☐ February - June	

Personal Development Plan for formal approval	Does the choice of the learning activity align with the Professional Identity and Vision development of the student and are his/her choices well-argued?	Yes
	Does the learning activity contribute to the development of the student?	Yes
	Does the chosen learning activity contribute to a balanced development in the Bachelor program of Industrial Design?	Okay
	Are the goals well formulated?	Yes
	Complete the aspects only for the chosen learning activity:	
Internship (worth 25 ECTS) (requisites: P1, P2, P3)	Does the company profile align with the requirements for internships?	Okay
	❖ *Doing an internship at one-man businesses is not allowed; unless the company owner is currently teaching at the Department of Industrial Design, Eindhoven University of Technology.* ❖ *The company must support development in several expertise areas.*	
	Does the company coach align with the guidelines for internships?	Okay
	❖ *The company coach must hold a MSc. degree in (Industrial) Design or has at least 10 years of professional experience as a designer.*	
	Can the student work on a clearly framed design project or tasks?	Okay
	Personal Development Goals (minimum 1 - to include on Assessment form as well)*:	
	❖ Technology and realization: learn new prototyping techniques	Business and enterpreneurship: Interdisciplinary and business thinking
	❖ Math, data, and computing: Simulation and pattern development	
	❖ Creativity and aesthetics: Expand communicative drawing skills	
	**Discuss goals and positive and negative points in the coach meeting to guide how the student can develop expertise areas that might not be covered within the internship. The same goals will be included in the assessment form at the end of the internship.*	
Exchange (worth 25 ECTS) (requisites: 100 ECTS when the student leaves on exchange)	Name Exchange University and Department	[Name exchange university and department]
Minor (worth 25 ECTS) (requisites: BoE approval for free minor)	Minor at Department of Industrial Design at University of Twente; or at the Department Industrial Design Engineering at Delft University of Technology. (No other departments at these Universities or other Universities in the Netherlands are allowed without permission of the BoE.)	[Name University and Department where Minor is done.] [Elective], [Elective], [Elective], [Elective], [Elective]
	Minor at a University elsewhere in the Netherlands	[Name University and Department where Minor is done] [Elective], [Elective], [Elective], [Elective], [Elective]
Electives (worth 25 ECTS)	What are the chosen electives?	[Elective], [Elective], [Elective], [Elective], [Elective]
	In case a student chooses to do more than 15 ECTS worth of electives outside of the Department of Industrial Design, the student needs, next to the formal approval of the coach, to file a request to the Board of Examiners.	[Generations before 2015-2016 choose 6 electives, later generations choose 5 electives]
Approval	The personal development plan and chosen learning activity are approved by the coach**:	[Select answer] [When the answer above is no, please explain why.]

More information:
This form needs to be completed and signed by the teacher coach. In case of an internship as activity, the student has to add their personal development plan plus this form signed by the teacher coach to the appendix of their internship report. In case of an exchange, the student needs to deliver (a copy of) this form to the International Office at the Department of ID.

TU/e Technische Universiteit Eindhoven University of Technology

***Provided the request is granted/supported by the BoE.*

Please note:

- For exchange and activities that take places abroad it is strongly advised to consult the exchange coordinator for arranging insurance and because there might be opportunities for receiving a scholarship. Please be aware that exchange students need to be nominated by the exchange coordinator.
- For an internships it is strongly advised to contact Annaluisa Franco (Internship Coordinator) for arranging your internship details.
- For all B3.1 options: In total students are allowed to choose a maximum of 45 ECTS of courses outside the Industrial Design Department next to the Industrial Design major. When they would like to choose more than 15 ECTS of electives outside the Industrial Design department, they have to motivate their choices and get approval of the Board of Examiners (next to the formal approval of the coach per this formal approval form).

Teacher Coach: Yaliang Chuang

Signature:

Reflection

It was a pleasure to work with a company which fit my vision so clearly. Solliance was a great place for me to learn about sustainable development and research. The integration and application team was also a good fit for me, as my vision encompasses seamless design. This entire experience reaffirmed my vision of design. I also feel like my identity as a designer grew as I've found my passion for origami.

I did many different activities in my internship which allowed me to explore most of the expertise areas. All of these activities still were focused on the goal for my internship, to create 3D shapes out of solar modules. My technology and realization expertise area was explored in almost all of the activities I did. I learned about new technology and used different machines and techniques for creating prototypes. My business and entrepreneurship competency area was developed, mostly by having weekly meetings with the other interns, as well as presenting to other companies. I feel like I learned a lot about how work at a research company, such as Solliance, is conducted. I felt that through this internship I have been able to define a more clear vision of how I want to work as a designer.

My creativity and aesthetics as well as my math data and computing competency area were both developed within my work with origami. I learned a lot about the mathematical principles which origami utilizes, both when creating patterns and when studying computer programs which emulate patterns. This research has taught me a lot about how to combine expertise areas and how they should be applied to design. I loved being able to explore this and hope to continue to apply the beauty of origami and math to future work.

The only competency area which I have lacked development in is user and society. While this is unfortunate, I felt like this gave me an opportunity to design and explore technology without the constraints of a concrete application or user. It has also given me a greater appreciation for the competency area. Being able to make design decisions based off of a user base is so important as the message of the design can get lost without it. There were times within my internship where I did feel a little bit lost without this to guide me, but I feel like I have learned a lot about how to look at design from different perspectives. Working at Solliance taught me a lot about how to look at design from an engineering standpoint. This really taught me how much I appreciate being a designer, who can tailor technology into reality. I'm really looking forward to bringing this newfound point of view to my FBP.

Overall, I feel very privileged to have had this experience as it has given me a great opportunity to grow. I feel like I was able to show my potential for explorative design and creative thinking within this placement.

PDP 3.1 (Before Internship)

Vision:

I think of my design as simplistic; I strongly believe that users should see my designs as clean and effortless in the ever evolving world. I hope to become the bridge between the technical and user centered design world and make technology both accessible and realistic.

Technology is becoming more integrated with society and users lives. Learning how to integrate products seamlessly within our surrounding is where I strongly believe the future of design is heading. Understanding smart, connected, adaptive technology is fundamental to designing products for the future.

Concerns about environmental impacts and life cycles of products is a concern of many modern day products. Developing patterns and harnessing math to gain new insights into how to solve modern day problems can help further both development and research into these concerns. Understanding material research is also becoming more important as limited resources require designers to choose materials that are best fit for not just the product but long term sustainability goals. I look forward to being able to work with companies which share this vision about sustainability and seamless interaction.

Identity:

Growing up I was always encouraged to create. I have a strong art background where I love to focus on eliciting an emotion from my audience. This ability to elicit emotion can help motivate my audience though design. While my art is a very emotional representation of me and shows how I want to connect with my audience, I am also drawn to much a more mathematical side of design. Math is ingrained completely within our world and harnessing that beauty through design is something that I'm working at becoming good at. This fascination is why I find things with very crisp clean lines exciting as it satisfies a craving I have for order and place in a mathematical and creative way. I feel like these interests have helped inform my design to become modern.

Because of these two contrasting interests I've been drawn towards things like laser cutters, 3D printers, and CNC routers, since they let me create in a very precise environment but also have the benefit of complete control and ability to design more emotional pieces. This freedom to design more emotional pieces allows me to communicate futuristic and sustainability goals to my users.

Goals:

Learn new prototyping techniques
(Technology and Realization)
Prototyping is a valuable activity for visualizing and communicating. Learning and practicing different prototyping techniques can help me better understand how to best solve an issue, how to think creatively, and how to communicate clearly. Within my internship I have the opportunity to improve upon these skills. My goal to help develop my prototyping techniques is that I am going to do extensive lo-fi prototyping with paper. The reason why I am going to use paper is that it has physical properties and similarities to the solar panels that I will be working with. I also intend to use new tools such as a flatbed die cutter and a laminator to explore 3 dimensional shapes and the limitations of the two dimensional solar panels. I aim to learn new techniques and draw insights from the explorations within the internship which takes place from August through December.

Simulations and pattern development
(Math, Data, and Computing)
A large part of design is learning how to develop patterns and express them within mathematics so they can be applied or expanded towards future developments and design. Within my internship I am aiming at understanding how complex 3D curvatures can be approximated by flat planes and what type of shapes require out of plane deformation. Being able to develop complex curvature, such as spherical or hyperbolic shapes, out of solar panels helps develop future applications. Throughout my internship I will be learning how patterns and tessellations are created and how they can represent 3D figures in different states of folding; this will help me develop my competence within the math, data, and computing field. I aim to explore upwards of 15 different types of patterns physically and model a few within CAD software. I will also be looking into how these patterns can cause changes in global geometry.

Expand communicative expression techniques
(Creativity and Aesthetics)
Drawing is a cornerstone of communication and creative thinking within industrial design. Within the workplace ideas for projects need to be communicated clearly and effectively. Within my new working environment I aim to use sketching to explain my thoughts on my projects in an effective manner. I will also be creating lo-fi prototypes to help explain and explore ideas. This will be especially important as I am working with creating three dimensional shapes so drawing it can help visualize the task at hand. I aim to learn how to communicate my ideas with both prototyping and sketching within the beginning of my internship.

Interdisciplinary and business thinking
(Business and Entrepreneurship)
Learning to work with other departments and thinking from different perspectives is key in developing professional skills and developing products which are successful. Within this internship I will learn how to work with other departments as I go through the design process. Since I have started my internship I have started a weekly meeting between interns and employees within the application and integration teams. Within this meeting I intend to learn about the other projects and learn how to present my own. This interdisciplinary weekly meeting will help me build an understanding of the role that other departments play within both research and application of technology. Going forward I believe that this could lead to future collaboration between the projects that are being worked on. To achieve my goal of developing my interdisciplinary skills I will be attending these weekly meetings where I intend to ask questions and encourage collaboration between projects as well as learn how to present my own work to others outside of my field.

Patterns Explored

Spiraled Strips

Strips is the first category because this is also the field of origami first started to think about how to efficiently wrap any shaped object. In 1983 a paper was published which explored how to fold any outline of a any regular polygon out of paper (Hilton). This was one of the first steps in exploring how to approximate any shape with the art of folding. Later Erik Demaine made even more progress in this area by exploring how strips could be used to wind themselves around any sort of polyhedral (Demaine, et al.).

Using these principles long solar panel strips could be used to cover complex curvatures. The main difference between these techniques outlined in these papers and utilizing this in practice is the fact that these papers use theoretically infinitely long and sometimes infinitely thin strips of paper while the solar modules that are worked with have very real bounds. The smallest strip possible, being 2.6cm across. This design also leads to a lot more edges to the backsheet allowing for the individual sheets to be peeled off easily as the overall amount of contact with the original shape is less. There is also a lot of overlap in these designs as the goal of the research papers was to cover the entire surface exactly with no regard for the amount of material used.

Pros	***Cons***
- Easy to manufacture	- Many seams → inefficient (not much cell space) - Does not fit the curvature of the shape and sheet does not continue so durability is compromised - Need to analyze each unique shape to apply - Difficult with complex curvatures - Still creates trapezoidal and parallelogram faces which are all different because the cells can not fold - Lots of material hidden

Miura- ori Tessellations

The miura-ori pattern is a repeating tessellation of parallelograms with alternating mountain and valley folds. This unique folding pattern allows for the sheet to be manipulated out of plane and allows it to form more complex curvatures such as hyperbolic shapes. Furthermore, when some of the mountain or valley folds are reversed out of pattern it can also form spherical shapes. Currently the challenges with this pattern are the fact that there are a lot of seams which decreases the efficiency of the sheet and the fact that it is very difficult to fold, especially with stiffer materials.

There are many different types of variations for the Miura-ori patterns. One of the variations is to alter the angles of the parallelograms. Or to extend the parallelograms so the pattern is more accurately described as a zig-zag lines of folds. This is also known as v-pleats and can form rather specific curvatures (Jackson).

Papers also explore how to generalize this pattern to fit many different curvatures more smoothly (Dudte) or how to just tweak some of the pattern a little bit to get it to behave differently (Silverberg). Unfortunately there are some limitations to this work as generalized Miura-ori is no longer “rigid-foldable or flat-foldable”(Dudte). Additionally, it has the issue where the faces are not the same anymore.

Pros	***Cons***
- Parallelogram tessellations are efficient at containing cells - Forms around complex curvature relatively easily - If able to switch between mountain and valley folds no need to pre-analyze most shapes to see if it will fit. - Forms both hyperbolic and spherical shapes - Flat foldable	- Faces will be rather large to be able to contain the cells efficiently - Lots of seams - Difficult to fold



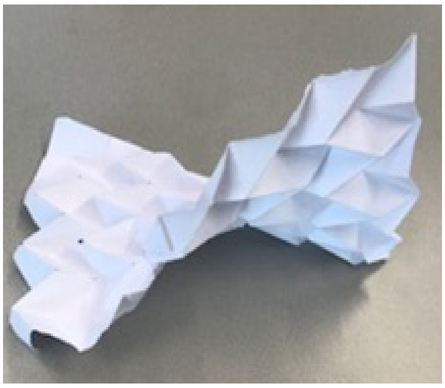
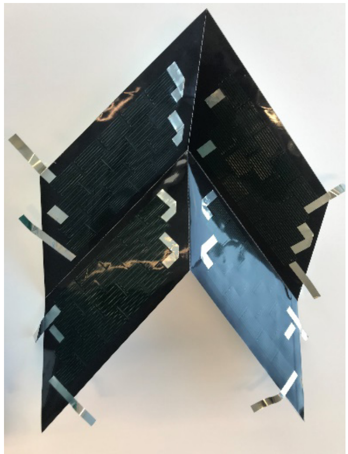


Figure 68-70: Paper model of the pattern showing the flexibility.

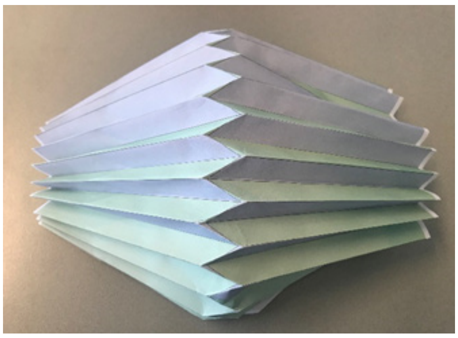
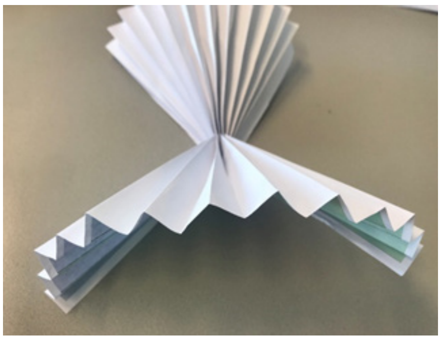
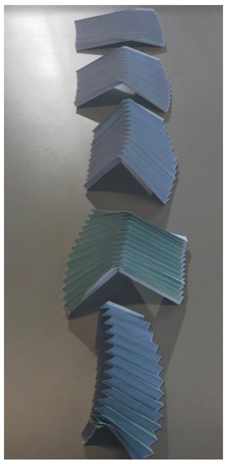



Figures 71-73: Prototype made in final materials. Full scale prototype displays the same flexibility and flat folding abilities.

Figures 74: Prototype made in final materials with cells

Miura-ori Variations

Pros	***Cons***
- Parallelogram tessellations are efficient at containing cells - Lots of the faces are pleats with points so the rectangular space can be used already	- Faces will be rather large to be able to contain the cells efficiently - Difficult to fold - Only forms specific curvatures

Figures 75-77: Paper prototypes showing different orientations that the pattern can be manipulated into. and how the angle of the fold can change the global shape.

Generalized Miura-ori

Pros	*Cons*
- Parallelogram tessellations are efficient at containing cells - Forms around complex curvature relatively easily - Can pre analyze most shapes to get perfect fits	- Faces will be rather large to be able to contain the cells efficiently - Lots of seams - Difficult to fold - Parallelograms are irregular so cells will need to be arranged carefully → need to analyze every facet to see if they can contain cells

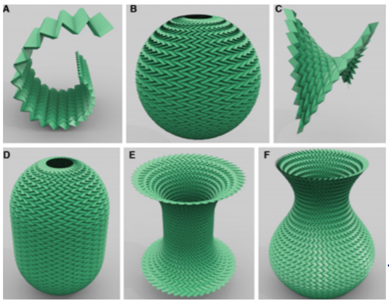


Figure 78 Citation: Optimal calculated origami tessellations and their physical paper analogs. Adapted from 'Programming curvature using origami tessellations', by L. H. Dudte, and E. Vouga, et al, 2016, Nature Materials

Resch Tessellations

Resch Tesselations are a repeating pattern which utilizes tucking to create very flexible textured surfaces. These patterns were proposed first by Ron Resch (Tachi, 2013). These types of patterns can be expanded or collapsed. There are two main types of these patterns one which has triangular faces and the other which uses square faces. These pattern have also been studied to see how to generalize them (Tachi 2013, Tachi 2015).

Pros	*Cons*
- Approximates curvatures well - Can form both hyperbolic and spherical shapes	- Large sheets with many cells can not be folded spherically (can have rounded edges though theoretically)? - Triangular surfaces might be difficult to fit cells into. - Not flat foldable

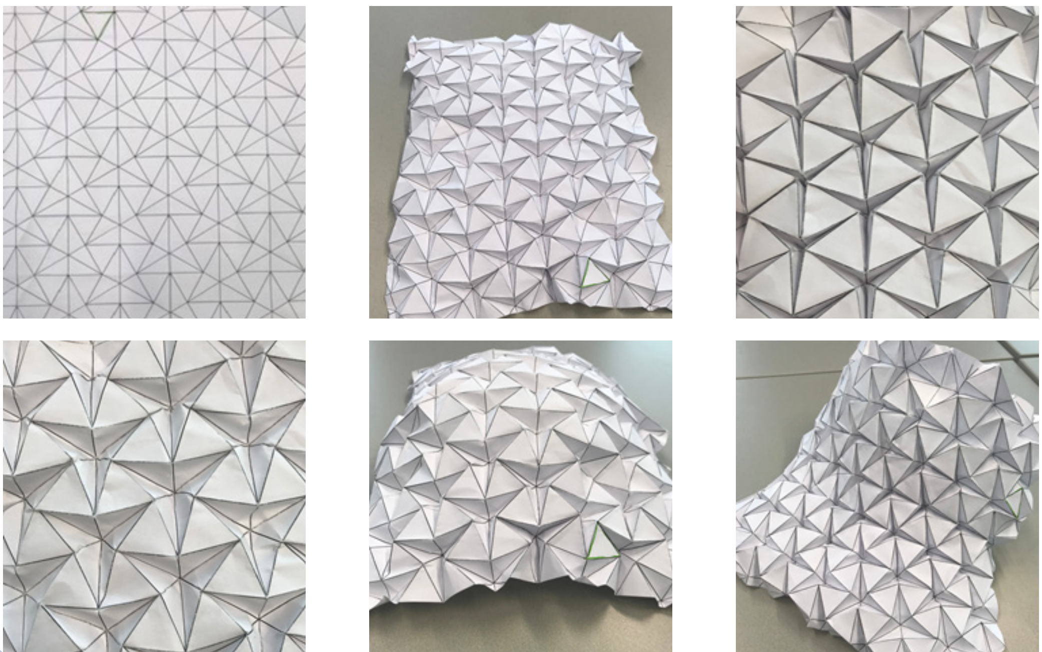


Figure 79 - 84: Paper model of the pattern showing the flexibility.

Square Resch Tessellation

Pros	***Cons***
- Approximates curvatures well - Can form both hyperbolic and spherical shapes - Can fit cells well within the square faces	- Triangular faces are harder to fit cells into - Not flat foldable

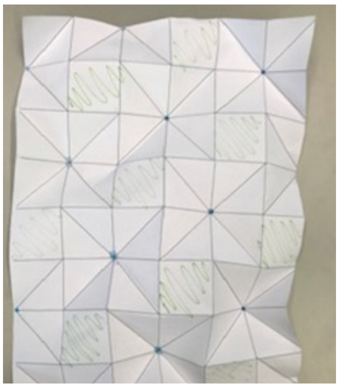
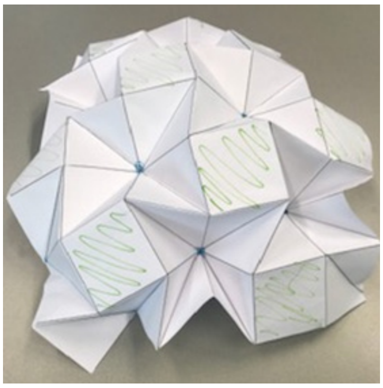


Figure 85 - 88: Paper model of the pattern showing the flexibility.



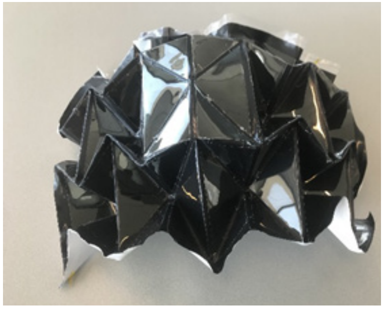
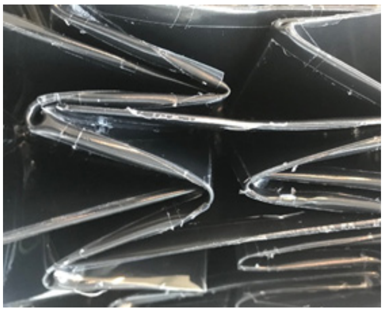
Waterbomb tessellations

A waterbomb tessellation is a specific type of triangulated origami tessellation. This pattern is the most flexible pattern explored but is also constructed of isosceles triangles. This pattern can also be generalized rather easily (Zhao).

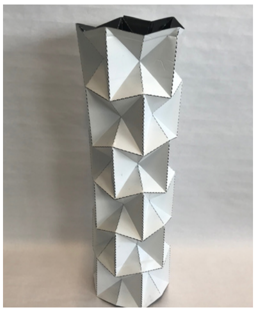
Pros	**Cons**
- Flat foldable - Most flexible - Can form hyperbolic and spherical shapes well	- Triangular faces are harder to fit cells into - Not flat foldable



Figures 88-90: Paper model of the pattern showing the flexibility.

Figures 91-92: Protoype of the waterbomb with the spacing method

Figures 93-94: Protoype of the waterbomb with the dashed line method

Generalized Waterbomb

Pros	**Cons**
- Can form hyperbolic and spherical shapes well - Can be designed to fit specific shapes very well	- Triangular faces are hard to fit cells into. - Difficult to fold - Every face is different

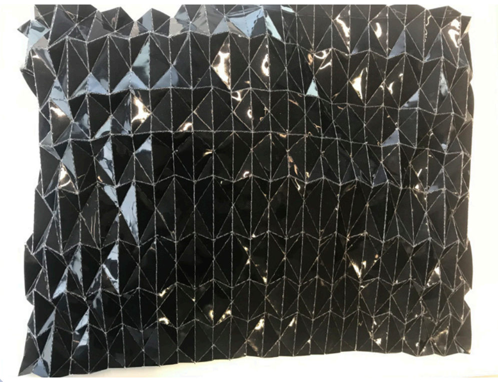


Figure 95: Protoype of the generalized waterbomb with the dashed line method . This shows that the generalized version reated faces too small to fold.

Curved-crease origami

This pattern is a series of curved creases and straight creases. Curved crease origami is one of the most promising methods for application. This is because it is not as textured as the other patterns. The other benefit is that it is easy to manipulate to different geometries by adjusting the curve (Mitani).

Pros	**Cons**
- Beautiful shapes - Not too many folds - Pretty much just pleating - Fits spherical shapes well	- Material is hidden - Not flat foldable

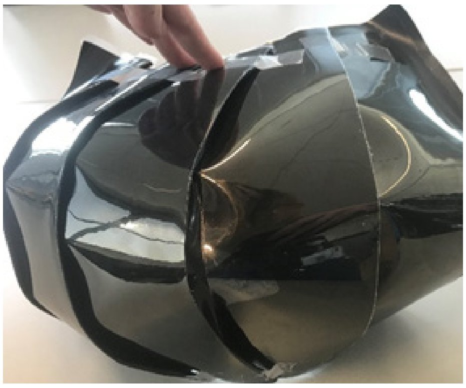
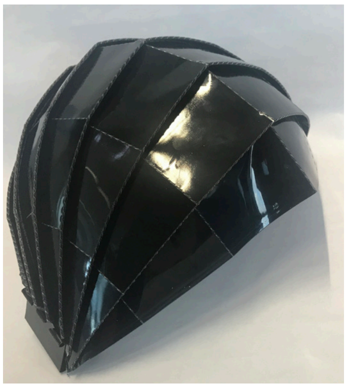
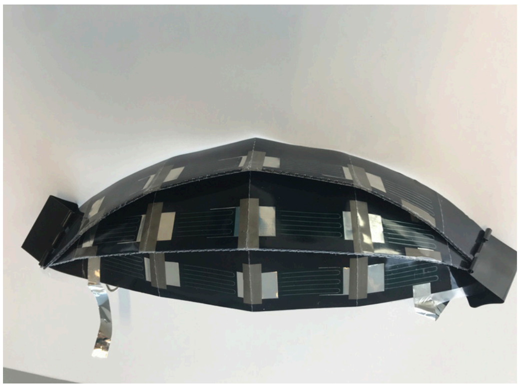




Figure 96: Protoype with no middle lines and spacing method. As seen in photo had issues with delamination
Figure 97: Protoype with dashed line method
Figure 98: Prototype with cells integrated.

Concentric Pleating

Concentric pleating is alternating mountain and valley folds in concentric shapes. The easiest is the pleated hyperbolic paraboloid which is a pattern of concentric squares although concentric circles are also common.

Pros	**Cons**
- Fits specific curves very flatly - Small amount of seams needed - Possible to form with rigid materials	- Faces are trapezoids or rings → harder to contain cells - All of the faces are different sizes - Difficult to form with rigid materials - Uncertain if only able to form hyperbolic shapes and not spherical ones - Not really flat foldable - High tension between faces

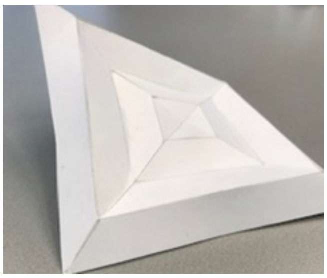
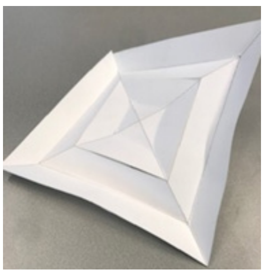



Figure 99 and 100: Concentric pleating made with cardboard, stress and breakage between the faces can be seen.

Rotational Pleating

Rotational pleating is a very elegant type of forming spherical shapes (Jackson). While this is the case it also can create odd shaped faces and the intersecting point can be problematic. There is also partial rotational pleating which mitigates the problematic intersection point. This type of pattern can be seen in forms like cupcake wrappers.

Pros	***Cons***
- Simple patterning - Fits spherical surfaces well - Can use small amount of seams	- Not really flat foldable - Faces are not well suited towards cells - Can only form concave or convex surfaces (spherical) not hyperbolic ones. - More edges needed to create better approximated curves.

Figure 101: Simple rotational pleating, forms slight globally spherical surface

Figure 102: More rotational pleating forms more defined globally spherical surface

Figure 103: Close up of point where all creases are rotated around, small amounts of tension and inexact folding causes deformations.

Partial Rotational Pleating

Pros	***Cons***
- Simple patterning - Fits spherical surfaces well - Can use small amount of seams	- Not really flat foldable - Can only form concave or convex surfaces (spherical) not hyperbolic ones. - More edges needed to create better approximated curves

Figure 103: partial rotational pleating displayed in a cupcake wrapper

Generalized patterns & CAD

There are a few different modeling softwares out there which develop patterns for three dimensional shapes out of a two dimensional planes. One of the most popular softwares is called Orgamizer (Hardesty) (Demaine, Tachi). Overall CAD modeling software and programs like this almost entirely use "tucking" or "star tuck" moves to form 3D shapes. While this is efficient mathematically and for software this can be problematic when dealing with complex shapes because a lot of these faces start to become very small. This method can be used with rigid materials. Often these softwares develop patterns which are not tessellations though so fitting cells into the shapes can be problematic. Uncertain if there is software out there currently which develop patterns for 3D shapes with uniform "faces".

Currently it is fairly easy to develop a "mesh" or normalize curvature geometry into connected flat polygons with any CAD software such as fusion 360. Theoretically these polygons could be cut out individually and pieced together like a puzzle without needing to tuck any extra material, but once again because each of these shapes is a unique polygon, fitting cells into them is problematic. Furthermore, it also creates similar issues to the strips method, where there are too many edges which does not lie perfectly flat on the surface of an object with no other backing behind it.

Pros	***Cons***
- Entire surface is covered	- Can have a lot of seams
- Mathematically perfect	- Requires a lot of CAD work for each new shape
- Any surface can be approximated	- New cutting pattern for each new shape
	- Shapes are irregular → can lead to issues arranging cells
	- Lots of small folds and crimping
	- Lots of wasted material
	- Lots of material beneath the shape → might make it harder to put onto objects
	- To make the folding big enough to be realistic the entire object needs to be scaled (cannot form smaller curvatures) or the faces need to be spread further apart (this leads to wasted material, and lots of excess material on the reverse side)
	- Not flat foldable

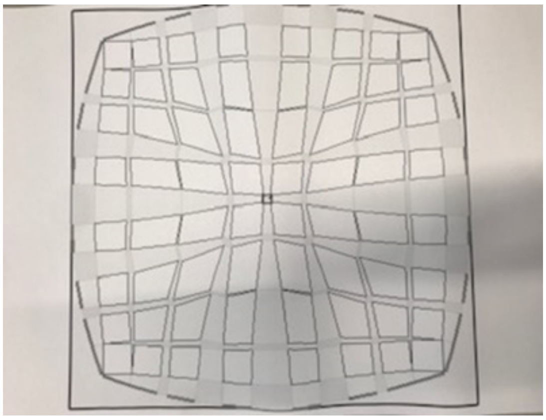


Figure 104: Printed out pattern for a bell curve, black square outlines one of the many tiny sections where star tuck creases need to be made.

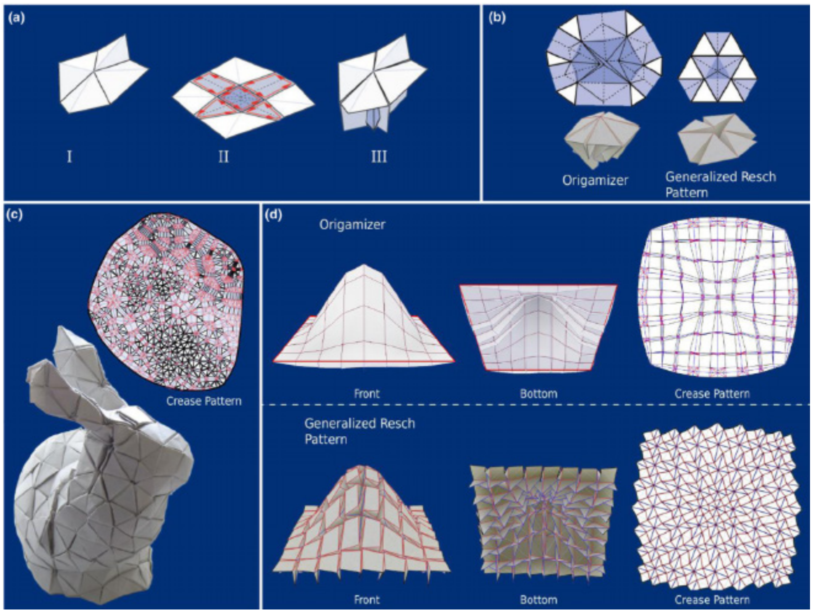


Figure 105. Computer aided design patterns. Adapted From 'flat sheets to curved geometries: Origami and kirigami approaches' by S. J. Callens and A. A. Zadpoor, 2018, Materials Today.

Kirigami

Cutting out shapes in origami can result in a surprising amount of flexibility and can form very geometric shapes quite easily. There are multiple different methods explored but ultimately this wasn't looked into that much as creasing new edges might compromise how durable these modules are. There are two different categories of kirigami the first cuts out shapes and then the edges are pulled together to create new global geometries. The second type creates cuts to pull apart the sample to form around shapes. Rotational pleating is a very elegant type of forming spherical shapes (Jackson). While this is the case it also can create odd shaped faces and the intersecting point can be problematic. There is also partial rotational pleating which mitigates the problematic intersection point. This type of pattern can be seen in forms like cupcake wrappers.

Hex pattern

Pros	***Cons***
- Small amount of seams needed - Should be the easiest to manufacture	- To develop accurate curvature small faces are needed - Faces are often triangular which is difficult to fit the cells into

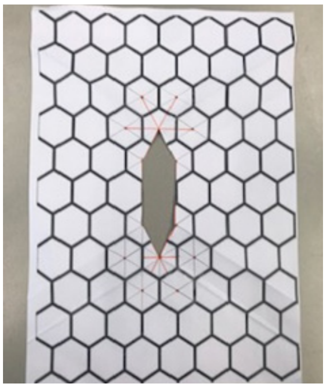


Figure 106: Pattern for the basic step. Hex pattern helps visualize where cuts and creases can be made.

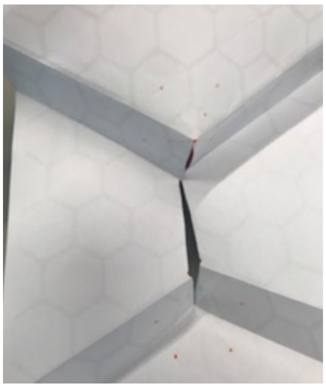


Figure 107: Folded step pattern, one side as a mountain fold the other as a valley

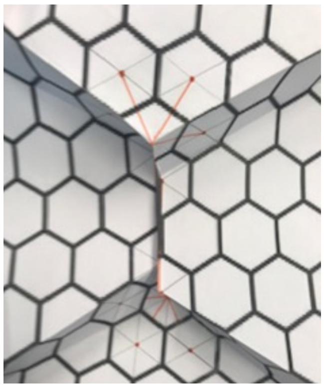


Figure 108: Folded step fold with hexagons showing how the plane lines up.

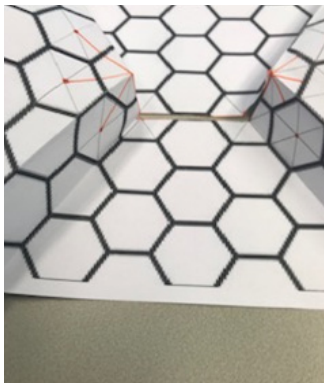


Figure 109: Same pattern with one of the steps reversed to create a new surface

Sixon pattern

Pros	***Cons***
- Small amount of seams needed - Lots of the faces are rectangular	- To develop accurate curvature small faces are needed - Faces are often triangular which is difficult to fit the cells into - Complex pattern

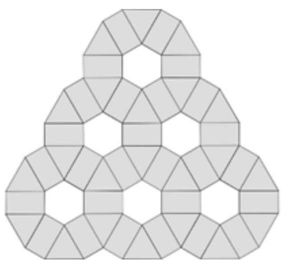
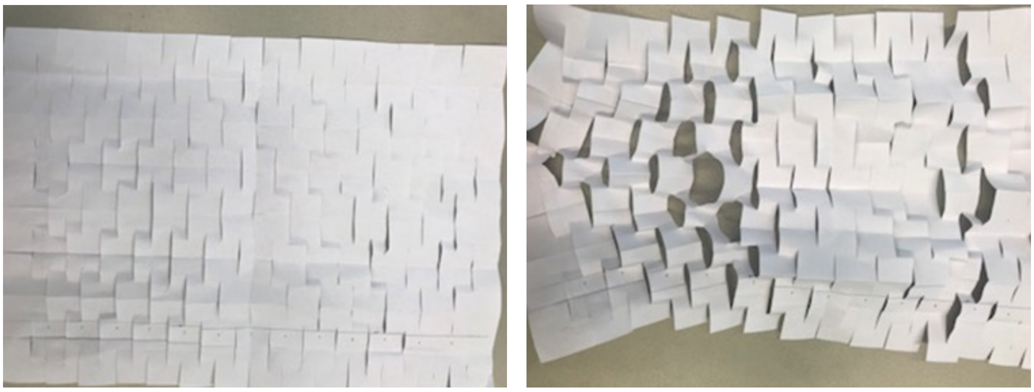


Figure 110: 'Sixon' design, composed of triangles, hexagons, and rectangles

Figure 111: Folded and taped together sixon.

Kirigami Engineered Elasticity
Parallel Cuts

Pros	***Cons***
- Easy to manufacture - Easy to fit around objects	- Lots of edges - Does not fit around objects well - Unpredictable



Figures 112 and 113: Paper model of the pattern showing the flexibility.

Fractcal Cuts

Pros	***Cons***
- Forms around complex spherical curvature - Aesthetically pleasing	- Delicate - Does not cover entire space - Many edges

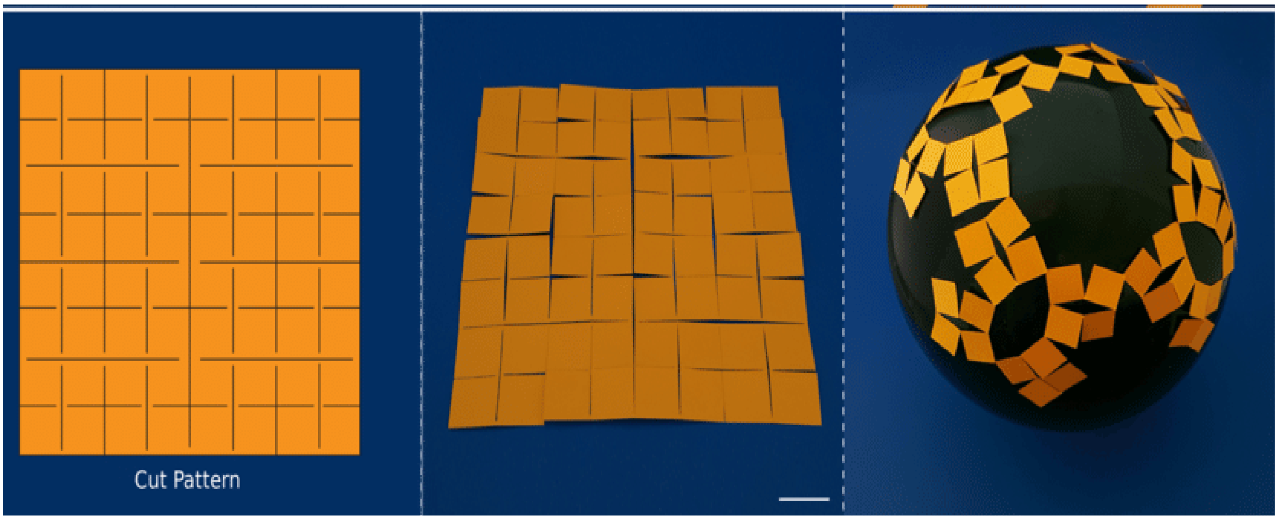


Figure 114. Fractcal Cuts. Adapted From 'flat sheets to curved geometries: Origami and kirigami approaches' by S. J. Callens and A. A. Zadpoor, 2018, Materials Today.