UNIVERSITATEA TEHNICĂ CLUJ-NAPOCA

Acta Technica Napocensis: Civil Engineering & Architecture
*Volume 61, No. 3, (2018)*
**Journal homepage: http://constructii.utcluj.ro/ActaCivilEng ISSN 1221-5848**
***Special Issue– International Conference- Architecture Technology and the City***
***Workshop Questions***

ACTA TECHNICA NAPOCENSIS

# DIY Smart Materials

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*(Published online 23 October 2018)*

## Abstract

*From optimal shapes, parametrically designed to match exterior conditions, to adaptive envelopes for all types of buildings, the word "smart" seems to be used and abused more and more. By contrast, smart materials and nano-technology seem futuristic for most architects still used to conventional building materials and techniques. But is this future so far away? Is this current gap between architecture and material technology so wide?*

*The purpose of this paper is to relate some of the findings of a recent experiment we undertook in order to familiarize students from different faculties with not only the design of smart material envelopes but also with their creation as well from accessible ingredients. Based on prior research from other technical universities in Europe and the US, an effort was made to replicate and improve several materials that have the capacity to react to exterior stimuli, thus earning themselves the label of "smart" or "information materials".*

*The experiment focused on the creation of dye sensitized solar cells (DSCs) by using common titanium dioxide and blueberry juice following the findings of Michael Grätzel. The final purpose was to design and build at a larger, pavilion-size, scale, thus combining the technical aspects of material recreation with the architectural qualities inherent to the design process of an energetically autonomous and mobile public space.*

**Keywords: smart materials, dye sensitized solar cells (DSC), parametric design, do it yourself (DIY).**

## Rezumat

*De la formele optime, proiectate prin metoda design-ului parametric, la învelitori adaptabile pentru orice clădire, cuvântul ”inteligent” este tot mai des folosit şi chiar abuzat. Prin contrast, tehnologiile materialelor inteligente şi nano-materialelor par străine multor arhitecţi tributari în continuare materialelor şi tehnicilor tradiţionale de construcţie. Dar sunt ele cu*

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*adevărat atât de futuristice sau distanţa dintre practica arhitecturală şi tehnologia materialelor este în fapt una artificială?*

*Scopul lucrării de faţă este să relateze câteva dintre descoperirile unui experiment menit să familiarizeze studenții de la mai multe facultăţi nu doar cu design-ul învelitorilor pe bază de materiale "inteligente" ci şi crearea acestor materiale din ingrediente relativ accesibile. Bazat pe cercetări de la universităţi tehnice din Europa şi S.U.A., demersul a încercat replicarea mai multor materiale care au capacitatea de a reacţiona la stimuli exteriori, câştigându-şi astfel eticheta de materiale "inteligente" sau "informaţionale".*

*Experimentul s-a preocupat în principal cu replicarea celulelor fotovoltaice pe bază de pigmenţi organici, folosindu-se albul de titan ($TiO_2$) şi pigmenţii naturali din mure, după cercetările lui Michael Grätzel. Scopul final a fost proiectarea la o scară ceva mai mare, de dimensiunile unui pavilion, combinând astfel aspectele tehnice ale replicării materialelor cu calitatea arhitecturală implicită unui spaţiu public mobil şi autonom din punct de vedere energetic.*

**Cuvinte cheie: materiale "inteligente", celule fotovoltaice pe bază de pigmenţi organici, design paramtetric, producţie proprie.**

## 1. Introduction

It is widely accepted nowadays that buildings are accountable worldwide for around 40% of the current air pollution levels and more than 50% of the energy consumption [1],[2]. Sustainable design is no longer just a fashion, it is an imperative. But how do we implement sustainable or green design in architecture in a realistic way and on a larger scale?

One of the myths skeptics have about sustainable design, is that it implies giving up on comfort or escalating construction prices in order to achieve a better environmental impact. In fact this is not true. We find more examples, some rooted in centuries old technologies that actually come cheaper than more recent traditional building techniques and more than pay off in just a few years of use. Examples, such as the Bullit Centre in Seattle or Shanghai Tower proud themselves for having a positive impact on the environment, producing more energy than they actually need to function and having an insignificant electricity bill. The first one is not even connected to a sewage system and reuses all human waste and gray water for fertilizing and irrigation.

There are just a handful of principles that need to be taken into consideration during the design phase for buildings to have less of a negative impact and they seem to revolve around the idea of energy and material savings and/or reuse. First is the need to better insulate the building so as to lower the costs of heating and air conditioning that make up for most of the energy consumption in the first place. Then it is common to have the building generate some if not all the energy it needs through green methods like solar or wind power. There is also the aspect of the building materials employed and of the way waste and materials are being reused in the process.[3:158-160] It is of no use to employ solar panels that are so energy costly that use up all the energy they will provide freely just to be created in the first place. Last but not least, the building should take into account what it replaces. If it is built on a former green field, chances are it will be harder to have the same impact but if it replaces a former, less optimal building, chances are it will be an improvement overall [4].

It is in this context of sustainable design that a new specter of materials seem to have emerged on the market, promising an almost surreal solution to most problems the constructors seem to have been faced with so far - smart materials. More and more is expected of them and, although it is a fairly new sector, it is prophesized a very promising future in the decades to come.

## 2. Smart materials - is it just a pretentious label?

From smart phones and watches to smart cities, everything seems to be smarter than before. But is it really? The abuse of the word smart seems to offend most critics and for good reason. Just labeling something as smart is surely not going to convince anyone, especially since we all know that artificial intelligence is still not achieved yet.

So what do we understand by smart materials? Basically they are not intelligent in any way but they are adapting to environmental changes in predictable, reversable and useful ways. For example there are materials, such as thermo-bimetals (TBM) that employ a simple yet effective technique of welding two metals with different dilation coefficients meaning that when heated (by the sun rays, for example) they dilate differently, resulting in the material bending out of shape. It is most useful for a shading device that does not need a human and/or an engine to operate it and it can be used intelligently to adequately and automatically shade a working space, for example. This technique is rather new but the principle has been used for thermostats for decades without the "smart" label attached.

There are smart nano-materials that self clean in the rain, mimicking the lotus effect of the lotus leaves, and even self heal [5: 56-57]. Needless to say they save up a lot of energy and effort that traditional materials would need for cleaning and repairing by workers. Basically smart materials can be divided into two main categories - property changing and energy changing (smart) materials [6: 79-83], with their distinct uses.

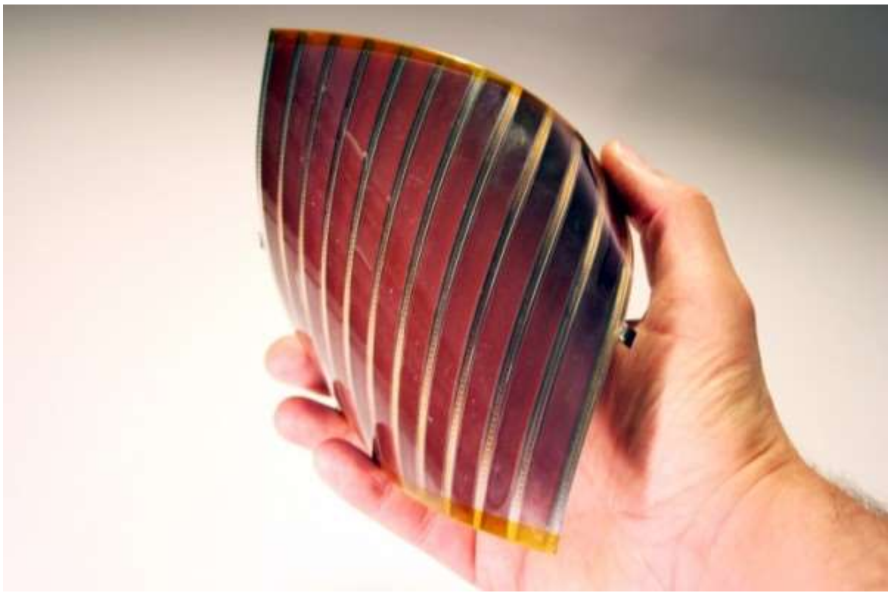


**Figure 1. Dye sensitized solar cells are thin, lightweight and flexible [7]**

Of these, the second group seemed more interesting for us in attempting a practical workshop with our students. The idea evolved around the revolutionary invention of the Grätzel Cell by Michael Grätzel in 1988 who was awarded the 2010 Millennium Technology Prize for it. Also known as a Dye Sensitized Solar Cell, it is a cheap and flexible film based solar cell that can convert sun rays into electricity and is most appealing because it can be easily replicated by enthusiasts with off the shelf ingredients. Another great application is that the film can be bent to accommodate any shape, making it possible to be used as an envelope for all sorts of architectural forms. Although it has been around for some years, the invention has not been deemed commercial until recently because of some technical issues with the electrolyte solution and outdoor durability. It is still a focal point for many research articles around the world which improve yearly on the formula and it is estimated that it will have a large impact on the global energy market in the decades to come, maybe even replacing more conventional silicon based solar cells [8].

Our idea was to create the first energetically independent pavilion in the country that would be entirely home made with off the shelf cheap ingredients (more or less because some ingredients, like the ITO covered film, can only be purchased from professional vendors and at quite steep prices as we were soon to find out). It was deemed a very unrealistic scenario by most people because of the fact that it had not been attempted before and because many believed the costs would skyrocket and we would need the know-how that architects clearly didn't possess. In reality, on a much smaller scale or different context it is true, this effort has been undertaken by others, including architectural schools, in the recent years and we saw no impediment in us trying to improve on their findings.

## 3. Similar examples around the world

Smart materials started as an oddity in research milieus and soon made their way into temporary museum exhibitions because of their spectacular behavior. It is the case of the Reef exhibit - a responsive architectural installation by Rob Ley from Urbana and Joshua Stein from Radical Craft. First exhibited in 2009, Reef performed seemingly as a living organism, interacting with the people visiting the exhibit like a *Mimosa pudica* would. Quoting from the presentation site: *Reef investigates the role emerging material technology can play in the sensitive reprogramming of architectural and public space. Shape Memory Alloys (SMAs), a category of metals that change shape according to temperature, offer the possibility of efficient, fluid movement without the mechanized motion of earlier technologies. Operating at a molecular level, this motion parallels*

**Figure 2. Rob Ley's and Joshua Stein's *Reef* exhibit mimics a coral reef [9]**

*that of plants and lower level organisms that are considered responsive but not conscious. A field of sunflowers as they track the sun across the sky or a reef covered with sea anemones, offer images of* *the type of responsive motion this technology affords. Its use in practical applications has been limited to the medical and aerospace fields as well as novelty toys - the super exclusive vs. the trite. Despite the potential of this technology, there have been few serious attempts to test its possibilities at the scale of architectural environments. Reef's unique exploration of technology shifts from the biomimetic to the biokinetic while liberating and extending architecture's capacity to produce a sense of willfulness* [10]

Another example of an interactive installation based on the properties of smart materials is *Phototropia*, which is actually a part of a series of applications and workshops developed by the Master of Advanced Studies class at the Chair for CAAD at ETH Institute, Zurich that is still ongoing every year. Based on four different types of smart materials (DSCs, electroluminescent displays, electroactive polymers and bioplastics), each replicated by a small group of students, *Phototropia* was an autonomous installation that could draw its energy from direct light and use it to illuminate on its own and to move certain parts that were electroactive (changed shape when the electrical current passed through them). According to M. Kretzer, *the final design was supposed to consist of 102 custom made dye-sensitized solar cells, 90 electroluminescent displays, and 12 electroactive polymers. Since the required power was more than the custom made solar cells could generate 24 industrially fabricated solar cells had to be integrated*. [11:118].

Another notable example, also from the CAAD at ETH was *Resinance*, in 2013. *Resinance*, as the name cleverly suggests, is another instalation, based on thermochromic leuco resins that change from coloured to colourless when electrical current passes through them. The instalation also used thermal resistances and fans to transmit warmth and coolness and interacted to touch (and intrinsic temperature transfer), delivering the warmth in a wave like motion from one module to the next [11:153-155].

**Figures 3-5. *Phototropia* (top) and *Resinance* (bottom), two projects at ETH Institute, Zurich [12], [13]**

**Figures 6,7. *Volvo V60 Pavilion*, a mobile rechargeable hub for electric cars [14], *Engie Pavilion* in Cluj Central Park**

While these are playful and less than pragmatic installations, they do however hint at serious applications if used on a larger scale or different context. On such application, far less spectacular but far more practical is the V60 Pure Tension Pavilion. Basically it is a collapsible solar pavilion for the Volvo V60 car that can easily fit in its trunk, be deployed anywhere, especially on a sunny day, and is able to charge the car's electrical battery in a matter of hours in the middle of the desert, for example. Arguably, even when folded, it takes up a lot of space and the process of dismantling and reassembling takes a lot of effort, it is still quite a remarkable achievement by all standards and its parabolic, organic shape is not at all undesirable.

Lately more and more cities promote the development of solar panel pavilions, albeit with small capacities. Even in Cluj we can already find several Engie pavilions where one can freely charge their smart phone.

## 4. The physical principle behind the DSCs

Dye sensitized solar cells function based on the simple semiconductor property of titanium dioxide ($TiO_2$), a very common substance used for painting because of its powerful white color. Semiconductor means that it behaves like an electrical insulator until a certain threshold in static electricity is reached when electrons can pass through its layer to the other side, resulting in a (sudden) polarization. It is prone to only allow a unilateral flux of electrons from one side to the other. So when the sun illuminates the surface, it becomes an anode and the backside becomes a cathode.

Since the $TiO_2$ layer is naturally white, it deflects most of the sunlight, resulting in a very low yield, hence the use of a ruthenium or organic dye (such as raspberry or blueberry juice) used to capture light more effectively. The electrons that departed from the excited dye coating and through the $TiO_2$ substrate need to be replenished by an iodine electrolyte solution that does the opposite, accepting 2 electrons and turning from $I_3$- to 3I- so the circuit can then restart all over again.

Thus, a dye sensitized solar cell has five major components:

- a top glass or film layer with a transparent conductive oxide on the backside (usually consisting of indium tin oxide - ITO) [15]

- a nano-porous layer of $TiO_2$ that is usually sintered (compacted upon heating and pressure). It has roughly 10 µm width but a surface 1000 times higher than its projected surface due to its 60-70% porosity.
- a layer of dye (originally ruthenium based - later on organic dyes were found to be almost as effective but a lot cheaper), the dye is infused in the white $TiO_2$ layer
- an electrolyte solution based on Iodine and ethylene glycol
- a bottom glass or film layer with a transparent conductive oxide on the upper side (usually consisting of indium tin oxide - ITO) [16],[17:143-145]

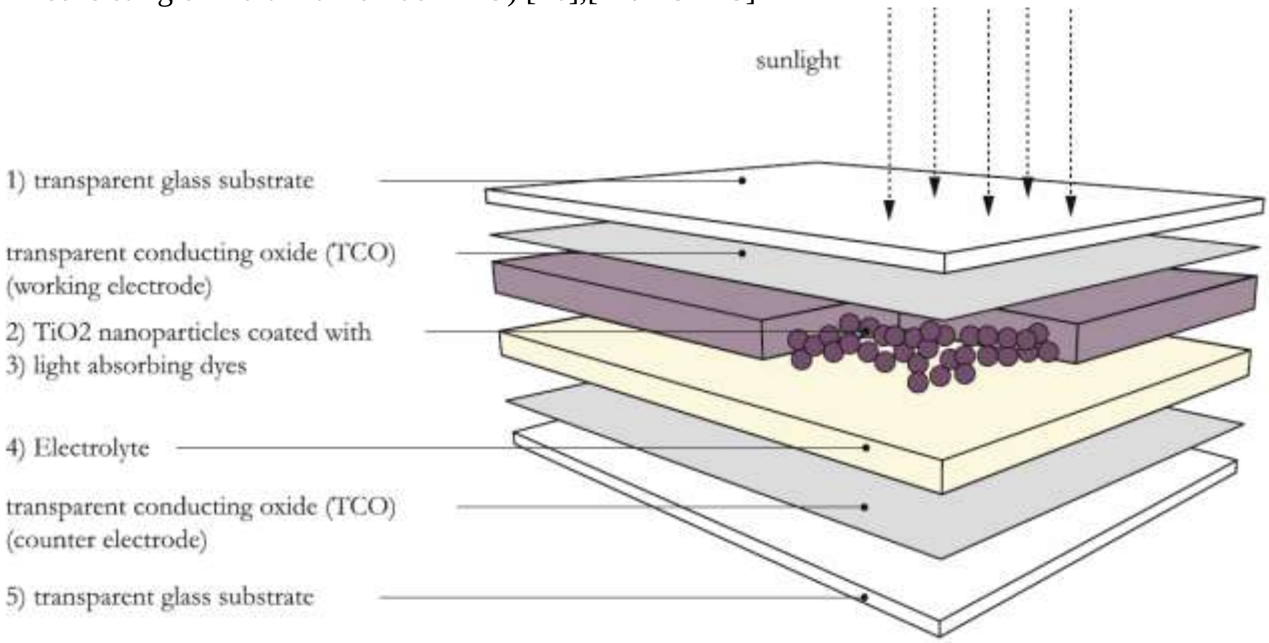



**Figure 8. DSC layers, Manuel Kretzer after Kalyanasundaram and Grätzel [11:113]**

Hence, in theory, all materials needed for the manufacture of the DSC were, for the most part, easy to procure and relatively cheap. In fact there are starter up kits for schools that actually allow teachers to demonstrate live and construct a DSC in the course of one hour for students to better see how they work [11:113]. A microscope glass lamella has one side coated with ITO for example and is good for such an experiment although it has a very small surface and yield in current intensity. Of course, the step from a small 3 by 3 cm solar cell to a more utilitarian and flexible cell, able to be used as a module in a larger structure, would be much more challenging.

## 5. Our intentions

Departing from the work of our Swiss colleagues at ETH, after enquiring more about their findings with Manuel Kretzer who was kind enough to tell us their experience, we intended to organize a workshop on Smart Materials and Parametric Design to promote these ideas and learn ourselves how to create DSCs from scratch. I started with three colleagues, Andrei Kiss, Daniel Șerban and Mihai Grama and several students. We received the help of Horațiu Vermeșan, vice-dean of the faculty of Material Engineering from our university and we completed a collaboration and research agreement with the Insitute for Research and Development of Isotopic and Molecular Technologies (INCDTIM). We would like to give thanks to director Adrian Bot who was very open to this research project and helped us with logistical and technical aid. Also we would like to thank chemist Alexandrina Nan from INCDTIM who was in charge of finalizing the prototype and to whom we owe this project having reached the end of its first stage. She also agreed to tutor our students with technical advice through the second stage - the workshop.

As such, our endeavor was meant to have three different stages: first we would create the DSC prototypes with our partners at INCDTIM and then attract some funds for the second and third stages, and see if they were possible to finalize. The second stage would be a student workshop with students from the Faculty of Architecture and Material Engineering where each would complement the others in their study. Understanding and improving on the prototypes in order to find the balance between efficiency and low manufacturing costs would be the main target of this workshop. Finally, the third stage would require a larger sum to fund but would involve a higher impact of our work. It would end with the realization of a pavilion like structure that would be entirely (or mostly) covered with DSCs and, therefore, would be energetically independent from the main grid. Such a pavilion could be deployed in a public square and promote our research among passersby. At this stage, the work would not imply much research as this would be the aim of the workshop before hence, but would be more about promoting our finds to the public so as to have a visible impact.

## 6. Our findings

As the purpose of our project was to find easy to replicate and cheap DSCs that could be produced *en masse* by our students and then connected to each other to generate larger amounts of electrical current, most of the ingredients we used are quite cheap.

As an exception, we had to import the ITO covered films which were quite expensive for the prototype. We would like to thank SC SRL for providing us with the necessary funds for this stage. The $TiO_2$ powder was easily available and it was then diluted in a solution of acrylic acid to form a paste. The paste was then spread with a spatula on the film but, as we discovered, the layer was not thin enough and it cracked when sintered.

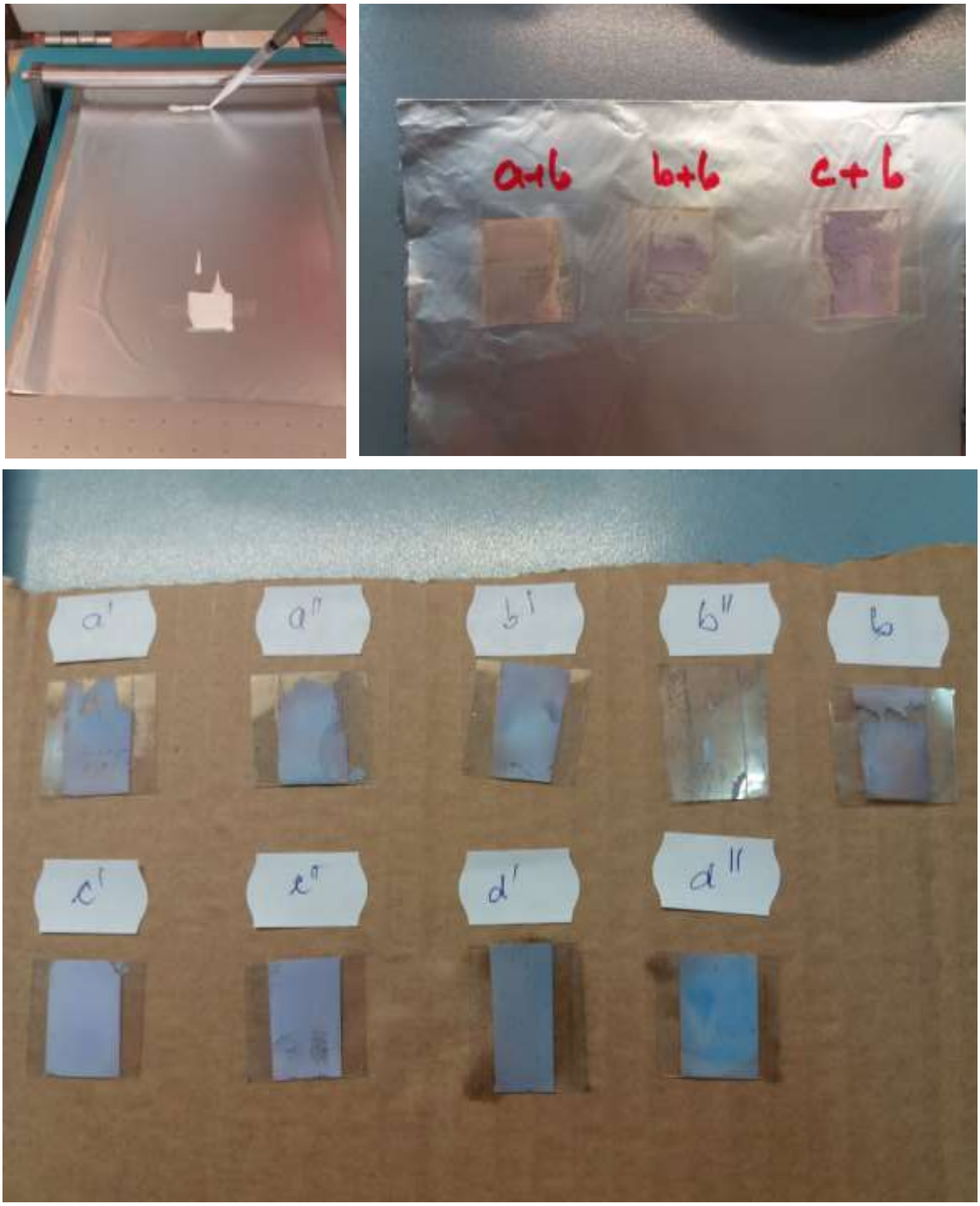
The glass prototypes were easier to manufacture because glass can be heated at a higher temperature and the $TiO_2$ paste would sinter easier on it. Microscope lamellas were used for this purpose. The film prototypes were however harder to produce due to several factors. First there were the aforementioned problems with sintering and then there were issues with cutting them perfectly so as not to create a short-circuit.

After managing to stabilize the $TiO_2$ layer, came the easier part of infusing it with blueberry dye and ethanol. Initially, the Grätzel cell used Ruthenium polypyridine dye but that is an extremely expensive solution and the blueberry dye works almost as efficiently and at only a fraction the cost. Due to the fact that the $TiO_2$ layer is extremely porous (and thus has an active surface of 1000 higher than the projected surface), the consumption of dye is quite high. Following the immersion in the dye for 24h, the cell would have to be cleaned in ethanol of the dye residue.

Finally there was the problem of the electrolyte solution that had to be anhydrous for it not to cause short circuiting. The solution used ethylene glycol and iodine. It was used as a redox solution, to connect the two sides of the cell, the anode and the cathode together.

In the end, the glass prototypes seem to have a slightly better yield in electrical current produced and are easier to manufacture. Yet for our distinct purposes, the film cells are more flexible, can support a higher opening, are lighter and are less dangerous to use for covering up a pavilion like structure. Due to their flexibility, we can parametrically design an optimal shape for the pavilion that could take aesthetic aspects into consideration and would be safer for users.

As mentioned, we are now reaching the end of the first stage, which took a longer time than initially expected to complete. In the end, we have completed several viable prototypes, both on ITO glass and film support at INCDTIM. As can be observed (in figures X and XX), the glass prototypes produce between 300-500 mV of electricity under direct sunlight, even for a very small surface cell.



**Figures 9-11. DSC prototype creation, courtesy of INCDTIM Cluj, July 2018. First stage - applying the $TiO_2$ coating paste evenly with a machine. Second stage - sintering at 150º C and then dipping overnight in an organic blueberry concentrated dye solution. Several tries were necessary for a stable and even coating to be achieved on ITO films**



**Figures 12, 13. DSC prototype output measurement, courtesy of INCDTIM Cluj, August 2018. Voltage was measured at 50 to 500 mV, depending on solar radiation and intensity ranged between 50 and 150 µA for a 3 by 3 cm cell.**

The next two stages of our project are yet to unfold. The workshop will take place early in the first semester of this academic year and will target students from Architecture as well as from Material Engineering but will be open to all other applicants from the Technical University. We will have to restrict the total number of students to about 30 so that we can work in manageable teams. The aim would be to learn ourselves, teach and develop the most efficient cost-benefit solution for a large scale implementation of the technology. Also, half of the team would be involved in the parametric design of the pavilion, design that would include factors like optimal structural shape, flexibility and ease of assembly and disassembly, modulation (since we hope to afterwards divide the pavilion into several smaller component that can function independently in different exhibitions) and, last but not least, optimal orientation for direct sunlight - the most important part of the demonstration.

Finally, the ambitious part of trying to construct the pavilion per se is still uncertain because it needs funding from the private sector. It would be beneficial for both the idea to take shape and to manifest itself in the public space of Cluj and also it would be a good opportunity for publicity for private investors, for INCDTIM and for the Technical University as well.

## 7. Conclusions

Dye sensitized solar cells are undoubtedly easier to create than their silicon counterparts because of cheaper materials and less energy involved in their manufacturing. Also they can use thin film technology which would make them more flexible, more appealing to architectural innovative solutions and lighter than current silicon based photovoltaic panels. The only drawback is their short life span and fragility to weather conditions that is currently being worked upon by many scientists around the world. They undoubtedly represent a distinct possibility for the future of solar energy harvesting through buildings and there are several examples in progress even today.

It is in this context that familiarizing both students and public with this technology comes as an imperative. Our project is one of many that follows this distinct direction. It is ambitious in scale but the most important aspect are the individual findings and the perspectives they open to others interested to further pursue a research in the creation and design of DSCs and related architectural objects, not the size of the pavilion or even its durability in time. As each year brings up new and better components to this remarkably simple DSC design, the possibilities of practical use multiply exponentially.

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