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# Applicability of Flexible Photovoltaic Modules onto Membrane Structures Using Grasshopper Integrative Model

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## Abstract

The potentials of integrating thin-film photovoltaic technology into buildings make it the recommended renewable energy source not only for traditional architectures, but also the most innovative applications that favour envelopes characterized by free morphologies such as membrane structures. The integration of Photovoltaic technology into membrane structures offers a promising significant step in the market development. However, some challenges and questions are arising relating to the applicability of such systems and how they are significantly dependant on a list of complex aspects that have to be taken into account during the design phase. These aspects include the wide variety of membrane three-dimensional geometries that in turn govern the modules distribution, orientation and shadowing as well as the distribution of stresses and deflections for each single project and how both the structure and modules react to them.

The interference between the aforementioned aspects makes it hardly investigated without using a parametric tool that's able to analyze multiple parameters in an integrative real time process. Therefore, a parametric Photovoltaic model using Grasshopper was developed as a part of the PhD dissertation of the first author, Ibrahim H., With the target to analyze the aspects that impact the payback time of the PV system such as the layout orientation, the effect of shadowing and the maximum deflection allowed for the membrane surface under different loading conditions concluding with calculating the total clear surface area available for allocating PV modules. This paper presents how Grasshopper parametric tool can be efficiently used for analysing and evaluating the feasibility of applying flexible PV systems on tensile structures geometries. The outcomes of this research work will be applied to the structures designed and manufactured by Inside2Outside Ltd within the research activities founded by

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*Keywords:*MIPV Membrane Integrated Photovoltaics; Parametric Design; Grasshopper; Membrane Structures.

## 1. Introduction

Photovoltaic (PV) solar technology is considered among the best product renewable energy sources for building applications. Flexible thin-film technology has potentials not only for traditional architectures, but also the most innovative applications that favour envelopes characterized by free morphologies such as membrane structures. Integrating flexible solar modules in pre-tensioned membrane structures allows for wide design varieties of shapes and geometries. However, many questions remain related to the applicability of such systems on the wide variety of membrane structures and the behaviour of both the structure and the modules under different environmental and mechanical conditions. A solid background of know-how is required to well exploit the integrated elements which researchers are likely to do.

## 2. Membrane Integrated Flexible Photovoltaic

### *2.1. State of the Art*

The first trials involving the integration of flexible PV modules into membrane fabrics came out in 1998 in national design museum exhibition in New York when FTL studio presented the first tensile fabric pavilion of 9.7m high made of transparent PVC fabric incorporating flexible PV technology into its design [14]. But because the fabric material doesn't provide a long-term stability, searching for more stable materials with the potentiality of accommodating solar technology was required. Further applications were investigated by integrating modules into PVC coated polyester fabrics followed by PTFE coated glass fibres using techniques that were especially developed for compatibility with the used material properties. The first trials were performed by Hightex by welding an amorphous silicon module directly to a four-points sail structure made of PTFE/Glass. The system was then developed through embedding the module between two layers of EVA layers surrounded by fluoropolymeric film for back and front sheets. The front sheet extends over the module area for welding to the PTFE/Glass. But a vapor condensation problem came out one year after module installation, see Fig.2.

Fig.1. Right: Flexible solar modules on PTFE/Glass (Cremers J., Hightex)
Fig.2. Left: The damaged attachment system of PV module [15]

A multi-layer attaching system is then developed by Saint Gobain performance plastics in USA that can mount flexible solar modules to PTFE/Glass fabrics. The system composes of a first layer of single coated PTFE/Glass which is laminated to a thin layer FEP on the side of PTFE coating which can't be hot welded. Therefore, the FEP layer with melting point of 280°C is used for the heat sealing with temperatures over 280°C. This temperature would destroy both the butyl adhesive and the polyester of the Velcro hook. For this reason, the single-side coated PTFE/Glass strips are welded before a special type of Velcro hook strip is glued onto it. The velcro layer is the key solution to the targeted temporary use of modules and is finally adhered to the thin-film solar module. Fig.3 indicates the structure of the attaching system.

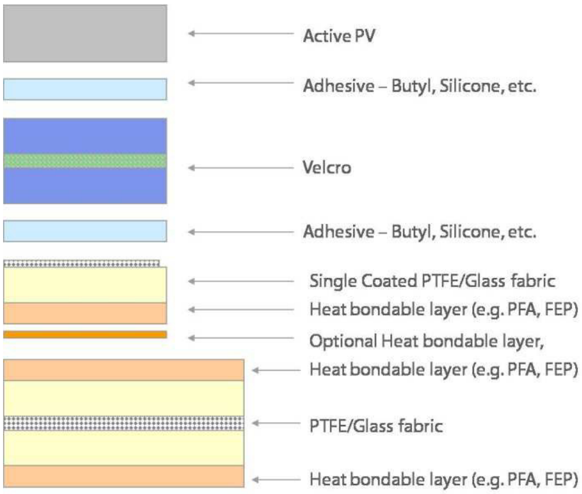

Fig.3.: Layers structuring of the the System attaching Flexible PV to PTFE/Glass (Cremers, Hightex)

More recently, integration of lightweight flexible photovoltaic has been demonstrated by Inside2Outside Ltd since 2008. Three types of photovoltaic active layer had been trialled: Organic PV, printed onto tensile membrane; amorphous silicon PV and perhaps more effectively, inorganic compound PV. There is also considerable potential for a Perovskite based TensilePV. TensilePV structures have been prototyped and trialled by Inside2Outside Ltd and have been installed in a number of locations across the UK. These TensilePV remain in use demonstrating both the use of the structure and the generation of useful quantities of power generation, which is currently being used by the building owners, with unused generation being fed back into the national grid, to provide a significant income for the tensile structure owners. But apart from material issues, many questions are arising related to the applicability of such systems on the wide variety of membrane structures and the behaviour of the structure and the modules under different environmental and mechanical conditions. The successful integration of flexible Photovoltaic into membrane projects are significantly dependant on a list of complex parameters that have to be taken into account during the design phase such as the overall lifetime of the PV layer, together with the wide variety of membrane three-dimensional geometries that in turn govern the modules distribution, orientation and shadowing aspects and the distribution of stresses and deflections within each single project.

### *2.2. Challenges Facing Photovoltaic Integration into Membrane Structures*

Although the potentials of integrating flexible Photovoltaic technology into membrane structures could open up market opportunities and thereby contribute to a greater acceptance of PV technology, the challenges facing the combined technologies which can be tackled as follow:

- As stated by Cremers [1], that despite the achieved progress in the field of membrane design that facilitates realizing new technical solutions for innovative technologies, it’s still the question of know-how which is required to push the architects and involved specialists to introduce such new technologies to the market. Integrating flexible photovoltaic modules into membrane surfaces is a complex process that involves a lot of aspects that have to be analysed for each single project such as: I. Estimating the yield of PV system attached to membrane geometries which are characterised by single or double curvature. II. The distribution of stresses and deflection over the membrane surface and their impact on PV modules arrangement. III. The optimum orientation of PV modules to solar radiation in the determined geographic zone. IV. The complex forms for membranes make it difficult to follow the areas under shadowing effect that should be avoided for locating modules. V the lifetime and stability of the PV layer itself within the TensilePV membrane.

Recent research projects [12,13] investigated the technical and manufacturing aspects related to the manufacturing of a smart façade system with OPV integrated into ETFE foils and highlighted the risks related to the level of stress and curvature of a typical ETFE cushion for pneumatic roofs and facades. In addition, a series of mechanical tests analyzed the behavior of laminated lightweight, thin-film, organic solar cells and ETFE foils in presence of biaxial stresses [5]. The results showed that, despite the relative high stress introduced into the membrane, the highly extensible encapsulant used in the lamination process (and positioned between the upper ETFE oil and the lower solar cell) can accommodate a considerably different elongation in correspondence of the upper and lower surface reducing in a drastic way the loads on the solar cell.

### *2.3. Design Consideration of Integrating Flexible PV into Membranes*

Because the membrane surface, in which the modules are integrated, should have the maximum yield of the PV system which is affected by the orientation and the incidence of solar radiation that reaches a PV surface, the following considerations should be taken into account when considering the layout of the membrane which can be determined by using the parametric photovoltaic evaluation model developed in the PhD research [3].Based on performed tests for the characterisation of flexible Photovoltaic module under weathering conditions by Lakatos [4], modules should be positioned flat with a tilt of 30 ° facing south with a maximum slope of 60˚ for an optimized performance. Regarding the performance of modules when aligned at North-South and East-West orientations, which means that the longitudinal module's axe is aligned to these directions, the performed tests showed that a slight difference exists between modules output at north-south and east-west and thus can be negligible. East and west orientations shouldn't be used for accommodating PV modules as they receive low levels of radiation, only in the morning and evening respectively.

To enable maximum power generation (yield) from the PV modules, they must be connected in series at areas with similar orientation and curvature and therefore having a very similar solar radiation flux. But if large PV surfaces can't avoid being shaded, then parallel connection between modules would be recommended. In the parallel circuit, the voltages applied to the segments are constant. The currents through the individual segments on the other hand vary from one another. Since there are now different radiation intensities, the power module is then determined by the segment with the lowest radiation. The tests under real conditions showed also that the orientation and curvature of the PV module significantly affect the yield. Both an increase and a decrease in yield of nearly 5% is possible. Membrane forms with less curved and clear orientations are recommended for higher PV output. Because of varying forces action on the membrane surface and the material relaxing that occurs after a while, the tilt angle of solar module can change from its optimised positions and therefore the adjustment of the tilt angle would be possible in mechanically pre-stressed PTFE/Glass membrane roofs, but would require more investment. Regarding the architectural aspects, architects enjoy presenting PV as a surface that gives a clear visual impression and the rhythm imposed by the grid of the solar modules plays an important role in the visual perception of the membrane if well exploited. Linear arrangements of modules within parallel patterning are preferable than radial ones.

## 3. Parametric Design with Grasshopper

Parametric design appeared around new smart 3d modelling tools which have evolved to incorporate complex relationships between multiple parameters at the same time [10]. Not only these parameters - represent modelling variables as well as performance criteria - generate new architectural ideas, but also they can simulate complex 3d shapes such as Membrane Structures. In Parametric modelling tools, one can change and manipulate with various parameters and develop many design iterations which much more advance than other the liner 3d modelling tolls. Salim and Burry [7] Categorized the parametric tools into two groups; the first group called associative-geometry, which characterized by mathematical associations between the 3D elements such as points, curves and surfaces.

This group includes Grasshopper for Rhino and Generative Components by Bentley. Building Information Modelling or BIM tools are the second group which is based on developing relationships between components of a building design that can across multiple disciplines without too much effort [2]. Grasshopper plugin-for-Rhino as a parametric modelling tool graphical node interface which includes various components, parameters, constraints to generate and mange any 3d parametric model [6]. All these features that Grasshopper has facilitate the exploration process especially at early design stage [7].Multiple parametric workflow succeed to optimize many environmental aspects such as daylighting and energy through genetic optimization as well as exhaustive search methods [11,9]. Their applications go behind optimizing static designs into dynamic responsive systems.

The above review demonstrated that a limited number of publications were concerned with the optimization of the thin PV over Membrane Structures for the improvement of energy performance. It also provided evidence to the potential of utilizing parametric workflows and optimization in identify the appropriate locations for PV that can more energy efficient.

## 4. Parametric Photovoltaic Evaluation Model

The parametric Photovoltaic model is dedicated to evaluating environmental factors that impact the payback time of the PV system such as the structure's solar access, shading aspects and the site's latitude, which influences the optimum MIPV system orientation and tilt. In addition to analysing the daylighting pattern on the geometry, the parametric design is developed to incorporate the membrane deflection into the process using a definition to measure the maximum allowable fabric deflection under different loading conditions of wind and snow in the fabric areas that would allow accommodating PV modules. The model works on checking the applicability of PV modules on the selected geometry through calculating the total clear surface area available for PV integration. The script is designed with Grasshopper program by a specialist in parametric design (Ayman Wagdy) who developed special techniques for parametric workflow of daylighting parameters (Wagdy, 2012).The model is divided into three stages performing as a filtering process through the sequential defined parameters of deflection, orientation then shadowing.

### *4.1. Allowable Deflection Test*

The numerical design and analysis of the membrane geometries is firstly performed using special form-finding and structural analysis software programs developed by Form_TL ingenieure für tragwerk und leichtbau.The first form to be analyzed is a 5x5m hypar structure with 1:5m height to length form ration, see Fig.4. The structure's analysis results in three deflected geometries under the three loading conditions of Pre-stress, wind and snow. The deflected forms are then tested by the deflection definition while controlling the maximum allowable deflection value within the same module surface;Fig.5 shows a screen shot for the deflection definition.

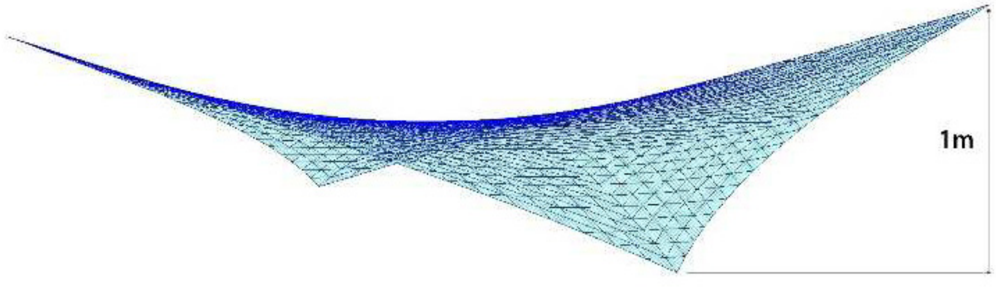

Fig.4: 5x5 m hypar structure with a 1:5 m height to length, form-ratio of 0.2

All surfaces with excess deflection values are to be excluded from the total surface available for accommodating PV modules. As indicated in Fig.6& Fig.7 for a hypar structure, by controlling the maximum allowable deflection distances between the two deformed geometries under pre-stress and snow from 0.95 to 0.84 m, the model considers all membrane surfaces below determined values. It should be taken into account that this value should be obtained from the PV module's mechanical testing. The output from this process will consider only the meshes within the determined deflection range [3].

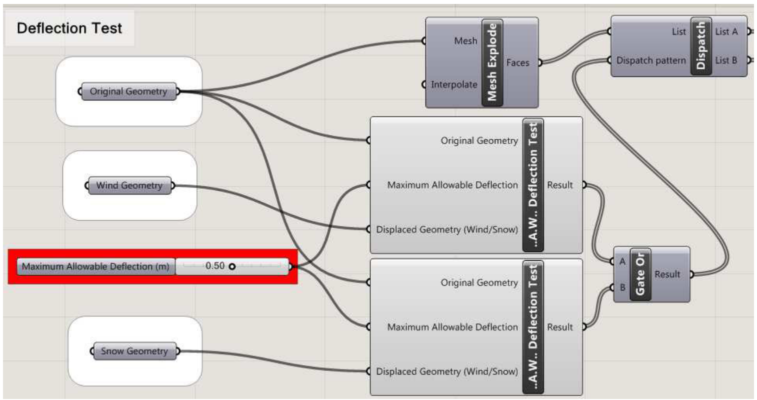

Fig.5: Screenshot of the deflection test definition (Ayman Wagdy©)

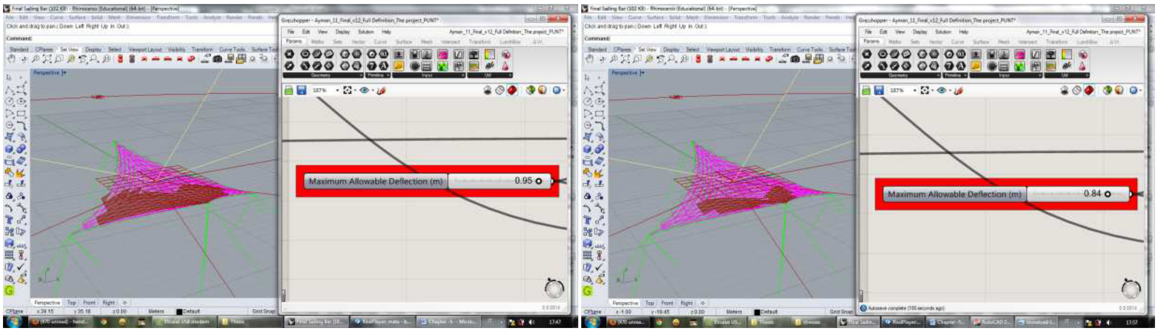

Fig.6& Fig. 7: Filtering membrane surfaces below different values of allowable deflection

## *4.2. Orientation Test*

A second filtering process by the structure's orientation aspect follows the deflection test. As the daily and yearly movement of the sun must be taken into account when considering the layout of the membrane, a separate definition is designed to check the surfaces subjected to solar radiation by defining the north direction, the horizontal and vertical angles in which the modules should be constrained as indicated in Fig.8. The maximum zenith angle of 60 degrees is defined, corresponding to the maximum angle recommended for inclination of a surface accommodating PV modules. The grasshopper model is linked to another definition for solar database of global solar radiance that was developed by Oregon laboratory. Fig.9& Fig.10 show how the model detected different surface areas within the defined solar radiation angles of an arch structure for 21 September and 21 November, 12 p.m..The angles are selected for the sun path of Milano city.

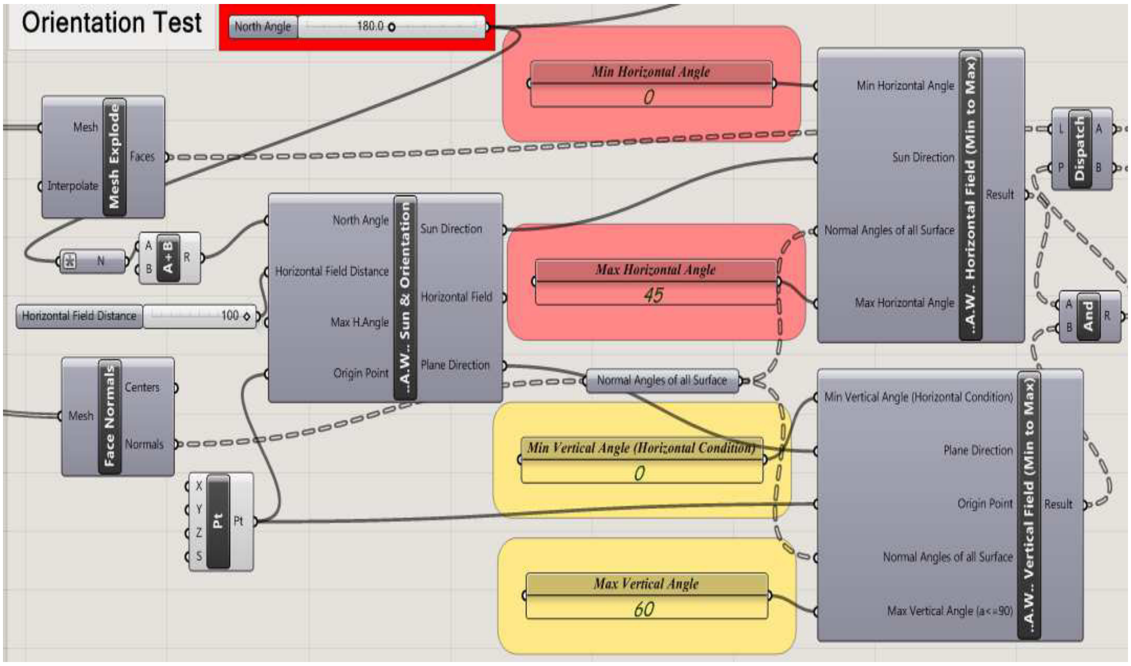

Fig.8: Screenshot for the Definition of Orientation test (Ayman Wagdy©)

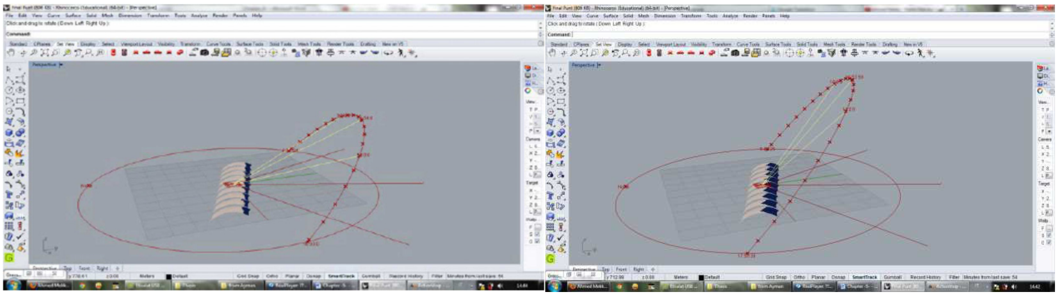

Fig.9& Fig.10: Sun path for Milano City in 21 September and 21 November, respectively.

### 4.3. Surface Shadow Test

The last filtering definition is concerned with surface shadow test. The process, as indicated in Fig.11, relies on excluding all membrane surfaces subjected to shading under the specified date and times. The input geometry in this process is the membrane surfaces that fulfilled the previous conditions of deflection and orientation. The results are expressed by the final clear surface area available for PV integration giving a percentage to the total membrane area, see Fig.12. For comparative results between different membrane geometries of clear areas percentages for adding PV modules, the projects are analyzed by applying different scenarios of sun zenith angles simulating different seasons' conditions [3].

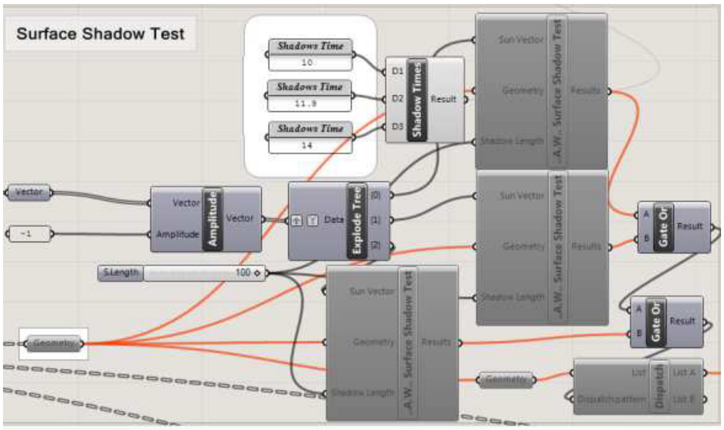

Fig.11: Screen shot for the Definition of Surface shadow test (Ayman Wagdy©)

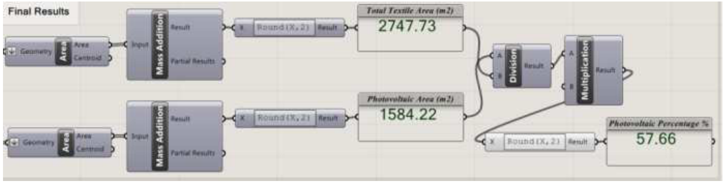

Fig.12: Calculating clear membrane area for PV integration (Ayman Wagdy©)

## 5. Conclusion and Future Research

The wide varieties of membrane forms and the complexity of factors that impact the integration process will require more research to deeply analyze more geometries and may include other structural parameters in the Grasshopper model. This would be investigated through a new KTP project between the University of Nottingham and Inside2Outside Ltd in UK. The planned outcomes of this collaboration include the commercialization of TensilePV, both into the built environment and in the exploitation of clean green power generation to contribute towards the global energy requirements.

## 6. Acknowledgements

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