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# Knowledge based expert system tool for optimization of the complex glass BIPV system panel layout on the cable net structural skin

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## Abstract

Nowadays, digital tools in architectural performance-based design have become almost inevitable in creation of Nearly Zero Energy Buildings (nZEB). Rising the number of performances to be included in the building simulation, rise also the need for optimization of building geometry and performances. Current optimization techniques, mostly developed as black-box models, offer great features and target detailed design phase, but they do not provide enough user control during the optimization process. This paper, however, presents knowledge-based expert system with user-interactive features, integrated within Rhinoceros 3D environment, that guide optimization in early design phase. Single criteria optimization of energy generation potential has been done to show and evaluate the effectiveness of the process in qualitative and quantitative manner. One typology of complex Building Integrated Photovoltaics (BIPV) components was chosen as a case study to demonstrate and evaluate potential of the early design phase optimization of paneling considering aesthetical criteria. Results indicate the software is capable to support architects by providing crucial information, allowing them to optimize overall performance while keeping integrity of the design decision-making.

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*Keywords:* complex BIPV; cable net; knowledge based expert ssystem; early design phase optimisation; Radiance

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## 1. Introduction

Over the past decade architectural design process has been constantly changing influenced by novel digital design tools that have become inevitable in creation of complex free forms like cable nets, especially when implementing parametric modeling and programming. Flexibility of the design process and complexity of the forms it can offer has put parametric explorations into the first choice when contemporary architectural expression is desired. Moreover, multiple interconnections and mutual relationship between parameters, together with domain of variables, represent an ideal ground for connecting design geometry parameters with performance simulations. This connections in form of feedback loop allow forming Performance-Based Design (PBD) process, where performances directly influence creation of new solutions. Having variables to form design search space, various optimization methods can be used to search for better performing solutions. This process is usually automated and majority of the current techniques are developed as black-box models, offering great features and targeting detailed design phase with almost no user control during the optimization process [1]. They are particularly developed for optimizing only performances, without taking into consideration design aspects. Furthermore, in order to design optimal buildings, architects need considerable amount of knowledge and expertize in all simulation fields to be included early on. This is not always the case, especially for small practices and design competitions, when maybe only part of the simulations are performed. Finally, optimization usually takes substantial time and is suitable for later design phases when crucial design decisions have already been made. This leads to the questions of design and decision making integrity of the users, and how these optimization techniques can better adopt to the earlier phases of the design process. In other words, how PBD can be adopted to every phase of the design process and offer adequate tools and support users with knowledge in the best possible way and without disintegrating the design process.

This paper proposes one such methodology for optimizing overall energy generation potential of complex Building Integrated Photovoltaic (BIPV) components dry placed over the cable net structure. As BIPV represents one of the best sustainable design strategies for designing Zero Energy Buildings (ZEB) [2], it is crucial for the acceleration of these technologies to have design tools that can efficiently assess their performance and help users designing structures including them. This methodology particularly addresses issues of design decision making, lack of knowledge in the PV field or inability to predict behavior of complex BIPV, and discontinuity of the design process caused by long computation times of black-box optimizations. It is adopted specifically for the early design phase to interactively assist users to improve performances of their solutions in time efficient manner.

## 2. Methodology

Knowledge based expert system [3] has been chosen as a methodology that can provide consistent and creative PBD process. The process covers two phases. The first phase consist of building knowledge base for the four complex BIPV system components with light trapping features. These components are created as topological components with self similar properties and with different performances in relation to incidence light angle. In this phase, robust and time-consuming annual cumulative radiation simulation is carried out to assess energy potential for each component. Every component is then iterated over the whole domain of possible angle-settings, discretized in regular angle steps. Only top hemispherical angles were taken into consideration as methodology assumes that complex BIPV should not be oriented downwards. Automation script for creating knowledge base was done in Python scripting language. This script takes three arguments, three axes, and combine them in nested loops to ensure each rotation step of each three axes are mutually combined to form all possible combinations and stores them in temporary dictionary. At the end of the process the dictionary, containing key-value pairs of orientation and cumulative irradiation values, is stored in an excel file. Performances of each component were stored in separate spreadsheets.

The second phase represents early design process and optimization by using data from the knowledge base excel sheets. Optimization is based on comparing values of each component for the same particular place and orientation on the cable net. Assuming that user may be interested in two different approaches, one starting from desired paneling layout and other acquiring best performing layout, tool offers these two modes for optimization. First one is manual mode that takes initial layout as a starting point, according to the previously set performance increment percentage, and upon request offers incrementally optimized layout to the user. In this way, user can understand where the worst performing panels are located and if initial layout should be modified for that increment in performance or not. In this mode, user can explore each of the components on the layout separately and get a preview of the performances of the other topological components for that location and angle setting. Again, decision making is left to the user. Second mode is automatic and it updates paneling layout with every change of initial base surface of cable net. In this way, user can also explore different forms and how it reflects on the performance. If some modification is needed, this mode should be switched off and should continue with the same procedure as in manual mode but in reversible way, meaning that performances are decreasing in the favor of aesthetics. Since, in this second phase, tool only reads and compares performance values from the knowledge base excel sheets, process is very time efficient and user is not obstructed by long computation time nor requires substantial knowledge in performance simulation. Simplified Pseudocode of the expert system tool is shown on Fig. 1.

```
procedure find_better_one (N, n, x, y, z, v):                                        #make definition
  for i in N:                                                  #start iteration to replace each component
    find X rotation; find closest value in database; set X;
    find Y rotation; find closest value in database; set Y;                        #calculating orientation
    find Z rotation; find closest value in database; set Z;
    find variation                                                          #search orientation in database
    if automatic replacement with best one is true:       #condition to start replacing components automatically
      new n = n[0]; new v = v[0]
      for j in n:                                                    #start comparing values of components
        if new v<=vj then vj=new v; nj = new n
        j=j+1
      return new n, new v                                       #return best component for this itteration
      place new n on location N                                                        #replacing component
    else:                                                             #start replacing with goal based value
      new n = n; new v = v
      for j in n:                                                    #start comparing values of components
        if vj>new v and new v * threshold <=vj then vj=new v; nj = new n
        j=j+1
      return new n, new v                              #return best matching component for this itteration
      place new n on location N                                                        #replacing component
```

Fig. 1. Pseudocode of the expert system tool

For the purpose of this paper, one criteria, total annual irradiation on PV surface, was chosen to explore and evaluate possibilities of the tool. Later on, it is planned to include fuzzy rule logic to set rules for tool to be able to make suggestions for improvement. For this time though, only annual cumulative radiation analyses were performed to asset energy generation potential of tiles. This is done by setting conversion rate to the value of total annual irradiation and therefore obtaining total energy generation potential of each component. Separating this value from database should eliminate updating the database, only converting it at the end of the process, and should allow calculation for different PV cell technologies and their conversion rates accordingly.

## 3. Case study and descriptions

In order to demonstrate capability of the expert system tool to optimize any arbitrary component geometry and paneling layout of any arbitrary free-form surface, double-curved hyperbolic paraboloid cable net surface was chosen as a base surface and Complex Fenestration System (CFS) were chosen as panel components. Topological BIPV components made from CFS, recognized by their highly angle dependent properties, helped getting more diverse results among components. Variable performances of the components, depending on the angle setting, insured improvement in the overall performance, comparing to single glazing, as each of the components were optimized for particular angle of incidence. In this way, it is guaranteed that each component has the best value, comparing to others, in some parts of the database. Moreover, optimizing performances of the CFS is not trivial task and their computational time is much grater comparing to simple glazing, so they represent ideal choice for case study where efficient PBD is required.

Geometry of the base cable net surface and CFS was modeled parametrically in the Grasshopper plugin for Rhinoceros 3D, using visual programming features to develop parametric definition, see Fig 2. Top part of the definition shows parametric elements creating the base surface, while bottom part shows element for creating CFS components. Orientation of CFS parametric meta-model is defined by the values in sliders representing three axes. This was crucial for automating creation of knowledge base changing only these sliders.

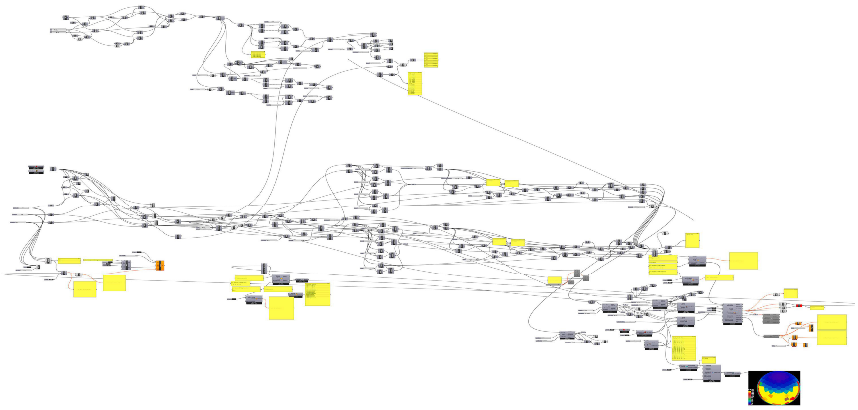

Fig. 2. Parametric definition of CFS in the Grasshopper plugin for Rhinoceros 3d

CFS components are defined as rectangular boxes, each with the same dimension of 25x35x1cm and with the various groves' dimensions on both sides. Some of the tiles have grooves with the extrusion direction outwards and some inwards. Top side has smaller grooves and its function is to capture light, while bottom side has less groves and provides solid substrate surface for PV. Detailed geometrical parameters are shown on Fig 3.

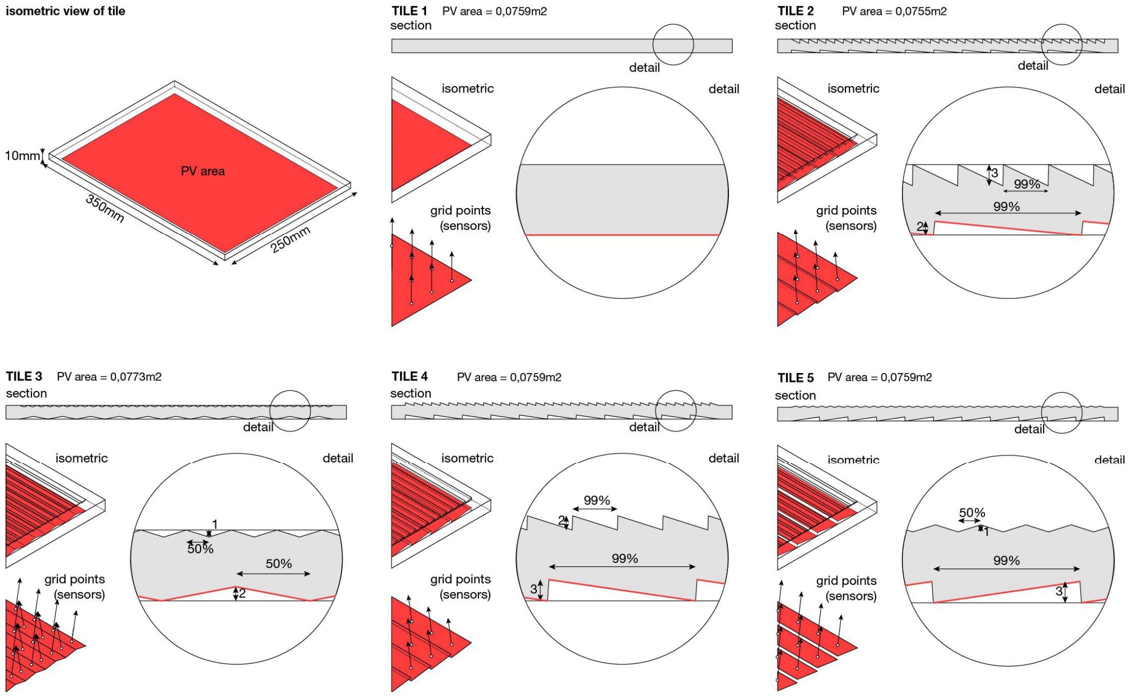

Fig. 3. Complex BIPV tiles

## 4. Simulation parameters and results

For the first phase, simulating annual irradiation levels on PV surface, validated Radiance daylighting simulation [4] was used implemented through the tools Ladybug and Honeybee [5]. It allowed simulation of CFS component with dielectric radiance material description that takes into account Fresnel equations and total reflectance needed to simulate light trapping grooves. Point grid was placed behind the CFS and in front of opaque element described by mirror radiance material. This layered structure ensured light only comes to the PV surface through CFS. Due to the small difference in irradiance values that can appear among points in the grid, point values are averaged and stored as a single value.

In order to perform computationally time efficient, yet accurate results, GenCumulativeSky method was chosen to generate an annual cumulative sky vault radiance distribution image, that the ray tracing program can reference at simulation run time [6], see Fig. 4 (a). Method takes information from a weather data file and calculate separately diffuse and direct component and merge it as a total radiation for every 145 discretized Tregenza sky vault patch. Location for the simulation was set to Milan, Italy with weather data provided by NREL website.

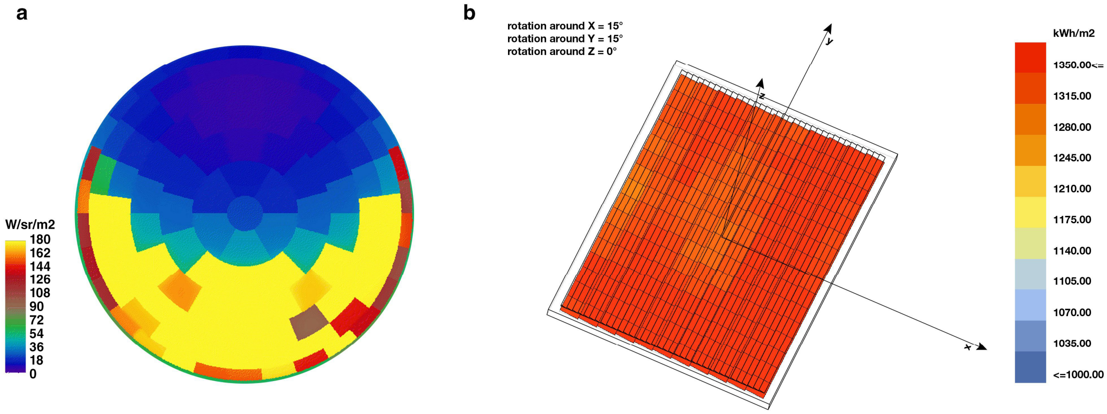

Fig. 1. (a) False color image of annual cumulative sky radiance distribution for Milan, Italy, (b) performance result for one of the variation

Referent global horizontal irradiance for an unobstructed test point under created annual cumulative sky was 1265,637 KWh/m2. This value was then compared with the values on the point grid under CFS and it was concluded that CFS generally improves performances up to around 30%. In the Fig. 4 (b), one variation in the knowledge base is presented together with rotation angles and performance range. Fig. 5 shows first 100 variations with their associated values and it can be clearly seen that tiles are constantly changing their leading role over the range. In this part of the knowledge base tiles 3 and 5 have better performances then others. Graph also shows performances can vary significantly in unpredictable way, and therefore expert system tool is exploited to facilitate decision making.

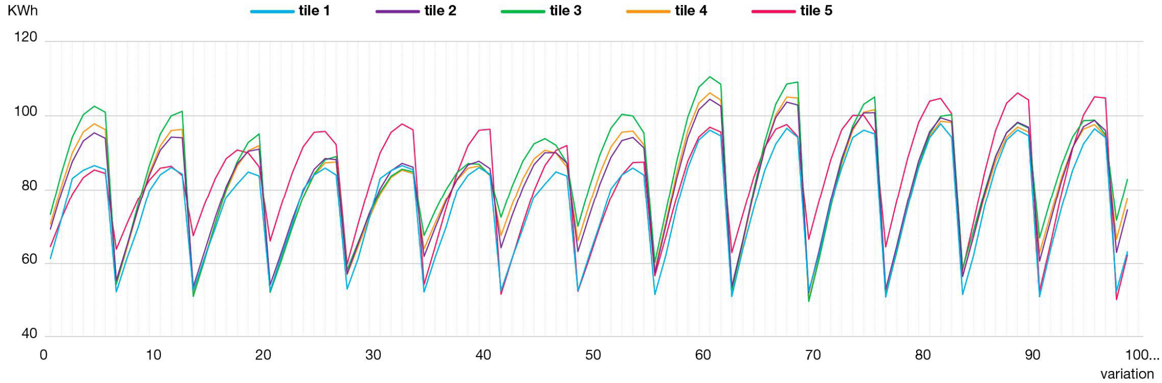

Fig. 5. Visualization of the first 100 variations in knowledge base

## 5. Conclusion

Second phase of the methodology, PBD using expert system tool, has only confirmed improvement range in the knowledge base, meaning possible improvement can be up to 30% for this range of tiles. In the Fig. 6 two paneling layouts are shown. On the left, layout is composed only of flat tiles 1 forming homogenous appearance. After turning automatic mode on, tool immediately suggest significant improvements shown on the right side. In this case layout is composed of three different tiles. This optimized layout setup can be obtained similarly by accepting all suggestions in incremental optimization in the manual mode.

These results clearly demonstrate that methodology is suitable to provide user guidance and optimization efficiently. Furthermore, two step process explained in this paper can be exploited as a general approach to designing buildings with other complex and non-complex BIPV elements where producers and PV engineers can be responsible for the first phase leaving architect freedom and support during their PBD process. Finally, knowing the performances and possible great benefit of BIPV from the very start can help persuading architects to decide on employing these technologies and lead potentially to the acceleration of BIPV implementation in the market.

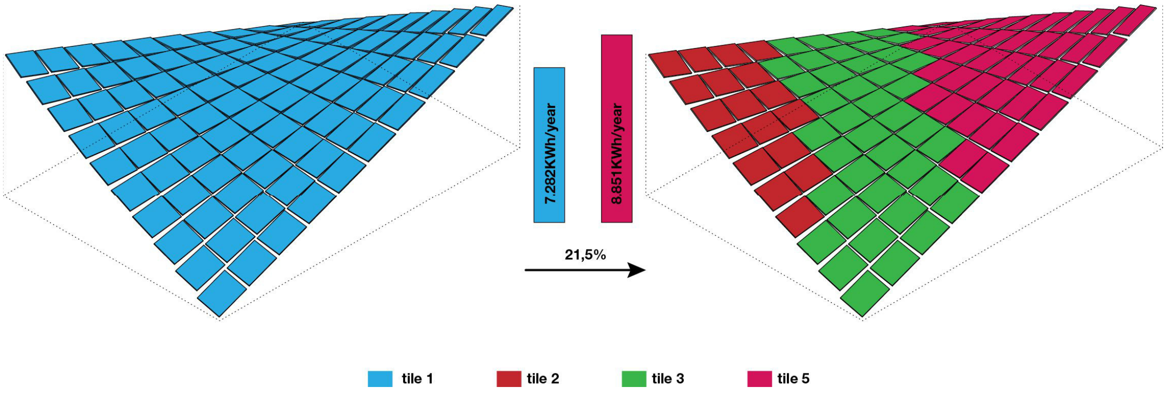

Fig. 6. Evaluation of tool optimizing potential

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