Assessment of Solar and Farming Systems Integration into Tropical Building Facades

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Abstract

Singapore has committed to reducing greenhouse gases emissions as a part of the Paris Agreement. Increasing energy and food self-sufficiency through integration of solar and vertical farming systems into buildings' envelope could play a significant role in achieving Singapore's targeted reductions. This paper focuses on the design optimization of the façade systems that are to be installed at the Tropical Technologies Laboratory at the National University of Singapore. In particular, the paper presents the results related to five performance indicators which include solar energy and farming potential as well as the impact of the façade design on the indoor daylight conditions, shading and thermal performance. The multi-criteria decision analysis (MCDA) method VIKOR was adopted in the evaluation of the created design alternatives. The results from the computational simulations on radiation, daylight, and thermal conditions were used as inputs. Final optimal façade design is selected for four types of facades according to BIPV and farming systems arrangements for north and south orientations.

Keywords: BIPV, vertical farming, façade systems, solar architecture, tropical architecture

1. Introduction

Singapore has a high dependency on energy and food imports in order to cope with the growing domestic demand. Despite the currently favourable political and market conditions in the region, there are arguments, mainly for security reasons, for a gradual increase of locally produced food and energy in the future. Given the high population and urban density of the city-state, a limited land area available for conventional agriculture, as well as a lack of mineral resources, Singapore is seeking both the alternative solutions to reduce the dependency on imports and the means by which to meet the commitments of the United Nations Framework Convention on Climate Change Paris Agreement (United Nations, 2015) in combating the intensity of greenhouse gas (GHG) emissions and preventing them from peaking by 2030. Therefore, the contribution of the urban environment in increasing Singapore's self-sufficiency through the application of Building Integrated Agriculture (BIA) and Building Integrated Photovoltaic (BIPV) systems could play a crucial role in achieving those goals.

More than 90% of power production in Singapore is generated from fossil fuels. As for renewable energy sources, the rooftop integration of PV panels is very limited and does little to increase the share of renewable energy. Façade integration is therefore necessary to achieve a significant increase of solar energy production. Land in Singapore is scarce and expensive and although solar irradiation is much lower on vertical surfaces than on horizontal surfaces (at cca. -48.5% (for east) up to -64.3% (south)) (Khoo et al., 2014) façade integrations may justifiably present a sustainable solution. The design of façade integrations is a complex task requiring careful consideration and good optimization of various parameters such as: the tilt, shading effects, position, visibility from the inside and the outside of the building, accessibility, function, and overall aesthetics. Another factor to consider is that façade integration often relies on custom-made PV panels, hence, the attending costs, although exhibiting a gradual downward trend, still pose an important challenge in the design of façade integrations. Façade surfaces are visually more dominant than the rooftops of high-rise buildings and offer a

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wider range of aesthetically pleasing, high-quality solutions that can in turn serve as a positive influence on the behavior of the people and provide motivation for furthering similar projects.

Urban farming has recently come into attention since it represents a significant step towards reconnecting food producers and consumers. By shortening the food mile, urban farming saves time, reduces costs as well as GHG emission related to food transportation. At the same time, urban farming provides city residents with fresh ingredients, enabling a healthier life style and creating a more pleasant living environment. Urban farming also creates educational and interacting opportunities for city dwellers. Additionally, farming in the city may contribute to rainwater storage thus alleviating urban storm water flooding and run-off.

Several studies have been conducted on the integration of PV panels into building facades in Singapore (Luther and Reindl, 2014; Saber et al., 2014). The application of farming systems on building facades from the construction point of view was reported by Suparwoko and Taufani (2017) but there are no other references on the façade arrangement and the potential yield. The integration of both solar and farming systems on building facades was investigated by Tablada & Chao (2016) and Tablada et al. (2017) at the urban and façade scales respectively.

This paper therefore focuses on the design optimization of the productive solar façade (PSF) systems to be installed at the Tropical Technologies Laboratory (T2 Lab) located at the university campus. The research is based on the hypothesis that the performance of building facades should exceed the traditional functions of indoor–outdoor boundary and climatic regulation by also providing a portion of the energy and food that residential buildings demand. BIPV and vertical farming systems provide dual benefits: on one hand, they help produce electricity and food, and on the other, act as a passive device for solar gains reduction and the improvement of both visual and thermal comfort indoors.

The development of a PSF prototype involving both BIPV and BIA systems should employ a holistic iterative process that includes conflicting quantitative and qualitative parameters. The aim of the said process is to arrive at an optimal solution – a solution that meets and balances specific architectural and techno-economic requirements but also allows for different constraints that elements such as safety, accessibility and others may additionally impose. For the purposes of this study, the VIKOR method is employed (Opricović and Tzeng, 2004; Opricović and Tzeng, 2007). It is a multi-criteria compromise method that enables comparisons and assessment of otherwise incommensurable or conflicting criteria while offering relatively easy modelling and flexibility according to the preferences of the decision-maker (Kosorić et al., 2011; Krstić at al., 2012), especially if the decision maker has a complex structure and/or insufficiently clear preference in the optimisation process. MCDA VIKOR method used in this paper will therefore help provide a comprehensive evaluation and selection of the optimal design alternatives. Grasshopper parametric simulation tool (McNeel, 2010) is used together with necessary plug-ins to calculate several environmental performance criteria for the analysed cases on north and south façade orientations.

2. Method

2.1. Optimization method framework

Figure 1 presents the overall MCDA framework followed in this study. The first step is to define the potential façade components for the BIPV, vertical farming and the fenestration or voids. A series of preliminary simulations and technology selection is carried out for each system based on the available reference literature and discussions with local experts for both BIPV and BIA. Thereafter, the design strategy and decision goals are identified considering the potential PSF installation in residential buildings.

Quantitative and qualitative assessment criteria are also defined as well as the weights for each criterion. The impact of the façade design on sunlight availability for the BIPV and farming systems, as well as on indoor daylight conditions, shading and thermal performance are also taken into account by conducting computational simulations using Grasshopper's plug-ins.

While always accounting for the coherence with the overall building logic, mainly geometrical, functional and aesthetical characteristics of residential buildings, the design alternatives are then generated for two types of facades: (1) facade wall and (2) facade with balcony. Both façade systems are analyzed separately for four orientations: north, south, east and west. This paper presents the results for north and south oriented façade walls. The façade design alternatives were developed according to the T2 Lab dimensions and layout. As shown in figure 2, eight test bed cells are located inside a 60 m2 building and are also used for other investigations of tropical technologies.

Optimal design alternatives are selected by means of the VIKOR (MCDA) method i.e the method was used to evaluate the PV integration design variants, rank determined alternatives, and then select a compromise solution Q from a set of m alternatives: A1, A2... Am, while those alternatives were evaluated on the basis of a set of n criteria functions. The alternative with the lowest Q value represents the compromise solution. This means that the said solution achieves a compromise between 2 decision making strategies: maximum group benefit defined by the value Sj (a better alternative is considered good according to the majority of criteria), and minimum of maximum deviation of ideal values defined by the value Rj (a better alternative must not be very bad according to any criteria). Vikor method also verifies “acceptable advantage” and “acceptable stability” of variant ‘optimality’ (Opricović and Tzeng, 2004). The details of the VIKOR method applied in this study can be found in Tablada et al. (2017).

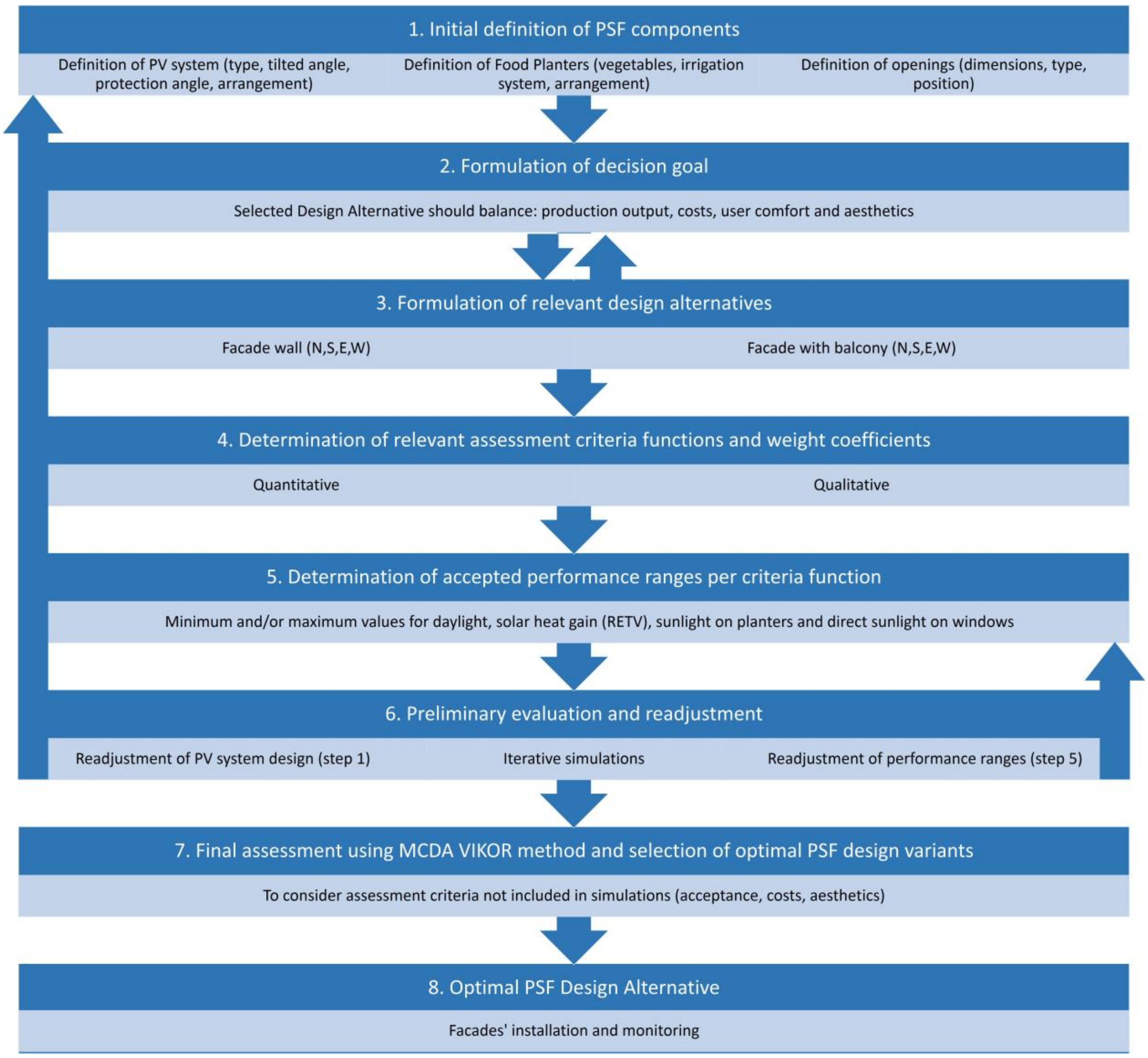

Fig. 1: Overall methodology for the development and optimization of the Productive Solar Façade (PSF) systems.

2.2. Model and simulation setup

Figure 3 presents four façade arrangements for façade wall and façade with balcony types. The façade arrangements are the following: façade with a single PV panels attached on top of the façade (I-F), façade with two PV panels attached to the top of the façade (II-F), façade with a single PV panel attached to the planter of the level above (I-P) and façade with two PV panels attached to the planter of the level above.

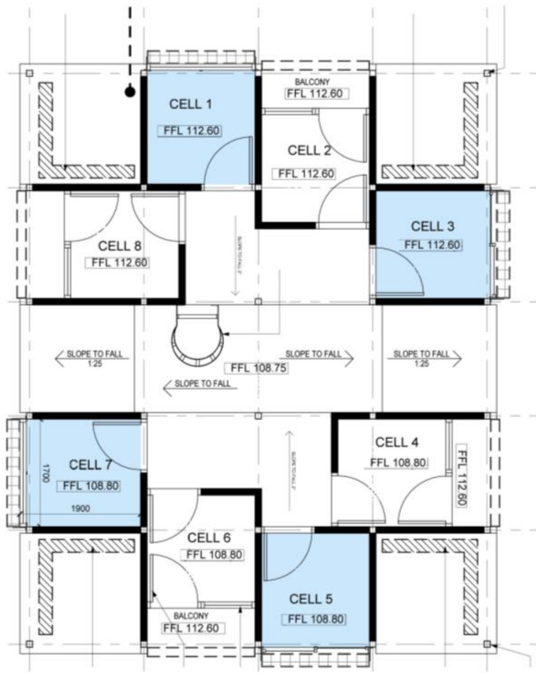

Fig. 2: Floor plan of the Tropical Technologies Laboratory (T2 Lab). Highlighted the cells analysed in this study. Adapted from: AWP Architects based on author's preliminary design.

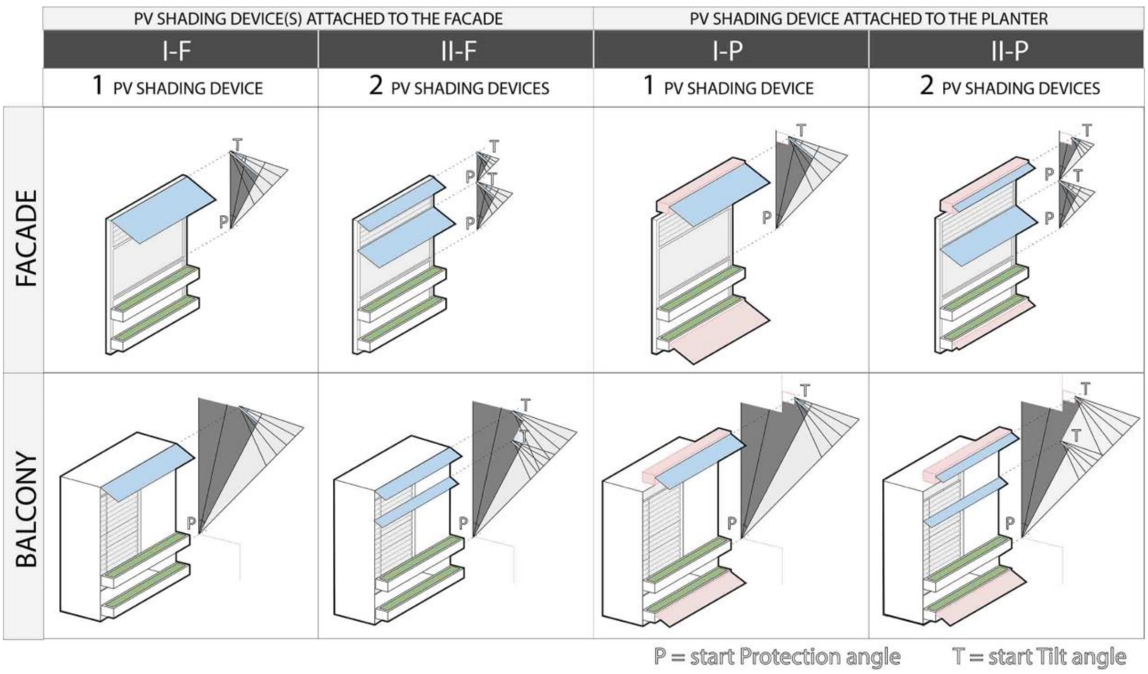

Fig. 3: Types of PV configurations and corresponding start of the protection and tilt angle.

A modular façade is used in order to obtain a high-quality sustainable solution: a cost-effective, time-efficient, and flexible multifunctional façade. Considering the restrictions of the building site - the typical floor to floor height of a Housing Development Board (HDB) flat of 2.8m, the module will be 2.8 m in height (2.6 m ceiling height) and 1.8 m in width. According to the Approve Document by the Building and Construction Authority (BCA) (BCA, 2017), the height of a barrier should not be less than 1.0m in order to protect people from falling from height. However, in order to have more design alternatives (e.g., to provide more space for planters installed at the lower part of the module), a window sill height of 1.1m is considered in this study which will allow accommodating planters at the height of 100mm, 300mm, 500mm, 700mm and 900mm, in two or three rows, with a minimum height difference of 400mm between planters. A trapezoid cross-sectional planter will be used in the case of multiple-row planters, making it possible to provide more sunlight for lower level plants, while allowing more growing space for plants below. The size of the planter is set to be 190mm high and 150mm wide.

Optimizing the design of BIPV as shading devices on different façade orientations requires a careful definition of the objectives of the façade elements. The shading BIPV elements should be able to maximise the electricity generation and solar irradiance protection while allowing required illuminance levels in the interior, view towards the exterior and a minimum required amount of sunlight on the planters and BIPV on the same and lower stories respectively. The most influential geometrical parameter in achieving an optimal design alternative is the protection angle which together with the tilt angle defines the width of the BIPV shading element. The protection angle is defined as the angle between the vertical plane of the façade and the outside end of the BIPV shading element. The angle is taken from the bottom of the window for single shading and also on top of the lower shading for the cases with double BIPV shading as shown in figure 3. The protection angle should be understood as a response to the incidence angle; the angle of the sun to a specific target at a moment in time.

This study takes into account the minimum protection angle required by the Building Code Authorities of Singapore (BCA, 2008), through the Residential Envelope Transmittance Value (RETV) calculations. Additionally, for extreme incidence hours a minimum threshold of direct sunlight hours was set to before 8:30 and after 16:30. Lastly the minimum for the range of the protection angles was set so that no substantial impact on the operative temperature would be gained above a temperature of 28°C. Through this optimization the ideal intersection of protection and tilt angle of the shading device was arrived at. For the north and south orientation, protection angles from 28° to 37° met the specified requirements. For south the specific angle of 28° is only sufficient to comply with RETV requirements in combination with a tilt angle of 50°.

2.3. Farming considerations

A selection of leafy vegetables and herbs was deemed suitable for cultivation on building façades since the whole final produce is edible and usually shallow-rooted which makes it space-efficient. Additionally, leafy vegetables and herbs are less prone and less vulnerable to the attack of pests than fruited vegetables.

There are several factors affecting the growth of vegetables, including light, temperature, water and cultural practices. Among them, light is the key factor as it drives photosynthesis and affects plant development, morphology and yield (Inada and Yabumoto, 1989). With regards to the building façade farming, the demand for light is the most crucial factor to be considered due to the inconsistent light condition of building façades. Among the most common locally grown leafy vegetables, shade-tolerant crops with a lower daylight demand like Leaf Lettuce (Lacttuca Sativa) and Kangkong (Ipomea Aquatica), should ideally be grown on building facades. Also, most species of herbs like sage and basil are also quite suitable for the building façade cultivation.

Daily light integral (DLI), expressed in mol/m²· day, is defined as the total number of photo-synthetically active photons that plants receive in 1 sqm of growing space in one day. DLI reflects the combined result of the light intensity and duration of the photoperiod. Compared to other measuring methods, DLI is more accurate in determining the exact lighting condition for plants and is therefore commonly used in the agricultural industry. Commercial farms aim to keep minimum DLI of 10-12 mol/m²· day for optimum growth of plant (Morgan, 2016). A DLI of 12-13 mol/m²· day or higher is generally required for lettuce production (Dorais, 2003). The optimal DLI for production of sweet basil is about 28.8 mol/m²· day (Beaman, Gladon, & Schrader, 2009). Although leaf lettuce normally needs 12-13 mol/m²· day or more to achieve maximum production, it can still be grown with as little as 4-10 DLI. However, its quality is usually low below 8 mol/m²· day (Schiller, 2017)(Glenn, Cardran, & Thompson, 1984). Hence, 8 mol/m²· day is set as the minimum DLI requirement for lettuce growth. Converting the DLI to illuminance levels, this is equivalent to 10 000 lux.

2.4. Simulation settings

Combining the 3d-modeling software Rhinoceros with the programming software Grasshopper supports the parametric design generation. Utilizing these combined instruments the results of over 1.000 plausible cases can be approximated precisely, without requiring intermittent manual interference. The plug-ins Ladybug and Honeybee (Roudsari & Pak, 2013; Grasshopper3d.com, 2017) utilize the flexibility of Grasshopper to read local weather data, add detailed design information and run these through validated software such as Daysim (Reinhart and Walkenhorst, 2001) (Lagios et al., 2010), Radiance (Ward and Shakespeare, 1998) and Energyplus (Crawley et al., 2011) (Jakubiec & Reinhart, 2011), In return these results can be read, disseminated, organized and visualized by Ladybug and Honeybee in Grasshopper.

Since PSF has multiple quantifiable performance indicators, a multi-objective optimization process was chosen supported by VIKOR. This method chooses the optimal result by balancing 5 conflicting performance indicators: daylight autonomy (DA), energy flow, electricity potential of the PV shading device(s), farming potential and view angle. A fitness value indicating the performance of each case on each indicator is established by comparing their results with the highest (100%) and lowest value (0%) returned by all cases. Strict requirements were predefined for each performance indicator according to literature and local regulations. This ensured overall quality of all cases within the VIKOR optimization process and reduced the total amount of cases by around 90%.

DA is defined as the percentage of time during the year in which a certain pre-defined illuminance value (200 lux) is achieved from 8 AM till 5 PM. Since the size of the testbed cell is reduced in comparison to actual room dimensions in residential buildings, an equivalent DA was used instead of the actual values obtained in the simulations. The energy flow is defined as the interior net heat gain (heat gain minus heat loss, kWh). Electricity potential is defined as the potential electricity generation from the PV panel taking the lowest incident radiation on the PV multiplied with the total area of the shading device, as the PV cells are connected in series. At this stage no definition was made regarding the type of PV and also other performance coefficients affecting electricity generation were not considered. Farming potential is defined as the percentage of days per year where planter area receives DLI > 8 $mol/m^2 \cdot$ day. View angle is defined as the average view angle from two points inside the testbed cells towards the exterior. The two points are located at 1.5m from the façade at 1.17m and 1.56m height from the floor, which correspond to sitting and standing viewing height for an overall height of 1.68m. The obstruction effect from the planters and the PV panels are taken into account. A minimum of 20° was set as required for all cases.

3. Results

This section summarises the results obtained for the north and south oriented Façade Wall. Figure 4 presents the preliminary design of the optimal cases for four types of façade arrangements: I-P, I-F, II-P and II-F (see figure 3 for nomenclature). For the 4 façade types the optimal position of the planters is at 100mm and 700mm from the floor level. This assure the best sunlight access to both planters disregarding the dimensions and positions of the PV panels. The optimal position of the planters for the 4 façade types stands at 100mm and 700mm from the floor level respectively. This ensures the best access of sunlight to both planters disregarding the PV panel dimensions and position. The optimal solution for north and south orientation is the same - a single PV attached to the planter above with a protection angle of 28° and a tilt angle of 50°. Higher position of the PV panel with respect to the upper window allows higher value of Daylight Autonomy (DA), however, in order to achieve the required solar protection according to the RETV, the tilt angle should be larger than the recommended 30° from the horizontal position (Luther and Reindl, 2014) (Saber et al., 2014) for Singapore facades. The second and third best cases for south and north oriented façades respectively are those with a single PV attached to the top of the façade. Double PV configurations are not favourable for any of the two façade orientations, especially for the north façade. The small dimension of the upper PV panel results of in the need to avoid overshadowing on the panel underneath. However, such small dimension may not be feasible and cost-effective.

Figure 5 presents the results of five performance indicators for each optimal case of the four façade arrangement types. The left-side axis displays actual values of each performance indicator while the right-side axis presents fitness values relative to the best and worst cases per façade type. The fitness value (Fv) is defined as:

$$Fv = (PI - Min) * (100 / (Max - Min) \qquad \text{(eq. 1)}$$

Where PI is the obtained value per performance indicator, Min and Max are the minimum (worst) and maximum (best) values on the list of cases per façade arrangement type.

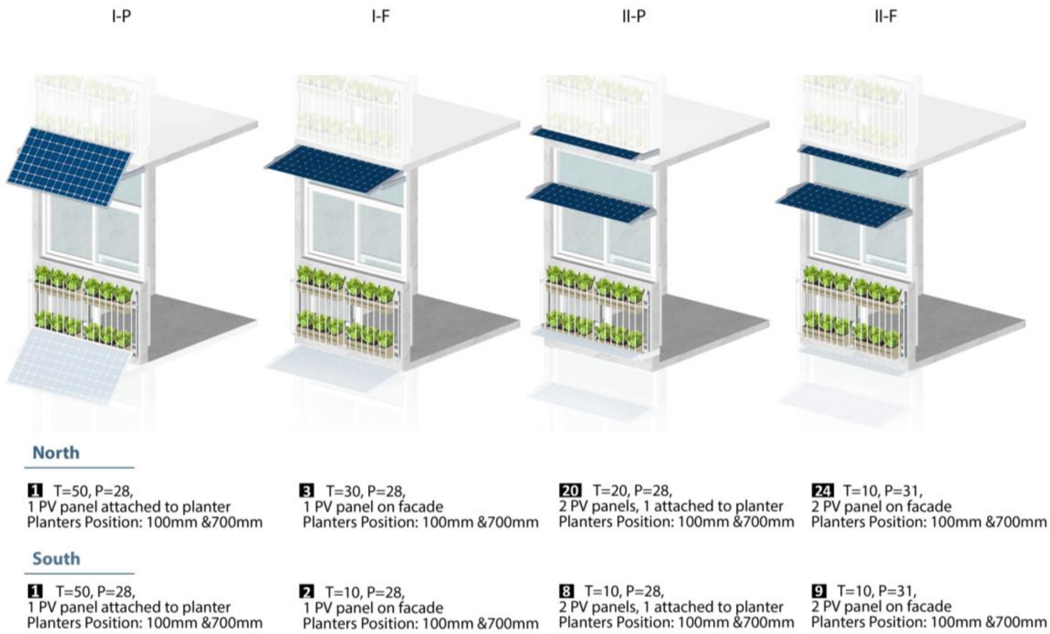

Fig. 4: Best cases per type, with overall rank and specifications for north and south orientations.

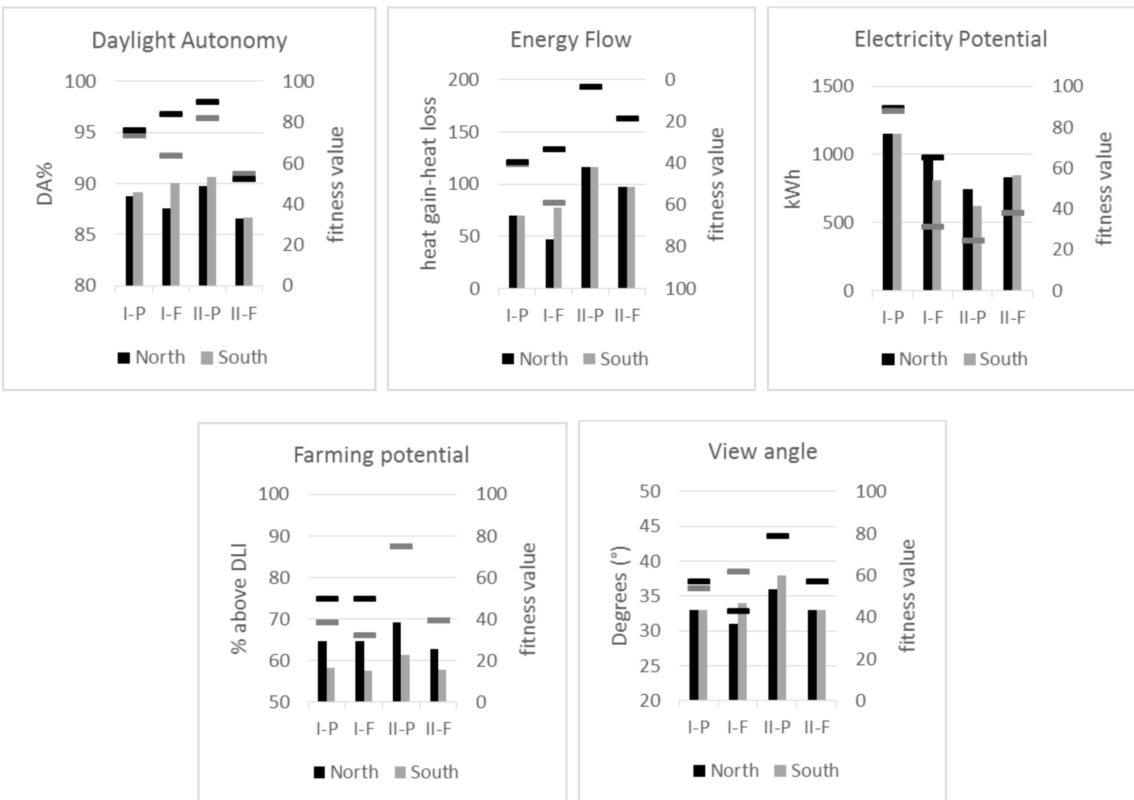

Fig. 5: Performance indicators for four façade types on north and south orientations. Bars correspond to left-axis values and lines represent fitness value.

Regarding DA, all cases achieve values above 85% representing the time period in a year with the average illuminance levels above the threshold of 200 lux. The performance in two cases when PVs are attached to planters above (I-P and II-P) is better (fitness value > 75%) than in the two cases where PVs are attached to the highest point of the façade. Larger separation of PVs from the upper window allows higher penetration of diffuse daylight. South façade arrangements receive higher illuminance levels than north façade arrangements.

With regards to the energy flow indicator, the lower the value of the net heat gain from the exterior, the better its performance and fitness value. Also, in terms of this indicator, the number of PV panels has a higher impact than their position on the façade. A single panel will provide better protection from solar radiation than two panels. Sunlight inter-reflection between the two panels and the reflection of the lower panel towards the interior may be the reason for the higher heat gain. Only in cases when a single PV is attached to the façade, substantial differences on energy flow exist in relation to the facade orientation.

As for electricity potential, once again, a single PV panel will perform better than two panels. If two PV panels are utilized, then the top device, although small, shades the bottom one during the hours in which the incidence angle is smaller than the protection angle. Since PV cells are connected in series, the shaded cell will define the overall electricity production by lowering it. The differences are more evident between the cases I-P and II-P with fitness values around 90% and 25% respectively. The electricity potential on the north façade is overall higher, most likely due to frequently clear skies from March to September equinoxes. If we consider a conventional 13% efficiency Si-monocrystalline PV module the estimate of electricity generation of the optimal cases of north I-P, I-F, II-P and II-P are 150 kWh, 130 kWh, 97 kWh and 108 kWh respectively which represent 48%, 48%, 33% and 34% of the same PV module type and area located on a rooftop without obstruction.

The four façade types exhibit smaller differences regarding the farming potential. In all cases the percentage above the required DLI is not higher than 70%. However, DLI values are substantially higher for the north than the south façade orientation. For the latter, the fitness values are around 40% or below except in the II-P case. The last performance indicator considered at this stage of the study is the view angle from the interior. Facades with PV panels attached on the planters above provide higher view angles, which is well within expectations considering the higher position of the panels with respect to the upper window.

Figures 6 presents fitness value for all façade types facing north and south respectively. The average fitness value of the optimal case I-P is 62.0% and 59.1% for north and south orientations respectively. The average fitness values for the second best façade type are 56.0% and 48.5% for north and south orientation respectively. Figure 7 presents the fitness values of the two best and worst cases for north façade orientation.

At this stage, the strategy to determine the best among facade types presupposes that all criteria used are of equal importance. Consequently, since the selection of the optimal solution strongly depends on the criteria weight coefficients, all five criteria used were allocated the same weight of 0.2. However, different weights may be applied for east and west façade orientations given the larger exposure of glass windows to direct solar radiation. For these orientations, the weight of criteria functions with larger value variation –for example, those related to the energy flow- will be proportionally higher than the weights of criteria functions with smaller variation.

4. Conclusions

This paper describes the design optimization of SPF facades with the integration of PV and farming systems and analyses the performance of four façade types for north and south orientations. The facades systems are to be installed at the Tropical Technologies Laboratory at the National University of Singapore. The impact of the façade design on five performance indicators - daylight autonomy, energy flow, PV electricity potential, farming potential and view angle - are obtained from computational simulations and subsequently used as inputs in the MCDA method VIKOR.

The above results reflect the values relative to facade types deemed to be the best, and are not representative of all instances. However, a comparison with the fitness values of other cases of the same type has served as a confirmation of trends. With these practical considerations in mind, the following conclusions can be made:

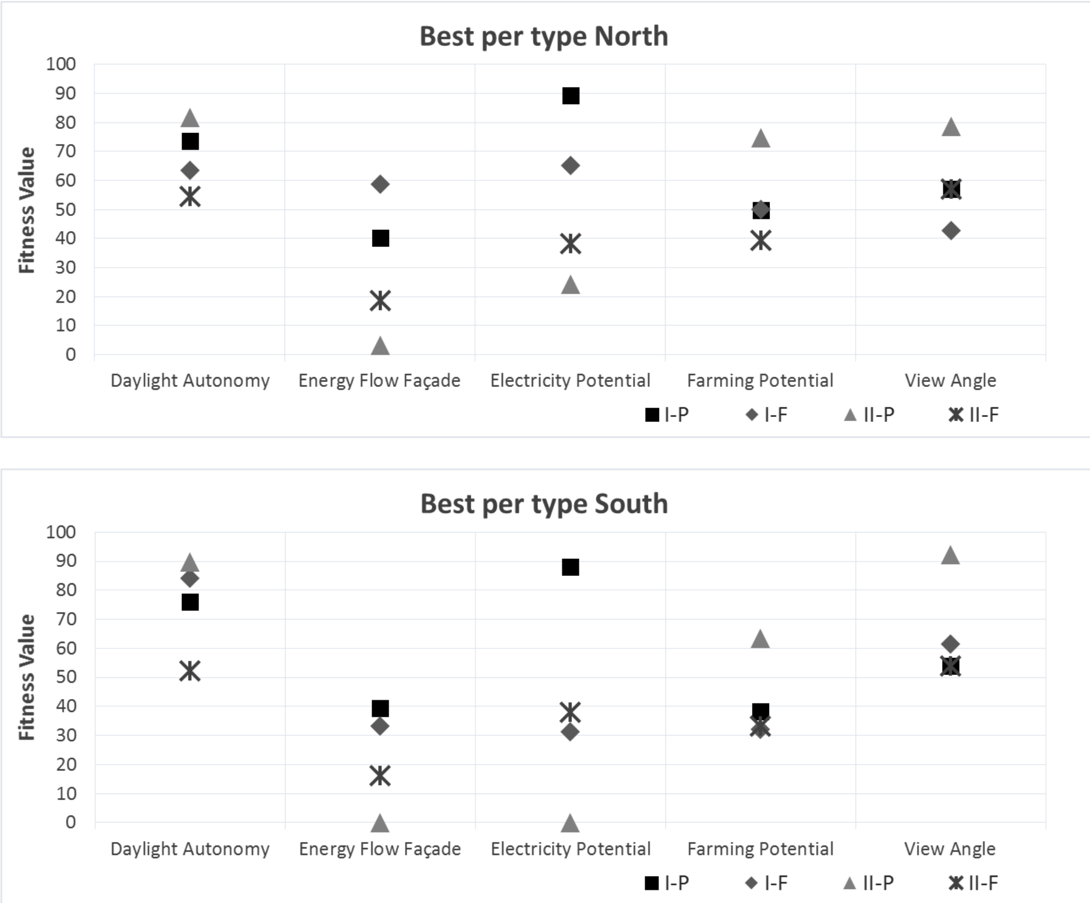

Fig. 6: Performance indicators of the optimal facade designs for north (top) and south (bottom) orientations

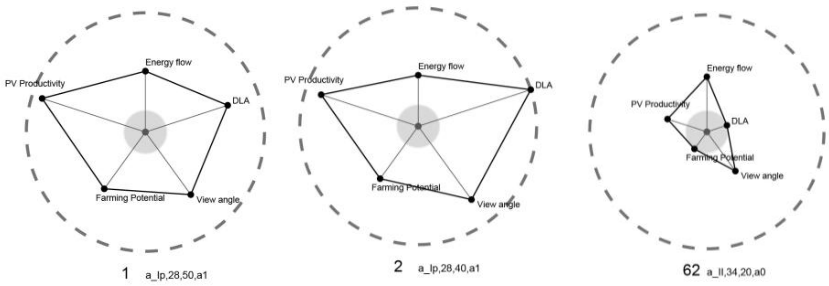

Fig. 7: The two best and worst cases for north, small (0%) to large (100%) circle represents fitness value.

- The optimal position for BIPV shading device is next to the planters at the above level. This position maximizes solar energy yield while also achieving a high fitness value for other four performance indicators related to food production and indoor visual and thermal conditions. The result indicates that even with no farming system installed, the best compromise between solar energy yield and indoor conditions is achieved by using the lower portion of the façade of the level above for the installation of larger sun-exposed PV panels.
- For north and south façade orientation, systems with two rows of PV panels will produce less electricity than the system with one row of PV panels. With two PV shading devices, the topmost device shades the bottom one during the hours in which the incidence angle from the vertical plane is smaller than the protection angle. It should be noted this occurs around midday when the incident solar radiation is at its highest.

- Overall, north facades achieve slightly higher fitness value than south facades. Farming potential on north facades is higher than on south facades as the planter area receives the required Daily Light Integral for longer periods of time during the year. Similar trend is observed for the electricity yield potential although not for all cases.

The results of the study prove the importance of using a holistic approach and a multiple objectives criteria analysis in the design of such complex façade systems, especially for BIPV and BIA systems which compete for receiving the maximum sunlight. The VIKOR optimization method helped obtain a solution according to a tight set of requirements. It also created a framework that enabled iterative strategic learning based on reciprocity and the understanding of project strengths and weaknesses. The impact of the façade systems on indoor visual and thermal conditions in residential buildings are also crucial and are not to be ignored or underestimated. Otherwise, the benefits of the electricity and vegetable production are minimised or reversed.

The study will continue with further analysis aimed at finding the optimal façade design alternatives for east and west orientation. In addition, the same optimisation process will be applied for the façades with balcony that already have solar protection to a certain degree. Different BIPV configurations and dimension are expected for those façade types and orientations. In this first part, the design process of SPF was focused and based mainly on quantitative parameters, resulting in optimal solutions with balanced technical performance. The subsequent steps will include costs and qualitative criteria, which will ensure sophisticated sustainable high-quality solution in terms of both techno-economic performance and architectural value.

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