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Single-step vs sequential optimization of Building-integrated Photovoltaics (BIPV) façade allocation

Summary

Façade allocation of Building-integrated Photovoltaics (BIPV) is a dual function solution for integrating PVs as both energy providers as well as building envelope component. Facades are, however, complex systems that simultaneously influence both the energy demand, as well as the daylight comfort & glare aspects of a building. Allocating BIPVs in a suitable manner renders the problem into a complex optimization with multiple objectives, thus requiring detailed design inputs, typically unavailable at the start of the design process. On the counter, optimization at a late stage reduces the PV allocation potential. The aim of this paper is to investigate a sequential, stepwise optimization process, such that the BIPV allocation process can match the building design process, with reduced complexity & computation time. The outcome of this work aims to inform on the impact of defining different baselines and transfer of optima through the steps, to preserve the maximum number of Global optima, as generated in a full optimization process. This will be repeated for two different climates (Oslo and Madrid). Initial test runs with conservative baselines preserved around 35% of optima.

Keywords: BIPV, Façade, Optimization, Energy-efficiency, Daylight

Field of application for the findings: Energy Efficient Buildings

Addressed audience: Architects, solar consultants, building energy consultants, academics

1. Introduction

In high performance buildings, integrated design processes are essential to ensure balanced design decisions can be taken such that a variety of design-performance criteria are met. This also means dealing with inter-dependent variables that can be highly constrained and compete against each other to maximize their goals at the cost of others. For high-performance buildings, there are two ways of lowering the net energy demand – the first is to design it to be ultra-efficient, and the other is by offsetting some or all the energy need by local energy generation – also termed a net Zero Energy building. While the former seems straight-forward, it can often be quite expensive and also challenging in some scenarios. The latter has however gained more popularity and brings the solar PVs into the picture; the economic benefits during the use phase are advantageous also justifying increased initial investments. As tools for solar applications and building designs improve, integrated design for solar PVs or BIPVs makes logical sense. The possibility of combining two functions – building envelope and energy generation into the same building element benefits both in terms of material and energy cost reductions, as well as emissions - both relevant ambitions in current High-performance buildings. In this paper, the aim is to evaluate a stepwise optimization approach in place of a complex multi-objective optimization problem solving for the just allocation of windows, shading devices and opaque PV on a south façade, for a representative case in Madrid and Oslo. The two chosen locations represent two extreme latitudes of different solar conditions across major European cities and help in validating the process in different scenarios. The results reflect on defining appropriate baselines and the transfer of Optima across the steps.

2. Background

Façade are responsible for both the climate protection of the building indoors, and for sufficient daylight and outward views. The competing parameters – PV area and the window area benefit from maximizing to have higher solar incident radiation, while the façade area is better insulated and favours lower energy demand with reduced energy losses through fenestrations. These are, thus, elements with competing goals, to be allocated within the same area, with trade-offs of maximizing one, affecting the other. This makes the façade design process a multi-objective optimization problem, where the conflicting performance objectives generate not one single solution, but often a range of optimal solutions, spread along a pareto front. These solutions offer the best trade-offs between the competing objectives, where change in one parameter makes the other worse.

Multi-objective optimization of building facades using various tools is quite common proving its relevance. A recent review study could find around 50 search results, even for such a specific topic, after removing duplicates and screening across various databases (Shan and Junghans, 2023). There has also been a higher output in the last decade, with developments in optimization tools, especially Genetic Algorithms. The paper also documents the increase in façade optimization studies looking into thermal-visual comforts since 2012, whereas the energy alongwith economic concerns have always been a popular theme for MOO searches. In addition, Offices typology is a popular study case with well documented standards, energy use documentation, daylight studies, found in many case-studies as well as prior façade studies (Goia, 2016; Goia et al., 2013; Taveres-Cachat et al., 2019).

Multi-objective optimizations, inspite of their advantages for solving complex problems, require detailed inputs of all the variables to extract useful outcomes. They also tend to be computationally resource- & time-intensive. In addition, the design & development of projects regarding developing facades remains a stepwise process with thumb rules and simple assumptions informing initial decisions. More detailed components and material information which is generally available at a later stage is of limited benefit for PV allocation, as the scope to benefit from optimization is reduced. A better approach is to develop a stepwise optimization where the variables can be optimized in steps, passing on the optima in steps while keeping other variables fixed. It also has a higher potential of being replicated in the stepwise development stages in real world architectural projects. While there exist some well developed research, the focus has been primarily with whole building optimizations as done for different building form and systems design stages (Gagnon et al., 2019; Talami et al., 2021, 2020). A focused approach specific to facades only is being explored in this paper, adding novelty to this research.

3. Methodology

In this paper, the aim is to break down the complex, high order optimizations into a simpler, sequential approach, where stepwise optimizations with limited variables are deployed while aiming to achieve values similar to from the Global optima. Such a process should be easier to deploy, enabling higher chances of a fair allocation of BIPV elements in a typical façade design process. Without having to go for a full optimization, this would still retain a good number of Global optima values. A single office BESTEST case scenario - 8x6x2.7m (Fig.1)is selected with the South façade exposed to full outdoor conditions where the windows, shading elements and the BIPV allocation occurs (Ron Judkoff and Joel Neymark, 1995). The primary concerns being investigated here are Energy demand (minimize), Daylight Autonomy (meet threshold and maximize), Glare (meet comfort criteria and minimize) and PV production (maximize). Energy demand and PV production are combined to keep it a 3-objective problem. As a starting point, full factorial search is chosen as the method to explore all possible combinations over other optimization algorithms or genetic algorithm. Such algorithms, although quite popular, can be computationally extensive requiring careful adjustment of grouping and selection, and are also prone to getting trapped in local maxima/minima as well as producing different results in different runs (Talami et al., 2020). Full spectral search benefits from extracting a pareto front from the total possible outcomes conceivable from the chosen combination of variables such that the stepwise assessments are easier to conduct from an extensive set of inputs-outputs data.

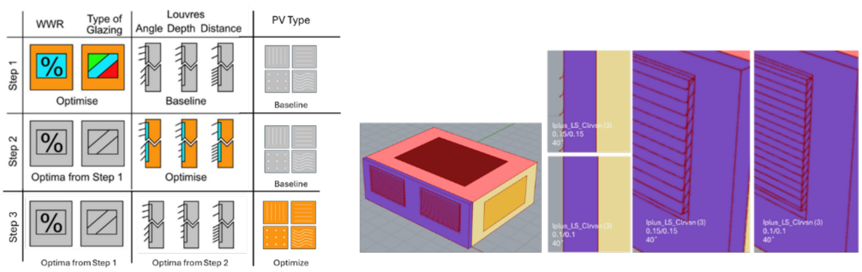

Fig.1 (L-R) 1. Steps of Optimization 2. The BESTEST case building model 3. Detailing of window, louvre and PV modelling

To test this out, a full factorial search is carried out with 6 design variables – WWR, Window Technologies, PV types and shading element designs: louvre depth-distance-angles. This leads to an optimization routine of 2880 design variable combinations in the search for global optima. For the global optima, the parameters collected are – Heating energy intensity, Cooling energy intensity, Lighting Energy intensity, PV production intensity, Net delivered energy intensity, Daylight Autonomy-DA (500, 50%), Glare autonomy-GA (0.45,95%) and UDI>3000Lux, both the average of the sensor grid, as well as the maximum value at any single grid point. A combination of these values will helps determine the final objective, mainly between the net delivered energy intensity (taking into account the energy contributions from the PV generation), the DA and the UDI>3000, whereby basic goals of the DA and GA are being met, such that the optima points meet the expected daylight and glare-risk thresholds.

In the stepwise optimization, at each design step, one or a grouped combination of variables will be iterated, while the remaining variables are constrained at a baseline value (Fig.1 (1.). The optima attained from the previous step will define the design variable to be iterated against in the subsequent steps. The challenge here is therefore to define good baselines and approaches to transfer optima, that will help retain as many Global optima outputs as possible. The study is performed in two locations – Madrid and Oslo, that represent two extents of solar availability, climate and extremes of the range of weather conditions across Europe that help evaluate the validity of this approach in varying conditions.

4. Results

The data is in the process of being analyzed but as a preliminary run, a sequential study for Madrid was conducted with 'middle values', one of the lower baselines. As presented in Fig.2, a stepwise process through the 1st step generated two optima for the WWR and Window technology that were fixed. In the 2nd step, 13 optima were generated, of which the window shade arrangements were of 9 unique combinations. Combinations carried over were 12 due to selection of a range in continuous variables. The 3rd & final step generated a total of 7 optima, of which 5 matched the global optima (14) from the full run, generating a ~36% recovery rate even for a lower baseline. This was also at considerable savings for computation and resource, from just ((16+400)x2) 832 runs (29%) instead of 2880 in the full spectral search. More importantly, the possibility of retrieving some of the original optima is promising, which indicates that a stepwise optimization, matching typical stages in building element allocation and level of information, does not necessarily lead to a loss of the possibility to attain such optima. Similar analysis is being conducted with various baselines as starting points, and transfer of Optima approaches to find relative percentages of retrieving optima compared to full optimization. Different sequences of steps will also be explored. It will be repeated both for Madrid and Oslo to test robustness and consistency.

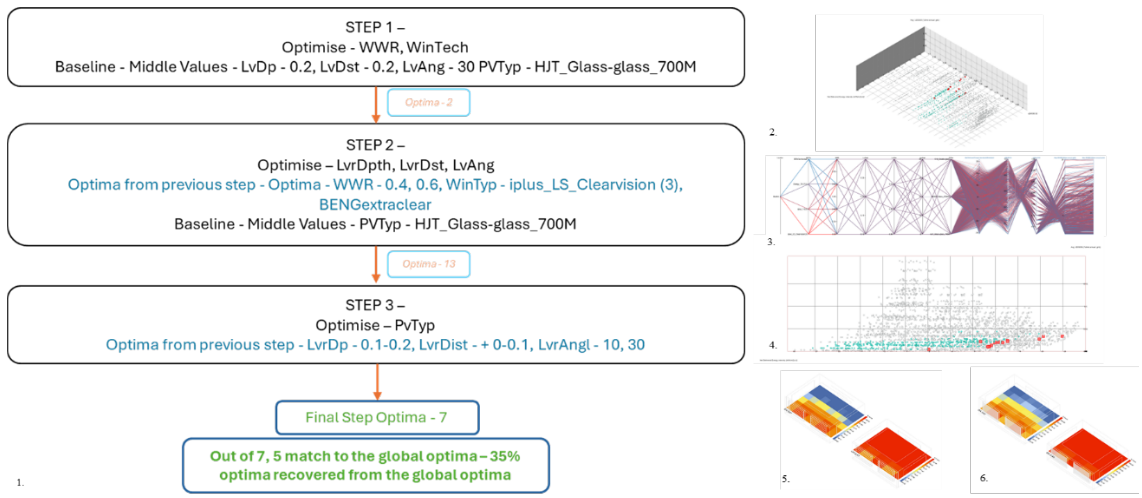

Fig.2 (LeftTop-RightBottom) 1. Stepwise optimization for 'Middle Values' 2. 3d pareto front for the full spectral search for the Net Delivered Energy vs DA vs UDI>3000 3. Design Explorer visualization of the full spectral search 4. Pareto Front (red) out of the qualifying outputs (cyan) of the full spectral search (gray) in UDI>3000 vs Net Delivered Energy 5-6. DA and GA visualization of two pareto combinations that emerged in the stepwise optimization

5. Bibliography

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