An integrated optimization design framework for BIPV applications in office buildings

Summary

Office buildings are significant contributors to urban energy use and carbon emissions due to their intensity of consumption. BIPV offers a promising solution by enabling on-site renewable energy generation and enhancing building energy performance through design integration. However, BIPV system optimization is challenging due to trade-offs among energy consumption, system energy output, indoor comfort, cost, and aesthetics. Current tools lack comprehensive integration with building performance simulations, limiting both design flexibility and prediction accuracy. To address this, the study proposes a multi-objective optimization framework for BIPV within a parametric BIM environment, balancing energy, thermal, economic, and comfort-related goals to support efficient, data-driven deployment in urban contexts.

Keywords: BIPV, Optimization design

1. Introduction

Office buildings are major contributors to Australia's energy consumption and carbon emissions. Building-integrated photovoltaics (BIPV) offer a promising solution by enabling on-site renewable energy generation through the utilization of extensive building surfaces in urban areas. This technology supports local energy production and consumption, reduces reliance on new infrastructure, and minimizes transmission losses and related grid impacts.

Although BIPV systems offer significant environmental benefits, their adoption is hindered by high design complexity and uncertain economic returns. Existing PV design and simulation tools often lack integration, automation, and the ability to efficiently explore diverse alternatives. With advances in parametric design, BIPV workflows are shifting from manual modeling and isolated assessments to integrated, visual, and data-driven processes. Platforms such as Rhino/Grasshopper enable rapid generation of multiple BIPV layouts based on building geometry, while integration with simulation tools like Ladybug and Honeybee allows real-time evaluation of solar radiation, shading, and thermal loads (de Sousa et al, 2020). Key design parameters, including module layout, tilt, and orientation, can be dynamically adjusted to optimize system performance. To address the conflicting objectives of energy output, daylight quality, energy demand, and cost, multi-objective optimization (MOO) algorithms such as NSGA-II and MOEA/D have been adopted, systematically exploring the design space and generating Pareto-optimal solutions (Zhao and Guo, 2025). These capabilities support coordinated optimization across performance dimensions, bridging the gap between architectural design and system performance evaluation.

In recent years, the design optimization of BIPV envelope structures has emerged as a research hotspot, leading to significant advances in the understanding of BIPV system integration. However, existing studies still exhibit notable limitations. Many focus on a single objective, such as maximizing solar irradiance, electrical output, thermal performance, or cost-effectiveness, without systematically addressing the trade-offs among these often-conflicting performance indicators. Furthermore, MOO studies typically rely on simplified case studies, such as a single room in high-rise office building, and often overlook the shading impact of surrounding buildings in complex urban contexts, which may compromise the practical feasibility of the proposed solutions.

In addition, current BIPV design workflows remain constrained by low integration, fragmented performance analyses, and a lack of intelligent decision support. While Rhino/Grasshopper is widely adopted for early-stage BIPV form-finding due to its parametric flexibility and generative modeling capabilities, it presents several limitations in comprehensive system modeling and performance analysis. Specifically, it lacks dedicated plug-ins for physical modeling of PV modules, electrical configurations, and system-level simulations, including temperature effects, photoelectric conversion and inverter matching (Yang et al, 2024). Although Ladybug plug-in enables solar irradiance analysis via Radiance, its output must be post-processed to estimate energy generation, increasing complexity and reducing accuracy (Walker, 2019). Moreover, the absence of a standardized PV product database within the Rhino/Grasshopper environment limits component selection reliability and increases user dependency on manual inputs. The platform also lacks mature modules for economic evaluation, making it difficult to assess key financial indicators such as payback period and levelized cost of electricity (LCOE).

To address these challenges, this study proposes a comprehensive multi-objective optimization framework for BIPV system design within a parametric Rhino/Grasshopper environment. The framework enables rapid deployment of BIPV systems tailored to specific building requirements, while integrating electrical performance simulation, economic analysis, building energy efficiency assessment, and indoor comfort evaluation. This approach supports rapid comparison of design alternatives and facilitates informed decision-making, ultimately promoting effective BIPV deployment in urban settings and providing strategic guidance for stakeholders.

2. Method

In this study, a parametric multi-objective optimization framework was developed within the Rhino/Grasshopper environment. By incorporating flexible parametric controls, the framework facilitates the optimization of BIPV component configurations on building envelopes and supports informed decision-making. Key design variables, such as panel size, electrical characteristics, orientation, mounting position, and layout, are dynamically manipulated to generate a wide range of design alternatives. Through iterative simulations and real-time feedback, the design is progressively refined to achieve optimal performance. This process not only enhances the energy efficiency of BIPV systems but also ensures seamless integration with architectural forms, thereby maximizing sustainability and economic viability.

The proposed simulation workflow, illustrated in Figure 1, comprises several stages: geometry generation based on commercial BIPV products, irradiance simulation, electrical output estimation, building energy modeling, indoor daylight and thermal comfort analysis, and coupled economic evaluation. BIPV modules are parameterized in Rhino/Grasshopper according to product specifications and automatically arranged based on defined parameters, enabling rapid generation and evaluation of design schemes. To address the limitations of Honeybee in electrical modeling, a Python module was embedded into the Grasshopper environment to link hourly irradiance results with PVlib-based electrical performance prediction, incorporating temperature effects. Additionally, a separate Python script was developed for economic analysis, coupling energy output with building energy demand and incorporating cost parameters (e.g., product price, electricity tariffs) to assess financial feasibility. Multi-objective optimization is conducted using the Wallacei plugin. Finally, all results are visualized and explored interactively using Design Explorer, enabling comprehensive analysis and stakeholder-driven decision-making.

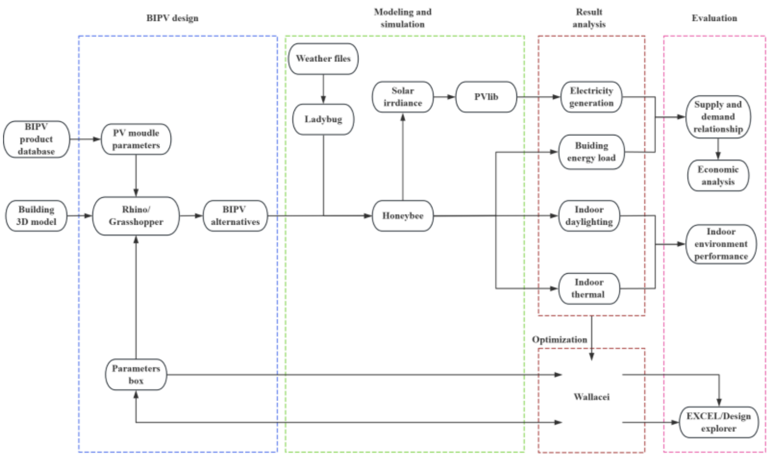

Fig. 1: Optimization design flow in Rhino/Grasshopper

The developed framework was validated based on a case study. The case study is based on an office building located in Victoria, Australia. The parametric simulation model is developed for evaluating PV shading devices (PVSD) performance. Given that the case study is an office building, its internal layout is simplified and partitioned into five distinct areas: four long-term occupied office spaces in the outer regions and a central area comprising other transiently occupied zones. This study considers three commercial PVSD products and sets the tilt angle, orientation, and deployment floor of the shading device as design parameters. The goals of MOO are to maximize life cycle energy (LCE) and Useful Daylight Illuminance (UDI), and minimize life cycle cost (LCC).

3. Results

The 10 Pareto-optimal BIPV shading design alternatives offer a diverse range of options tailored to varying stakeholder priorities. Each alternative specifies the optimal tilt angles for respective façades and the most suitable BIPV product for the given design scenario. Alternatives 2, 4, 6, 7, and 8 demonstrate notably low life cycle costs (LCC), achieving a favorable balance between cost-effectiveness and performance, including acceptable levels of daylight comfort (UDI), making them well-suited for budget-conscious projects. Among these, ALT 6 emerges as a particularly balanced solution, offering both low LCC and satisfactory UDI, making it ideal for scenarios prioritizing affordability with moderate energy performance. ALT 4 also presents a strong compromise between cost and visual impact, with moderate economic returns, suitable for projects requiring a more balanced design strategy. In contrast, ALT 9 and ALT 10 perform exceptionally well in terms of daylighting efficiency, making them attractive options for daylight-driven design objectives.

Optimal Design	North Tilt	East Tilt	West Tilt	PV Type	LCC (AUD)	LCE (kW)	UDI
ALT 1	0	0	0	1	859257.6	590226.8	0.252697
ALT 2	0	0	0	2	232118.1	373494.6	0.148899
ALT 3	0	0	30	1	859557.1	569912.3	0.288177
ALT 4	0	10	0	2	232706.0	375032.7	0.154605
ALT 5	0	20	0	1	406961.5	467337.8	0.180651
ALT 6	0	20	0	2	232129.5	375366.3	0.159041
ALT 7	0	30	30	2	220075.6	359360.0	0.197681
ALT 8	10	0	30	2	225506.3	351809.2	0.149714
ALT 9	10	20	0	2	882481.8	592149.8	0.294054
ALT 10	10	30	0	1	889608.6	591620.9	0.323714

Fig. 2: Optimization design solutions

4. Conclusion

In summary, the proposed simulation-based optimization framework enables automated layout generation and multi-angle performance simulations of BIPV components, allowing for comprehensive system evaluation. This facilitates informed decision-making for stakeholders across disciplines and supports the broader adoption and development of BIPV.

5. Reference

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