

EVOLUTIONARY-BASED MULTI-OBJECTIVE OPTIMISATION OF BIPV ENVELOPE DESIGN: BIPV CURTAIN WALL

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Multi-criteria decision-making is crucial in construction management, where diverse objectives often compete for prioritisation. Optimisation strategies are essential to navigate this complexity. This research optimises Building Integrated Photovoltaic (BIPV) envelope designs at the conceptual stage, aligning with sustainability goals. Using an evolutionary-based genetic algorithm (NSGA-II), the study generates optimal BIPV curtain wall solutions considering life cycle cost and energy generation. The results highlight the significant influence of factors such as BIPV module selection, tilt angle, orientation, and application type on the energy and economic performance of BIPV facades. The ability to select optimal designs tailored to financial and energy requirements empowers stakeholders to make informed decisions early in the design process. This is particularly crucial at the conceptual stage, where decisions have far-reaching implications. The study's outcomes serve as a valuable resource for building designers, aiding in selecting suitable BIPV façade designs during the conceptual design stage. This facilitates informed decision-making by providing stakeholders with clear insights into the implications of different choices, enabling them to select the most favourable design based on their priorities and constraints

Keywords: multi-criteria decision making; conceptual stage; BIPV; energy; life cycle cost; optimisation

INTRODUCTION

In the realm of construction, particularly during the conceptual stage, multi-criteria decision-making holds paramount importance. This stage lays the foundation for the entire project, where critical decisions shape the trajectory of the construction process. With diverse objectives often vying for attention, the need for robust decision-making frameworks becomes an imperative. Additionally, optimisation strategies play a crucial role in enhancing decision-making processes by systematically exploring and evaluating various design alternatives to identify the most favourable solutions.

Within this context, this study sheds light on the significance of multi-objective optimisation (MOO) in the construction and building design domain. By employing an Evolutionary Multi-Objective Optimisation Algorithm (NSGA-II), this research demonstrates how MOO techniques can effectively address the complex and

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conflicting objectives inherent in building design. Specifically, the study focuses on optimising Building Integrated Photovoltaic (BIPV) envelope designs, where multiple performance criteria, such as lifecycle energy (LCE) and lifecycle cost (LCC), need to be simultaneously maximised and minimised, respectively.

Through this investigation, the study underscores the pivotal role of MOO in aiding decision-making processes during the conceptual stage of construction projects. By generating alternative BIPV envelope designs that strike an optimal balance between conflicting objectives, the research provides stakeholders with valuable insights into the implications of different design choices. This facilitates informed decision-making, empowering stakeholders to select the most favourable BIPV design solutions based on their priorities and constraints.

LITERATURE REVIEW

In construction management, the application of multi-criteria decision-making (MCDM) is crucial for optimising design and operational processes. MCDM methods, such as Analytic Hierarchy Process (AHP) and Multi-Attribute Utility Theory (MAUT), facilitate the evaluation and prioritisation of competing objectives, enabling more informed decision-making in the planning and execution of construction projects (Keeney and Raiffa, 1993; Saaty, 2008). For instance, MCDM has been effectively used in selecting sustainable building materials, optimising construction project scheduling, and assessing the environmental impact of construction activities. The integration of MCDM in BIPV design optimisation enhances the decision-making process by systematically analysing various design options against predefined objectives, such as cost, energy efficiency, and aesthetic appeal (Ahmad and Thaheem, 2018; Ahn, Pearce, Wang, and Wang, 2013; Gluch and Baumann, 2004).

Optimising BIPV envelope design holds significance in construction management for several compelling reasons. Firstly, BIPV systems offer a sustainable solution by enabling buildings to generate renewable energy while serving as structural components of the envelope, thereby reducing reliance on fossil fuels and enhancing sustainability (Norton *et al.*, 2011). Secondly, optimising BIPV design can lead to long-term cost savings through reduced energy consumption, operational costs, and potential revenue generation from electricity generation and incentives (Crawford and Treloar, 2004). Thirdly, BIPV systems offer flexibility in design and aesthetics, enabling architects and designers to seamlessly integrate renewable energy generation into building architecture while maintaining visual appeal (Heinstein, Ballif, and Perret-Aebi, 2013).

‘Building-integrated photovoltaic modules are building components installed as part of the building envelope, such as glazing, curtain wall and roof, which are simultaneously photovoltaic electricity generators’ (IEA-PVPS, 2018). BIPV systems offer numerous advantages, including decreased building energy consumption, enhanced energy autonomy, minimised environmental footprint, and the facilitation of aesthetically pleasing architectural designs. BIPV envelope design is an interdisciplinary process that involves combining building science, architectural design, and engineering to create an optimal solution that meets the energy efficiency, performance, and aesthetic goals of the building. BIPV systems, like any other building components, should be designed in such a way that can withstand the environmental loads, provide thermal and lighting comfort and at the same time, generate electricity. Hence, it can be derived that building functionality, and the

energy system are influenced by BIPVs. BIPV offers many benefits, such as reducing energy costs, increasing energy independence, and reducing greenhouse gas emissions. Hoseinzadeh *et al.*, (2021) conducted a study evaluating the energy performance of a high-rise building integrated with photovoltaic technology. Their findings demonstrated that incorporating BIPV systems can substantially reduce greenhouse gas emissions and decrease thermal energy consumption. However, the design of the BIPV envelope can be complex due to several factors (Tharushi I Samarasinghalage, Wijeratne, Yang, and Wakefield, 2022a). BIPV modules integrated into building envelopes can be used in different application types such as roofs (Fan and Xia, 2017), facades (Lau *et al.*, 2018), external shading devices (Yoo and Lee, 2002), double skin facades (Gratia and De Herde, 2007) and curtain walls (Benemann, Chehab, and Schaar-Gabriel, 2001). For BIPV envelopes to play these multi-functional roles in different applications, numerous factors should be considered, such as shading, irradiance, PV module properties, orientation and installation angle (Peng, Huang, and Wu, 2011).

The complexity of the BIPV systems is higher than that of conventional PV systems as BIPV systems consist of modules oriented in various directions and the shading effects are often more distinct (Walker, Hofer, and Schlueter, 2019). Different surfaces of an optimised building (roof, façade, window) may have different PV integration options or PV technologies. For instance, for buildings that have flat roofs, industrial roofs, semi-flat roofs, or east/west facing roofs and façades, thin-film technology could be an effective option (Henemann, 2008). Further, the external facade can be integrated as a solid wall with opaque PVs or windows with semi-transparent PVs (Youssef, Zhai, and Reffat, 2015).

Hence, the BIPV envelope design optimisation study needs to consider alternative BIPV products (technologies) for different building surface application types and select the optimal product for each surface. Moreover, each application type and PV technology have its own design constraints. As an example, for skylight applications, opaque PVs are not applicable and solid walls applications cannot have transparent A-Si PV glazing (thin film) (Youssef *et al.*, 2015). Consequently, optimising BIPV envelope design is paramount for enhancing sustainability, energy efficiency, cost-effectiveness, aesthetics, and technical performance in building projects, with construction management professionals playing a pivotal role in ensuring successful integration and compliance.

Worldwide urbanisation, high demand for resources, climate changes and resource depletion feed the demand for high-performing buildings. Optimisation methods search for optimal design variables that increase pre-defined performance measures. Thus, optimisation provides more promising design solutions with better performance which leads to an efficient built environment (Wortmann, Costa, Nannicini, and Schroepfer, 2015). Currently, with the advancement of simulation tools and technologies, it is possible to predict and assess the performance of buildings at the conceptual stage. Building-integrated photovoltaic (BIPV) envelope design optimisation is an area of research that has been studied extensively in recent years. While these studies have contributed significantly to our understanding of BIPV envelope design, some issues can be criticised.

Numerous research studies on BIPV optimisation have focused only on a single objective, such as maximising solar radiation, electrical performance, thermal performance, or cost-effectiveness, to name a few (Tharushi Imalka

Samarasinghalage, 2022). However, practical building envelope design optimisation scenarios typically involve multiple objectives that need to be considered simultaneously. These objectives could encompass a combination of energy production, cost, thermal efficiency, and other factors, reflecting the complexity and real-world challenges faced in optimising BIPV systems. While many studies have focused on the technical aspects of Building Integrated Photovoltaic (BIPV) envelope design (Cuce and Cuce, 2014; ElSayed, 2016; Kämpf and Robinson, 2010; Paul, Mandal, Mukherjee, and Chaudhuri, 2010), the economic viability of various design options is underexplored (Cuce and Cuce, 2014; ElSayed, 2016; Kämpf and Robinson, 2010; Lovati, 2014; Paul *et al.*, 2010; Sui and Munemoto, 2007; Vahdatikhaki, Salimzadeh, and Hammad, 2022). This is critical because BIPV systems, though beneficial, can be costly to install and may not always be cost-effective.

Addressing economic feasibility is essential for broader adoption in the construction industry. The practical application of building envelope design optimisation to guide the design process is also underdeveloped. The complexity arises from numerous variables that need to be parameterised, such as orientation, shading effects, and thermal performance. Integrating different simulation and optimisation tools, which require significant computational resources, adds to the challenge. Most studies have not effectively bridged the gap between theoretical models and practical implementation. Moreover, the construction management field lacks sufficient multi-criteria decision-making (MCDM) approaches for BIPV optimisation. MCDM methods are ideal for addressing the multiple, often conflicting objectives in BIPV design—such as maximising energy production while minimising costs—but are not widely applied in this context.

Thus, the research gap lies in the lack of emphasis on economic viability and the inadequate application of systematic optimisation and MCDM techniques in BIPV design. This research aims to address these gaps by developing an optimisation framework that considers both technical and economic aspects, enhancing decision-making in the conceptual stage of construction projects. This research investigates alternative designs for a BIPV curtainwall as a case study by optimising life cycle energy (LCE) and life cycle cost (LCC) simultaneously considering multiple BIPV products and a set of building envelope features to support BIPV envelope design at the conceptual stage. The following sections first discuss the method employed and the framework used for the optimisation of a BIPV façade for conceptual design support and then investigate the optimal results generated for a commercial building in Australia.

METHOD

This study follows the optimisation framework presented in (Samarasinghalage, Wijeratne, Yang, and Wakefield, 2022b). The framework utilises tilt angle, PV placement, and BIPV product type as design variables to optimise LCC and LCE simultaneously for a BIPV curtain wall design. The optimisation process considers Payback less than the BIPV product life span and positive NPV as constraints. Building envelope design optimisation is a multi-objective optimisation process and most of the objective functions are often conflicting, i.e., maximise energy production, minimise cost, minimise carbon emissions, etc. (Amouzgar, 2012). In Multi-Objective Optimisation (MOO) or Pareto optimisation, optimisation decisions are made between multiple (two or more) often conflicting design objectives. The major advantage of MOO is that it facilitates designers to utilise multiple objectives and

specify the trade-offs between them. Evolutionary algorithms follow the Darwinian principle of survival of the fittest and in each iteration, the weakest one is eliminated from the population. Mutation (introducing random changes) and crossover (switching elements from different solutions) are common operators used in evolutionary algorithms (Evins, 2013). NSGA-II which is a MOO algorithm is selected based on the behaviour of the preferred optimisation criteria. The optimisation Algorithm takes inputs processes several design alternatives and outputs the optimum design alternatives based on the given evaluation criteria. Thus, generated optimised alternative designs have non-dominated LCC and LCE. Furthermore, the designs satisfy the constraints and include optimal values of the design variables accordingly.

Initially, Revit software is used to determine the irradiation conditions on each surface of the case study building. The building model depicted in Figure 1 was chosen as the basis for integrating Building Integrated Photovoltaics (BIPV) in the form of a curtain wall application.

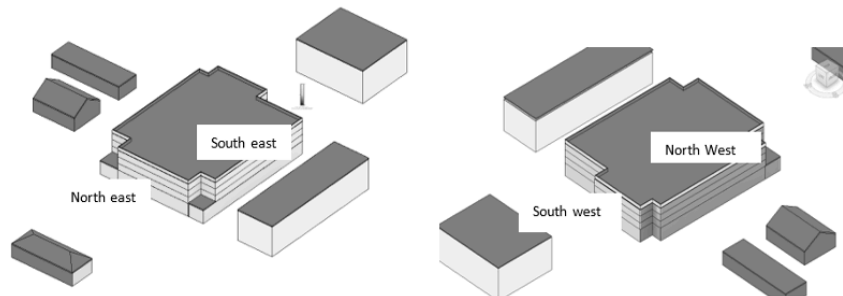


Figure 1: Case study building

Table 1 lists the design variable set for the optimisation process. A total of 32 BIPV products were selected, comprising spandrel glass and vision glass, for the optimisation process.

Table 1: Parameters of the optimisation process

Design variable	Values
BIPV products	32 products (spandrel glass and vision glass)
PV placement	YES/NO
Façade Tilt angle	75 -90
Objective function	Aim
LCC	Minimisation
LCE	Maximisation
Constraints	Values
NPV	> 0
Payback period	< PV life span

Additionally, an alternative material value was considered, which was determined based on the cost comparison between the aluminium frame and the glazing alternative material. Maximising LCE and minimising LCC are selected as the objectives. The payback period and the net present value (NPV) are selected as the

constraints on optimal results set. The output of the current optimisation process includes optimal values for the tilt angle, BIPV product type and PV placement along with other features such as LCC, LCE, payback period and NPV value.

Table 2 lists the configuration settings of the NSGA-II optimisation algorithm

Table 2: NSGA-II algorithm configurations

Parameter	Value
Population Size	40
Number of Offspring	40
Number of Generations	40

FINDINGS

The analysis of curtain wall applications resulted in three distinct design options for integrating Building Integrated Photovoltaics (BIPV). Figure 3 depicts the Pareto-optimal solutions alongside the Life Cycle Cost (LCC) and Life Cycle Energy (LCE) values of alternative designs generated during the optimisation process. The final design solutions significantly deviate from the initial population values, with only three designs identified as optimal solutions. Table 3 provides the parameter values for these design alternatives along with their corresponding LCC and LCE values.

The three optimisation alternative designs (ALT) present distinct configurations for the BIPV curtain wall application. ALT 1 features a southeast tilt of 80 degrees with 266 PV panels placed in that direction, coupled with a northeast tilt of 55 degrees and 175 PV panels placed accordingly. This design yields a life cycle energy of 2,303,426 kW and a payback period of approximately 10.45 years, with a total PV area of 780.0849 sqm. In contrast, ALT 2 opts for a simpler configuration with a southeast tilt of 90 degrees and no PV panels placed in that direction, while 175 PV panels are positioned in the northeast direction with a tilt of 40 degrees. This alternative achieves a lower life cycle cost of AUD 35,356.71 and a shorter payback period of approximately 5.34 years, albeit with a reduced life cycle energy of 1,322,701 kW and a smaller total PV area of 309.5575 sqm.

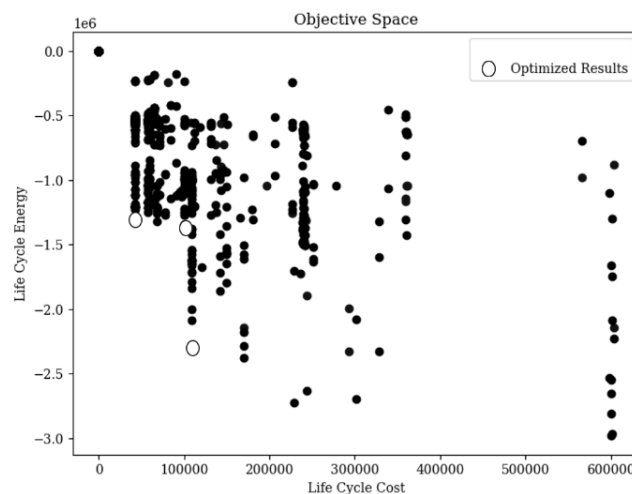


Figure 3: Curtain wall optimisation results

Meanwhile, ALT 3 mirrors ALT 2 in terms of southeast tilt and PV placement but introduces a substantially higher number of PV panels (448) in the northeast direction.

Although this yields the highest life cycle energy among the three alternatives (1,369,337 kW), the design incurs a longer payback period of 23.369 years and a comparatively higher life cycle cost of AUD 83,768.80, with a total PV area of 322.56 sqm. Overall, while ALT 1 emphasizes maximising energy generation efficiency, ALT 2 prioritises cost-effectiveness.

The stakeholder with the preference for quick payback may opt for alternative design 2, while others might choose alternative 1 due to its superior life cycle energy performance.

Furthermore, the proposed framework presents the Pareto optimal solutions alongside essential parameter values such as capital cost, first-year energy generation, Net Present Value (NPV), payback period, and total PV area. This enables building professionals to select designs based on a comprehensive set of parameters.

Table 3: Optimal alternative BIPV designs

Parameter	ALT 1	ALT 2	ALT 3
Southeast tilt (degrees)	80	90	90
Southeast PV placement	1	0	0
Southeast No of PVs	266	0	0
Northeast tilt (degrees)	55	40	40
Northeast PV placement	1	1	1
Northeast No of PVs	175	175	448
PV Type	109	109	904
PV Life Span (years)	25	25	25
Life cycle cost (AUD)	89098.9	35356.71	83768.8
Life Cycle Energy (kW)	2303426	1322701	1369337
Payback Period (Years)	10.4455	5.3406	23.369
NPV	48294.21	48139.69	2323.05
Capital Cost (AUD)	69918.35	27745.37	66985.04
LCOE	0.047132	0.032571	0.073449
First Year Energy Generation (kW)	97785.32	56151.45	58510
Total No of modules	441	175	448
Total PV area (sqm)	780.0849	309.5575	322.56
	ALT 1	ALT 2	ALT 3
Southeast tilt (degrees)	80	90	90

CONCLUSIONS

The evolutionary-based multi-objective optimisation of BIPV envelope design carries significant implications for both design management and construction management in sustainable building projects. Optimised BIPV envelope design not only maximises solar energy capture, leading to reduced reliance on traditional energy sources and lower utility bills but also optimises space utilisation by converting passive building

elements into active energy generators. This aligns with sustainability goals and helps mitigate the environmental impact of buildings. Furthermore, optimising the BIPV envelope design can result in long-term cost savings through reduced energy expenses and potentially increased property value, especially when combined with government incentives and rebates for renewable energy installations.

Building Integrated Photovoltaic (BIPV) façade design stands out as a promising yet underutilised approach in sustainable building projects. Despite the availability of numerous optimisation models for sustainable building design, their application in BIPV façade design remains limited. This paper presented a case study employing an NSGA-II-based optimisation framework, showcasing the potential of such tools during the conceptual design phase of BIPV facades. This approach provides valuable insights into the design space and trade-off patterns among various design objectives, assisting designers in determining optimal parameters such as tilt angle, placement areas, and BIPV product type to achieve maximum Life Cycle Energy (LCE) efficiency while minimising costs.

Optimisation plays a crucial role in aiding multi-criteria decision-making by systematically analysing various design options against predefined objectives. Through mathematical algorithms, optimisation evaluates trade-offs and identifies solutions that best balance competing criteria, such as cost, energy efficiency, and aesthetics. This facilitates informed decision-making by providing stakeholders with clear insights into the implications of different choices, enabling them to select the most favourable design based on their priorities and constraints.

The outputs of optimisation provide crucial information regarding the potential return on investment (ROI) of implementing BIPV systems, aiding owners and investors in assessing economic feasibility. For architects and designers, optimisation outputs offer insights into performance and aesthetics, helping create visually appealing and energy-efficient building designs. Engineers and construction managers can evaluate technical feasibility and construction implications, ensuring the successful implementation of BIPV technology. Regulatory authorities can use optimisation outputs to evaluate compliance with standards, promoting sustainable development practices.

By integrating sustainability objectives and optimisation into the conceptual stage of design management and considering the implications for construction management, project teams can effectively leverage BIPV technologies to enhance the energy performance and overall sustainability of buildings. This holistic approach not only addresses the challenges of sustainable building design but also fosters innovation and fosters the uptake of sustainable innovation within construction, thus contributing to the advancement of the construction management field.

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