e-BIM: a BIM-centric design and analysis software for Building Integrated Photovoltaics

Gui Ning\textsuperscript{a}, He Kan\textsuperscript{a}, Qiu Zhifeng\textsuperscript{b,c,⁎}, Gui Weihua\textsuperscript{b}, Deconinck Geert\textsuperscript{c}

\textsuperscript{a} College of Information, Zhejiang Sci-Tech. University, Hangzhou, China
\textsuperscript{b} College of Information Science and Engineering, Central South University, Changsha, China
\textsuperscript{c} ELECTA/ESAT, KU Leuven, Heverlee, Belgium

**Abstract**

Building Integrated Photovoltaics (BIPV) has gained large popularity in recent years. However, its effective design remains challenging. Different but often related design concerns regarding BIPV are normally treated, in the current practice, in multiple but separated design phases with different models and tools. The complexities in maintaining the consistency between those models employed in separated phases make seamless PV and building integration, one of the major concerns of BIPV design, far from satisfying. To this end, this paper proposes a uniform BIPV design platform: e-BIM, which is a BIM (Building Information Modelling) - centric BIPV design and analysis software platform, to address the related design concerns via one uniform data model. The concept of domain-specific models is introduced to allow the external PV-related models to be integrated into the uniform model. To simplify model synchronization problem, the domain-specific views corresponding to specific domains are provided to designers and meanwhile a synchronization engine is developed to automate data consistency among views and the uniform model. The current prototype is developed based on Autodesk® Revit and tested in a practical BIPV application. The results show that this platform achieves seamless BIPV design for architects, PV system designers and electricity professionals. Moreover, compared to the initial BIPV design, the photovoltaic system cost is reduced by 11.7% and the transmission losses by 2.95%.

**1. Introduction**

Nowadays buildings account for 40% of the world’s energy consumption and become one of main resources to produce CO$_2$ emissions [12]. Necessary actions shall be adopted to aggressively reduce/optimize energy consumption in the new and existing buildings. Meanwhile, photovoltaic (PV) solar power has been regarded as one of the best renewable energy resource to alleviate the climate change and reduce greenhouse gases. The integration of photovoltaic technologies in buildings, well known as Building-Integrated Photovoltaics (BIPV), is one of the best ways to integrate solar power into building with the advantages, e.g. generating electricity, offsetting the cost of construction elements, adding to buildings new aesthetical features and reducing buildings CO$_2$ emission [25].

In BIPV, PV modules replace the conventional building materials and become parts of building envelope, rather than being installed afterwards. In the building envelope, PVs play multiple roles, and this leads to the new and coupled design concerns in the initial design stage, e.g. the tradeoff between placement of PV from architectural perspective and energy efficiency from electrical perspective, the altered and more complex building power flow due to the fact that BIPV building is complex with both generator and consumer of electricity. Therefore, to achieve the perfect integration of PV into buildings need to bring together all issues in terms of architectural, electric and aesthetic aspects and the design concerns given rise by BIPV need to be carefully addressed, e.g. the seamless integration of energy conservation, energy efficiency, building envelope design, PV technology and placement and energy savings [33].

Current BIPV design generally is divided into several separated and subsequent design phases, e.g. architecture design phase and PV design phase. In each phase, design is performed by respective experts or engineers with proprietary models regarding specific domain concerns. For instance, an architect designs the building and a PV engineer designs the PV system. Consequently, even for the same BIPV project, there would be various approaches or software tools to represent the same model and concept in different design phases. In architecture design phase, the architectural design software tools include the tools like AutoCAD, MyArchICAD and Sketchup. All of them provide the rich supports for architectural design, yet rather limited supports with respect to PV system design [30]. In PV design phase, many tools and...
approaches have been proposed to cater for the various PV design concerns [11,15], ranging from general design tools, e.g. PVsyst [1] and Retscreen [24], to peculiar solutions for special PV design concerns, e.g. partial shade model for PV design [4,20] and the optimized connection model for PV panels [9]. As stated, with such BIPV design pattern, it is hard to achieve seamless integration of PV system since the proprietary models employed in each phase are not compatible. The modification and updating made in one phase could not be recognized, synchronized and adapted in other phases if without a systematic synchronization supports. The complexity in maintaining the consistency between different models makes BIPV designs rather expensive, inefficient and highly dependent on experts' knowledge. Larsson and Poel [23] pointed out that the improvements of the existing BIPV design methods and process are a prerequisite to enhance BIPV applications.

The BIPV in itself is one specific part of buildings and can be supported with accurate digital models. Building Information Modeling (BIM) is an extensible approach to digitally represent physical and functional characteristics of buildings and facilities. It works as a shared knowledge resource for information about building and facility components and forms a reliable basis for different stakeholders, e.g. the design team, owner, contractor, and facility manager, from the earliest conception to the demolition of a building [3,27].

This paper proposes a BIPV design system called e-BIM: a BIM-centric design and analysis software to provide a uniform platform for solving the related concerns for the entire BIPV design process. The proposed platform provides an integrated design methodology, not just the integrated analysis which has been considered in the existing research. Firstly, with the introduction of BIPV-specific models, e-BIM directly integrates the BIPV design knowledge into the BIM authoring tools. This approach allows the seamless design of BIPV as BIPV design can be directly performed in the existing BIM authoring tools, rather than exporting the data of BIM model to other domain-specific models for analysis. Secondly, e-BIM wipes out the data inconsistency between different design phases, with the support of the proposed data synchronization mechanism. e-BIM supports automated mapping and synchronization between different data views in order to facilitate different designers. By doing so, experts or engineers majoring in different fields can simultaneously develop a BIPV project by using the uniform platform without toing and froing data transformation among design phases. Thirdly, in this software platform, the design concerns with respect to PV system are encapsulated into several functional modules, e.g. solar radiation, shadow analysis, power flow calculation, etc. Those modules are designed to be reusable by third-party developers to enhance reusability. Finally, the developed e-BIM software platform is realized on the Autodesk® Revit Architecture, one of the mainstream BIM authoring tools, as a set of plugins to reduce the users' learning curve. The effectiveness of the proposed software platform is verified by a practical BIPV project.

The rest of this paper is organized as follows: Section 1 investigates the limitation of current practices and proposes a new design methodology with the aim to realize the integrated BIPV seamless design. Section 2 illustrates the detailed software architecture as well as its key modules. A set of analysis modules and their supporting domain-specific models are described in Section 3. Next, this platform is evaluated via a practical BIPV project. Conclusions and research perspectives are provided in Section 5.

2. Uniform BIPV design methodology

In this section, a typical BIPV design practice is firstly elaborated and its limitations are presented. Finally, a new design methodology is proposed.

2.1. Typical BIPV design practices vs. related design concerns

The BIPV design is a complex process. In order to simplify the design process, the BIPV design is generally supported via the so-called “divide and conquer” principle. Each design principle is tackled in the respective phase, in which the different design concerns can be effectively addressed by the different designers with the corresponding tools. Therefore, in each software platform, the specific model needs to be maintained.

However, those “divide and conquer” approaches can only be effective when all those design concerns are orthogonal towards each other. In contrast, BIPV design concerns are often related. Some related perspectives regarding BIPV design are analyzed as follows:

♦ Architecture vs. radiation relations: Due to the complexity of building exteriors and buildings' locations, PV modules installed on building exteriors are often shaded by surrounding trees, buildings even themselves. The previous studies pointed out that the shadows can significantly impact PV power outputs [5,29]. As PV devices work as building exteriors, the building exterior design, e.g. orientation and inclination, will greatly influence both PV systems' power output and building aesthetics. Thus, the optimal BIPV design demands that building architecture and PV system should be designed collaboratively rather than isolatedly.

♦ PV vs. electricity relations: The electricity generated by PV system is characterized by great fluctuations. When the weather is PV-friendly, BIPV can generate adequate electricity to buildings, while there is zero power output during the night. The design choices of PV system e.g. connection modes, number and places of accessing points, can significantly alter buildings' power flows, and therefore influence the effectiveness and security of the building power system. Thus the design of PV systems, the major electrical equipment and power lines are actually mutual-influenced. However, to the best of our knowledge, a few researchers consider the co-design of those systems.

These two relations are by no means the only relations with respect to BIPV design. Other relationships, e.g. power safety vs. PV deployment, are also common in BIPV design. The strong relationships among different design concerns demand that one design change should be reflected to different related models in a timely and accurate way. However, the synchronization between different domain-specific models is very difficult to be achieved when each phase maintains a respective and possibly partial repetitive model. BIPV design practices with multiple but isolated design phases are infeasible to achieve the seamless and efficient PV integration.

2.2. e-BIM: a uniform model for related concerns

In this paper, the e-BIM is proposed to deliver a uniform model to integrate the different BIPV phases. Rather than using multiple and possibly repetitive models, this new methodology aims at using one data model that has description capabilities for the BIPV-related knowledge, e.g. buildings, electricity and PV. BIM in itself provides rich expression capabilities for building, but limited definition for electricity and totally no definition for PV devices. The e-BIM can be viewed as an extended BIM being capable to provide the PV-related knowledge. The structure of e-BIM is shown in Fig. 1.

2.2.1. Extended data model

As shown in the lower part of Fig. 1, two types of information description models are identified to describe the data and knowledge required by BIPV design:

♦ BIM-based models: As BIPV is mainly used for a building construction, it is important to have BIM support for the BIPV design. PV devices can be digitalized as BIM-based models which include the geometric model, electrical features, materials and PV-related features etc. Those models are mainly data-centric and can be easily
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