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

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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 CO₂ 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 aesthetic features and reducing buildings CO₂ 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

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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 majored in different fields can simultaneously develop a BIPV project by using the uniform platform without doing 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 or 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 researches 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 knowledges 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

Fig. 1. The structure of e-BIM: one uniform model integrating BIM-based models and domain-specific models; the domain-specific views congregate data from both BIM-based model and BIPV-related models.

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 expressed by BIM models.

- ◆ **BIPV-specific models:** The major reason to introduce BIPV-specific model is due to the fact that BIM focuses on data description, while lacks operational description supports. Most of BIPV-specific design knowledge is rather difficult to be expressed by BIM. For instance, the position of the sun depends on many factors, e.g. time, location, etc. It is more appropriated to express this model by procedure model rather than BIM which is data-centric. The other BIPV models include, e.g. sun radiation model needed for radiation analysis, Direct Current (DC) link model needed for PV device wiring, etc. Normally, BIPV-specific model will not change during the entire BIPV design process.

The combinations of BIM-based models and BIPV-specific models provide the adequate data and knowledge expressions required by BIPV design. A reliable data center for different BIPV designers is established. All BIPV related designers, no matter architects, electricity designers or PV experts, can work with one uniform model.

2.2.2. Domain-specific view

Another important concept proposed in the e-BIM is the “Domain-specific View (DV)”. DV provides the domain-specific data abstraction by acquiring, transforming and presenting data from the underlying BIPV model with BIM objects and BIPV-specific models. Designers, with the assistant of DV, can focus on their particular design concerns. In this respect, the views are similar to the downstream models used in the references [10,31]. However, in order to avoid duplicated data models, DV contains no persistent data. Instead, only a domain-specific data snapshot of BIPV data model is kept in the view. A DV can keep updated if it always fetches updated data from the BIPV model. This design simplifies the processes in identifying possible inconsistency between different views, and refrains developers from the obligation to manually maintain the consistency between different models. Furthermore, all views can be (re)used by different designers. Thus, designers can focus on their particular design concerns, rather than digging into the details of the underlying data models. For instance, the *Geometry view* can be used in *Radiation analysis*, *Shadow analysis* and *Power Flow analysis* modules.

3. Discussion

Through a verification study, Kuo et al. present the needs for a general BIM-based analysis procedure that supports the collaborative design between different designers [22]. However, as concluded by the International Solar Heating and Cooling Programme (SHC) [19], most

simulation software (The eleven solar design software programmes were evaluated) lacks a 3D environment or sufficient visualization functions for integrating the whole building designs with PV systems.

Only some tools, e.g. Ecotect and eQUEST, provide BIPV design support by exporting building information to other models for simulation. For instance, Ecotect and eQUEST rely on an external model - the gbXML (Green Building XML) - for building simulation by transferring *green* building properties in 3D BIM models to energy analysis software. Other custom solutions include: Yang et al. translate BIM into a Modelica model and Radiance model for thermal and daylighting simulation [31]. Cemesova et al. propose PassiveBIM that extends the Industry Foundation Classes (IFC) specification with an energy schema so that external PHPP (Passive House Planning Package) tools can perform building performance simulation [10]. Those approaches fail to support collaborative design between different models because only one-way model transformation is provided.

With the popularity of BIM, a few researchers recently adopted BIM-centric approaches. Gupta et al. present a conceptual framework that supports IFC-based radiation analysis for BIPV [18]. Dixit et al. [14] proposed a Revit-based approach for BIPV analysis. Those approaches allowed radiation analysis performed with BIM authoring tools without the need to recourse to external software. However, they failed to provide a systematic transformation support for the automated adaptations of modification or updating between models. The lack of such support only can realize “integrated analysis” rather than “integrated design” which is really needed for BIPV.

4. Platform design and implementation

In order to realize the proposed design platform of BIPV with one uniform model, an efficient supporting software architecture is designed and a prototype is implemented afterwards.

4.1. Key design concerns

In order to support the new design methodology, several key requirements for the supporting software platform are identified:

- ◆ **Easy-to-use:** As BIPV is mainly designed by architects, this platform should be built on a widely-used BIM platform. Then architects can work with familiar software to reduce the learning curve. Moreover, analysis results should be represented in a user-friendly way.
- ◆ **Extensibility:** As pointed out in the Section 1.2, BIPV design involves the multiple design concerns. This platform should be able to integrate different BIPV design knowledge as well as different data views. In order to perform different analysis, it is also important to support future and un-prescribed analysis modules in the design-time. Moreover, the software platform should provide an extensible architecture.

- ◆ Consistency: As the same BIPV model will be used and modified by different designers, the consistency among different views should be kept. Moreover, any modifications towards BIPV model should be popularized into affected views in a timely and efficient way.

4.2. Pluggable software architecture

In order to shorten the learning curve of potential users who are supposed, in most cases, to be architects, Autodesk® Revit is adopted as the basic software platform since it is one of the most widely used BIM design software and provides custom data model extensions, i.e. custom family. Moreover, it provides the programing SDK to external plugins. Based on the Revit SDK, a pluggable software architecture is defined to support the new BIPV design methodology. This software architecture is composed of four major parts: BIPV-specific models, domain-specific views, Data Synchronization Engine (DSE) and a pluggable analysis engine with a set of analysis modules.

- ◆ The model interface: It is defined to allow developers to introduce/build the new BIPV-specific models. In the current prototype, sun motion model, radiation model and building power flow model are built.
- ◆ The DV interface: This interface is designed to allow the view of domain-specific data. This view inquiry, congregate and transform data from the underlying BIM-based models and BIPV-specific models. Programmers can adopt their specific solutions to the query and transformation of which BIM lacks [13]. Moreover, each view can provide data manipulation interface to modify the related data as well as an event handler to listen for the interested modifications.
- ◆ Data Synchronization Engine: A DSE is designed to handle the modifications from views in an order way. Whenever a modification event is raised by one view, DSE checks all registered event handlers. For all the views interested in this type of modification event, their event handlers will be invoked. Each view takes necessary actions to update its data. DSE can ensure the view consistency, while avoid unnecessary view updates.
- ◆ Pluggable Analysis Engine: Based on the data provided by different domain-specific views, different analysis modules are built to assist designers. In order to accelerate the development of prototype, the existing research results are reused. Thus the third-party developed analysis modules are allowed to be plugged-in by analysis engine. In the current prototype, the radiation analysis modules (implemented by the authors) and power flow analysis modules (reusing the Matpower toolbox [34]) are implemented. The detailed descriptions of those modules are provided in Section. 3.

In what follows, several key modules of e-BIM are described. Then, two major analysis modules and their related views are introduced.

4.3. Data synchronization mechanism

In a BIPV design process, the designers from multiple disciplines are involved. To satisfy with the different designers' requirements, the multiple domain-specific views co-exist by abstracting data from the central model in the e-BIM. In order to keep the consistency among views, an event-based DSE (data synchronization engine) is designed. The view retrieves the latest data from the central model and is kept updated only when necessary. In this way, the heavy resource requirements and high computational complexity of data retrieval caused by the frequent refreshing updates can be avoided.

Fig. 2 shows the DSE mechanism that synchronizes the data between views and the central BIPV model. Each view registers a set of interested events to DSE in the initialization stage. When a user changes the data of a view, e.g. PV configuration view, a modification event is sent to the event pools of DSE. The *Data Processor* synchronize the modifications in the view to the BIPV model and then forwards the

corresponding data modification events, e.g. changes of PV location, connections and property, to the *update engine*, which searches any view that might be interested in this event. If any view is found, the *update engine* dispatches the event to the registered views. In Fig. 2, three kinds of designers are supported by the DSE for the collaborative designs. The changes made by any designer will be automatically reflected to the coupled views used by other designers.

The current prototype of the e-BIM is based on the Revit plugin extension. The plugin has only limited control on the Revit platform. Designers might change BIPV model directly through the BIM authoring User Interface (UI). That might bypass the synchronization mechanism mentioned above. In order to deal with un-handled modifications, as shown in Fig. 2, the data modification events sent from the Revit are also monitored. If the related elements are modified, the related views will be notified. View developers can also opt to regenerate data views from the BIPV model to avoid the use of obsolete data.

4.4. BIM-based PV extensions

Currently, most BIM platforms provide rich featured elements for building design, while little support for PV-specific devices. In order to support the integrated design and analysis of BIPV, a set of PV components (families in Autodesk® Revit) are developed. Those components include inverters, photovoltaic panels, photovoltaic curtain wall, photovoltaic awnings, solar skylights, photovoltaic tiles, etc. Fig. 3 shows an example of BIM-based PV components. In summary, each PV model has two major sets of properties:

- ◆ Geometry model: In order to provide the compatible supports for the BIPV design based on BIM, the designed PV modules contain all the geometry information, e.g. shapes, sizes and materials. The parametric 3D modeling is supported as well. Fig. 3a displays the PV panel tilt angle parameter setting and BIM models.
- ◆ PV-specific properties: The characteristics and specification of PV panels are described in this model, e.g. silicon type, conversion efficiency, power output, etc. In order to simplify the power wiring between panels, the PV panel is defined as Revit electrical device. By doing so, PV panels can directly reuse the electrical subsystem defined in Revit. Note that the special care should be taken for the connections between PV panels as they are DC since the Revit provides the limited supports for DC connection.

In this platform, in addition to different types of PV elements, other PV-related devices, e.g. inverters, junction box and DC lines, are also provided. With those devices, architects can design BIPV within their familiar environment.

4.5. Domain-specific views

Two major views are designed to facilitate the BIPV design for different designers: the geometry view and the PV configuration view.

The geometry view: The building elements, e.g. walls and windows, play important role for BIPV design. Thus, it is important to provide data abstractions for the geometry features of building exterior elements. In the current prototype, this view is implemented by wrapping the active document instances that contain all BIM-based elements of the BIPV model. This view works as a data source for analysis modules, e.g. it is used for shadow analysis module to check the obstacle between PV device and sun. However, it does not provide data modification functions as the changes to the geometry model are normally performed by the Revit UI. As the geometry view contains the instances of active documents, the synchronization of this view is not necessary.

- ◆ The PV configuration view: The PV configuration view is constructed by filtering and searching the PV elements in the documents. This view contains a set of PV device instances including

Fig. 2. The event-based data synchronization mechanism

their locations and connections. A set of data modification method is provided for adding, editing, removing PV devices as well as their connections. For instance, the position of a device can be changed by modifying its XYZ coordinates. The angles of PV panels can be

modified to a given degree. Those changes will automatically be integrated into the BIPV model and reflected in other related model, e.g. the Geometry model.

a) Geometry model

Parameters	Value
Electrical features	
NOCT	45±2°C
components efficiency (%)	15.290000
TK Isc	+0.049%/°C
Isc	8.66 A
maximum power current	8.24 A
maximum power voltage	30.35 V
TK Pmax	-0.43%/°C
maximum power	0.00 W
maximum fuse rated current	15.00 A
TK Voc	-0.34%/°C
Voc	37.88 V
working temperature	-40~+85°C
power tolerance	0~+5W
Common	
components weight	18.5kg
components size(length*width	1650x992x30
battery specification	single crystal

b) PV Properties

Fig. 3. Photovoltaic panel model

Fig. 4. Display form of analysis result

4.6. Integrated visual display

In order to show the results of analysis in BIM model, the e-BIM platform provides a 3D visualization data display method which integrates and displays data results within the Autodesk® Revit 3D BIM model. Fig. 4 shows an exemplar visual display of simulation results from irradiance analysis. When analyzing the irradiance of photovoltaic panels, all data can be displayed in the corresponding position on device surface. The results can be displayed in the color cloud form (Fig. 4a) and the numerical value form (Fig. 4b). The color cloud emphasizes variation trend, while the numerical value emphasizes accurate results. This integrated visual display is realized by using Revit spatial filed manager. So BIPV designer can examine the analysis results directly in the Revit environment.

5. Analysis modules

In the e-BIM platform, a set of analysis functions is provided. In this section, two major analyses together with the related models and views are introduced.

5.1. Solar radiation analysis

The radiation efficiencies of a PV panel are influenced by many factors in the interval of one year. Some factors are hard to be well-predicted, e.g. clouds, rains or dusts; while the obstacles and the radiations of the sun which influence the shadow towards PV panels are modeled in the e-BIM platform. Several BIPV-specific models and views are developed.

5.1.1. Solar motion model

The solar motion model is defined for shadow and radiance calculation. Three major metrics are used to describe the motion of the sun:

1. Declination angle, denoted as δ , is the angle between the planes of the equator and a line drawn from center of the sun to the center of the earth. The declination angle depends only on the day of the year. It has a maximum value of $+23.45^\circ$ on the June 21st/22nd ($n = 173$) and a minimum value of -23.45° on the December 21st/22nd ($n = 356$).

2. Solar elevation angle, expressed as α , is the angular height of the sun in the sky measured from the horizontal 0° at sunrise and 90° when the sun is right overhead.

3. Solar azimuth angle, denoted as φ_s , is the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere.

Those three angles can be determined by the Eqs. (1)–(3) proposed in [28] which are accurate within 1° , and are sufficient for the most

Fig. 5. Illustration of the ray method (uncross这个词对吗)

terrestrial photovoltaic applications [2]. They are easy to be calculated compared to the more accurate solutions in [7]:

$$\delta = 23.45^\circ \cdot \sin\left(360 \cdot \frac{n - 81}{365}\right) \quad (1)$$

$$\alpha = \sin^{-1}(\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \tau) \quad (2)$$

$$\varphi_s = \cos^{-1}\left(\frac{\sin \alpha \cos \varphi - \cos \alpha \sin \varphi \cos \tau}{\cos \alpha}\right) \quad (3)$$

where n denotes the day number in the year, φ represents the local latitude, τ is the solar hour angle. These three variables determine the solar motion model.

5.1.2. Shadow analysis

To calculate the shadow on PV devices, the Geometry view, the PV configuration view and the solar motion model are needed. The shadow calculation is performed based on the ray method supported by Revit. Fig. 5 illustrates the ray method.

The so-called ray method is, through a starting point and a vector, to create a ray and then return the objects that the ray passes through. The starting point is the studied point. The ray vector is the direction of solar ray, determined by the *solar motion* model. Then, this method returns all the geometry objects between the points and the sun. If the returned object is empty, the point is not shaded; otherwise it is shaded.

5.1.3. Solar radiation model

The solar power received on a surface mainly consists of direct radiation, diffuse radiation and reflected radiation [17]. Direct solar radiation is the component scattered by the atmosphere and is calculated as follows [8]:

$$A = 1160 + 75 \cdot \sin\left[\frac{360}{365}(n - 275)\right] \quad (4)$$

$$k = 0.7 + 0.035 \cdot \sin\left[\frac{360}{365}(n - 100)\right] \quad (5)$$

$$m = \frac{1}{\sin \alpha} \quad (6)$$

$$I_B = A \cdot e^{-k \cdot m} \quad (7)$$

$$I_{BC} = I_B \cdot (\cos \alpha \sin \beta \cos(\varphi_m - \varphi_s) + \sin \alpha \cos \beta) \quad (8)$$

where A is an apparent extraterrestrial flux, k is a dimensionless factor and called as optical depth, m is the air mass ratio, I_B is the direct solar radiation on horizontal plane, I_{BC} is the direct solar radiation on module surface, β is the module inclination angle, φ_m is the module azimuth angle.

The diffuse radiation is the radiation received from the sun after its direction has been changed by scattering in the atmosphere. The diffuse radiation value depends on the beam portion with a constant is defined

as:

$$C = 0.095 + 0.04 \sin \left[\frac{360}{365} (n - 100) \right] \quad (9)$$

$$I_D = C \cdot I_B \quad (10)$$

$$I_{DC} = I_D \cdot \left(\frac{1 + \cos \beta}{2} \right) \quad (11)$$

where C is the sky diffuse factor, which changes with the number of the day, I_D is the diffuse solar radiation on horizontal plane, I_{DC} is the diffuse solar radiation on module surface.

The reflected radiation is reflected from surface features. The reflected radiation generally constitutes only a small proportion of total radiations, except for the locations surrounded by highly reflective surfaces such as snow cover. The reflected irradiance is calculated as follows:

$$I_R = \rho \cdot I_B \cdot (\sin \beta + C) \quad (12)$$

$$I_{RC} = I_R \cdot \left(\frac{1 - \cos \beta}{2} \right) \quad (13)$$

where I_R is the reflected solar radiation on the horizontal plane, I_{DC} is the reflected solar radiation on the module surface, ρ is the reflectance of the surface.

The radiation calculation method is similar to the one used in the reference [8], rather than the approach that estimates the hourly-average values of solar irradiance based on a database or meteorological models [16,32]. The field conditions, e.g. the partial shading, are important to simulate the performances of PV systems. The uniform and non-uniform irradiance conditions on PV systems might have huge impacts on PV system performances [6,8].

5.1.4. Radiation analysis with shading

Fig. 6 shows the radiation calculation process which calculates the harvested solar radiation for any given surface. In order to calculate the solar radiation for PV devices with different shape, each PV panel is

Fig. 6. Flowchart of shadow and radiation calculations

divided into a set of size-adjustable blocks. The received radiation intensity of each block is represented by the radiation received by the central point. The smaller the block is, the more accurate the results are, and the more complex the computation is. The size of block can be determined by balancing between the two factors.

For each block, the ray method is used to determine whether this block is shaded. In order to simplify calculation, if the center point of the block is shadowed, we denote the whole block is shaded. Otherwise, the whole block is un-shaded. If the block is not shaded, all solar radiation components are assigned to the blocks for that time. Otherwise, only diffuse and reflected solar radiation components are assigned. This step continues until all the blocks are calculated for the targeted panels. Except for the PV panels, this analysis module can be used for the radiation study for any given surface.

5.2. Power flow analysis

BIPV transforms building from a unit with one power source to a one with multiple power generators, which results in the significant changes of operation states. Thus, the electricity system designs for BIPV differ from the ones for common buildings. However, in the existing approaches, to what extent the PV system might influence the power flow of building remains unsolved yet. This is especially true for the large-scale and complex BIPVs which are growing common with the developments of BIPV practices.

In this section, a power flow analysis module is introduced to provide the scientific way of power flow analysis. To calculate the power flow of BIPV, it is important to acquire the information about all electric devices.

5.2.1. Power line model

The power line model is built for power flow analysis. This model calculates the capacitive reactance, impedance and inductive reactance for transmission power line. Since the wires in building are short, the capacitive reactance can be ignored. The impedance and inductive reactance are given as:

$$R = \frac{2\rho l}{S} \quad (14)$$

$$L = 0.2S \cdot \left[\ln \left(\frac{4S}{d} \right) - 1 \right] \quad (15)$$

where R is the impedance, ρ is the resistivity, l is the wire length, S is the cross sectional area of wire, L is the inductive reactance, d is the wire diameter.

5.2.2. Electricity view

Normally it is very hard to estimate the accurate electric power of a building since it is complex to maintain an electrical model consisting of a variety and huge amount of electric equipments and complex layout of circuits. The e-BIM platform digitalizes all the electrical devices and then is capable to automatically generate an accurate electrical topology model from the BIPV model. Although Revit provides the views for electricity devices, the support for the PV-related devices are not adequate. Since the Revit cannot handle the DC connections between PV devices, the *electricity view* is implemented as domain-specific view. This model queries electrical parameters from a variety of electrical equipments, e.g. transformer, PV inverters, and different loads. It also maintains an electricity topology among those devices as well as their wire connections. As the outputs of inverters depend on the outputs of its connected PV panels, the power outputs of the inverters are dynamically calculated by accumulating the power harvested from its connected PV devices.

In the current prototype, the *electricity view* provides two major revisions for elements in the electricity view: the property-based modifications and the wiring modifications between connected elements.

Those modifications are synchronized into the BIPV model with the support of DSE.

5.2.3. Power flow calculations

Based on the defined Power line model, electrical topology model and load model, the steady-state of the power flow can be calculated.

In the current prototype, the MATPOWER toolbox is used for power flow calculation. It provides a set of power flow calculation modules, e.g. the Newton's method, the fast decoupled load flow and the Gauss-Seidel method [8,26]. The power flow calculation module of MATPOWER is compiled into dynamic library so it can be reused by the external applications. A wrapper class is designed to wrap the functions of the library so it can be invoked by the analysis engine. This wrapper class also provides data format conversion from the electricity view to the MATPOWER inputs based on Matlab vectors. The default link model of MATPOWER is not fit for the short distance link. Thus, the link model matching with the short-distance link is adopted.

6. Case study

The proposed e-BIM platform has been employed to design a practical BIPV project, i.e. the Qinfeng Substation Control Center in Jiaxing city of Zhejiang province, China. The contour of control center is shown in Fig. 7. It has two parts of roofs with different heights and angles. The orientation of the building is 15° south west. The control center contains a set of loads, transformers as well as life-supporting facilities. The building as a whole is like a micro-grid: the power generated by the PV systems, via PV inverters, serves the loads in the building firstly; if the power outputs of the PV systems are abundant, then the surplus power will be transmitted to the grid.

6.1. Design procedure

The evaluations are performed in the following steps: Firstly, an architect was invited to design this BIPV system by using the conventional PV design experiences. The Autodesk® Revit is employed as the design tool. This means that the architect considers the design mainly

from the architectural perspective, and, to some extent, it is the typical design method for the present BIPV design practice. Moreover, on the account of economic considerations, most of PV devices adopted are regular PV panels with small revisions to facilitate mounting. In this building, PV panels are installed in two types of locations: one is rooftop and the other is southern wall. Finally, the initial design conducted by the architect is analyzed and optimized by the e-BIM platform. The differences of the results using the proposed platform compared to the architectural one are presented.

6.2. Shadow and radiation analysis

The shadow and radiation analysis engine are evaluated for the PV designs for both parts of the rooftop and curtain wall.

6.2.1. Result analysis

Fig. 7a shows the calculated average daily radiation of a year for PV devices layout. Firstly, as can be seen in Fig. 7a, due to the orientation of the building and the difference of roof inclinations, the rightmost area in the lower roof part harvests the lower radiation. The front parts of PV rows are light-yellow, while the un-shaded areas are orange-yellow. This shows that they are partially shadowed in the certain periods of a day. Secondly, the distances calculated by e-BIM among PV panel rows are very short; while, for BIPV designers, it is very hard to calculate the 'best' inter-row distance on the rooftop with complex inclinations.

Fig. 7b shows the radiations harvested from the PV facade on the southern wall. As can be seen from the figure, a large part of PV panels is over-shadowed by the rooftop and eaves. They receive the smaller amount of radiations. Thus, the power outputs of those PV panels are considerably attenuated. The PV panels on the lower position of the wall are not influenced by the shadow and therefore can be retained. Furthermore, comparing Fig. 7a and b, it is shown that the radiations on the curtain panels are less than the half of those received by the rooftop panels due to the differences of installation inclination.

Fig. 7. The analysis results for irradiation for rooftop and southern wall

6.2.2. Design optimizations

The BIPV design normally involves multiple design goals [21], e.g. payback period, capital cost and energy production objectives. For this project, the optimization goals are: 1) to achieve the largest total power generating capacity; 2) to minimize the investment of electricity generation units to reduce payback time; 3) to maintain the aesthetic effect of the building. Since the aesthetic factors cannot be easily quantified and the selections of PV panels are pre-determined by investors, the existing multi-objective optimization techniques are not adopted. (The building investors insist that the PV façade is needed whenever possible; while, from the economic point of view, it is not so cost-effective). Instead, the optimization suggestions are made as follows:

- 1) Rooftop PV array optimizations: As can be seen in the Fig. 7a, the rightmost part of the left part roof harvests comparably lower radiation. Those 8 panels should be removed. Moreover, in order to reduce the overshadow effects among rows, the distances among rows are enlarged with 30 cm;
- 2) PV façade array optimizations: In the original plan, some panels, especially in the left parts, are too close to the roof, they are very likely shadowed by the roof. In the refined version, those panels are removed. Most panels are too close to the sunblind and should be removed. In total, 41 panels are removed in the southern wall.

The optimizations mentioned above are reviewed and adopted by the architect later. The improvements are performed in the radiation analysis module by revising the PV configuration view. Afterwards, they are automatically integrated into the central BIPV model.

6.2.3. Comparisons

Table 1 lists the comparisons between the original and the refined design. As can be seen, after optimizing with e-BIM, the number of layout PV panels in the rooftop is reduced from 368 to 360. The number of PV layout panels on the wall is considerably reduced from 80 to 39. According to the specification of the selected PV panel, the efficiency of panels is about 15%. For simplicity, the temperature impact and the efficiency decay of PV panels are ignored. The annual radiation is adjusted with the typical meteorological year (TMY) weather conditions according to the weather records of the past 30 years. System connection loss is arbitrarily set as 10% according to the general practices.

As shown in Table 1, the total radiations from both wall panels and rooftop panels harvested by the new design PV system reduce from about 672 kWh to 661 kWh, i.e. declined with 1.6%. The annual outputs of the refined plan are about 98.446 kWh compared to 99.385 kWh of the original plan.

With the support of the e-BIM platform, the total cost for the PV panels are reduced at 11.7% with only 1.6% power output decline. The accounting income per kWh with subsidy, when all the generated power is self-consumed, is about 1.46 RMB/kWh (about 0.23 dollar/kWh). The static investment-return rate for the refined plan is about 6.32 years. Compared to the original plan of 7.09 years, 10.9%

Table 1
Comparisons before and after optimization

	Before	After
Num. of roof panels	368	360
Roof annual radiation/kWh	646,192	642,456
Num. of wall panels	80	39
Annul curtain radiation/kWh	25,373	18,848
Total installed capacity/kW	117.52	105.15
Total annual power generation/kWh	99,385	98,446
Cost (roof PV system)/¥	828,920	810,900
Cost (curtain PV system)/¥	200,000	97,500
Combined total cost/¥	1,028,920	908,400
Annual generation revenue/¥	145,201	143,830
Static investment payback period/Year	7.09	6.32

Fig. 8. Power system topology

improvements are achieved (Here, the efficiency decay of PV device is ignored).

Note that the power output estimations ignore the power mismatch effects which are mainly caused by the shadows on PV arrays. However, as the optimized design considerably reduces the number of shaded panels, it can be logically and safely expected that the refined plan has much less power loss which is caused by the power mismatch.

6.3. BIPV power system optimization

The introduction of PV system might significantly change the electrical power grid characteristics of a building. As the usages of both PV systems and building power shift along with time, data and weather, normally it is very difficult for designers to analyze the best design choice for PV design. One of the key design criteria is to see at which point the PV generated power is interfaced to the building grids. The e-BIM, by combining the shadow analysis, radiation analysis as well as the power flow analysis, is able to provide quantitative analysis for the temporal changes of power flow and power loss at different accessing points.

Fig. 8 shows the simplified electricity model of a building with major loads (transform equipment and the life supporting facilities for the workers), transformers, inverters and switchboards. The power from the grid is transferred from power distribution cabinets to three switchboards (#4, #5 and #6) and to loads. The power inverters of PV systems can be interfaced to the cabinet #2 and the switchboards #4, #5 and #6. The information and data of the wirings between different nodes are retrieved from the BIPV model.

Fig. 9a shows the PV systems' output and the power usage curve in the day of Feb. 10th in 2015. Fig. 9b shows, in the same day, the calculated link loss with different PV system interface plans. As can be seen from Fig. 9a, the maximum power output of PV system is about 88.25 kW with zero reactive power output. The maximum power usage of the building is about 270 kW for active power and 131 kVar for reactive power. Seen from Fig. 9, all the power generated are consumed by the building itself. Fig. 9b shows that, with the installed PV systems, both the maximum power consumptions from the grid and the power transmission losses are significantly reduced. The maximum power consumed from the grid is reduced from 304 kVA to 230 kVA, i.e. dropping at 24.2%. Seen from Fig. 9b, the introduction of PV system provides a better balanced power flow. The power consumed for transmission is reduced significantly. Considering the minimal power transmission loss, the best access point is #6 which has 12.395 kVAh link loss. It is against the general practice in which the PV system is normally attached to the major distribution cabinet. In fact, #2 is proved to be the worst accessing point. The reason is that the power line between the cabinet #2 and the switchboard #6 is longest and the line of the switchboard #6 consumes 33% of the total power. The introduction of the PV system in the point #6 rather than other points can

a) Generation and consumption curve in Feb. 10th, 2015

b) Power transmission overhead

Fig. 9. BIPV power system consumption, generation and transmission overhead on Feb. 10th, 2015Table 2
Power loss comparisons for different access points

Access location	Without PV system	2	4	5	6
Link loss/kVAh	16.410	12.732	12.632	12.514	12.395
Annual link loss/kVAh	59,076	44,051	43,668	43,212	42,753

optimize the power flow of the building. Table 2 shows the average power loss from 6 am to 6 pm in one day as well as the annual power transmission power loss for the different accessing points. It is concluded that the #6 point is also the optimal accessing point considering the losses of the whole year. Compared to the #2 point, the power transmission loss can be reduced about 1298 kVAh, and about 2.95% improvements can be achieved. This improvement is quite significant considering the selected day is in February, in which the PV systems normally generate the less power than the most of the other days during the whole year. Note that this conclusion ignores the impact of weather.

After the analyses, the #6 point, instead of the #2 point, is taken as the accessing point by electrical system designer. This modification is then automatically synchronized into the central BIPV model. Simultaneously, the PV configuration view is notified by the modification to keep the data consistency.

Although the case studied above is a small BIPV case, it can be concluded that the traditional isolated design practice cannot satisfy the complex and multi-discipline requirements of a BIPV. Too many factors influence the 'best' design of the PV systems. If without the supports of an efficient computer-aided system, the BIPV designers are hard to

figure out the effective solutions for a large and complex BIPV. The e-BIM platform, by providing a uniform model, extensive computer-aided analyses supports and UI-friendly display of results, shows the great potential to enable the optimized design of a BIPV from both aesthetic and scientific perspectives.

7. Conclusion

In this paper, a BIPV platform with a uniform data model is proposed. By providing the extensions of the domain-specific models towards BIM-based models, this design allows both BIPV data and design knowledge to be described as one consistent model. This model is congregated and transformed into the different domain-specific views. The synchronization between different views is achieved by the introduction of DSE. A supporting software platform is designed and implemented based on Autodesk® Revit. Currently, the radiation analysis and the power flow analysis modules are implemented. The results of a practical BIPV case show that the design conducted by the e-BIM platform reduces the PV system cost by 11.7% and the power transmission loss by 2.95%. The proposed e-BIM platform is free for evaluation via <http://www.bipvanalysis.com>, where the software and the sample projects can be found. The e-BIM platform has been extended for optimizing PV array deployment in complex rooftop environments. The relative work has been published in [35].

Currently, the proposed approach has only been implemented within the Revit environment. The future work is to validate the tool with a wider range of BIM authoring tools. Ongoing work might include the integration of the power mismatch model [6,20] into the system so as to optimize the link topology for the PV panels, and to integrate the power safety support for BIPV design, e.g. the ground grid design for short-circuit and lightning protection.

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