Automation in Construction 82 (2017) 59–74

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

BIM-based collaborative design and socio-technical analytics of green buildings

Tamer El-Diraby[a,*], Thomas Krijnen[b], Manos Papagelis[c]

[a] University of Toronto, Canada
[b] Eindhoven University of Technology, The Netherlands
[c] York University, Canada

ARTICLE INFO

Keywords:
Building Information Modeling (BIM)
Industry Foundation Classes (IFC)
BIM Collaboration Framework (BCF)
Socio-technical analytics
Thermal simulation
Green building

ABSTRACT

As Building Information Modeling evolves into becoming the central mean for coordinating project design and planning activities, we notice a few limitations/opportunities in the way current BIM tools address the needs for integrated design, collaboration and analysis (the initial objective of BIM). First, substantial communications and interactions about the design exist outside the BIM environment — typically in e-mail formats. This may cause distractions, delays to the project, and could waste valuable knowledge (contained in these interactions). Second, the need of engaging end-users and their keen interest in selecting "green" features. Professionals can develop different designs that achieve varying levels of energy conservation, but these will always require changes based on usage patterns. So, it is important that end-users are involved in the design process early on to make sure that they receive adequate information/ education before they make decisions. This is the nature of limitations that we try to address in this research. This paper builds around the design and development of an online system, named *Green2.0* that tries to leverage advancements in Building Information Models (BIM), energy-efficiency simulation tools, and online social network analysis methods to enable a data-driven approach to building planning, construction and maintenance. Fundamentally, it allows participants (end-users or professionals) to comment and share views about building designs. Social network analysis and semantic modeling tools are then used to extract information from these interactions. At the same time, it connects BIM to energy analysis software to allow users to select different products from a catalog and assess the impact of each on energy consumption. The platform aims to advance the current state of the art by bringing about a fundamental shift in the way that AEC professionals, end-users and public policy makers work together throughout a building's lifecycle. Designed as an open platform, it provides access to information that enables researchers and practitioners to build new, more efficient theories and methods of building design. The premise of our work is that by providing new insights into the building design process it is likely to have a profound beneficial effect for both AEC professionals and the society at large.

1. Introduction

As the world is experiencing a period of extreme urbanization, professionals and researchers of the AEC (Architectural, Engineering & Construction) industry, as well as, public policy makers are challenged by the increasing complexity and need to improve our understanding of the social, technical and business dimensions of green building design. Green building design (or sustainable building design) refers to the process of designing buildings (or other facilities) that are environmentally responsible and resource-efficient throughout a building's life-cycle [23]. This typically requires close cooperation of the design team, the architects, the engineers, and the rest of the stakeholders (clients, manufacturers, contractors) at all project stages. However, current common practice assumes that semantic building model information is typically not existing or not available online (i.e., it lies in local repositories and is typically accessible through proprietary stand-alone desktop software). Moreover, sharing of building project information is either not feasible or done in a way or at a level that is considered inadequate and inefficient, such as through email, paper printouts or other traditional channels of information exchange [2]. Therefore, the scope of collaboration and analysis is typically still limited to single projects in isolation and valuable knowledge about functioning of the various teams is lost in ad-hoc decentralized and traditional forms of communication.

* Corresponding author.
E-mail addresses: tamer@ecf.utoronto.edu (T. El-Diraby), t.f.krijnen@tue.nl (T. Krijnen), papaggel@eecs.yorku.ca (M. Papagelis).

http://dx.doi.org/10.1016/j.autcon.2017.06.004
Received 26 September 2016; Received in revised form 25 April 2017; Accepted 9 June 2017
Available online 29 June 2017

Furthermore, green building design emphasizes the increasing role of end-users in selecting green features. While the role of end-users is especially important, their early engagement and education is required to overcome adoption barriers [30,64]. As an example, professionals might develop alternative designs that achieve varying levels of energy conservation [24]. But, since these designs always require changes in usage patterns, it is essential that end-users are engaged in the design process early on and they receive adequate information/ education before making decisions [19]. However, current common practice is to perform energy efficiency simulations after the design stage. As such, design-simulation iterations are slow and operate on disjoint models, hampering sustainable design. Therefore, there is need for collaborative design of BIM in an integrated environment — one that can engage not only the professionals, but also non-expert end-users [27].

At the same time, the changing trends in the use of Web technologies that aim to enhance interconnectivity, interoperability and information sharing are transforming the way in which information is accessed and disseminated online [15]. Most importantly, availability of new standards, methods, tools and strategies that are enabled by emerging technologies in the domain of AEC suggest new ways of sharing and working with Building Information Models (BIM). Designing and developing services that provide a data-driven approach to operate on building projects, is therefore, a global imperative and defines a number of research and engineering challenges and opportunities [9].

1.1. Aim and objectives

Our research aims to alleviate the aforementioned limitations of building project design by advancing the state-of-the-art in two dimensions.

1.1.1. Managing interactions “around ” BIM.

We provide means to capture user input by integrating a commenting and annotation tool into BIM technology. Unlike existing tools, the communication model proposed benchmarks social and information network systems and is semantically rich. Recording and tracking comments by all users (professional or non-experts) is coupled with a full analysis of the resulting social and information network structure and data, which allows to understand the social connections between participating stakeholders and the dynamics of their communication. In the era of the knowledge economy, these networks and user-generated data constitute a rich source of creative ideas regarding design/operations plans. Indeed, this could provide the spark for a new realm in innovation democratization and bottom-up decision making.

1.1.2. Linking BIM to sustainability analysis.

BIM models are large and complex-yet they currently have little focus on green-oriented features. The solution is not just to expand IFC (Industry Foundation Classes) to encapsulate all data related to green design, as this would just compound the data management tasks. Rather, establish a middleware that can loosely couple BIM and independent third-party building energy analysis software and libraries, such as OpenStudio, without forcing a full merger. Such linkage will make consideration of energy usage easy-allowing for an early-stage and iterative consideration. The bridge developed between IFC and third-party energy efficiency software is not meant to provide a 100% accuracy in analysis (more fundamental and substantial rethinking of product models is needed before that). Rather, we present a novel, easy, scalable method to provide automated, fast and highly accurate means to compare the energy performance of alternative designs and model features. The aim is to provide adequate level of analysis with the end-user as a main target (i.e. we want the end-user to be able to test/ compare the approximate energy performance of two or more alternatives to support their educated-input or decision making).

1.2. Methodology and contributions

This paper builds around the design and development of an online system, named *Green2.0*, that tries to leverage recent advancements in building information models, energy-efficiency simulation tools, and social network analysis methods for enabling online socio-technical analysis of green buildings in *an integrated environment*[20,53]. In particular, *Green2.0* brings about a fundamental shift in the way we investigate and assess green buildings at multiple fronts:

- *Efficient BIM Management*: It consists of an online BIM management system that enables the efficient storage, indexing, querying and visualization of BIM elements on the Web.
- *Online Sharing and Collaboration of BIM*: It provides an integrated environment for uploading, sharing and commenting on building information models. That enables meaningful distributed online communication and collaboration of researchers and professionals of the AEC industry, but also non-expert end-users.
- *Real-time Social Network Analytics*: Mining and analysis of the collaboration data and information networks that become available in the system can reveal interesting patterns of communication. Visualization of these patterns in a meaningful way can help researchers and professionals to identify, re-design and optimize business processes, discover synergies, streamline the workflows of different stakeholders, as well as, to optimize information flow between decision makers.
- *On-demand Energy Efficiency Analysis*: It provides an integrated on-demand energy efficiency analysis for buildings that enables researchers and professionals to better study and understand the complexity of building sustainability, suggest alternatives of design options, and develop new more efficient design processes.
- *Monitoring of BIM-enabled Business Processes*: It provides an integrated environment to analyze and improve industry performance by monitoring, storing and visualizing business processes that occur during the building design and collaboration procedures.
- *A Sandbox for BIM Developers & Researchers*: It provides to researchers and third-party developers access (through a RESTful API) to a repository of (i) building information models, (ii) BIM-related communication and social analytics, (iii) Energy efficiency analysis reports, (iv) BIM-related business processes.

Green2.0 takes BIM from the realm of a stand-alone proprietary software into the realm of a socially-aware collaborative service for decision making. We aim to give people (professionals and non-experts) the controls of BIM software in order to suggest, choose, assess and innovate new means to design, build and operate their facilities.

1.3. Paper organization

The rest of the paper is organized as follows. Section 2 discusses background and related work. Section 3 provides an overview of the system's functionality and high-level architecture. Section 4 presents our approach for managing interactions between buildings and people and our methods for analyzing the dynamics of information and collaboration networks. Section 5 presents a novel method for automating the sustainability analysis of buildings within the context of BIM. Finally, a few extensions of this work are discussed in Section 6. We discuss the significance and limitations of our work in Section 7 and conclude in Section 8.

2. Background & related work

The impact of the AEC industry on the environment is substantial. Manufacturing building materials account for 10% of global energy usage; the operation phase produces at least 30% of all greenhouse gas emissions; and, demolishing buildings is responsible for 40% of all solid waste [36,56]. Therefore, designing more sustainable buildings are of vital societal importance. In addition, successfully engaging citizens in early phases of building design decisions, and educating them about the various design tradeoffs acts as a catalyst for embracing such buildings in a community, ensuring their longer life. This paper subscribes to the idea that the confluence of modular web services and a recent design paradigm, called Building Information Modeling (BIM), provide the means to reduce the energy footprint of the building life cycle.

2.1. BIM and the IFC model

A Building Information Model [18] is a digital representation of physical and functional characteristics of a building project. Each object in a real building is represented by an equivalent digital object in a BIM. These objects are characterized by geometrical representations and semantic and relational metadata. BIM software is used by professionals, businesses and government agencies who plan, design, construct, operate and maintain diverse physical infrastructures. BIM is often associated with the Industry Foundation Classes (IFC) model. The IFC model specification is an open standard registered by ISO as an official International Standard ISO 16739:2013. It is a platform-neutral, object-based structured file format that is intended to describe building and construction industry data. Contemporary BIM software provides an option to export a BIM model to the IFC file format. A typical IFC file consists of thousands of lines that adhere to the IFC model and can consume hundreds of MBs, or sometime GBs in a hard drive. IFC plays critical role in the design of *Green2.0* architecture, as it offers interoperability among BIM models that have been developed using different BIM software. By sharing all information in one open format, such as IFC, all building project actors can access relevant information when they need so that everyone can work efficient together. We elaborate more on this issue in Section 3.

2.2. Managing interactions “around ” BIM

Within the field of architectural design, typical problems that are encountered as a result of current manners of communication range from the use of inappropriate media, a failure to interpret the associated semantics and a limited effectiveness to the inability to reach the right person [10,17]. In many cases, less optimal designs or even errors are explicitly attributed to a lack of vertical communication, between successive entities (within the project design and management supply chain), and poor horizontal communication between individual team members within the same entity [47].

Simultaneously, the advent of modern web technologies, such as cloud computing, web services and the semantic web are generally considered to have the potential to shape future online collaborative environments [44,58]. This is equally expressed in the advent commercial initiatives in the AEC industry[1234]. BIM carries potential towards implementing more sustainable design construction and operation [52]. In particular, the need for comprehensive web-based tools and integration of design, construction and facility management stages as a crucial pillar to reduce carbon emissions is recognized [62]. The BIM paradigm constitutes a shift from designs as collections of two-dimensional sets of lines, into models in which buildings are represented as machine readable knowledge models. This paves the way for an automatic assessment of sustainability throughout the entire design cycle [32]. In addition, the need to expose this in an online context is ubiquitously recognized, evidenced by a body of RESTful APIs, web-services and interlinked semantic web ontologies that help information exchange across heterogeneous representations of building data and disciplines [1,14,34,37,49,57]. Consequently, standards and services are originating around BIM that enable a more collaborative context [8]. Furthermore, it is recognized that the exposure of such systems on the web enables more detailed analysis of stakeholder interaction and the evaluation of design processes [2].

Moreover, researchers have developed models to analyze the networked nature of project internal actors [16,55]. Others have considered the impact of project internal networks on the evolution of project scope [59,63]. The most advanced approach is the proposal by Chinowsky et al. [12] to model construction projects as social networks. Van Herzele [61] found that inclusion of non-expert knowledge was beneficial to the planning process given that the diversity of perspectives (especially of those who are outside of the professional bubble) can (re)discover creative solutions. In fact, citizen science often results in superior solutions [40,41]. Further, such solutions are by default, context-sensitive [13].

2.3. Linking BIM to sustainability analysis

BIM technology has been developed and promoted as means to integrate all information of building designs. However, it is overly focused on the traditional design of facilities, i.e. not green-oriented. Designers and operators have to use an increasing set of heterogeneous software systems to complement the missing features in BIM, facing multitude of challenges in relation to interoperability and data integrity. With the increasing size and sophistication of BIM files and the increasingly iterative development cycles, the burdens of transferring data between software and the management of design changes is hindering fuller analysis. Becerik-Gerber and Rice [6] found that the top three BIM functions are visualization, clash detection, and creation of as-built models. While most professionals believed that sustainability analysis is of great importance, they didn’t consider it to be a priority of the BIM agenda [11]. More alarming, researchers in green buildings found that BIM-based energy management is still an immature domain [63]. More recently, the integration of sustainability assessment and BIM has attracted attention [4,29,35,38,65]. However, these typically operate on specific sustainability measures, such as heat accumulation due to lighting or placement of photo voltaic cells or provide limited options to transfer the full semantics encapsulated in a building information model.

Another body of research is directed at quantitative scoring mechanisms to evaluate building performance as a whole. Ilhan and Yaman[31] describe an approach in which output from BIM authoring tools is enriched with a predefined set of manually assessed building characteristics related to the *BREEAM* environmental assessment method. Similar research has been conducted for other assessment methods, such as *LEED* in Alwan et al. [3].

3. Green2.0 system overview

The system presented in this paper, named *Green2.0*, brings together recent developments identified in the literature in order to advance multi-disciplinary collaboration, socio-technical analysis, comprehensive simulation and stakeholder participation in an integrated and comprehensive web-based environment towards the goal of sustainable building design. In this section, we present an overview of the system's functionality and high-level architecture.

3.1. System functionality

Central to the system is the notion of a BIM project that a project actor (user) can operate on. *Green2.0* distinguishes between two types of BIM projects —*owned* and *shared*. A user can either be the *owner* of a BIM project or can be an *invitee*— invited by an owner to join a project. The two types of users define different authorization policies and

[1] http://www.bim360.com/.
[2] https://bimsync.com/.
[3] https://www.bimplus.net/.
[4] https://flux.io/.

control access to resources. Actors participating in projects are assigned *roles* (e.g., architect and engineer). There are two ways of assigning roles to actors in *Green2.0*. The most popular way is to assign one of the popular *AEC industry roles*, coming from an AEC domain ontology [22]. To add flexibility and accommodate ad hoc roles of participation in a project, the system allows owners of the project to assign *user-defined roles*, in the form of free textual tags, a practice commonly seen in Web2.0 services.

As an *owner*, a user has unrestricted access to the projects she owns. The main functionality of the system is described below and a flowchart is provided in Fig. 2:

Creating/editing/deleting BIM projects. The IFC format of the BIM project needs to be uploaded to the service from a local computer. Most popular BIM software (e.g., Bentley AECOsim Building Designer, ArchiCAD, Tekla Structures, Autodesk Revit, Synchro PRO, VectorWorks) provides an interface to export a BIM model to an IFC file (typically having file extension ".ifc").

Exploring & Interacting with BIM. Once a BIM model is uploaded to the system, a user can visualize it as a 3D model. The 3D model is interactive, allowing the user to zoom in/out and rotate the model in any direction. Moreover, the user can select a specific BIM element, and explore its properties. The navigation is supported by a tree-like textual hierarchical view (see Fig. 1).

Sharing BIM Projects and Collaboration. A user can share a project with other users and start collaborating by participating in discussions about BIM elements (see Fig. 1). User feedback allows project owners to update the model in a timely manner and look for further feedback. The outcome of this iterative refinement process is increased coordination due to easy retrieval of information, speed of delivery and reduced costs, therefore improved overall productivity.

Performing Ad Hoc Sustainability Analysis. A user can interact with the building by substituting specific BIM elements with alternatives that are available in an interactive inventory. One can also perform ad hoc energy analysis and obtain a detailed report of the energy efficiency of the building in relation to the alternative designs.

Monitoring Activity and Trends. A user can monitor the collaboration activity and participate as required. A user interface is provided that essentially turns data coming from various sources of interactions into useful information that is summarized and visualized into a *dashboard*. Furthermore, trending discussions and useful network insights are visualized that can reveal interesting patterns of communication, therefore enhancing monitoring capabilities and better supporting decision making.

As an *invitee*, a user has limited access to the projects owned by other users including viewing, exploring and interacting with a shared BIM, participating in a discussion and monitoring the social activity around a shared project.

3.2. System high-level architecture

Green2.0 has been designed and deployed following a software delivery model known as Software-as-a-Service (SaaS) [60]. Conforming to this model, a single centrally hosted version of the application is deployed, with a single configuration (hardware, network, operating system) and users of the system typically access the software using a thin client (i.e., web browser), through a web-based user interface. The SaaS model overcomes many limitations that constrain traditional software use, deployment, and evolution and as the software is globally accessible online, collaboration among users becomes easier. In addition, the SaaS model is a suitable model for supporting integration with third-party protocols and application programming interfaces (APIs), making it easier to combine data, presentation and functionality from multiple services (e.g., cloud services).

In order to better facilitate the SaaS model, the high-level architecture of *Green2.0* is consisting of a number of loosely coupled independent components. Software components emphasize the separation of concerns in respect of the wide-ranging functionality available throughout *Green2.0*. Fig. 3 illustrates the components and how they relate to each other. In particular, three components are presented:

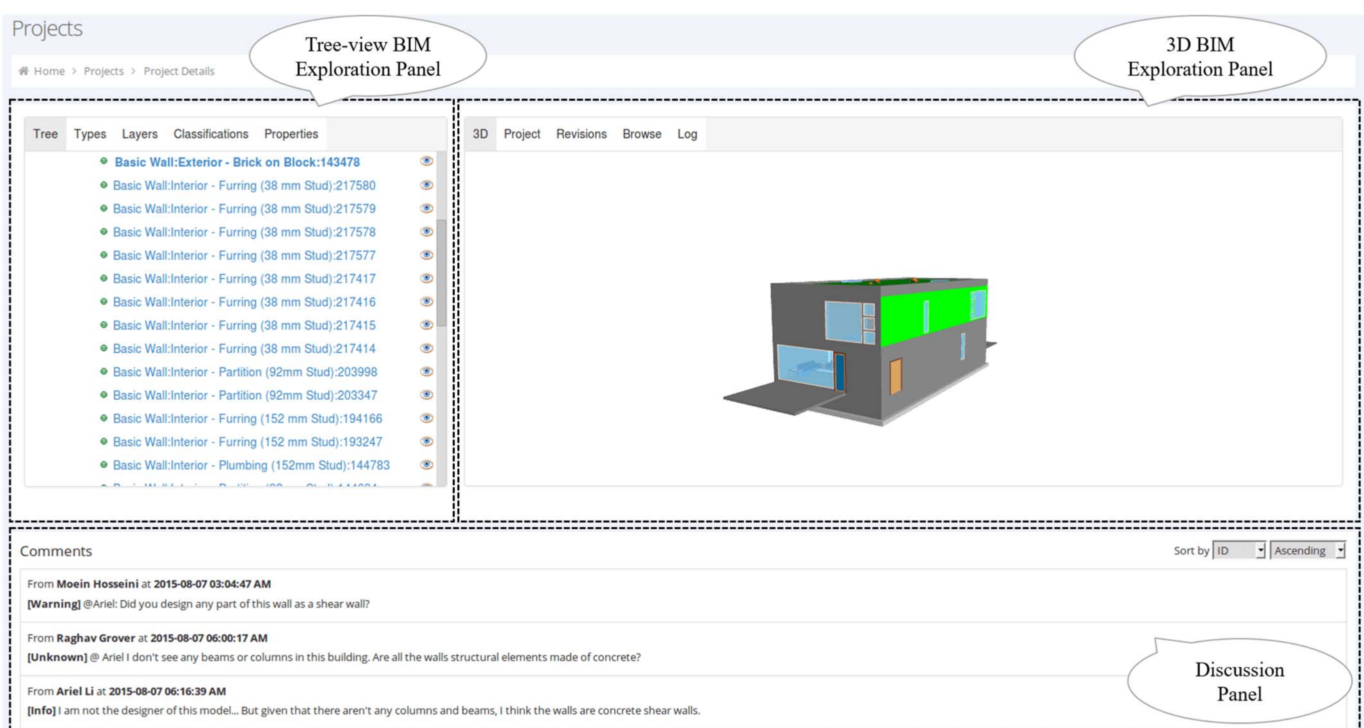


Fig. 1. BIM exploration & interaction in *Green2.0*. A user can explore elements through the 3D visualization (upper right pane) or the textual tree-hierarchy (upper left pane). Once an element is selected, comments can be submitted (bottom pane).

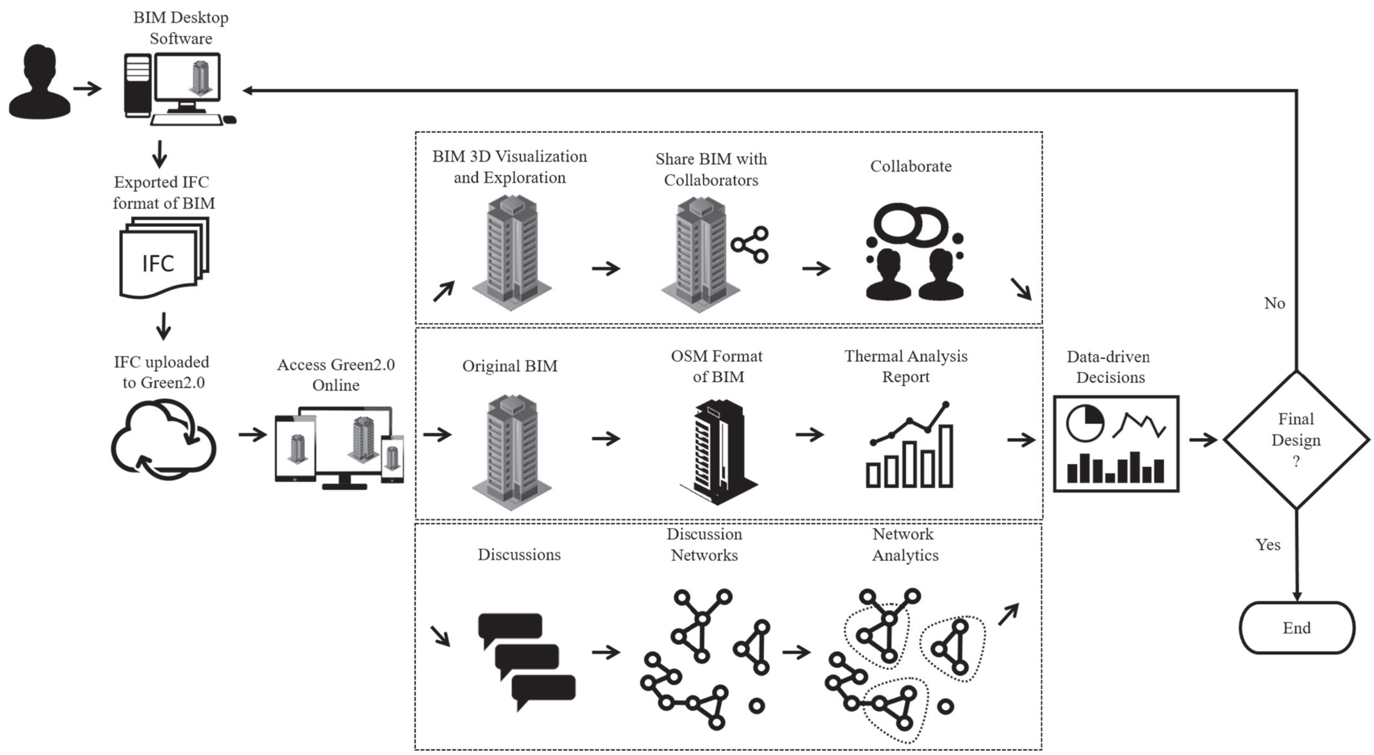


Fig. 2. Flowchart depicting the *collaboration*, *thermal analysis* and *network analysis* workflows in *Green2.0*.

- Green2.0 BIM Management (Blue).
- Green2.0 MVC (Green).
- Green2.0 Modules (Orange).

In the next paragraphs, we analyze each of these components in more detail and present the architectural design of their programming components, as well as, implementation details, interchange protocols and programming challenges.

3.2.1. Green2.0 MVC (Green)

The main part of the Green2.0 core infrastructure is a web service that is based on a *Model-View-Controller (MVC) web architecture*[42].

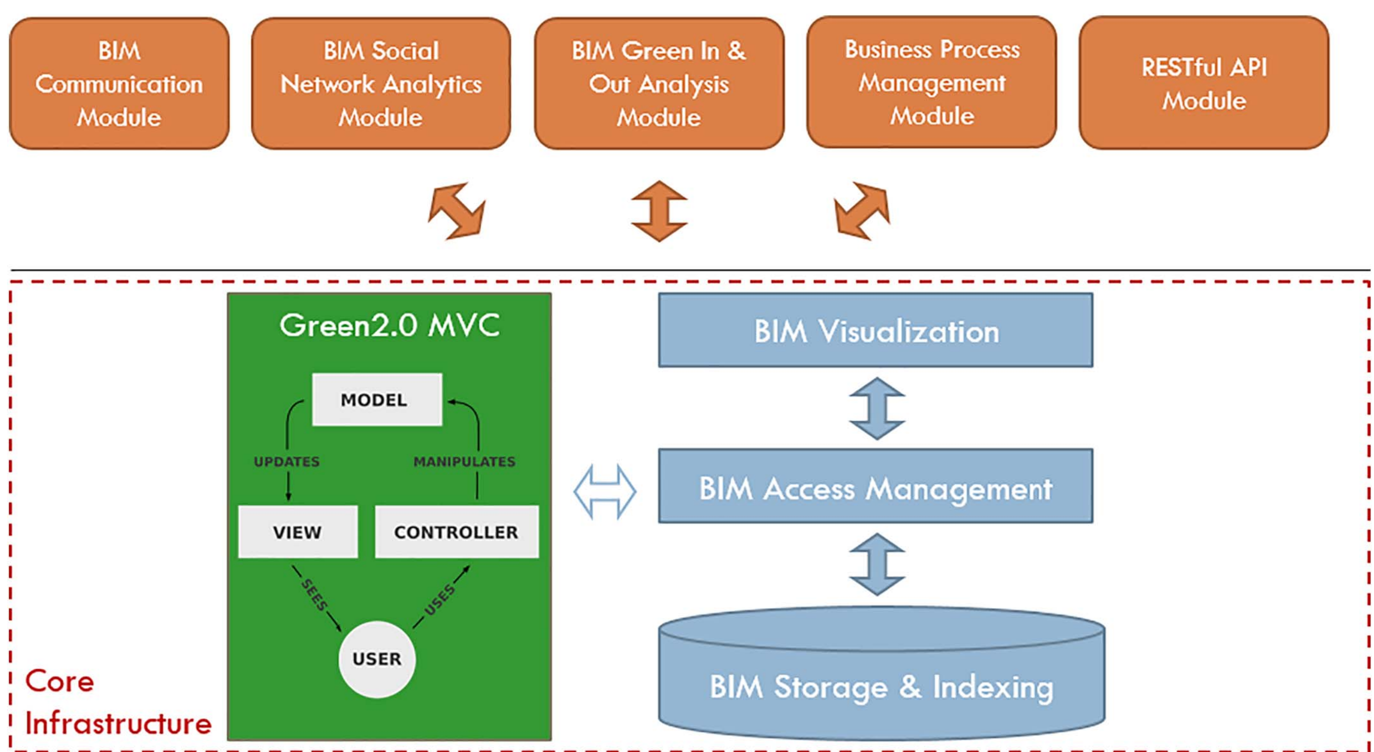


Fig. 3. Green2.0 High-level Architecture. The core infrastructure consists of a web-based service (lower left or *Green*) that is tightly integrated with BIM open source technologies (lower right or *Blue*). A number of modules are independently developed to support domain functionality (top or *Orange*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

MVC is a popular software architectural pattern for implementing user interfaces. It divides a given software application into three interconnected parts, so as to separate internal representations of information from the ways that information is presented to or accepted from the users. This component is responsible for managing all user interactions and domain-specific functionality. It is also responsible for integrating the BIM open source technologies, and facilitating the communication with the various independent components of the system.

3.2.2. Green2.0 BIM Management (Blue)

The most critical functionality of the *Green2.0* platform's core infrastructure is the efficient management and visualization of BIM models. Towards this end, *Green2.0* relies on a number of tightly-knit open source technologies:

BIM Storage & Indexing (BIMServer). The BIMServer [7] enables to centralize the information of a building design project. The core of the software is based on the open standard IFC (Industry Foundation Classes) and therefore knows how to handle IFC data. The BIMserver is not a fileserver, but uses the model-driven architecture approach. This means that IFC data are interpreted by a core-object and stored in an underlying database (BerkeleyDB[5]). The main advantage of this approach is the possibility to query, merge and filter the BIM-model and generate IFC files on the fly.

BIM Access Management (Service Interfaces). The Service Interfaces is a set of defined interfaces for interaction with BIMserver. These interfaces are defined as (heavily annotated) Java interfaces. All interfaces with namespace `org.buildingsmart.bimsie1` are implementations of the *BIM Service Interface Exchange* standard (BIMsie[6]). All calls in the `org.bimserver` namespace are BIMServer specific calls. *Green2.0* uses a JavaScript Object Notation (JSON[7]) interface (one of the three available channels to access BIMServer, along with SOAP and Protocol Buffers) to access the methods of the Service Interfaces. The JSON interface is mainly there to facilitate connecting to the BIMServer from web applications/web sites. An alternative way to access IFC elements stored in BIMServer is offered by BimQL [46]. BimQL (BIM Query Language) is an open, domain specific query language for Building Information Models. The query language is intended for selecting and updating data stored in IFC models and it is currently implemented on top of the BIMServer. Green2.0 currently doesn't support querying of a BIM model through BimQL. However, the plugin is readily integrated to BIMServer, so it can probably be easily provided as a service to professionals.

BIM Visualization (BIMSurfer). BIMSurfer[8] is an open source web-based viewer for the visualization of BIM models described as IFC models. It is based on WebGL[9] (Web Graphics Library), a JavaScript API for rendering interactive 3D and 2D computer graphics within any compatible web browser without the use of plug-ins.

3.2.3. Green2.0 Modules (Orange)

The *Green2.0* high-level system architecture emphasizes separating the functionality of the system into independent, interchangeable modules, such that each contains everything necessary to execute only one aspect of the desired functionality. With modular programming, concerns are separated such that modules perform logically discrete functions, interacting through well-defined interfaces with the core architecture. Currently, *Green2.0* consists of the following modules:

- BIM Communication Module.
- BIM Social Network Analytics Module.
- BIM Green In & Out Module.
- Business Process Management Module.
- RESTful API Module.

We further elaborate on the functionality of these modules in the rest of the paper.

4. Managing interactions "around " BIM

The first objective of our work is the efficient management of the various interactions that occur between BIM elements and people. In principle, the system provides means of online communication and collaboration of the various actors (engineers, owners, contractors, end-users, etc.) around building design elements. But, it also provides the means of structural and textual analysis of the underlying collaboration networks and discussions. In addition, it offers the means of directly interacting with the building model, substitute building elements to test alternatives and perform energy analysis, all within an integrated environment. This section provides implementation details about the modules that facilitate the management of these complex interactions.

4.1. BIM Communication Module

Green2.0 supports online communication and collaboration through *shared* BIM models. In order to share a BIM online, it first needs to be uploaded by its owner in the system, typically as an *IFC file*. Then, the *owner* can share it by sending email invitations to known actors or by browsing the user database seeking for experts to join the project. Once users have access to a shared BIM model, they can use the 3D building model visualization tool to navigate, explore, and select specific elements of the model (see Fig. 1). Once an element is selected, the various element properties are listed that provide useful information to the expert. The collaboration is facilitated by means of a rich comment management tool that allows to submit, edit, delete, and filter comments about selected BIM elements. The functionality is similar to that found in an online discussion forum, with the exception that the discussion is domain-specific and thus domain-specific features are supported. To facilitate interoperability and support the openness of the platform we made a decision to model comments so as to adhere to the *BIM Collaboration Format* bcfXML-v1[10][8], an open standard that supports workflow communication in BIM processes. According to the standard, comment types are one of *info*, *error*, *warning* or *unknown* (see Fig. 4 (a)). A user can navigate comments in chronological order or other semantic properties. Notifications are also available that inform actors for new dialogues or updated conversations.

4.2. BIM Social Network Analytics Module

As various actors interact with building information models online, large amounts of data become available to the system. This module is responsible for the collection, storage, analysis and visualization of such data in a meaningful way. Reporting real-time aggregate information about BIM project activity is essential. Fig. 4 (a) and (b) shows aggregate analytics about an example BIM project.

Social interactions that occur among the various actors (engineers, owners, contractors, etc.) during collaboration processes consist valuable information for analysis [48]. Revealing interesting patterns of this communication can further enrich user experience and support decision

[5] BerkeleyDB is a family of embedded key-value database libraries providing scalable high-performance data management services to applications. The BerkeleyDB products use simple function-call APIs for data access and management.

[6] https://buildingsmart.github.io/BIMSie/.

[7] JavaScript Object Notation, is an open standard format that uses human-readable text to transmit data objects consisting of attribute-value pairs. It is used primarily to transmit data between a server and web application, as an alternative to XML.

[8] http://bimsurfer.org.

[9] https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API.

[10] http://www.buildingsmart-tech.org/specifications/bcf-releases/bcfxml-v1.

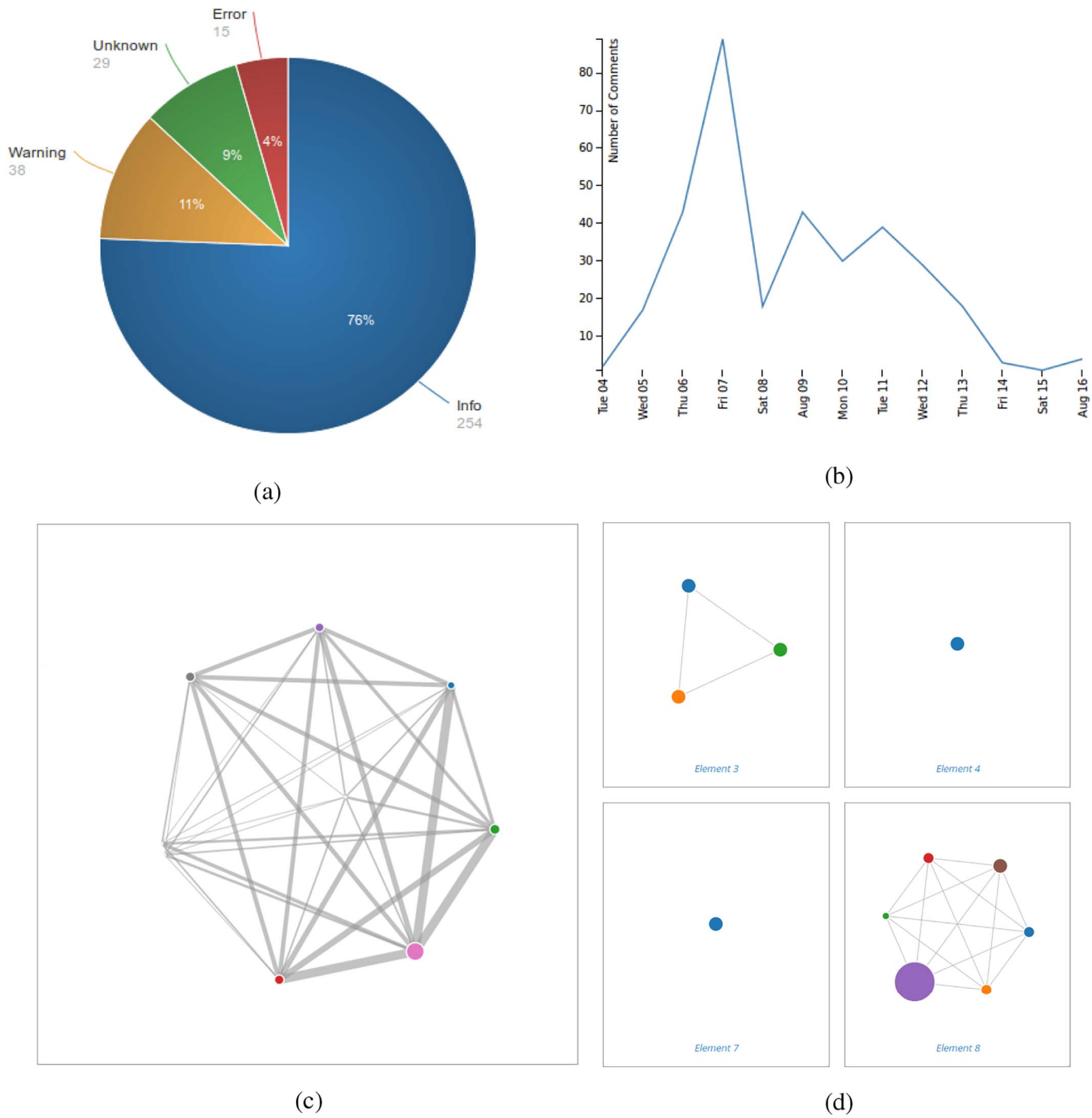


Fig. 4. Example analytics in *Green2.0*. (a) Distribution of project comments by *type* according to the bcfXML-v1 open standard, (b) Distribution of project comments *over time*, (c) Example project-level network (PN), (d) Visualization of trending discussions (element-level networks (EN)).

making [54]. The approach we follow is to define *discussion networks* based on interactions of actors and building elements and perform analysis on the underlying networks [28]. These networks can be defined at many different levels of granularity. Aiming for a platform as flexible and open as possible, we made the decision to define networks at three different levels of operation:

- Element-level Networks (*EN*)
- Project-level Networks (*PN*)
- Cross-project-level Networks (*CN*)

For each of the operational level above, a graph $G(V,E)$ is defined comprising of a set of vertices V and a set of edges E. In the case of *EN*, each node represents a user and each edge represents that two users have contributed in a discussion thread about a specific building element. Accordingly, in the case of *PN*, each node represents a user and each edge represents that two users have contributed in discussion threads of at least one common building element of a BIM project.

Finally, in the case of *CN*, each node represents a user, and each edge represents that two users have contributed in at least one discussion thread of a shared project. It is easy to see that a user always represents a node in the network, while the type of interaction between two users defines the exact semantics of an edge in that network. For the various definitions of a network (*EN*, *PN*, *CN*), a number of network insights are possible, based on network analysis. For each network, *Green2.0* reports a number of important network structure measures, such as *network size*, *diameter*, *density* and *characteristic path length*. Note that due to the system's architecture, it is easy to plug-in more network measures to meet the needs of the various actors of the AEC domain.

As mentioned earlier, this module is also responsible for the visualization of the various networks. Fig. 4 (c) shows an example *PN* network, while Fig. 4 (d) illustrates a number of *EN* networks about various elements of a specific project. See how a user can easily depict trending discussions visually. For example, the element-network (EN) representing BIM “Element 8” in Fig. 4 (d) is trending because there is a lot of discussion going on around it, as depicted by the large size of the network. A user can navigate there directly by means of selecting (clicking on) the network. There is a number of ways to make the network visualizations more informative. Nodes can be labeled with user-specific information, such as the role that a user is assuming in the discussion; edges can be labeled with properties, such as the time of interaction or the frequency of interactions over a time period. Essentially, *Green2.0* informs about the network structure and BIM-related semantics of network nodes and edges, then analysis can be performed in a number of meaningful ways.

The BIM Social Network Analytics Module is possible due to integration with third-party network analysis libraries. In particular, the NetworkX[11] software package is used for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks. Our system exports instances of a network based on the various definitions of a network (*EN*, *PN*, *CN*) and provides them as input to the library. The library performs optimized computations and computes the graph metrics, which are then communicated back to our system and stored locally in the *Green2.0* database. For network visualization purposes, we employ the D3.js JavaScript library[12].

4.3. BIM Green In & Out Module

The second objective of our work is to allow users to examine energy performance of several design alternatives ahead of making decisions. This is particularly important in educating them ahead of making “green” choices. For this purpose the *Green In & Out Module* is introduced. It provides a comparative energy analysis of building models by interfacing with a third-party energy analysis tool, OpenStudio. OpenStudio[13] is a cross-platform (Windows, Mac, and Linux) collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. It is an open source project to facilitate community development, extension, and private sector adoption. Other software applications for energy analysis, such as DesignBuilder, eQuest, and IES try to present a state-of-the-art User Interface to users. However, these software applications are commercial (proprietary). As a result, users are constrained by the provided UI to make limited analyses. In contrast, OpenStudio is open-source, cross-platform and cross-language. In addition, OpenStudio provides a rapid development mode and open application programming interface (API), which makes it highly extensible and customizable. All of these aspects suggest OpenStudio as a suitable platform for supporting the data exchange needs of building energy modeling in *Green2.0*. In particular, the module provides the following end-user functionality:

- *Building Model Decomposition into Building Elements*: The module supports a detailed visualization of a building model as a decomposition of elements that affect its energy behavior (see Fig. 5 (a)).
- *Building Element Catalog*: IFC is a relational data model in which building elements (subtypes of IfcProduct) are related to type information that groups common traits of building elements of the same class (subtypes of IfcTypeObject). As an example consider an IfcWall, which can be related to an IfcWallType. The product type tree, used for substitution, is built from subtypes of the IfcTypeObject in the IFC file. Upon synchronizing the data with the main platform, the IFC files are scanned for such instances and recorded in the local database. This way the types in a model become available for substitution to all models in the *Green2.0* database (see Fig. 5 (b)).
- *Building Element Substitution*: The aim of the *Green In & Out Module* is to provide a comparative energy analysis of alternative building models. One key component of such a framework is to make assessments on the performance of an individual building element in relation to the complete building assembly. For example, an engineer might want to assess multiple window systems for the same building. In order to facilitate this, a building element substitution API is presented that allows to locally replace building elements, such as a window, with a comparable element (see Fig. 5 (a) and (c)).
- *Sustainability Assessment of a Building*: In order to support sustainability analysis of alternative building designs in *Green2.0*, building models need to be interpreted by software tools that support energy modeling. The results of the analysis are presented to the user by means of an HTML report (see Fig. 5 (d)).

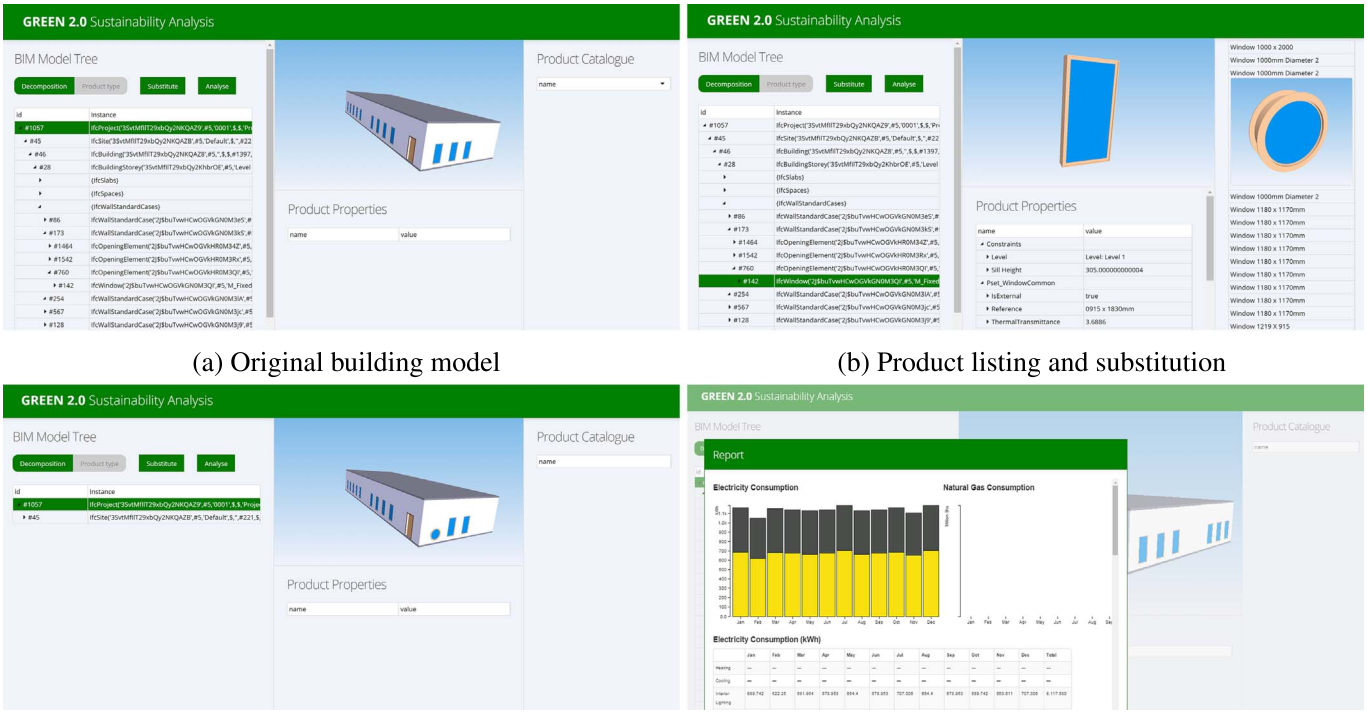
The integration of OpenStudio into the platform is critical for the *Green2.0 In & Out Module*. The main challenge is to map the information represented in an IFC file to information that can be represented in an OpenStudio Model (OSM) file [65]. A crucial difference between the two formats is that IFC files describe a building as a decomposition of individual components, which have one or more solid-volume geometrical representations and are enriched with semantic and relational information. An OSM file describes the building from the viewpoint of thermal zones and thin-walled space boundaries. Therefore, not only does the information need to be encoded differently, the geometrical information needs to undergo a translation process that flattens the solid-volume geometry for space bounding elements (such as walls, roof and floor slabs) into thin-walled thermal zone boundaries. Section 5 provides detailed description of this translation process that enables to link IFC models to sustainability analysis libraries.

5. Linking BIM to sustainability analysis

One of the main objectives of the *Green2.0* project is the parametric analysis of the sustainability of alternative building designs. In the system presented here, a quantitative approach is emphasized based on simulation results directly obtained from the processed BIM model. As such, alternatives for selected building components can be individually evaluated in context of the overall building design while maintaining that information is up-to-date and accurate. On the other hand, geographic and demographic considerations, such as public transport policies, that are assessed in quantitative scoring approaches, such as Ilhan and Yaman and Alwan et al. [3,31], are not the focal point of this research.

There are a number of motives for building green, including environmental, economic, and social benefits. However, modern sustainability initiatives call for an integrated and synergistic design approach that integrates the building life-cycle with each green practice. The goals of a green building are usually related to life-cycle assessment

[11] https://networkx.github.io/.
[12] http://d3js.org/.
[13] http://openstudio.nrel.gov.



(a) Original building model

(b) Product listing and substitution

(c) Original model after undergoing a window substitution

(d) Example sustainability report of a model

Fig. 5. The *Green In & Out* user interface. (a) A BIM model is loaded and model elements are nested under their relating type in the model tree, (b) A window element of the BIM model is selected; alternative products (i.e., windows) are automatically listed, suitable for product substitution, (c) A transformation occurs to the original model, (d) A sustainability report is generated for each model that enables comparative sustainability analysis of alternative designs.

(LCA), structure design efficiency, energy efficiency, water efficiency, materials efficiency, indoor air quality, waste reduction. The essence of green building is an optimization of one or more of these principles.

The focus of *Green2.0* has been on *energy efficiency* and in particular, *thermal performance*. For detailed thermal assessment of a building, a representation of its Heating Ventilation and Air Conditioning (HVAC) system is essential. However, the interpretation of these data in the IFC models is not currently in place. Yet, when it comes to reliably predicting building energy uses, the configuration and functioning of the HVAC system plays an important role [50].

When information flows between stakeholders in a construction project these different actors have distinct modeling paradigms. For successful communication one needs to transliterate into an idiomatic representation of information native to the receiver. For the needs of *Green2.0* the main challenge is to map the information represented in an IFC file to information that can be represented in an OpenStudio Model (OSM) file [65]. For the case of thermal analysis in particular, this means that the model needs to undergo some geometrical transformations. The BIM model describes a building as a decomposition of solid volumes, that needs to be translated into a watertight assembly of thin-walled thermal zone boundaries [5]. In addition, classifications of element types can be used to filter out irrelevant elements that do not affect the thermal behavior of the system [51].

5.1. Prerequisites

The geometry in IFC has traditionally been known to be lower order tessellated geometries, where semantically richer and more precise models could have been more appropriate [25,33].

The abstract `IfcRepresentation` entity is the base for the majority of the typical three-dimensional view on a BIM model. Relational meta-data can also be annotated with geometrical elements. In the context of thermal simulation, most notably, this is reflected in the concept of spaces boundaries `IfcRelSpaceBoundary`, which relate spaces to their bounding elements by means of a surface where the two elements touch. Similarly, `IfcRelConnectsPathElements` can be used to model how wall elements connect into closed loops. However, space boundaries in general can be missing or inaccurately defined [45].

`IfcRepresentationItem` has 124 subtypes in the IFC2 $\times$ 3 schema. This creates a wide variety of constructs that can be used to model geometry in IFC. On top of that, geometry contained in representation items can be altered by relations on a product level. In particular, and very commonly, `IfcOpeningElement`s are used to model cavities in walls and slabs, which subsequently are filled by other building elements, such an `IfcWindow`.

A boundary representation (BRep) is a data structure for representing solid volumes by describing its oriented bounding surfaces. It describes the topology (or connectivity) into types such as: *vertices*, *edges*, *wires*, *faces*, *shells*, and*solids* and associates the geometry (typically in Cartesian space), such as *points*, *curves* and *surfaces*. Solid volumes with the same topological characterization can have different geometric forms. For example moving the underlying points of the vertices only affects the geometry. In contrast, edge curves or face surface can be altered without affecting the topology. Topological elements from a hierarchy, and hence, a BRep is in fact a tree structure, in the sense that a solid encapsulates one or more shells, which in turn encapsulate one or more faces, and so on. The elements that are not paired with a geometrical elements, aggregate one or more lower level topological entities.

Algorithm 1. Collapse solid wall volumes.

1: **function** COLLAPSE(w)
2: **for all** rep in $w.Representation.Representations$ **do**
3: **if** $rep.RepresentationIdentifier$ =“Axis” **then**
4: $\mathcal{A}_w \leftarrow$ BREP(rep) ▹ Create Boundary Representation
5: **else if** $rep.RepresentationIdentifier$ =“Body” **then**
6: $\mathcal{B}_w \leftarrow$ BREP(rep)
7: **assert** EDGES($\mathcal{A}_w$) $\neq \emptyset$
8: **assert** FACES($\mathcal{B}_w$) $\neq \emptyset$
9: $C_{\mathcal{A}_w} \leftarrow$ CURVE(e) $\mid e \in$ EDGES($\mathcal{A}_w$) ▹ Random edge from set, wall assumed continuous
10: $d \leftarrow \emptyset$
11: $u \leftarrow (\infty, -\infty)$
12: **for all** $\mathcal{F}_{\mathcal{B}_w}$ in FACES($\mathcal{B}_w$) **do**
13: **if** SURFACE($\mathcal{F}_{\mathcal{B}_w}$) $\parallel \mathcal{P}_{XY}$ **then** ▹ Parallel with XY plane
14: **if** SURFACE($\mathcal{F}_{\mathcal{B}_w}$) $\cap C_{\mathcal{A}_w} \neq \emptyset$ **then** ▹ Intersects with axis curve
15: **for all** $\mathcal{V}_{\mathcal{F}_{\mathcal{B}_w}}$ in VERTICES($\mathcal{F}_{\mathcal{B}_w}$) **do**
16: $\mathcal{P}_0 \leftarrow$ POINT($\mathcal{V}_{\mathcal{F}_{\mathcal{B}_w}}$)
17: $u_0 \leftarrow$ PROJECT($\mathcal{P}_0 \rightarrow C_{\mathcal{A}_w}$) ▹ Project point onto axis curve, returns curve parameter
18: $u \leftarrow (\min(u(0), u_0), \max(u(1), u_0))$
19: $\mathcal{P}_1 \leftarrow C_{\mathcal{A}_w}(u_0)$ ▹ Evaluate curve at u_0
20: $\vec{v} \leftarrow \mathcal{P}_1 - \mathcal{P}_0$ ▹ Find difference vector
21: $d = d \cup \vec{v}$ ▹ Add to set
22: **assert** $|d| = 2$ ▹ Modulo modeling precision
23: **return** EXTRUDE(TRIM(OFFSET($C_{\mathcal{A}_w} \rightarrow$ avg(d)), u))

5.2. Proposed solution

As has been mentioned in previous sections, the geometry simplification module presented in this paper transliterates from an architectural or structural modeling paradigm into an idiomatic thermal analysis model. From literature and own experiences it appears that space boundary geometry can be unreliable [45], therefore the module operates to a large extent only on the explicitly visible information, the representations of the building elements. This ensures no operations incur based on data that is invisible to end-users.

IFC Representation of building elements are converted into generic Boundary Representations, for the purpose of having a generic view on the geometry, agnostic of what exact geometrical entities (e.g. extrusions and explicit meshes) define the shape of the elements. For example, in the case of wall elements, two key representations are targeted: their Body and their Axis. The former is converted into a *Solid* or *Shell*, the latter is interpreted as a *Wire*. The following are the main steps used. Fig. 6 shows a sample of the transformations conducted. In general, we start by a full IFC model (Fig. 6 (a)). we then select a zone or subset for analysis (Fig. 6 (b)). Six transformation processes/algorithms are then used to reach the final thermal zone representation shown in Fig. 6 (h).

5.2.1. Collapse solid wall volumes (Fig.6(d), Algorithm1)

Algorithm 1 defines a surface ($\mathscr{C}_{\mathscr{A}_w}$) parallel to the longitudinal direction of the wall (w) that can replace the solid geometry of the wall in a water-tight surface model of thermal zones. Vertices from the footprint of the wall are projected onto the parametric space of the `Axis` curve. The difference vector to the projection of these vertices is stored in the set created at Line 10. For walls with uniform thickness, these will fall into two bins, modulo modeling precision, that represent the distances of the two vertical faces in the longitudinal direction of wall w to $\mathscr{C}_{\mathscr{A}_w}$. Averaging these two distances yields to necessary amount by which $\mathscr{C}_{\mathscr{A}_w}$ needs to be offset in order to produce the center face. Note that this procedure is necessary as $\mathscr{C}_{\mathscr{A}_w}$ is not necessarily in the middle of the wall, this depends on the `IfcMaterialLayerSetUsage` associated to the wall.

5.2.2. Create subsurfaces (for wall openings)

Window and door geometries tend to be defined in great detail in IFC files, typically using detailed faceted geometry. Yet, from a thermal analysis point of view, a single surface, defined as a subsurface on the wall surface that harbors these elements is sufficient. Hence, the wall center surfaces, that are the result of the previous step A. are intersected with the opening element volumes to come to a simplified, yet accurate, subsurface for these elements. Since this is a straightforward boolean operation, no algorithmic description of this step is provided. The subsurfaces are shown in Fig. 6 (h).

5.2.3. Align wall end-points (Fig.6(e), Algorithm2)

Because thick wall volumes have been transferred into a single surface, these surfaces do not align at the corners where two walls meet. In some cases, this leaves a gap between them. In Other cases, this means that one surface extends beyond the other. Yet, for the thermal simulation, it is imperative that the thermal zone volume is water-tight. Hence, for every permutation of connected wall elements, the center face surfaces are intersected and trimmed or extended based on the found intersection curve (see Fig. 7).

5.2.4. Trim surfaces to create closed loops around spaces (Fig.6(f))

Walls can extend beyond the boundary of a single space and run alongside several spaces, as can be seen in Fig. 6 (c). In order to proceed from Fig. 6 (e) to (f) halfspace solids[14] are constructed from the wall center faces in Fig. 6 (e) and used to trim connected walls. This operation only needs to be applied to “ATPATH” wall connections.

5.2.5. Connect spaces vertically

Similarly to how walls have been collapsed to a single face, slabs that bound the spaces are flattened to a single center face, based on their orientation. The wall center faces are extended to these faces. And for the spaces, bottom and top faces are created on these slab center faces, bounded by the projections of the wall boundaries. Geometrically, this is similar to the horizontal alignment of wall end-

[14] A halfspace solid is a solid that divides the Cartesian space $\mathbb{R}^3$ into two sets, either on the one side, or the other side of the bounding surface

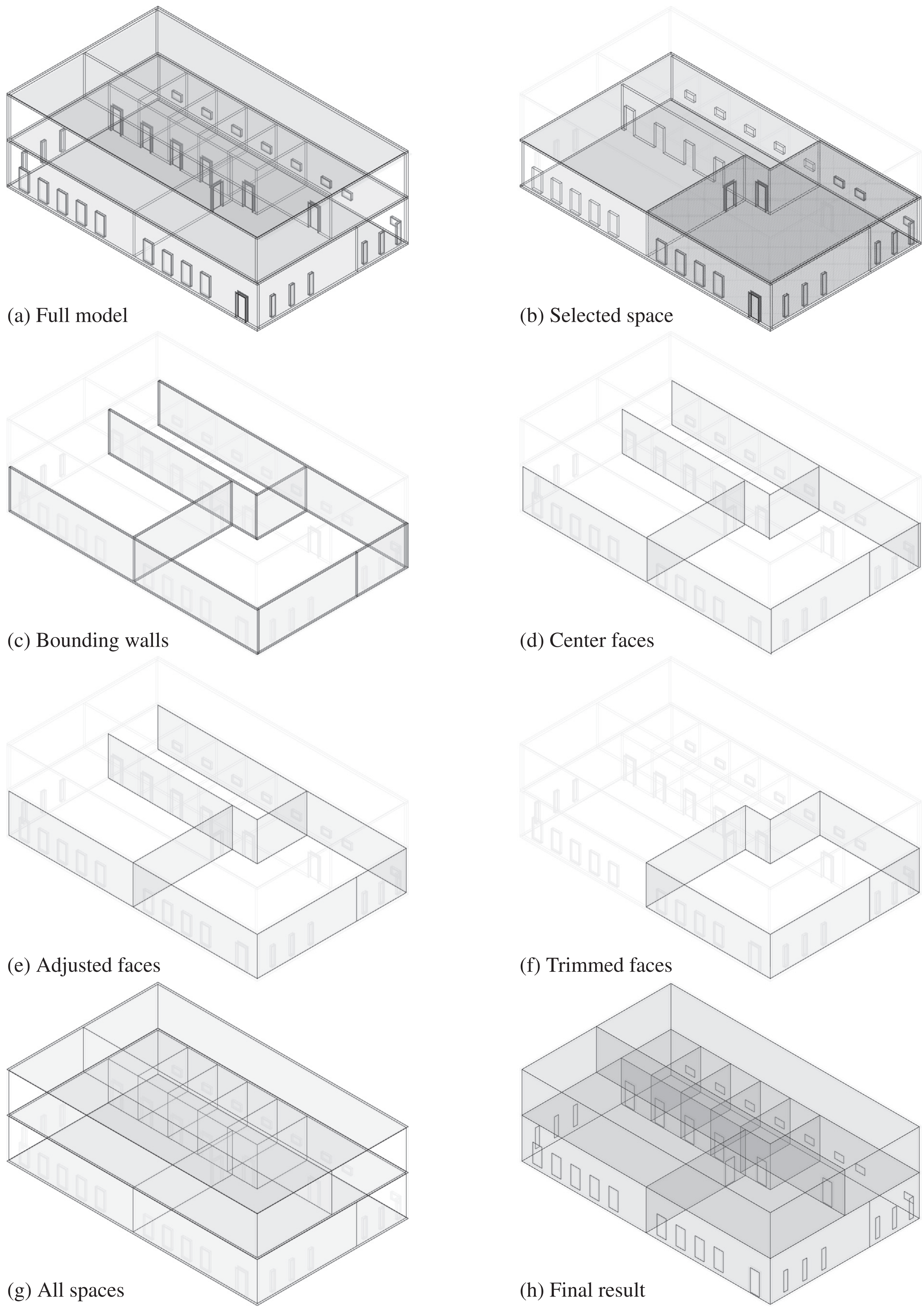


Fig. 6. Schematics of geometrical simplification steps.

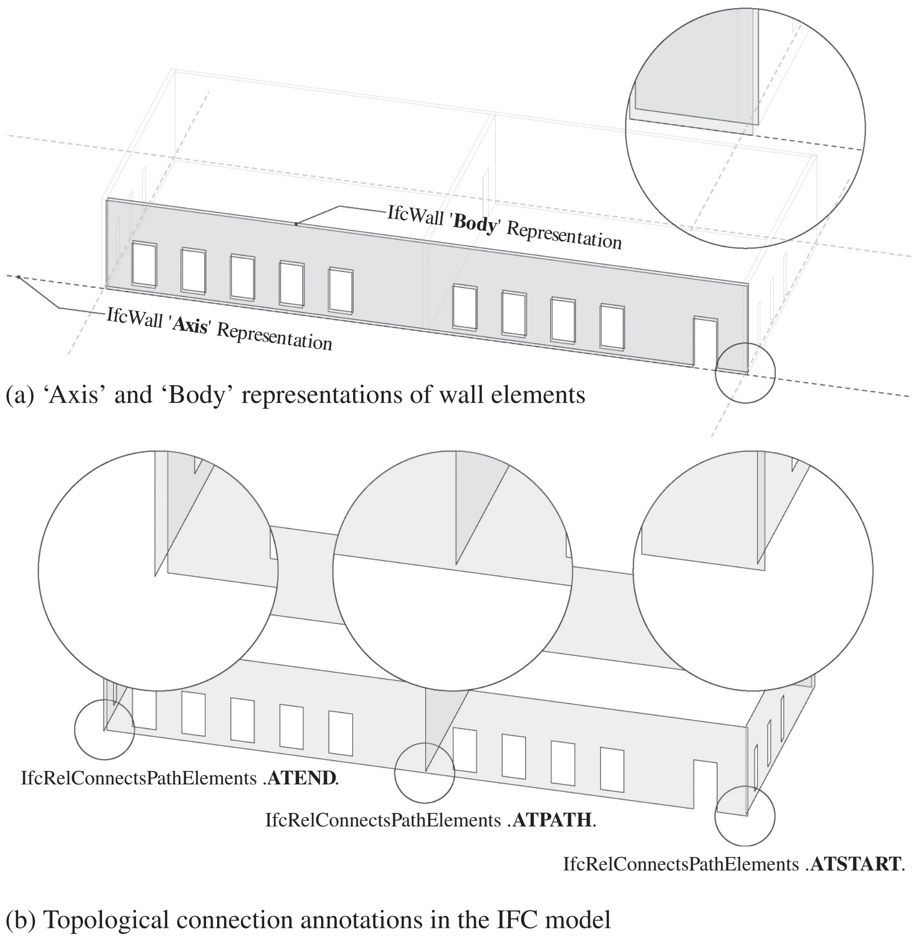


Fig. 7. Aligning wall end-points after collapsing solid volumes.

points, hence, an algorithmic overview is omitted for brevity. The result of the procedure can be seen in the transition from Fig. 6 (g) to (h).

5.2.6. *Create interfaces*

The result from the previous step is a single water tight volume for every space, that aligns geometrically with all neighboring spaces. However, similar to the concept of second order space boundaries, interfaces need to be created that map exactly from one thermal zone to another. For example, in case walls that extend beyond multiple spaces, one thermal zone boundary would map to several other zones. Hence, for all 2-combinations of spaces $\{\{S_0,S_1\} \mid S_0 \neq S_1; S_0 \in \text{IfcSpace}; S_1 \in \text{IfcSpace};\}$ if there is a building element B with $B \in \text{IfcSlab} \cup \text{IfcWall}$ that connects S_0 and S_1, the faces resulting from Step D. $\mathscr{F}_{S_0,B}$ and $\mathscr{F}_{S_1,B}$ need to be intersected such that there is one face exclusively interfacing S_0 and S_1. Since these faces share the same underlying surface, the boolean intersection can be performed in the two-dimensional parametric coordinate space of the surface. This step yields the completely converted geometrical model in Fig. 6 (h).

5.3. *Requirements and limitation of the current implementation*

The algorithm operates on the following constructs that need to be present in order for conversion to be successful. Workarounds, that are not currently implemented, are given in case they are deemed feasible.

5.3.1. *"Body" and "Axis" representation for walls*

Without "Axis" representations, the opposing longitudinal faces cannot be identified and the solid wall volume cannot be collapsed into a single face. In this case the algorithm will terminate. Alternative ways of identify the longitudinal faces can be implemented, for example by judging surface area or the width of the `IfcMaterialLayerSet`.

5.3.2. *Geometric continuity of walls*

Discontinuities in the wall axis will result in more than two projection vectors in Algorithm 1, Line 22. In this case, the algorithm will terminate. Note that according to Liebich [43], the `IfcWallStandardCase` concept dictates the same requirements. A possible solution to this include subdividing walls by the algorithm at discontinuities.

5.3.3. *Walls of uniform thickness*

A non-uniform thickness will yield different projection distances for the reduced surfaces. In this case the algorithm will terminate. Further, non- uniform thickness implies that the thermal conductivity of the wall will not be uniform either. The changing thickness can be approximated by subdividing the wall at regular intervals.

5.3.4. *Semantic relations to opening elements*

This is standard practice described in Liebich [43].

5.3.5. *Connectivity information for elements to spaces*

Without this, a thermal-zone centric view cannot be obtained. Several contemporary IFC exporters have the option to turn this on or off.

Algorithm 2. Align wall end-points.

procedure MERGE_ENDS(w_0)
  $\mathcal{F}_{w,0} \leftarrow$ COLLAPSE(w_0) ▹ Center face function from Alg. 1
  for all rel in $w.ConnectedTo$ **do**
    if $rel \in$ IfcRelConnectsPathElements **then**
      $rt \leftarrow rel.RelatingConnectionType$
      if $rt \in$ {ATSTART, ATEND} **then** ▹ If .ATPATH. only the related wall end needs to move
        if $rel.RelatedElement \in$ IfcWallStandardCase **then**
          $\mathcal{F}_{w,1} \leftarrow$ COLLAPSE($rel.RelatedElement$)
          $\mathcal{C}_{w,1,2} =$ SURFACE($\mathcal{F}_{w,0}$) $\cap$ SURFACE($\mathcal{F}_{w,1}$)
          $d_{min} \leftarrow \infty$
          $\mathcal{E}_c \leftarrow \emptyset$
          for all e in EDGES($\mathcal{F}_{w,0}$) **do**
            $d \leftarrow$ DISTANCE(CURVE(e), $\mathcal{C}_{w,1,2}$)
            if CURVE(e) $\parallel \mathcal{C}_{w,1,2}$ **and** $d < d_{min}$ **then**
              $\mathcal{E}_c \leftarrow e$ ▹ The edge closest to the intersection will be moved
              $d_{min} \leftarrow d$
          $\mathcal{V} \leftarrow \emptyset$
          for all e in EDGES($\mathcal{F}_{w,0}$) **do**
            if $e \neq \mathcal{E}_c$ **then**
              $\mathcal{V}_{e,c} \leftarrow$ VERTICES(e) $\cap$ VERTICES($\mathcal{E}_c$)
              if $\mathcal{V}_{e,c} \neq \emptyset$ **then**
                $p \leftarrow$ CURVE(e) $\cap$ CURVE($\mathcal{E}_c$)
                VERTICES(e) $\leftarrow$ VERTICES(e)$\backslash\{\mathcal{V}_{e,c} \rightarrow p\}$
          EDGES($\mathcal{F}_{w,0}$) $\leftarrow$ EDGES($\mathcal{F}_{w,0}$)$\backslash\{\mathcal{E}_c \rightarrow \mathcal{C}_{w,1,2}\}$

5.3.6. Topological connectivity information using IfcRelConnectPathsElements

The algorithm will not terminate, but will fail to create water tight volumes, as Algorithm 2 depends on this information. As an alternative, it is possible to compute topological adjacency based on geometrical proximity.

5.3.7. Correct classification of walls and slabs

Elements are selected for processing in relevant steps based on their IFC entity types. Sometimes these can be incorrectly classified [39]. There is no remedy for this.

5.3.8. Convex space volumes vertically

As far as the bounding loop of adjacent walls is concerned, a space can have concavities in its footprint. However, a concave elevation will yield incorrect vertical alignments.

6. Extensions

In this section, we discuss two extensions of our research. The *first*, manifested as the *Business Process Management Module*, allows to monitor and store information of all the BIM-related building design processes that take place in *Green2.0*. This is critical information, not currently available that can lead to further analysis and optimizations of the building design and collaboration processes. The *second*, manifested as the *RESTful API Module*, enables interoperability of our service to third-party services through providing access to *Green2.0* resources. We elaborate on these issues in the next paragraphs.

6.1. Optimization: business process management module

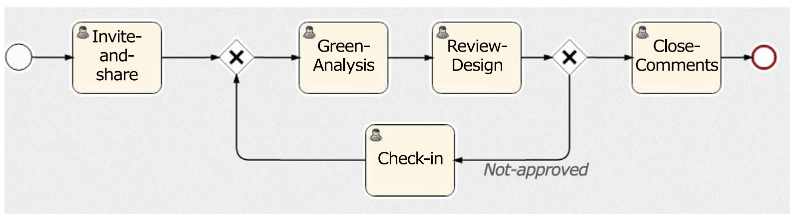
One of the long-term objectives of our research is to improve corporate performance by optimizing business processes related to the building design projects. To that end, we designed and developed a Business Process Management (BPM) module that operates on processes that become available in *Green2.0* and supports:

- Storage of the business processes that evolve in *Green2.0*.
- Monitoring and exploration of business processes.
- Offline analysis of BIM business processes.
- Access to BIM business processes through a RESTful API.

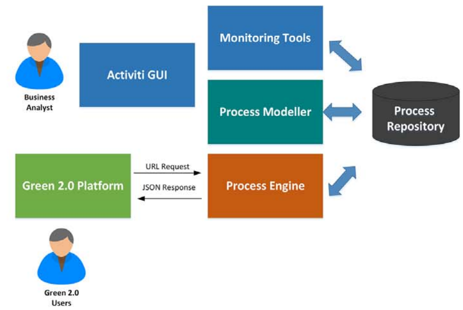
The above functionality becomes feasible by integrating *Green2.0* with Activiti[15], an open source light-weight workflow and Business Process Management (BPM) platform. Processes are designed in Activiti and are instantiated in Green2.0. As users perform tasks and interact with each other in *Green2.0*, Activiti RESTful calls are automatically invoked that inform and update the BPM engine. Fig. 8 (a) illustrates an example *Green2.0* business process. A user initiates a new process instance by creating a new project. The process instance saves information about the project owner, name, description, and creation time. A user then invites other users to comment on her building design and performs a green analysis. Based on the green analysis results and the comments received from other users, the user re-evaluates the design and may (or may not) check-in a new design. If the design is complete, the user stops accepting comments and hence terminates the process instance.

The integration of Green2.0 and the Activiti BPM engine is of great significance, as it provides a repository of all the BIM business processes that took place in the system. This defines an enormously interesting data set as it provides the ability to analyze and optimize BIM business processes offline. Fig. 8 (b) shows the three main components of the Activiti BPM engine: *process modeller*, *process engine*, and *monitoring tools*. The *process modeller* provides the visual design tool required to define a business process, as a collection of interlinked activities achieving a certain goal. Processes are defined using the Business Process Model and Notation (BPMN[16]) standard. The BPMN provides the notation required to communicate process information to business process actors. The *process engine* is responsible for the execution of the process model defined by the modeller. It keeps track of the different process instances created by the *Green2.0* users, the current state of each process instance, data associated with each task/process step, and the history of the user interactions. In addition, the *process engine* manages execution paths of each process instance by applying the

[15] http://activiti.org/.
[16] http://www.bpmn.org



(a)



(b)

Fig. 8. Business Process Management Module. (a) An example process definition in Green 2.0. Multiple process instances are instantiated based on a process definition, (b) The three components of the Activiti Business Process Management module that are integrated with *Green2.0*.

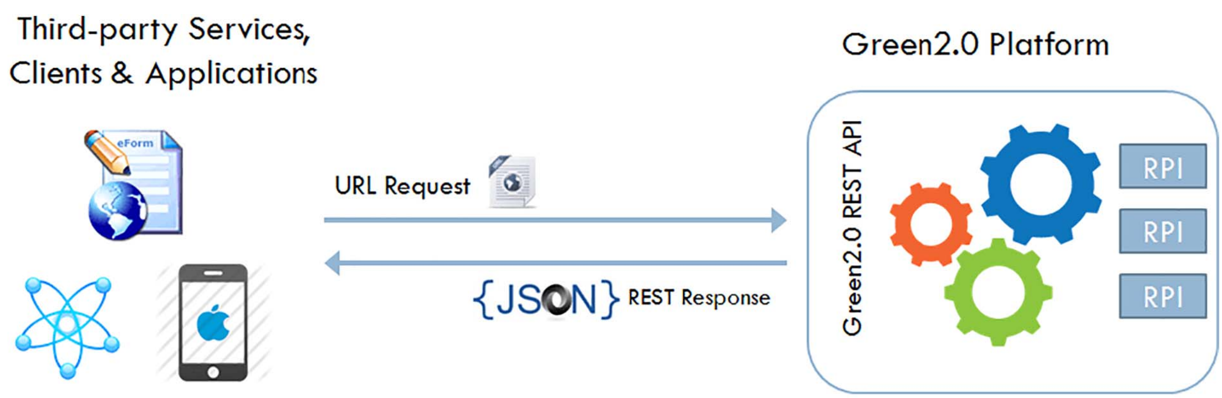


Fig. 9. The Green2.0 RESTful architecture allows third-party developers and services to access the Green2.0 resources.

Table 1
Services provided by Green2.0 via a RESTful API.

Service	Description
BIM Users	Provides access to BIM users
BIM Projects	Provides access to BIM projects
BIM IFC Elements	Provides access to IFC elements of given BIM project
BIM Comments	Provides access to comments of given BIM project
BIM Networks	Provides access to the discussion networks of given BIM project
BIM Processes	Provides access to BPM processes

associated business rules identified by business analysts. The *monitoring tools* component provides metrics about the process such as the number of running processes, number of completed processes, process duration, execution times of activities, and process specific key performance indicators (KPIs). Process metrics allow analysts to measure how the process is performing in general, identify critical tasks, and modify their design accordingly. This module also allows analysts to evaluate and compare possible process design alternatives based on some predefined objectives (e.g. reduce cycle time).

6.2. Interoperability: RESTful API module

One of the major architecture design decisions of *Green2.0* is to provide access to a cohesive collection of its resources (BIMs, BIM project information, BIM-enabled networks, etc.) to third-party services and applications. This is accomplished through the design and development of a Representational State Transfer (REST) application programming interface (RESTful API) [26]. A RESTful API is an architectural style that uses standard HTTP requests to GET, PUT, POST and DELETE data. Such an API is easily accessible by a variety of HTTP clients, including browsers and mobile devices.

Fig. 9 illustrates a typical architecture for supporting a RESTful API in *Green2.0*. Third-party applications and services are accessing the *Green2.0* RESTful API by submitting HTTP requests; our system performs the necessary computation and compiles a REST answer to the request, formatted and served to the requester as a JSON file. Through the API a number of resources become available to third-party services, clients and applications. For easy reference, Table 1 provides a summary of the *Green2.0* resources that are accessible via the RESTful API through a standard HTTP GET method.

7. Discussion

At the surface, and feature-wise, we developed a service (SaaS) to support interactions (commenting) by stakeholders of a green facility. All participants (professionals and end-users) can share views. To support testing of different design options, we connected BIM (IFC in particular) and EnergyPlus (through OpenStudio). The proposed algorithms to transfer IFC data into thermal zones represent a novel method to create a link between BIM and energy analysis systems. In combination, the platform allows for iterative and collaborative testing of alternative building design models potentially leading to more informed, more green decisions. At a deeper level, *Green2.0* is a manifestation and supportive tool of the opinion that design of green facilities is a socio-technical domain. And that knowledge is an evolutionary social phenomenon: it emerges through interactions between knowledge agents (based on iterative analysis). This is why comments were modeled in a semantic way and interpreted in the form of social and information networks. Exploration of the dynamics of these networks can reveal significant knowledge constructs.

Increasingly, we are noticing that green building research is a socio-technical process. This is because the decision of selecting energy/water saving measures, ultimately, rests on end-users. We have to match the advanced technical tools with socially-aware tools that capture end-users needs. At the same time this synergy can influence their attitude towards energy usage through providing access to relevant knowledge that is customized to match their needs and the very conditions of the project itself. This is quite a challenge given that the majority of analysis tools were developed by engineers for use by engineers. The shear diversity of the user profiles, their incentives/decision criteria, and their information aptitude is a major challenge to researchers. The prevalence of crowd sourcing and prosumerism purges the creativity/decision lines between professionals and end-users. Informed home buyers are expecting a full engagement in the design. In fact, they believe they should lead decisions — bottom-up. The first challenge here is not only to provide users with services to engage them but also how to customize these services to their specific needs. Further, how to integrate ad hoc services (developed by others almost on a daily basis) into the design process.

Researchers have advocated the use of social media to achieve higher levels of active participation of end-users in project design and operations. Further, with the evolution of the knowledge economy, Project Discussion Networks (PDN) are poised to be a source of creative ideas regarding project scope, funding and design/operations plans [21]. Indeed, this could also be the starting point for a new realm in innovation democratization and, more importantly, a bottom-up public decision making. However, the lack of means to analyze these seemingly chaotic discussions wastes these opportunities and is frustrating to end-users, engineers and decision makers. Of similar importance is to streamline the discussions of professionals, which is a salient feature of today's design environment-many disciplines are interacting in facility design and decision making. Through embedding commenting abilities and social network analysis into BIM, we facilitate better flow of the inevitable debate between practitioners. At the same time, we preserve their valuable input for analysis and knowledge harvesting. The premise of our work is that by opening the building design process to the world and providing new insights into the building design process it is likely to have a profound beneficial effect for both the AEC industry and the society at large.

8. Conclusions

Green2.0 defines an interesting and innovative, but complex engineering system for enabling socio-technical analysis and online collaboration capabilities around shared building information models. Designing and developing *Green2.0*, we had to identify the scope of the system, investigate alternative system design and architecture concepts, explore data collection methods and assess the relevant emerging technologies. Moreover, we tried to adhere to a formal approach of designing an open platform; a platform that can provide open access to information that can help researchers and practitioners to build new, more efficient theories and methods of building design. In designing and developing it as an open platform, our choices were limited to availability of open source technologies and libraries. This requirement becomes more challenging when one considers how fragmented the AEC industry is, with different disciplines operating different tools and producing distinct models of the construction work; how slow the rate of adoption of standards is; and, the large number of tools that might work well in isolation but do not necessarily provide an easy way to integrate them into third-party services. Materializing an open platform that integrates together different technologies for socio-technical analysis of buildings was a major challenge of this research. This describes a significant improvement over current practice and tries to advance the current state of the art in green building design towards sustainable development.

References

[1] F.H. Abanda, J.H. Tah, R. Keivani, Trends in built environment semantic web applications: where are we today? Expert Syst. Appl. 40 (2013) 5563–5577, http://dx.doi.org/10.1016/j.eswa.2013.04.027.

[2] M. Al Hattab, F. Hamzeh, Using social network theory and simulation to compare traditional versus bim — lean practice for design error management, Autom. Constr. 52 (2015) 59–69, http://dx.doi.org/10.1016/j.autcon.2015.02.014.

[3] Z. Alwan, D. Greenwood, B. Gledson, Rapid LEED evaluation performed with bim based sustainability analysis on a virtual construction project, Constr. Innov. 15 (2015) 134–150, http://dx.doi.org/10.1108/CI-01-2014-0002.

[4] M.R. Asl, S. Zarrinmehr, M. Bergin, W. Yan, Bpopt: a framework for bim-based performance optimization, Energy Build. 108 (2015) 401–412, http://dx.doi.org/10.1016/j.enbuild.2015.09.011.

[5] V. Bazjanac, A. Kiviniemi, Reduction, simplification, translation and interpretation in the exchange of model data, Proceedings of the CIB-W78 24th International Conference, 2007, pp. 163–168.

[6] B. Becerik-Gerber, S. Rice, The perceived value of building information modeling in the US building industry, ITcon 15 (2010) 185–201.

[7] J. Beetz, L. van Berlo, R. de Laat, P. van den Helm, Bimserver.org — an open source ifc model server, Proceedings of the CIP W78 conference, 2010 2–2.

[8] L. van Berlo, T. Krijnen, Using the bim collaboration format in a server based workflow, Procedia Environ. Sci. 22 (2014) 325–332, http://dx.doi.org/10.1016/j.proenv.2014.11.031.

[9] M. Bilal, L.O. Oyedele, J. Qadir, K. Munir, S.O. Ajayi, O.O. Akinade, H.A. Owolabi, H.A. Alaka, M. Pasha, Big data in the construction industry: a review of present status, opportunities, and future trends, Adv. Eng. Inform. 30 (2016) 500–521, http://dx.doi.org/10.1016/j.aei.2016.07.001.

[10] P.M. Bosch-Sijtsema, L.H. Henriksson, Managing projects with distributed and embedded knowledge through interactions, Int. J. Proj. Manag. 32 (2014) 1432–1444, http://dx.doi.org/10.1016/j.ijproman.2014.02.005.

[11] P. Bynum, R.R. Issa, S. Olbina, Building information modeling in support of sustainable design and construction, J. Constr. Eng. Manag. 139 (2012) 24–34, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000560.

[12] P. Chinowsky, J. Diekmann, V. Galotti, Social network model of construction, J. Constr. Eng. Manag. 134 (2008) 804–812, http://dx.doi.org/10.1061/(ASCE)0733-9364(2008)134:10(804).

[13] J. Corburn, Bringing local knowledge into environmental decision making: improving urban planning for communities at risk, J. Plan. Educ. Res. 22 (2003) 420–433, http://dx.doi.org/10.1177/0739456X03022004008.

[14] G. Costa, L. Madrazo, Connecting building component catalogues with bim models using semantic technologies: an application for precast concrete components, Autom. Constr. 57 (2015) 239–248, http://dx.doi.org/10.1016/j.autcon.2015.05.007.

[15] M. Das, J.C. Cheng, S. Shiv Kumar, Bimcloud: a distributed cloud-based social bim framework for project collaboration, Computing in Civil and Building Engineering (2014), 2014, pp. 41–48, , http://dx.doi.org/10.1061/9780784413616.006.

[16] M.K. Di Marco, J.E. Taylor, P. Alin, Emergence and role of cultural boundary spanners in global engineering project networks, J. Manag. Eng. 26 (2010) 123–132, http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000019.

[17] C. Durugbo, A. Tiwari, J.R. Alcock, Modelling information flow for organisations: a review of approaches and future challenges, Int. J. Inf. Manag. 33 (2013) 597–610, http://dx.doi.org/10.1016/j.ijinfomgt.2013.01.009.

[18] C. Eastman, C.M. Eastman, P. Teicholz, R. Sacks, BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, John Wiley & Sons, 2011.

[19] T. El-Diraby, B. Wang, E-society portal: integrating urban highway construction projects into the knowledge city, J. Constr. Eng. Manag. 131 (2005) 1196–1211, http://dx.doi.org/10.1061/(ASCE)0733-9364(2005)131:11(1196).

[20] T.E. El-Diraby, T.F. Krijnen, M. Papagelis, Green2.0: socio-technical analytics of green buildings, Proceedings of the International Conference on Smart Infrastructure and Construction, ICE, 2016, pp. 551–556, , http://dx.doi.org/10.1680/tfitsi.61279.551.

[21] T.E. El-diraby, et al., Communities of interest–interest of communities: social and semantic analysis of communities in infrastructure discussion networks, Comput. Aided Civ. Inf. Eng. 31 (2016) 34–49, http://dx.doi.org/10.1111/mice.12152.

[22] N.M. El-Gohary, T.E. El-Diraby, Domain ontology for processes in infrastructure and construction, J. Constr. Eng. Manag. 136 (2010) 730–744, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000178.

[23] EPA, Environmental Protection Agency: “Green Building”. (2015) https://archive.epa.gov/greenbuilding/web/html/ Accessed 12 July 2015.

[24] A. Feige, H. Wallbaum, S. Krank, Harnessing stakeholder motivation: towards a swiss sustainable building sector, Build. Res. Inf. 39 (2011) 504–517, http://dx.doi.org/10.1080/09613218.2011.589788.

[25] J. Feringa, T. Krijnen, BIM for robotic manufacturing, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, 2015, pp. 1–11.

[26] R.T. Fielding, Architectural Styles and the Design of Network-based Software Architectures, Ph.D. thesis, University of California, Irvine, 2000.

[27] D. Gomes, P. Tzortzopoulos, M. Kagioglou, Collaboration through shared understanding in the early design stage, 24th Ann. Conf. of the Int’l. Group for Lean Construction, Boston, MA, USA, 20-22 July, 2016, pp. 63–72.

[28] V. Gómez, A. Kaltenbrunner, V. López, Statistical analysis of the social network and discussion threads in slashdot, Proceedings of the 17th international conference on World Wide Web, ACM, 2008, pp. 645–654, , http://dx.doi.org/10.1145/1367497.1367585.

[29] A. Gupta, A. Cemesova, C.J. Hopfe, Y. Rezgui, T. Sweet, A conceptual framework to support solar pv simulation using an open-bim data exchange standard, Autom. Constr. 37 (2014) 166–181, http://dx.doi.org/10.1016/j.autcon.2013.10.005.

[30] A.J. Hoffman, R. Henn, Overcoming the social and psychological barriers to green

building, Organ. Environ. 21 (2008) 390–419, http://dx.doi.org/10.1177/1086026608326129.
[31] B. Ilhan, H. Yaman, Green building assessment tool (gbat) for integrated bim-based design decisions, Autom. Constr. 70 (2016) 26–37, http://dx.doi.org/10.1016/j.autcon.2016.05.001.
[32] F. Jalaei, A. Jrade, Integrating building information modeling (bim) and LEED system at the conceptual design stage of sustainable buildings, Sustainable Cities Soc. 18 (2015) 95–107, http://dx.doi.org/10.1016/j.scs.2015.06.007.
[33] Y.S. Jeong, C. Eastman, R. Sacks, I. Kaner, Benchmark tests for bim data exchanges of precast concrete, Autom. Constr. 18 (2009) 469–484, http://dx.doi.org/10.1016/j.autcon.2008.11.001.
[34] E.P. Karan, J. Irizarry, Extending bim interoperability to preconstruction operations using geospatial analyses and semantic web services, Autom. Constr. 53 (2015) 1–12, http://dx.doi.org/10.1016/j.autcon.2015.02.012.
[35] J.B. Kim, W. Jeong, M.J. Clayton, J.S. Haberl, W. Yan, Developing a physical bim library for building thermal energy simulation, Autom. Constr. 50 (2015) 16–28, http://dx.doi.org/10.1016/j.autcon.2014.10.011.
[36] S. Koeppel, D. Ürge-Vorsatz, Assessment of Policy Instruments for Reducing Greenhouse Gas Emissions from Buildings, (2007).
[37] M. König, J. Dirnbek, V. Stankovski, Architecture of an open knowledge base for sustainable buildings based on linked data technologies, Autom. Constr. 35 (2013) 542–550, http://dx.doi.org/10.1016/j.autcon.2013.07.002.
[38] S. Kota, J.S. Haberl, M.J. Clayton, W. Yan, Building information modeling (bim)-based daylighting simulation and analysis, Energ. Buildings 81 (2014) 391–403, http://dx.doi.org/10.1016/j.enbuild.2014.06.043.
[39] T. Krijnen, M. Tamke, Assessing implicit knowledge in bim models with machine learning, Modelling Behaviour, Springer, 2015, pp. 397–406, , http://dx.doi.org/10.1007/978-3-319-24208-8_33.
[40] K.R. Lakhani, L.B. Jeppesen, P.A. Lohse, J.A. Panetta, The Value of Openness in Scientific Problem Solving, Division of Research, Harvard Business School, 2007.
[41] K.R. Lakhani, J.A. Panetta, The principles of distributed innovation, Innovations 2 (2007) 97–112, http://dx.doi.org/10.1162/itgg.2007.2.3.97.
[42] A. Leff, J.T. Rayfield, Web-application development using the model/view/controller design pattern, Enterprise Distributed Object Computing Conference, 2001. EDOC'01. Proceedings. Fifth IEEE International, IEEE, 2001, pp. 118–127.
[43] T. Liebich, Ifc2x Model Implementation Guide, Version 2.0, BuildingSmart, (2009) http://www.buildingsmart-tech.org/downloads/accompanying-documents/guidelines Retrieved from 2–2.
[44] H. Lin, J.A. Harding, A manufacturing system engineering ontology model on the semantic web for inter-enterprise collaboration, Comput. Ind. 58 (2007) 428–437, http://dx.doi.org/10.1016/j.compind.2006.09.015.
[45] T. Maile, J. O'Donnell, V. Bazjanac, C. Rose, Bim-geometry modelling guidelines for building energy performance simulation, Building Simulation Conference, 2013, pp. 3242–3249.
[46] W. Mazairac, J. Beetz, Bimql — an open query language for building information models, Adv. Eng. Inform. 27 (2013) 444–456, http://dx.doi.org/10.1016/j.aei.2013.06.001.
[47] A.P. Neghab, A. Etienne, M. Kleiner, L. Roucoules, Performance evaluation of collaboration in the design process: using interoperability measurement, Comput. Ind. 72 (2015) 14–26, http://dx.doi.org/10.1016/j.compind.2015.03.011.
[48] M.E. Newman, The structure of scientific collaboration networks, Proc. Natl. Acad. Sci. 98 (2001) 404–409, http://dx.doi.org/10.1073/pnas.98.2.404.
[49] M. Niknam, S. Karshenas, Sustainable design of buildings using semantic bim and semantic web services, Procedia Eng. 118 (2015) 909–917, http://dx.doi.org/10.1016/j.proeng.2015.08.530.
[50] L. Norford, R. Socolow, E.S. Hsieh, G. Spadaro, Two-to-one discrepancy between measured and predicted performance of a low-energy office building: insights from a reconciliation based on the doe-2 model, Energ. Buildings 21 (1994) 121–131, http://dx.doi.org/10.1016/0378-7788(94)90005-1.
[51] A. Osello, G. Cangialosi, D. Dalmasso, A. Di Paolo, M.L. Turco, P. Piumatti, M. Vozzola, Architecture data and energy efficiency simulations: bim and interoperability standards, proceedings of Building Simulation, 2011, pp. 2210–2217.
[52] A.H. Oti, W. Tizani, Bim extension for the sustainability appraisal of conceptual steel design, Adv. Eng. Inform. 29 (2015) 28–46, http://dx.doi.org/10.1016/j.aei.2014.09.001.
[53] M. Papagelis, T.F. Krijnen, M. Elshenawy, T. Konomi, R. Fang, T.E. El-Diraby, Green2.0: enabling complex interactions between buildings and people, Proceedings of the 19th ACM Conference on Computer Supported Cooperative Work and Social Computing Companion, ACM, 2016, pp. 77–80, , http://dx.doi.org/10.1145/2818052.2874330.
[54] M. Papagelis, V. Murdock, R. van Zwol, Individual behavior and social influence in online social systems, Proceedings of the 22nd ACM Conference on Hypertext and Hypermedia, ACM, 2011, pp. 241–250, , http://dx.doi.org/10.1145/1995966.1995998.
[55] S. Pryke, Social Network Analysis in Construction, John Wiley & Sons, 2012.
[56] P. Rode, R. Burdett, J.C. Soares Gonçalves, Buildings: Investing in Energy and Resource Efficiency, (2011).
[57] J.H. Tah, H.F. Abanda, Sustainable building technology knowledge representation: using semantic web techniques, Adv. Eng. Inform. 25 (2011) 547–558, http://dx.doi.org/10.1016/j.aei.2011.02.006.
[58] A. Tapiador, A. Fumero, J. Salvachua, S. Aguirre, A web collaboration architecture, Collaborative Computing: Networking, Applications and Worksharing, 2006. CollaborateCom 2006. International Conference on, IEEE, 2006, pp. 1–4, , http://dx.doi.org/10.1109/COLCOM.2006.361841.
[59] J.E. Taylor, R. Levitt, Innovation alignment and project network dynamics: an integrative model for change, Proj. Manag. J. 38 (2007) 22–35, http://dx.doi.org/10.1002/pmj.20003.
[60] M. Turner, D. Budgen, P. Brereton, Turning software into a service. Computer. 36 (2003) 38–44, http://dx.doi.org/10.1109/MC.2003.1236470.
[61] A. Van Herzele, Local knowledge in action: valuing nonprofessional reasoning in the planning process, J. Plan. Educ. Res. 24 (2004) 197–212, http://dx.doi.org/10.1177/0739456X04267723.
[62] J.K.W. Wong, J. Zhou, Enhancing environmental sustainability over building life cycles through green bim: a review, Autom. Constr. 57 (2015) 156–165, http://dx.doi.org/10.1016/j.autcon.2015.06.003.
[63] K. Wong, H. Unsal, J.E. Taylor, R.E. Levitt, Global dimension of robust project network design, J. Constr. Eng. Manag. 136 (2009) 442–451, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000143.
[64] R.J. Yang, P.X. Zou, Stakeholder-associated risks and their interactions in complex green building projects: a social network model, Build. Environ. 73 (2014) 208–222, http://dx.doi.org/10.1016/j.buildenv.2013.12.014.
[65] N. Yu, Y. Jiang, L. Luo, S. Lee, A. Jallow, D. Wu, J.I. Messner, R.M. Leicht, J. Yen, Integrating bimserver and openstudio for energy efficient building, Proceedings of 2013 ASCE International Workshop on Computing in Civil Engineering, 2013, pp. 516–523.