# PERSPECTIVES AND PRACTICES OF COLLABORATIVE ENERGY DESIGN TECHNOLOGIES FOR CLOSING THE BUILDING ENERGY PERFORMANCE GAP

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Both researchers and practitioners have increasingly observed the significant deviation of buildings' actual energy consumption from their design predictions, which is known as the "performance gap". The organizational and procedural fragmentation of multi-disciplinary stakeholders has been realized to be a major cause of the performance gap. Nevertheless, little of previous research addressed the performance gap from the perspective of improving design stakeholders' collaboration. The widespread adoption of information technologies has generated a paradigm shift of stakeholders' collaborative design. The aim of this paper is to figure out technical characteristics of information technologies that help to improve stakeholder collaboration, so as to close the performance gap. The research takes the basis of information processing theory, and was carried out through the combination of a critical literature review, semi-structured interviews of ten industry representatives, and case studies of six state-of-the-art energy design tools. A comparative analysis was then conducted between academia research, industry perspectives, and technical practices. The findings of this paper suggest that there are mismatches between current practices and perspectives. Improvement strategies were finally proposed to contribute to the understanding and development of collaborative energy design technologies.

Keywords: building energy performance gap, collaborative design, BIM, information and communication technology

## INTRODUCTION

According to IPCC, building construction, operation and maintenance together account for 40% of the energy sources used, which has led to energy-related carbon emissions of 36% in industrialized countries (Metz and Davidson, 2007). However, noncompliance with building energy regulation and discrepancy between predicted and measured building energy performance has been widely reported (Pan and Garmston, 2012, Frank *et al*., 2015). Such discrepancy is often referred to as 'building energy performance gap', or 'credibility gap', and has attracted urgent and significant attention of government, industry and academia. Some researchers found that for some officially certified (e.g. LEED) low energy buildings, the measured performances are not in agreement with the credits they obtained (Newsham *et al*., 2009, Agdas *et al*., 2015). Building energy design is a dynamic, iterative information processing activity in order to cope with various uncertainties. In many cases, the

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Niu, S and Pan, W (2016) Perspectives and Practices of Collaborative Energy Design Technologies for Closing the Building Energy Performance Gap. *In*: P W Chan and C J Neilson (Eds.) *Proceedings of the 32nd Annual ARCOM Conference,* 5-7 September 2016, Manchester, UK, Association of Researchers in Construction Management, Vol 1, 415-424.

performance gap mainly result from inappropriate handling with building design information due to the lack of collaboration between multi-disciplinary stakeholders. Nevertheless, little of previous research addresses the performance gap from the perspective of stakeholder collaboration. This paper aims at investigating current perspectives and practices of collaborative building energy design technologies through strategic literature review, semi-structured interviews, and case studies. Two research questions are primarily investigated in the research:

What technical features can improve stakeholder collaboration, so as to close the performance gap resulted from the inability to process design information?

What are the knowledge gaps (academic research vs. industry perspectives), implementation gaps (industry perspectives vs. technical practices), and technology gaps (academic research vs. technical practices) in the development of collaborative design tools?

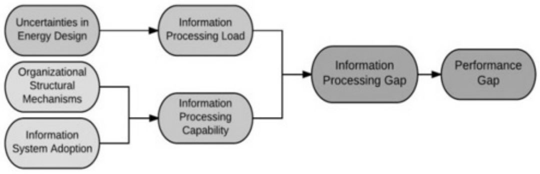
# RESEARCH BACKGROUND

Researchers and industry experts have realized that the performance gap results from various causes throughout multiple stages of a building project. De Wilde (2014) classified the root causes into three main categories: causes that pertain to the design stage, causes rooted in the construction stage (including handover), and causes that relate to the operational stage. Menezes *et al*., (2012) proposed another categorization that groups the casual factors into both prediction and actual parts. Previous empirical studies have revealed many situations in which the integrity of design information is harmed when information is transferred among project stakeholders, including omission, errors, and fuzziness (Opitz *et al*., 1997, Bordass *et al*., 2001, Stevenson and Rijal, 2010, Coleman *et al*., 2012, Dong *et al*., 2014). It provides another perspective of investigating the performance gap, i.e. the lack of information integrity in building energy design. Due to the lack of information integrity, designers cannot correctly estimate actual operation conditions, while design intentions are not fully comprehended by contractors and operators, so that the performance gap appears.

Building design stage is an information-intensive process in which most key decisions are made. The information processing theory identifies three important concepts: information processing needs resulted from internal and external uncertainties, information processing capability, and the fitness between the two to obtain optimal performance (Galbraith, 1973). The information processing capability refers to the ability to gather, synthesize, and disseminate information properly to cope with uncertainties, and is primarily supported by proper organization structure and implementation of information system (Tushman and Nadler, 1978). Achieving a fit between the information processing needs and the information processing capability to attain optimal organizational performance has been a primary focus of organization designers (Daft and Lengel, 1986). Project teams in construction project have long been viewed as information processing organizations. The performance gap issue can thus be regarded as the consequence of the mismatch between project team's ability to cope with design information and its information processing loads, i.e. information processing gap (see Figure 1). The implementation of collaborative technologies is therefore essential to achieve better information integrity in building energy design, so as to close the performance gap.

Current information management and interoperability solutions support a small amount of integration, either through the supply chain or along the design path. These approaches are typically vendor-specific and tie together a small number of design tools, which are unlikely to facilitate a fully integrated team involved in a construction project (Owen *et al*., 2010). Previous research has discussed a lot on the socio-technical feasibility of integrated, project-level collaboration platforms that enables teamwork of various stakeholders.

*Figure 1: Information processing gap and the performance gap*

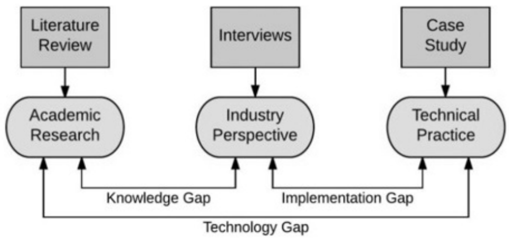



In the development of low energy building projects, performance-based evaluation and associated coordination is particularly required in the design process. Nevertheless, traditional energy design tools focus mainly on the mathematical simulation of sustainability-related aspects such as thermal, lighting, and airflow, and there is usually an overlook of technical collaborative features.

# METHODOLOGY

The research data were collected in three correlated phases. A strategic literature review of current document-based collaborative technologies and their application in building energy design was conducted in a meta-analysis approach. The transition and composition of research focuses were figured out in the review. Ten semi-structured interviews were conducted with representatives from five key stakeholder groups in Hong Kong building industry, i.e. developer (two), architect (three), engineer (two), contractor (two), and facility manager (one). The interviews aim to identify the awareness, expectations, and requirements of collaborative technologies across multi-disciplinary professionals. Six state-of-the-art collaborative tools for building energy design were analysed using an integrated evaluation framework. The aim of the case studies is to test functionalities, usability, and limitations of technologies that are currently available to building energy designers. The findings of the three phases are then analysed comparatively, based on which the knowledge gap, the implementation gap, as well as the technology gap, are identified (see Figure 2).

*Figure 2: Research methods*




# RESULTS AND ANALYSIS

## Literature review findings

The literature review was carried out through the examination of journal articles related to collaborative building energy design technologies, and the articles were generated in a searching and screening process from the Scopus, ScienceDirect, and ISI Web of Science. Searching keywords were identified and the criteria of searching control and screening were established, in order to keep the scope of the review manageable and to provide sound results. The searching was limited to topic only, including title, abstract, and keywords. Only technical solutions for collaboration in the design stage were considered, and the functionality of the tools was limited to whole building energy/sustainability design. The searching results indicate growing research outputs of collaborative tools to support building energy and sustainability design, which are in multiple levels of maturity and usability.

*Table 1: Literature searching keywords and screening results (total=106)*

| Searching keywords (OR is logically prior to AND) | Theoretical framework | Technical prototype | Practical tool | Review and analysis |
|---|---|---|---|---|
| Inter-disclin* OR multi-disciplin* OR integrat* OR collaborati* AND framework OR technology OR tool OR platform AND building AND "sustainab* design" OR "energy design" | 48 | 21 | 15 | 22 |

*Figure 3: Transition of research focuses in the reviewed articles (total=99)*

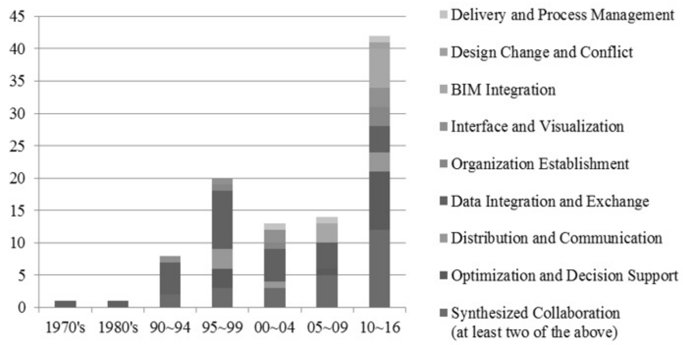



Figure 3 portrays a general picture of various research emphases over the past a few decades. A rising number of synthesized tools have appeared to facilitate design teams on all dimensions. Data integration is a perennial topic since 1970's, and it addresses the foundation of design information exchange. Visualization method and user interface design deeply affect the usability of the tool, and the booming virtual reality technology also provides promising space for further development. Another important feature to support collaborative design is the ability to help designers make right decisions, and many tools adopt optimization methods, e.g. genetic algorithm. Researchers also advocated the necessity that design tools support organization establishment and process management. Building information modelling (BIM) is a globally accepted platform for general multi-disciplinary collaboration and data integration. In the domain of energy and sustainability design, the integration of design tools with BIM platform has gained more and more attentions since 2005. Some other issues were also indicated in the reviewed articles, including tracking design change, conflict management, and establishing communication channels for distributed team members. In the review, some basic technical and implementation-related issues were identified, which are primarily related to:

*Simulation*: A fundamental functional requirement of collaborative energy design tool is the simulation of building system performance. In the context of low energy building, energy simulation provides basic evaluation of different design strategies. The majority of the reviewed tools denote their ability in this domain by integrating thermal simulation cores, e.g. EnergyPlus. More integrated software has been developed as other sustainability-related aspects become necessary.

*Data*: Data integration and exchange method is the basis of building project modelling. The ability of collaborative tools to organize project data relies heavily on the development of design platform. In the era of two-dimensional computer-aided design (CAD), while most design platforms were object-oriented program, the models they provided were merely graphical objects or "entities". Researchers in the 1990's focused mainly on the project database technologies and the representational schema of complex data types and relationships. Both relational database and object-oriented database were adopted. BIM technology brought about a paradigm shift in the data modelling of buildings. Object-oriented IFC format was widely considered, and its interoperability with various analysis tools was also discussed. Database technology was also adopted along with IFC to serve different functional layers. The gbXML schema, which was specially designed for data exchange between analytic tools, was also widely considered by researchers in the design of collaborative environment.

*Visualization and UI*: Kim and Degelman (1998) argued that user interface system for computer-aided building design (CABD) system is not a simple layer between user and simulation model, but rather a general interface strategy to control simulation models and relevant database. User interface design affects the usability of design tools by formatting the way designers interact with data, design patterns, as well as multidisciplinary collaborators. A primitive interface model is a binary system consisting of a building browser and a decision workbench. The building model browser usually evolves on condition that the data basis of representing model asset has updated. Different from design sketching tools, visualizing model for building analysis requires more 3D visualization of building data. The COMINE project in the 1990's realized the visualization and exchange of 3D models from CAD by establishing an integrated data model (IDM) based on the ISO-STEP initiative. Researchers in the BIM era rely either on interoperating and post-processing existing BIM models, or integrating specified model browser for building analysis, e.g. FZKViewer for xml file visualization. Some studies also took a further step by using virtual reality technologies for better end-user participation in the design process, such as the CAVE system.

*Stakeholder and workflow:* The collaborative nature of tools is mostly instantiated by to what extent various stakeholders are involved. Traditional tools were designed merely for separated design professional, and therefore no collaboration was considered. More synthesized frameworks for various designers were developed, in consideration of the possible delays, confusion, and harms to the final design when multidisciplinary communication is missing. Jansson *et al*., (2014) proposed a form of platform that is client-driven in order to handle the distinctiveness of building projects through an iterative design procedure between architect, engineer, and clients. Nevertheless, the reviewed tools seldom consider contractors and suppliers. Stakeholder engagement is also influenced by what collaborative technologies are adopted. For instance, virtual reality integrated design system is proposed in order to include occupants early in the design evaluation process (Christiansson *et al*., 2011, Niu *et al*., 2016). Computer-aided collaborative design tools also emphasis on parallel design generation and evaluation feedback via the simulation tools. One example is the integration of certificate submission process (e.g. LEED), and thus stakeholders in institutional groups are included.

*Decision support*: The greatest opportunity for low energy building design strategies resides in the early stages of design when most important decisions are made. In complex building projects, many decisions are made based on information obtained from a variety of sources that are well beyond the engineering disciplines. Collaborative tools facilitate decision-making mainly by fully support multidisciplinary information sharing. Another advantage is the ability to retrieve through the solution spaces and to optimize design for comparison and selection under multiple criteria.

### Interviews of industry perspectives

Building design process in Hong Kong is mostly an architect-centred process, surrounded by multidisciplinary consultants and engineers. Environmental consultants take charge of low energy/sustainability design, assisted by architect and system engineer. Regular project meeting is the major chance for collaboration and problem solving. Communication among industry professionals usually takes place through face-to-face meetings, emails, phone calls, and messages. As for data exchange, 2D drawings are mostly used in the project meeting, and paper-based documents are used for energy analysis. BIM serves basically for conflict detection, quantity take-off, and briefing to clients. Environmental consultants use building analysis tools in isolation from the tools of other professionals. The general interview results indicate the lack of technical knowhow and fragmented nature of the AEC industry (Singh *et al*., 2011).

Various energy certification schemes (e.g. LEED in USA, Green Star in China, and BEAM+ in Hong Kong) have become affirmatively chosen items for building developers due to strong political support (e.g. property tax reduction and GFA concession for BEAM+ buildings in Hong Kong). As those schemes focus mainly on design, there is a strong industry need for integrating the certification submission process into the main design workflow. Moreover, building energy design is an iterative process among clients' needs, engineers' knowledge, architects' design, and certification requirements. Thus decision-making support is required, especially the capability of making sensitivity analysis. User access control is also implemented, merely for security purpose, and there is a desperate lack of knowledge exchange interface. In a word, there are insufficient communication channels between the information demand (consultant) and supply (supplier) in most cases.

### Case study of technical practices

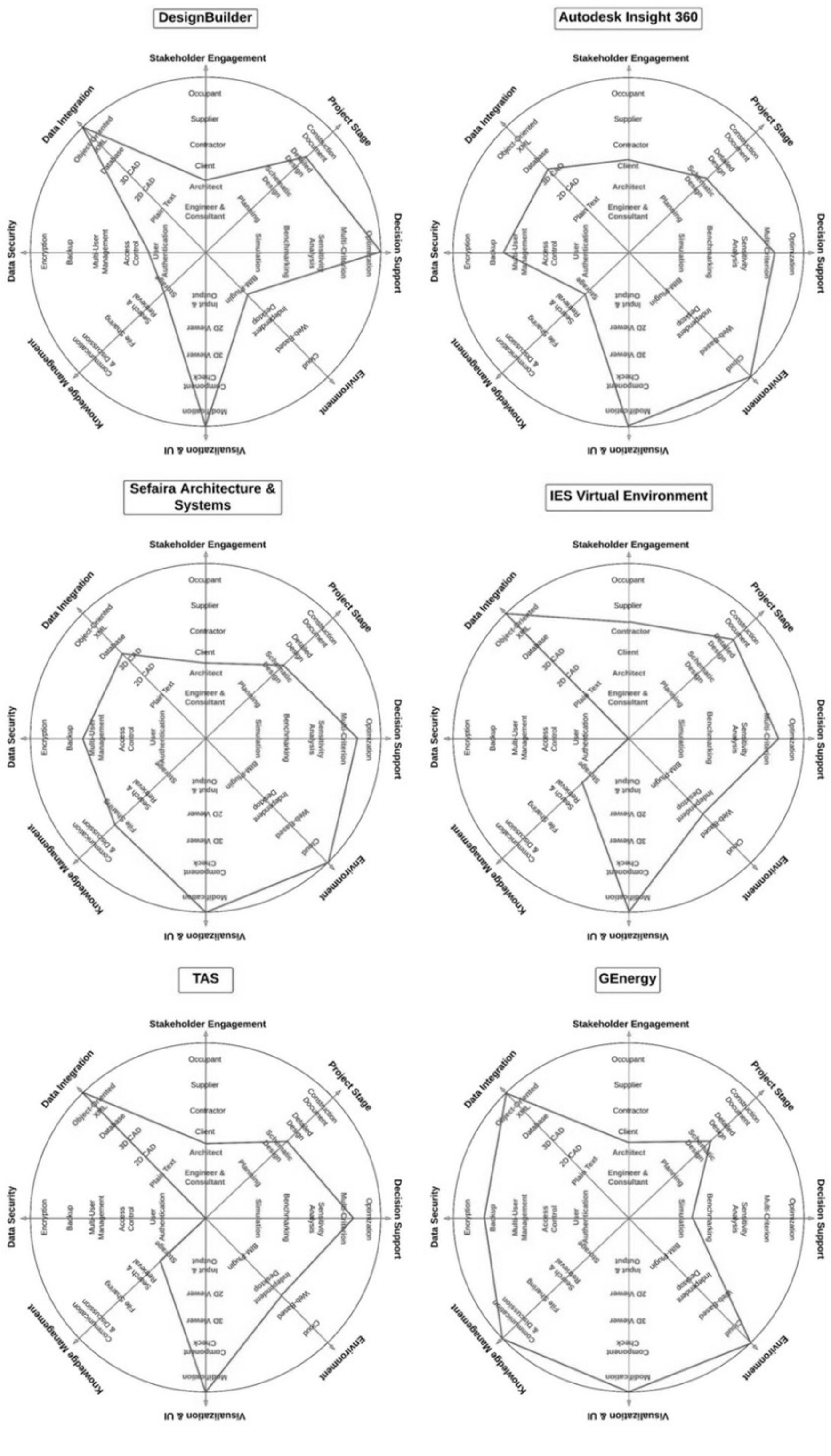
Hamedani and Smith (2015) concluded a set of four major selection criteria for building energy performance tools as design decision-making tool, including 1) input data required for simulation, 2) usability, graphical visualization, and interface, 3) interoperability of building modelling, and 4) accuracy and ability to simulate detailed and complex building forms and components. Based on the literature review analysis and interview results presented above, an evaluation framework was developed which categorizes the features and technical requirements for collaborative energy design tools. Eight major aspects were selected for evaluation purpose, and the evaluation criteria were selected on a developing basis. Six state-of-the-art integrated energy design tools were investigated (see Figure 4), i.e. DesignBuilder, Autodesk Insight 360, Sefaira Architecture and Systems, IES Virtual Environment (VE), TAS, and GEnergy. DesignBuilder and IES VE are more commonly used in Hong Kong building consulting industry.

### Comparative analysis

*Knowledge gaps*

The interview findings echo most of the literature review results that the accuracy of building simulation, easy-operable data format, and user-friendly interface are mostly expected by building designers. Nevertheless, major knowledge gaps also exist. Due to the lack of integrated delivery methods, contractors (especially sub-contractors) and facility managers are seldom involved in design, and thus there are few technical needs for later-stage stakeholder involvement and data integration.

*Figure 4: Comparative case study of state-of-the-art collaborative energy design tools*




Furthermore, design decisions are usually made centrally by the clients, whose main purpose is LEED or BEAM+ certification. Thus advanced decision support is poorly required. In the iteration of design process, there is a significant lack of holistic thinking and methods, but mostly fragmented modifications (e.g. simply alter the shading length or change the lighting to LED panel). Knowledge management also takes a very simple form, e.g. a shared ftp server for the storage and exchange of project documents. In a word, the adoption of technical solutions is constrained by traditional business procedure and the subordinate position of energy efficiency.

*Implementation gaps*

The development of technical practices keeps a close pace with industry needs. However, two major differences can be identified:

1. *Desktop vs. Web/Cloud:* The working environments of collaborative tools determine platforms' basic capabilities of supporting collaborative work. One the one hand, most interviewees agree that independent desktop tools are developed mainly for professional engineers, while architects and clients only get involved when less expertise is required; on the other hand, more international projects require remote collaboration through the web. The rapid-developing web service and cloud technology enable designers to get access to project data anywhere, and thus multi-user work becomes possible. Cloud technology frees the user from heavy computing burdens, and communication channels are also established through the integration of social media. Nevertheless, independent desktop applications take the advantage of providing more complex analysing services for decision support, and they usually outperform their web-based counterparts in supporting more data types. Considering data security, desktop-based tools seldom consider this issue, while most web-based tools have established a user management system to support teamwork among stakeholders.
2. *Independent vs. BIM/SketchUp Plugin:* The nature of BIM as a data centre gives rise to a symbiotic relationship between BIM and a variety of functional modules. Compared with independent tools, those plugged into BIM make the full use of its visualization interface and data resources, and thus workflows from architects' design to engineers' analysis can be more fluent. SketchUp is also a wide-adopted visualization interface, which provides designers with easy manipulation and modification of model, especially for complex building forms. Nevertheless, although independent tools perform not as good in solving graphical issues, they can be much more stable because missing and malposition problems occur frequently in the plugins' conversion process from BIM center.

*Technology gaps*

The comparison of research and practice implies that researchers focus mainly on digital foundation, while technical solution suppliers focus more on usability. Commercial tools are usually well wrapped with user interface that fully visualize building geometries, design options, and analysis results. Another difference is that researchers usually concentrate on specific aspects such as data transfer and optimization, while commercial tools are more integrated in the face of multiple user needs. Some decision support functions are constrained in commercial tools due to their functional complexity, e.g. the number of thermal zone for optimization, and the number of variables for uncertainty analysis. Academic research also discusses more on the compatibility of technology with organization structure and design procedures. On the contrary, most commercial tools work in isolation from project management tools, and thus the interoperability between technologies is necessary.

*Strategies for improvement*

1. *Knowledge gap*: Innovative collaboration technologies and integrated workflows supplement each other as building energy design tasks become more and more complicated. Nevertheless, current building energy design practice operates in the "comfort zone" in which low information processing capability is required. The main reason is that the industry claims a facile standard for energy consumption compared with traditional aspects such as safety and quality. Low information processing load implies poor attention to various uncertainties, and thus design analysis cannot fully anticipate actual circumstances. More attention, as well as a higher standard, is thus necessary to orientate the shift in building industry.
2. *Implementation gap*: Technical solution suppliers should not only be the followers of industry needs, but also layout the shift in the mode of design collaboration. Integrated measurements (e.g. cloud-based environment and BIM integration) provide chances for designers to establish communication channels at a lower cost. In the meanwhile, innovative technologies (e.g. optimization and multi-criteria decision support) fully exploit design information to better inform stakeholders.
3. *Technology gap*: The application and commercialization of research outputs should be better encouraged. Some academic tools have the potential to facilitate industry practice, especially in decision support, remain under-developed due to the lack of user interface. A close collaboration is therefore required between academia and technical solution venders.

# CONCLUSIONS

This paper contributes to the understanding of the building energy performance gap by emphasizing stakeholder collaboration and associated technologies on the basis of information processing theory. Current research progress, industry perspectives, as well as technical practices of collaborative technologies were investigated through a series of research methods, and were analysed comparatively. The results indicate that there are mismatches, i.e. knowledge gaps, implementation gaps, and technology gaps that undermine the development of collaborative technologies. Three improvement strategies were proposed in accordance with the three gaps, and collaborative technical features of digital solutions were also identified systematically based on both perspectives and practices. Future research will focus on other issues such as the initial set-up of collaborative tools, and the learning and training of collaborative technologies.

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