



A review of interdependence of sustainable building



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ARTICLE INFO

Article history:

Received 1 June 2015

Received in revised form 4 September 2015

Accepted 25 September 2015

Available online 21 October 2015

Keywords:

Sustainable building

Interdependence

System approach

Stakeholder

ABSTRACT

Despite the worldwide promotion of the sustainable building (SB) approach, its associated interdependence has seldom been explored. This knowledge gap is significant given the paradigm shift of regarding SBs as complex socio-technical systems embedded with multifaceted interdependence. The aim of this paper is to examine the interdependence of SB through a literature review. The literature review was guided by a framework comprising three dimensions of SB systems, i.e., building performance, methodology and stakeholders, on their theoretical grounds ranged from reductionism to holism. In order to articulate the integration of the three dimensions, this paper examined zero carbon building as a specific case of SB. The findings contribute an innovative approach to examining the interdependence of SB, and should guide the development of strategies for managing the trade-offs in delivering SBs.

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1. Introduction

According to the United Nations Environment Programme (UNEP, 2012), the building and construction sector directly employs over 111

million people worldwide, and contributes to global environmental issues such as 20% of water use, 25–40% of energy use, 30–40% of solid waste generation and 30–40% of global greenhouse gas emissions. Sustainable building (SB) has been promoted worldwide as an effective approach to reducing the impact of building and construction on human health and the environment. However, there exists no common definition of sustainable building, and this approach has been adopted in

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many cases without explicit explanation. Some researchers (e.g. Häkkinen and Belloni, 2011) acknowledged the description provided by ISO (2008:7) that “sustainable development of buildings and other construction works brings about the required performance and functionality with minimum adverse environmental impact, while encouraging improvements in economic and social (and cultural) aspects at local, regional and global levels”. This description implies the systems consideration of environmental, social and economic (ESE) aspects of SB.

However, this systems thinking, especially the interdependence of SB, has seldom been explored in the assessment exercise (Morrison-Saunders and Pope, 2013). This knowledge gap is critical, as SBs are being increasingly understood as complex systems (see Li and Yao, 2012; Summerfield and Lowe, 2012). The present paper argues for a systems approach to examining the interdependence of sustainable building. Guided by a framework which synthesizes three dimensions, namely, SB performance, methodology and stakeholder, this paper examines the interdependence that exists in each dimension through a literature review.

2. A conceptual framework of examining interdependence of sustainable building

The literature review of this paper was guided by a framework presented by Pan and Ning (2014, 2015) (see Fig. 1). The interdependence presented in this framework exists in three dimensions, namely the building performance, methodology and stakeholder on their theoretical grounds ranged from reductionism to holism. Interdependence may exist in any single dimension and/or sub-aspect, and/or in the integration of them.

- In relation to the area ‘building performance’, the reductionism approach examines one aspect of ESE or one element of a single aspect, e.g. carbon or energy, whereas the holism approach focuses on the interdependence among the ESE aspects as a whole.
- The methodological perspective comprises the temporal and spatial dimensions of the building. There are two trajectories describing the temporal dimension: 1) material flow that ranges from material extraction to the end of product life-cycle; and 2) work flow that starts from concept study and ends at demolition. The spatial dimension describes the location of physical subjects, from technology, building component through the building as a system to the broad context, e.g. community and city levels (Pan and Ning, 2015).
- The area ‘stakeholder’ is concerned with the stakeholders involved in SB and their interfaces with the project delivery (Pan and Ning, 2015).

In addition to the interdependence existing with each of the dimensions, the interdependence of SB also depends on an integrated

interpretation of the three dimensions (illustrated using ‘Point A’ in Fig. 1). For example, an examination of energy performance per se in the performance dimension underpinned by the reductionism approach may imply an ignorance of the interdependence between the ESE aspects. However, the methodological perspective would triangulate the interdependence from the temporal and spatial aspects. From the performance perspective, the focus on the energy performance indicates a reductionism approach, whereas this specialization could be a holistic attempt from the methodological perspective if the lifecycle energy associated with the building is taken into account. In order to articulate the integration of the three dimensions, this paper also examined zero carbon building as a specific case of SB.

3. Interdependence of sustainable building

3.1. Performance framework of sustainable building

Berardi (2011) argued that “the definitions of sustainable building often prove to be useless because they are unclear (p. 277)”. Defining SB is difficult because of its dependence on time, scale, domain and social uncertainties (Berardi, 2013a). Nevertheless, three types of sustainability impacts, namely environmental, economic and social impacts, are widely accepted in the current assessment exercise (e.g., Häkkinen and Belloni, 2011; ISO, 2011).

The typology presented by Chwieduk (2003) is adopted here, which consists of 1) energy-efficient buildings; 2) environmentally-friendly buildings; and 3) sustainable buildings. Energy-efficient buildings have the smallest performance scope, only dealing with energy performance of environmentally-friendly buildings. Furthermore, the main differences between green and sustainable buildings consist of the economic and social requirements of the sustainability (Berardi, 2013a).

3.2. Interdependence in relation to sustainable building performance

The ESE framework of SB has been widely adopted by prior studies (Calderón, 2000). In some specific cases other aspects such as technological performance are also added (Alwaer and Clements-Croome, 2010). From the reductionism approach, research focuses on a single aspect or elements of one aspect, whereas the holism approach emphasizes interdependence between multiple aspects or multiple elements of one aspect.

3.2.1. Single aspect, single element of one aspect of ESE

In the literature of SB, there are a huge number of studies examining a single aspect of the ESE or a single element of one aspect. This pattern is particularly evident when studying energy consumption or carbon emissions (e.g., Jiang and Tovey, 2009; Jack and Swaffield, 2009; Lomas, 2010; Summerfield and Lowe, 2012; Zuo et al., 2011). The terms in use also abound, e.g. nearly-zero energy, zero energy, zero net energy, energy plus, fossil fuel free, zero carbon, carbon neutral, climate neutral, climate positive, and positive development (Riedy et al., 2011). There exist some other terms, e.g. emergy analysis (Srinivasan et al., 2012) and exergy (El shenawy and Zmeureanu, 2013; Meggers et al., 2012, 2013) that complement or substitute energy analysis.

The specialization of previous research on energy consumption or carbon emissions may be attributed to three reasons. First, the global warming potentials constitute most of the environmental impacts resulted from building's heating energy consumption, compared to human toxicity, acidification, eutrophication and photochemical oxidation potentials (Cetiner and Edis, 2013). Second, achieving high energy performance is the most challenging. By analyzing 490 LEED certificated buildings, Berardi (2012) found that energy performance, albeit the most important, is less achieved than water efficiency and indoor air quality. Third, reducing carbon emissions of buildings is considered worldwide as a key part of government policy (Pan and Garmston,

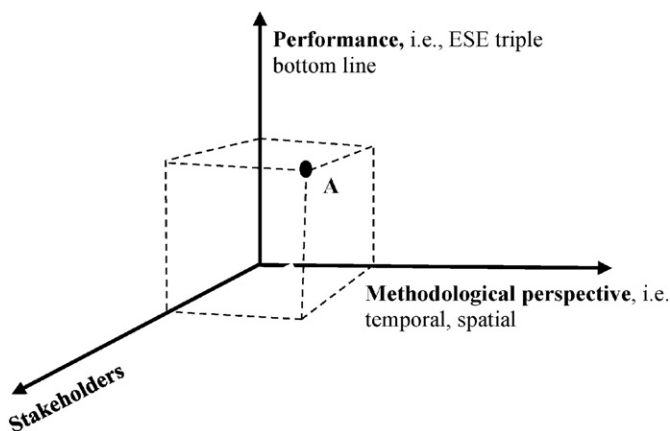


Fig. 1. A conceptual framework of examining interdependence of sustainable buildings. Source: Pan and Ning (2015)

2012), and energy is closely relevant to economic and social improvements (Kaygusuz, 2012).

The focus on one aspect of ESE in insulation has been criticized for its negligence of the interdependence in the system. The negligence of the economic and social aspects in research brings about a great limit for the assessment of building sustainability (e.g., Ding, 2008; Berardi, 2013a). Especially, there is a paucity of research on social sustainability except for a few. For instance, Valdes-Vasquez and Klotz (2013) identified 50 processes of the design and construction stages and categorized them into a framework for integrating social considerations in construction projects. Edum-Fotwe and Price (2009) presented an ontology to articulate the issues associated with the social aspect of sustainability assessment.

3.2.2. Interdependence between multiple aspects and elements

To realize sustainable development, the ESE aspects should be assessed together (Mwasha et al., 2011). However, how the ESE aspects could be addressed collectively remains a concern. Sustainability Index used to assess building and construction works can be defined as an aggregative function with weighted means, using either non-linear normalization procedure (Vučićević et al., 2013) or linear agglomeration (Kim and Todorovic, 2013). The reason for the non-linear process is the complex interdependency among all indicators (Hiete et al., 2011). However, du Plessis (2012) held that sustainability is not an aggregate of social-economic-technological solutions, but an emergent property arising from the interaction of all these systems. Hiete et al. (2011) particularly examined the interdependencies between the indicators used to assess SBs using the decision-making trial and evaluation laboratory method. It is suggested that users might prioritize the criteria belonging to the cause group as these criteria have higher impacts on the overall ratings (Hiete et al., 2011). Morrison-Saunders and Pope (2013) illustrated both process and substantive (i.e., outcome dimension) trade-offs associated with sustainability assessment. Also, they suggested that to deal with the trade-offs, the demarcation of acceptable from unacceptable impacts would be helpful.

Performance indicators play a critical role in depicting the systems that are often complex and interdependent (McCool and Stankey, 2004; Shen et al., 2010). Indicators are often used to reduce complex systems to a manageable number of variables (McCool and Stankey, 2004). However, many aspects of SB performance are not easily quantified. For instance, Dempsey et al. (2011) pointed out that social sustainability as a dynamic concept is neither absolute nor constant. It will change over time in a place. Thus, the adequacy and definition of indicators that evaluate environmental, social and economic impacts are critical to assess SB performance (De Azevedo et al., 2010). In addition, assessment tools were also criticized for their complicatedness and time consuming in use, although it is argued that tools should cover as many perspectives as possible (Häkkinen and Belloni, 2011).

Two contrasting findings emerge from the systems examination of the ESE aspects. On the one hand, many studies empirically supported that success in the ESE aspects is collectively achievable. For example, Schnieders and Hermelink's (2006) study of monitoring 11 passive house projects found that these buildings have achieved success in social, ecological and economic aspects. Fuerst and McAllister's (2011) study suggested that office buildings in US with Energy Star, LEED eco-labels, or both have also obtained satisfactory economic payback.

On the other hand, studies claimed that there exist trade-offs among the ESE aspects. Especially, achieving green may not guarantee the social and economic sustainability. For instance, Rajendran et al. (2009) observed that LEED certified buildings would incur a 9% higher injury rate than non-LEED projects. Safety strategies may not be cost-effective for all projects (Dewlaney et al., 2012). By investigating 144 buildings (65 LEED certified) and 21,477 individual occupants (10,129 in LEED buildings), Altomonte and Schiavon (2013) found that LEED certification does not influence occupant's satisfaction with indoor environmental quality significantly.

Besides the interactions between the environmental and social aspects, interdependence also exists between the economic and environmental aspects. For example, Leckner and Zmeureanu (2011) carried out a life cycle cost analysis of a NZEH in Montreal, and found that financial payback is almost unachievable due to the high solar technology cost and low electricity cost. Through case studies of two housing projects in Portugal, Coimbra and Almeida (2013) found that the cost increase by using very efficient techniques of insulation would reach 4.2%, although heat loss of a range from 30% to 60% could be yielded.

Apart from these two contrasting groups, some studies argued that ESE aspects do not necessarily contradict each other, suggesting that some optimal scenarios exist. Many studies aimed to determine the cost-optimal solutions in SBs. For example, Hamdy et al. (2013) identified cost-optimal solutions towards nearly-zero-energy. Through a case study of a single-family house in Finland, it is found that the economic aspect is unfeasible to achieve nearly zero if incentive is absent (Hamdy et al., 2013). Nikolaidis et al. (2009) dealt with the economic evaluation (i.e., Net Present Value, IRR, Savings to Investment Ratio and Depreciated Payback Period) of various energy saving measures in a domestic detached house in Greece. They found that upgrading of lighting is the most effective, followed by increasing the insulation of the roof of the building, and installing an automatic temperature control system.

Ouyang et al. (2009) analyzed the economic benefits from the energy-saving measures through the life-cycle cost method. They suggested that the cheap electricity price would inhibit the wide-scale implementation of energy-saving measures in China's residential sector. In addition, economical energy and power management strategies were examined in a grid-friendly hydrogen based Zero Energy Buildings through simulations (Milo et al., 2011). It is shown that an adequate energy and power management structure permits the optimal economic exploitation of a ZEB-H2 facility, providing not only a zero energy annual balance but also added-value features (Milo et al., 2011).

Overall, the literature shows that the interdependence associated with the building performance is of close relevance to the performance scope of SB (i.e., energy-efficient buildings; environmentally-friendly buildings; and sustainable buildings). The interdependence exists at two levels in relation to the performance scope of SB. The specialization of carbon/energy research at the narrowest performance scope might bring about the concern of overlook at the interdependence among the elements of environmental aspect in the first layer. As a consequence, it may cause oversimplification of interdependence on the breakdown elements of the environmental aspect. Meanwhile, it is widely recognized that the element of carbon/energy is placed as the priority in the face of anthropogenic climate change. Having recognized environment is one aspect of ESE framework of SB, the interdependence of SB may take place in the interdependence of ESE aspects in the second layer. Specifically, interdependence of the environmental and other two aspects (i.e. economic and social) is documented by prior studies.

3.3. Interdependence from the methodological perspective

The methodological perspective describes the temporal and spatial dimensions of SB products and works. The temporal dimension includes two trajectories, one ranging from material extraction to the end of life of the product and the other starts from planning and ends at demolition works. The spatial dimension describes the location of physical subjects, from technology, building components through the building to the broader context.

3.3.1. Interdependence in the temporal dimension

3.3.1.1. Work flow from concept study to the ends at demolition. Within the temporal dimension, early stage activities will affect the later ones

across the lifecycle (Ochoa and Capeluto, 2008). When designing SBs, identifying the most important design parameters is helpful to optimize design solutions (Heiselberg et al., 2009). However, the success of building performance can neither be predicted nor guaranteed at the completion of design clearly (Cole et al., 2013). Newsham et al. (2009) identified four gaps between the design and the products: 1) the pattern of occupancy differs from the assumptions; 2) the as-built product differs from the design; 3) technologies do not function as experimented; and 4) the pattern of plug loads differs from the assumptions. Post-occupancy evaluations also concurred that real building performance aligns poorly with design expectations (Gill et al., 2011).

3.3.1.2. Material flow from material extraction to the end of product life-cycle. The interdependence is often found in the material flow trajectory, i.e., ranging from material extraction to the end of product life-cycle. For instance, carbon emissions at the operation stage may be reduced at the expense of adding to other environmental impacts such as embodied energy. Photovoltaics and fuel cells technologies were suggested as substitutes for a pre-dominantly fossil fuel-powered energy system, but actually require more energy to produce than they themselves will ever generate (Kibert, 2008). Similarly, Eicker (2010) found that the insulation and triple glazed argon filled windows installed in passive houses actually require a significant amount of energy to manufacture. While adoption of durable materials might result in more embodied energy for the construction, it reduces embodied energy in the replacement (Habert et al., 2013). It is also possible there are less environmental impacts during the construction, but higher impacts resulted from the maintenance or recycle stages (Van den Heede and De Belie, 2014). Aye et al. (2012) found that prefabricated steel system will cause a significant increase in embodied energy compared to the concrete building. But, the potential for the reuse of materials is significant, resulting in 81% saving in embodied energy in an eight-storey multi-residential building.

To gain insights into the lifecycle impact of a building, the life-cycle approach is increasingly favored (Arpke and Hutzler, 2005; Guggemos and Horvath, 2005; Himpe et al., 2013; Kahhat et al., 2009). These studies are fruitful to depict the interdependence between embodied and operational energy/carbon. Junnila and Horvath's (2003) review concluded that "most of the previous studies have concentrated on either a limited set of life-cycle phases or only on one or two environmental impact indicators". Similarly, Ng et al. (2012) found that the assessment practices primarily focus on the operation stage.

Arpke and Hutzler (2005) concluded from a literature review that the operational phase of the life cycle causes the most significant environmental impact. However, Stephan et al. (2013) analyzed the life cycle energy use of a typical Belgian passive house, and found that the embodied energy constituted 77% of the total energy consumption. Notwithstanding this difference, it is worth noting that these studies are less comparable as the boundaries of these studies vary in the building type examined and the calculation methods adopted.

Berggren et al. (2013) indicated that upgrading a low energy building to net zero energy may increase the embodied energy. But, the increase could be further covered by the energy savings during the operation stage. The review by Berggren et al. (2013) indicated a linear relationship between embodied and life cycle energy use. In another study of examining new European and U.S. office buildings from material production to end-of-life treatment, Junnila et al. (2006) found that the proportion of the materials, construction, maintenance, and end-of-life phases of buildings would increase in the long term as buildings' function would become obsolescent more rapid, and the frequency of reconstruction and reconfiguration would also increase.

To sum up, different building lifecycle stages in the temporal dimension are closely linked with each other, between which interdependence may be triggered. Trade-offs exist between the different stages of the building lifecycle from the perspective of each element of ESE aspects.

3.3.2. Interdependence in the spatial dimension

3.3.2.1. Interdependence within the building systems. Buildings' sustainability can be evaluated at different levels in the spatial dimension, e.g. for single subcomponent, for the integration of building components as functional units, as well as for the building as a whole (Berardi, 2011; John et al., 2005). Within the physical boundary of a building, interdependence exists between various technology and design features. This is because architectural features and building elements within the building systems may influence various building performance simultaneously (see Su, 2011). Even different aspects of building performance may pose conflicting requirements for the design features or building components. For example, dwellings in tropical climates must be kept open for thermal comfort, whereas acoustic comfort is obtained by closing the windows (Garde et al., 2004). PV and solar thermal will compete for space on the constrained roof area (Day et al., 2009).

3.3.2.2. Interdependence between the building systems and their context. The influence of SBs is not only building centric, but also spreading into the local, regional and global contexts (ISO, 2008). This implies that interdependence may also exist between the building systems and their context. Conte and Monno (2012) argued the building centric approach is often limited. The importance of spatial relationships between a building and its context constrains the definition of sustainability at the building level (Berardi, 2013a). Koch et al. (2012) found that some of the energy saving measures are only available on a larger scale other than individual buildings. For example, Koch et al. (2012) proposed that the urban neighborhood scale would be more effective.

Berardi (2011) pointed out that the assessment at the product level may be insufficient to obtain SBs. This is because the assessment at product level, although takes into account few environmental parameters, fails to look at the product from all the point views of sustainability. A building is an element set within wider human endeavors and is dependent on its context (Cole, 2012). Conte and Monno (2012) thus developed a cross-scale evaluation approach which could be used to assess the reliability of SB design solutions for the building context.

To make up the disadvantages of building centric approaches, sustainable community focusing on a larger scale was proposed (Cho and Lee, 2011). The US Green Building Council has developed LEED for Neighborhood Development (LEED ND). Similarly, the Japanese system CASBEE released CASBEE for urban development (CASBEE-UD) in 2006. CASBEE-City in 2011 and BREEAM Community in 2012 are used to examine the sustainability of neighborhood development projects (Haapio, 2012). However, Sharifi and Murayama (2014) found that the neighborhood sustainability assessment is pluralistic as it takes into account the specific locations and needs of the key stakeholders.

As a whole, the spatial dimension describes the location of physical subjects, from technology, building components through building as a system to the broad context. Interdependence exists in the scope of the spatial dimension. Within the physical boundary of the building, interdependence between various technology and design features may cause trade-offs for the uptake of technology and design solutions. Meanwhile, an increasing number of studies call for looking beyond the building product given the interdependence between buildings and regional context.

3.4. Interdependence from the stakeholder perspective

3.4.1. Misalignment of parties in delivering SBs

The current project delivery processes were criticized for their shortfalls in delivering SBs (Lapinski et al., 2006). Horman et al. (2006) revealed that the traditional project processes used to produce SBs might cause a larger number of wasteful rework and delays. One of the reasons might be that delivering SBs requires a higher level of interdisciplinary collaboration (Magent et al., 2009). As the level of building

complexity increases, the need for integrating different disciplines would increase further (Berker and Bharathi, 2012). Berker and Bharathi (2012) found that difficulties in adopting new methods and technologies often hamper the SB project success. These difficulties might be caused by a steep learning curve in the SB delivery (Chong et al., 2009).

Therefore, aligning multiple stakeholders (i.e., policy-makers, occupants, building professionals) to collectively address the problems in the SB delivery is desirable (Gangoelle and Casals, 2012; Hoxie et al., 2012; Pilkington et al., 2011; Reeves et al., 2010; Summerfield and Lowe, 2012; Zhu and Lin, 2004). Various solutions to build an integrated delivery approach have been proposed. For instance, Gansmo (2012) suggested that plans could be carried out through collective actions in the long run, which would facilitate stakeholders' learning of new knowledge production. Swarup et al. (2011) emphasized the importance of owner commitment towards sustainability, early involvement of contractors and the early inclusion of green strategies. In the specific case of uptake of CHP and renewable energy technologies, Day et al. (2009) revealed that dialog is beneficial. These strategies overall highlighted the critical role played by the integrated delivery method (Berardi, 2013b; Bossink, 2007).

3.4.2. Independence of end users from the SB delivery

The research about the relevance of end-users to the delivery of SBs is salient in the extant literature. This is because performance of a house is seen to depend on how end-users operate the house and how end-users interface with the technology (Banfill and Peacock, 2007; Glad, 2012). An ecological footprinting exercise undertaken by Pilkington et al. (2011) showed that behavioral changes even have a larger impact on environmental sustainability than the technological and regulatory strategies.

However, there is a widespread reluctance of homeowners to accept the potential behavioral changes associated with sustainable building (NHBC Foundation, 2008). Also, there exist an information gap between end-users, construction professionals (Glad, 2012; Thollander and Palm, 2013) and government agencies (Ellegård and Palm, 2011). Garrett and Koontz (2008) found that inventing high energy-efficient technologies is only part of the solution, enhancing the adoption of the technologies would be another significant concern. After adoption, how to use the technology should also be further taken into account. Banfill and Peacock (2007), for example, found that the householders have little knowledge of operating the controls of condensing gas boilers in spite of its high efficiency, suggesting that energy savings are only accomplished when behavioral change is materialized.

Economic concern is still a serious obstacle to the adoption of SB and associated green features. Based on a questionnaire-survey in Singapore, Ling and Gunawansa (2011) found that the majority of the respondents are quite price sensitive, and could only accept 1% increase in the upfront cost. In addition to the economic influence, Gram-Hanssen (2008) particularly pointed out that household's sustainable behaviors are contextualized in the social and cultural aspects during the technology adoption and implementation. Thus, an in-depth insight about how their behaviors embedded within the social, cultural and geographic context is called for when addressing their resistance to changes. In addition, their attitudes towards environmental concerns are also influential to behavioral changes. A study of post-occupancy evaluation of two academic office buildings in Sydney found that occupants with a higher level of environmental concern were more forgiving of their building (Deuble and de Dear, 2012).

In conclusion, stakeholders often aim to pursue their best interests, thereby rendering difficulties in being aligned. This dilemma is compounded by the fragment nature of the construction project delivery. Interdependence would therefore exist between the value proposition of different stakeholders and their recognition of the importance of collaboration in delivering SBs. In addition, end-users' participation in the SBs is still seen to independent from construction professionals, although it

is increasingly recognized that making use of the information sharing conduits between them is helpful to the SB success.

4. Interdependence of ZCB as a specific case of SB

In order to articulate the integration of these three dimensions, an examination of zero carbon building (ZCB) which specializes in carbon/energy performance is carried out. ZCB is being considered as an innovative approach to reducing carbon emissions. However, little knowledge is available about the systems approach of examining ZCB. The exercise of examining ZCB in particular would help to bridge this gap in knowledge.

4.1. Interdependence in relation to specialization of carbon consumption

Notwithstanding ZCBs' contribution to the carbon reduction, the specialization of the research in carbon may represent an oversimplification of SB as carbon is only one element of the environment aspect. The elements other than carbon, for instance air quality, are not explicitly addressed in zero carbon building. Further, it is still not known if ZCB is economically viable and socially sustainable with the exception of a few attempts to explore the economic feasibility, for instance Kapsalaki et al. (2012) and Kurnitski et al. (2011).

4.2. Interdependence between the performance and methodological perspective

It is argued that articulation of energy alone is unable to make findings comparable primarily due to the methodological difference in terms of temporal and spatial dimensions. The dimension of the performance of ZCB is closely relevant to the methodology dimension. Achieving ZCBs is closely relevant to boundaries of the building energy balance (Koch et al., 2012). Torcellini and Crawley (2006) highlighted the difference between net zero source and net zero site energy building from the spatial perspective. The former deals with boundary of the building, the transmission system, the power plant, and the energy required to transport the fuel source to the power plant, whereas the latter refers to energy at the site only. This difference rests on the spatial dimension. In addition, some studies emphasized that the boundary of ZCB should not be restricted to the footprint of the building and the connection with the grid could be taken into account. This is because there exists a mismatch between the energy production and consumption (Lund et al., 2011; Koch et al., 2012).

Energy performance also interacts with the temporal dimension, for example, the difference between embodied energy and operational energy. The current definitions of ZCB mainly refer to the operational energy, for instance, regulated energy, i.e., for space heating, cooling, ventilation, lighting and hot water in UK (HM Treasury, 2011). Studies (e.g., Hermelink et al., 2013; Atanasiu et al., 2011) suggested that the energy use for appliances should be included in the ZCB energy scope. One reason might be that energy consumptions in lighting and appliances are on the increase. For example, between 1970 and 2000, energy use for lighting and appliances increased by 15%, while energy use for cooking decreased by 16% in the UK (Xing et al., 2011).

However, another stream of studies proposed to include the lifecycle energy as the incorporation of a part of the energy (e.g., operational energy or regulated energy other than energy use for appliances) consumptions may sub-optimize the lifecycle impact (e.g. Atanasiu et al., 2011; Goodchild and Walshaw, 2011). Thus, a lifecycle balance including both embodied and operational energy is suggested (Atanasiu et al., 2011). However, if considering the interaction with the stakeholder dimension, the concern of usability might arise. Winn (2013), for instance, found that it is unhelpful to take embedded energy and transportation energy into account because it would likely generate a very complex result, which will however hamper the usability. A survey in the UK found that consumers often feel that it is not easy to fully catch

the meaning of some terminologies (NHBC Foundation, 2012). This indicates that the performance and methodology dimensions have close relevance to the stakeholder dimension. In order to facilitate the up-take of ZCB in the market, a systems thinking of these three dimensions is essential.

4.3. Interdependence among the performance, methodology and stakeholder

Interdependence also exists among the overall integration of the performance of ZCB, methodology and stakeholder dimensions. The concerns of different stakeholders towards the concept and methodology vary widely. Torcellini et al. (2006) listed that building owners typically care about energy bills; governments more focus on primary or source energy; building designers may be interested in compliance with energy code requirements. In addition, house builders have little confidence about the suppliers' capability to provide satisfactory products (NHBC Foundation, 2012). The above review may indicate a misalignment between the key stakeholders.

The implication is that it is necessary to identify who are the key stakeholders. Their concerns should be then positioned into the performance and methodology dimensions. Through an iterative process, relevant stakeholders' concerns should be collectively addressed and their motivation should be aligned. It is also possible that integration may take place at certain stages of the life-cycle. Butera (2013) suggested integrated design approach becomes a must in ZCB at the design stage. Professionals should work collectively in the early stage of the design process (Butera, 2013).

For the end-users, a survey carried out by NHBC Foundation (2012) found that 96% respondents indicated that the energy bills are important to them, but this consideration is still minor when making decision to buy a house. ASBEC (2012) revealed that an additional cost of 15% and a payback period of around 11 years for an Australian Zero Emission House are too long to be attractive to most consumers. In addition to the concern of increased cost, NHBC Foundation (2012) found that a high percentage of end-users felt that they could benefit from solar thermal or solar electric system, but how to operate it correctly is still a big concern. Actions are thus needed to help them understand how to use and maintain renewable technologies (NHBC Foundation, 2012), for instance information and education (Butera, 2013).

As a summary, the examination of SB from an integrated perspective shows that the theoretical approach is able to depict the interdependence of ZCB in terms of performance, methodology and stakeholder on their theoretical grounds ranged from reductionism to holism. By presenting this approach, the interdependence of ZCB could be articulated in a systems manner.

5. Conclusions

The results suggest that interdependence exists of the building performance, methodology and stakeholders of SB. Knowledge of the interdependence would be too critical to be overlooked or made implicit in pursuing future research on and refining practice of sustainable building. Guided by a conceptual framework of interdependence of SBs, a literature review of SB was carried out. In order to articulate the integration of the three dimensions, this paper also examined ZCB as a specific case of SB, which specializes in the carbon/energy aspect.

The interdependence associated with the building performance is of close relevance to the performance scope of SB. The results are still inclusive in the area of assessing the ESE aspects together. Some documented a success of achieving all ESE aspects, whereas some found trade-offs among the ESE aspects. In the trade-off case, it is also possible to reach optimal scenarios. Future studies of comparing prior studies in terms of their calculating methodology are thus suggested.

Two dimensions (i.e., temporal and spatial dimension) constitute the methodological perspective. The different building lifecycle stages

in the temporal dimension are closely linked with each other, between which interdependence may be triggered. Interdependence also exists in the scope of the spatial dimension. Within the physical boundary of a building, interdependence between various technology and design features may cause trade-offs. Meanwhile, an increasing number of studies call for looking beyond the building product given the interdependence between the building and regional context.

From the stakeholder perspective, it is found that end-users' participation in the SBs is often independent from construction professionals, although it is increasingly recognized that making good use of the information sharing conduits enables the SB success.

In order to articulate the integration of these three dimensions, an examination of ZCB which specializes in carbon/energy performance is carried out. It supports that the theoretical approach is able to depict the interdependence of ZCB in terms of performance, methodology and stakeholder on their theoretical grounds ranged from reductionism to holism.

The contribution of this paper to the body of knowledge is that it enriches the understanding of the interdependence of SB in terms of three inter-connected dimensions, namely performance, methodology and stakeholder on their theoretical grounds ranged from reductionism to holism. The results will help researchers to position their research. In practices, the results should help increase practitioners' awareness that the interdependence of SBs is an important consideration in their practices. The interdependence of different dimensions is multifaceted and interwoven with each other. Also, the framework and associated literature summaries should help them to recognize and identify risks associated with interdependence within building performance, methodology and stakeholders in the SB delivery.

Acknowledgment

Reviewers' comments on the earlier draft are acknowledged with many thanks.

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