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An examination of factors affecting healthy building: An empirical study in east China

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ABSTRACT

With economic development, there is an increasing demand for healthy working and living environments. Health issues of buildings have become increasingly important because people spend most of their time in buildings. One of their major concerns is whether the building is healthy or not. Many research efforts have been made regarding building health from various perspectives, such as eco-building, sustainable building, low-carbon building and green building. However, these studies cannot represent the health status of building comprehensively and appropriately. Based on comprehensive literature review, the connotation of healthy building was defined and 30 impact factors that affect healthy buildings were identified by bibliometric analysis and expert interview. A questionnaire survey was conducted to identify the importance of these key factors. Sixteen factors were identified as key impact factors (KIFs) with the importance index above 80. Furthermore, these 30 factors were classified into three principal components by using principal component analysis (PCA). At last, a framework integrating all these impact factors of a healthy building during its life cycle was developed, which provides a thorough picture of the impact factors and their classifications. The findings in this study can also help people gain deep understandings of healthy building, provide theoretical support for the design, construction and operation of healthy building, and promote the development of healthy building.

1. Introduction

With the fast urbanization process in China, there is an increasing demand for buildings in cities. The health of buildings is also considered to be critical because it has a close relationship with people (Abdou, 1997). Nowadays, people spend up to 80% of their time in buildings (Sessa et al., 2002). The health of the buildings has become one of their major concerns (Marmot et al., 2006). For example, unhealthy interior decoration materials may cause headaches, nausea, nightmares, feeling of collapse and nasal irritation (Jaakkola et al., 2006). With the development of science and medical technology, people have a higher demand on healthy working and living environment than ever before (Davies, 2009). A healthy building environment provides good indoor air quality, adequate lighting, and comfortable temperature and humidity (Sessa et al., 2002).

However, it is undeniable that there are many health issues during building's life cycle. For example, construction dust contributes to air pollution, which causes various environmental and health problems (Tokmechi, 2011). Construction workers suffer from enormous stress on building sites due to various health and safety problems, such as noise, dust and falling from high structures or scaffolding (Gomes et al., 2002; Chen et al., 2012). Furthermore, some buildings may have hidden defects which threaten people's and buildings' health, such as fire hazard, deterioration of materials and poor maintenance (Dong, 2014). Some materials may produce odors that can cause health problems, such as headaches, nausea, nightmares, nasal irritation, sneezing and coughing, and the problems worsen if there is no adequate ventilation (Jaakkola et al., 2006; Fang et al., 2004). Sick building syndrome (SBS), like sleepiness, dizziness and chest congestion, did afflict nearly 25 million people in around 10 million American buildings (Murphy, 2006), and there are also many complaints about indoor air quality from occupants (Walsh et al., 2014). Therefore, the health of building is important for the safety and health of people, both physically and psychologically.

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However, little research effort has been made to examine the impact factors of healthy buildings during their life cycle. Most existing studies focus on a single stage of building's life cycle and ignore the changes of building health in different stages. Some scholars study the indoor health of occupants, without considering construction workers, maintenance workers, building operation staff. In the existing studies, the concepts of green building, eco-building, and low-carbon building are widely used. Therefore, there is a need to conduct a comprehensive review of healthy buildings and appropriately define the term *healthy building*. The paper aims to identify the key impact factors (KIFs) of a healthy building during its life cycle, develop a systematic framework that incorporates all these impact factors, and give a comprehensive connotation of healthy building. The findings provide useful theoretical support and practical guidance, with which to improve the health status of buildings and enrich the healthy building theories, as well as promote the healthy building concept in construction industry.

2. Literature review

2.1. Connotation and development of healthy buildings

Under the background from "Healthy City" (on 1984 Toronto International Congress) to "Healthy China" (in 13th Five-Year Plan beginning in 2016 in China), healthy building, initially regarded as a designing primer for a living environment, has been a gradual focus of research interest (Holdsworth, 1992). A model is provided for examining harmful indoor elements (Wyon, 1993). It is confirmed that interior environmental quality is positively correlated with people's health (Fisk et al., 1993). Building materials as potential contaminants should be used as less as possible to provide a healthy indoor space for occupants (Diasty and Olson, 1993; Gomes, 2004). Furthermore, it was explained in the Healthy Building Conference in Espoo, Finland in 2000 that healthy building is treated as a way to build indoor environments that incorporate layout, colors and individual mental needs, in addition to temperature, humidity, ventilation and illumination (Loftness et al., 2007). Bluyssen (2010) argued that not only need healthy building meet primary functional requirements, but make occupants feel comfortable as well. In 2015, the research themes of the Healthy Building Conference, which was held in Boulder, Colorado, still laid similar emphasis on some traditional focuses including harmful chemical reduction or relationships between indoor environment and occupants (Brunsgaard and Fich, 2016). Generally speaking, research studies on healthy buildings in recent years narrowly focus on the health of indoor environments.

Nevertheless, in the process of the global sustainable development, researchers made a breakthrough on views of healthy buildings from some other perceptions. As Ghaderi and Kasirossafar (2011) comments, the structure, which has everything to do with building's performance, should be taken careful consideration in the design stage to add architectural safety to building themselves. In the construction process, workers tend to suffer from heavy workload as well as psychological pressure, due to a series of dangerous construction activities, and these activities inevitably exert an adverse impact on the environment (Love et al., 2010; Zhang et al., 2014). Also, health management theory in building's operation and maintenance is successfully proposed because, at this critical stage, the health status of buildings could be greatly affected by many sorts of environmental pollution, such as air, light, water and soil pollution (Chang et al., 2007; Kahhat et al., 2009). Moreover, the demolition stage is another vital one that strongly affects building health in its whole life cycle. It is certain that, with the use of heavy machinery like bulldozers and excavators, demolition will cause both environmental problems and human diseases, including chronic and acute illnesses (Brown et al., 2015; Lee et al., 2015; Park et al., 2013). Revealed in the existing research studies above, they mainly focus on the health status of buildings in some single stage. Ortiz et al. (2010) believe that it is imperative to evaluate building life cycle thoroughly, but they did not conduct further study on quantitative analysis with respect to buildings' health. Unfortunately, the key assessment indicators (KAIs) for assessing sustainability performance are tailored to infrastructure projects rather than healthy buildings (Shen et al., 2010). Most researchers have expanded the scope of buildings' health in a broader sense, without a limitation to indoor health, but there is still a lack of systematic research on all the factors that affect healthy buildings from a comprehensive view of the whole life cycle of buildings.

Healthy building in the white paper revised in Europe in 2016 refers to a high-performance building or community which is characterized by comfort, health, safety, and environmental protection, aiming to meet the physiological, psychological, and social needs of occupants (Brunsgaard and Fich, 2016). The concept remains to be further perfected, in that it stresses more impacts on occupants in operation stage than workers in the construction process. Another relevant definition is currently proposed in a new evaluation criterion in China, putting emphasis on providing healthy environments, infrastructures, and public services to promote the health of humans and buildings (Healthy Building Evaluating Standard T/ASC02-2016). The definition, however, does fail to be involved with lifecycle, which still results in some one-sided focus on healthy buildings. Thus, in line with the various attributes embodied in the whole building life cycle, the health of buildings should be considered across all stages, including design, construction, operation and final demolition stages.

2.2. Differences between healthy buildings and relevant buildings

Revealed in domestic and international research studies, traditional building concepts, such as green building, low-carbon building, sustainable building, and eco-building, have been already discussed with their own focuses. However, they all cannot be equivalent to healthy building regarding buildings' health.

Derived from Arcology, green building is a preliminary concept that is connected to the health of buildings (Soleri, 1969; Grierson, 2003). It is regarded as the building aiming at energy conservation and environmental protection (Gowri, 2004). Similarly, Yudelson (2008) took it as a building, which is symbiotic with nature, helping reduce environmental pollution and maximize resource utilization (energy, land, water, material, and the like) in its whole life cycle. There is no doubt that the emphasis of green construction lies on the reduction of energy and emissions (Kats, 2003; Pan et al., 2008; Castleton et al., 2010). Furthermore, it enhances the health of occupants and returning on investment to developers and local community (Zhang, 2015).

Afterward, low-carbon building emerged on the scene with the advancement of the low-carbon economy (Stafford et al., 2011). It is a building which functions as decreasing fossil fuel consumption as well as improving utilization efficiency during its life cycle (Chen et al., 2011). It reduces carbon dioxide emissions by changing the ways in which buildings are designed, constructed, managed, and used (Glaeser and Kahn, 2010). Besides, fuel conservation is universally accepted as a critical step to developing low-carbon building (Phil, 2008). Moreover, the goal of it is to add more comfort to interior environments with less CO_2 and solid waste emissions by using low-carbon materials and innovative technology (Adedeji et al., 2013; Zhang et al., 2011). It is evident that the focus, when it comes to low-carbon building, is on the reduction in carbon emissions (Cabeza et al., 2013; Chau et al., 2015).

Sustainable buildings are developed using the sustainable development theory, which covers different dimensions of environment, society and economy (Kibert et al., 2000). Analogously, it covers a cocktail of resource, environment, and ecology (Kibert, 2016), with the purpose of energy conservation and pollution reduction in the long term (Baharetha et al., 2012). Furthermore, the promotion of sustainable building is now shaping toward more sustainable practices in the planning, design, specification, and procurement stages (Zhang et al., 2011; Baharetha et al., 2012). However, it seems to be quite equivalent to green buildings to some extent due to many similarities in designs, functions, and their development objectives (Hwang and Tan, 2012).

Eco-building is an integrated carrier that plays a decisive role in the coordination between ecology and architecture (Zeng et al., 2008). It is regarded as a sort of building which reflects the combination of resource, environment, and ecology (Kibert, 2016). As Zeng et al. (2008) comments, eco-building should assume responsibility for a harmonious living environment as well as the rational use of natural resources. The emphasis of it, to increase building's ecological benefits, lies on reducing environmental damage according to local natural conditions (Li et al., 2005). Also, other studies on eco-building are mainly concentrated on green technology, ecological benefits, and energy performance (Kam-Biron and Podesto, 2011).

The research studies mentioned above reveal that previous relevant concepts, such as green building, low-carbon building, eco-building, and sustainable building, all narrowly involve some aspects of building health, especially regarding the environment. Although building life cycle is mentioned in green construction and low-carbon building concepts, these concepts still have shortcomings regarding the consideration of the health of construction workers. Simultaneously, healthy building, without a clear and unitary connotation, is still being discussed in this phase. Therefore, this paper aims to examine the specific impact factors that affect building health and put forward a comprehensive connotation of healthy building on the basis of building life cycle.

3. Identification of factors affecting healthy building

Gordon introduced life cycle cost management theory in 1964. After that, life cycle management has been applied in various industries. Life cycle management for buildings can be divided into five stages: planning, design, construction, operation, and demolition (Grussing, 2014). The formation of a building entity actually begins during the design stage in that there is a focus on preparatory work in the planning stage (Clark, 2009). Therefore, the four stages including design, construction, operation, and demolition, were studied in this paper.

A significant number of papers from databases like ASCE, EI, Web of Science, CKNI (Chinese), WANFANG (Chinese) were retrieved using keywords, such as “healthy building”, “green building”, “low-carbon building”, “sustainable building”, “energy conservation”, “environmental protection”, “impact factors in life cycle”, “design stage”, “construction stage”, “operation stage” and “demolition stage” to identify the factors that affect a healthy building during its life cycle. 264 references (year 2000–2015) regarding building health were reviewed. Seven experts from the construction industry and academic institutions were then interviewed to promote the affecting factor list, making up for the deficiency of literature retrieval. As a result, 30 factors that impact healthy buildings were identified based on the comprehensive results of bibliometric analysis and expert interviews, shown in Table 1. For the convenience of further study, these impact factors were coded.

4. Research methods

4.1. Questionnaire development

Questionnaire investigation was adopted to analyze these identified impact factors further. The purpose of the questionnaire is to investigate different perceptions on the importance of factors above and determine the importance index of them, based on which, KIFs will finally be identified.

There are three main sections in the questionnaire. Section 1 is about the background of respondents. Four questions (Q1-Q4) were designed regarding the highly-specialized profession of this research to collect basic information about interviewees (gender, age, job and working experience), which ensures the authenticity and validity of collected data. In Section 2, 30 questions (Q5-Q34) were designed to determine the importance of each factor that affects building's health during its life cycle from the responses. A five-point Likert scale method was employed to grade factor importance: 5 very important, 4 important, 3 moderate, 2 unimportant, and 1 very unimportant. Section 3 is about additional factors. Respondents can add other important factors which were not mentioned previously.

4.2. Data collection

Questionnaires were distributed to the respondents by e-mail or mail. The target sample was selected from several cities in the east of China in line with the purpose and convenience of questionnaire investigation, including building designers, contractors, occupants, and experienced professionals in the field of construction, all of whom are stakeholders during the whole building life cycle. Consequently, it is more scientific and reasonable to identify key impact factors that actually affect building's health from their responses.

A total of 200 questionnaires were sent out from April to May 2015, and 167 valid responses were collected with an effective response rate of 83.5%. The background information about the respondents is shown in Figs. 1–3.

4.3. Data analysis

PCA is a multivariate ordination technique used to display patterns in multivariate data. It aims to graphically show the relative positions of data points in fewer dimensions while retaining as much information as possible and explore relationships between dependent variables (Bartholonew, 2010). SPSS 20.0 were used to analyze the data and research the principal components of impact factors of a healthy building.

5. Results and discussion

5.1. Reliability analysis

Cronbach's alpha is often used to test the internal consistency of collected data. Cronbach's alpha measures internal consistency (reliability) on a scale between 0 and 1 based on the average inter-item correlation. The reliability is acceptable if the Cronbach's alpha value is more than 0.7 (Aigbavboa and Thwala, 2013). Cronbach's alpha was used in this study to test the internal consistency among the impact factors. All Cronbach's coefficients are more than 0.7, as shown in Table 2.

5.2. Ranking of factors

The importance index of impact factors was calculated to

Table 1
Impact factors in life cycle of healthy building.

Stage	Code	Factor
Design	F111	Site plan
	F112	Structural design (Optimization of design)
	F113	Architectural design (Optimization of design)
	F114	Cost plan
	F115	Building envelope
	F116	Renewable energy and material recycling
	F117	Ecological protection
Construction	F121	Construction safety
	F122	Project objectives (Time, Cost, Quality)
	F123	Air pollution
	F124	Waste water
	F125	Solid waste
	F126	Noise pollution
	F127	Light pollution
	F128	Radioactive contamination of materials
	F129	Vibration
	F1210	Workload of construction workers
	F1211	Mental health of construction workers
Operation	F131	Living environment (Natural environment, neighborhood and community facilities)
	F132	Safety performance
	F133	Energy performance
	F134	Light pollution
	F135	Toxic pollutants from building materials
	F136	Occupant satisfaction with indoor environment quality
	F137	Indoor environmental quality (thermal, lighting, acoustic and air)
Demolition	F141	Dust & air pollution
	F142	Contamination of water
	F143	Demolition waste (solid or semi-solid)
	F144	Vibration & explosion
	F145	Noise pollution from demolition

identify the key factors affecting healthy building during its life cycle by the approach proposed by Shash (1993):

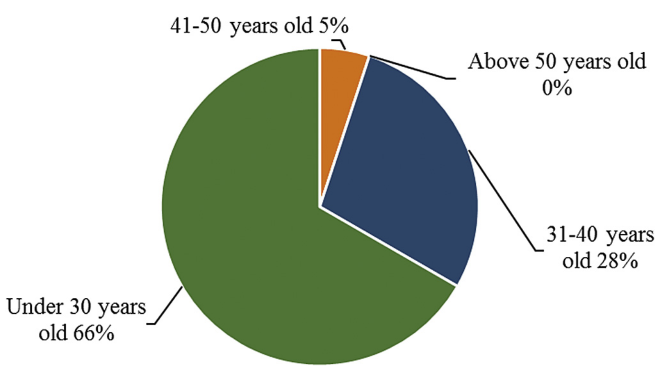

Fig. 1. Distribution of the returns from different age groups.

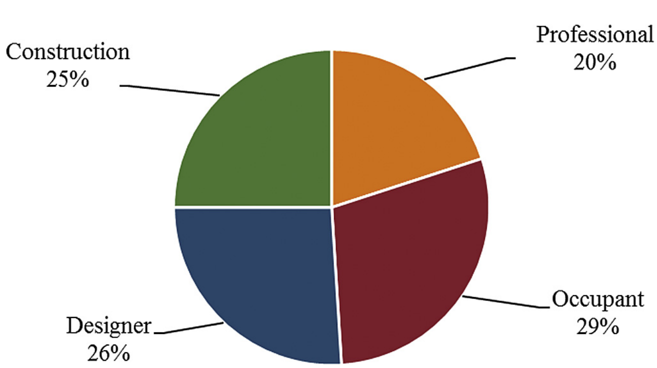

Fig. 2. Distribution of the returns from different target samples.

$$I_i = \sum_{i=1}^{n=5} (A_i X_i) * 100/5$$

I_i: Importance index,
A_i: Point of a factor by a respondent, $A_i = 1, 2, 3, 4$, or 5.
$X_i = n_i/N$, n_i: the number of respondents who score a factor A_i, N: the number of all valid respondents.

With collected data, the importance index of factors was calculated and listed in Table 3. In the five-point Likert scale, 5 represents very important, and 4 represents important. Factors, whose Likert scale are 4 or above (importance index above 80), are defined as key factors (Tan et al., 2014). Consequently, 16 factors with the importance index above 80 were then identified as KIFs.

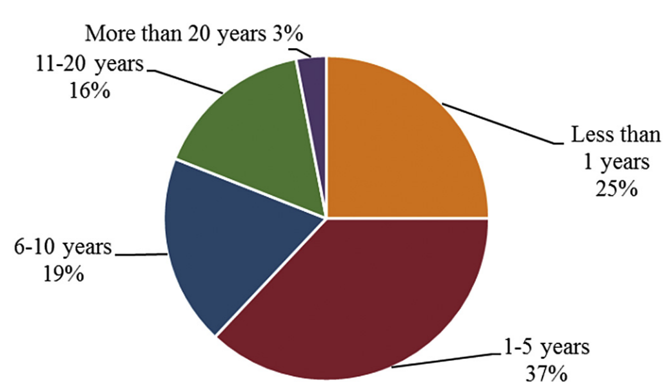

Fig. 3. Distribution of the returns from different work experience.

Table 2
Reliability test results.

	All	Design	Construction	Operation	Demolition
Cronbach's Alpha	0.920	0.743	0.830	0.777	0.831
Cronbach's Alpha Based on Standardized Items	0.921	0.746	0.835	0.777	0.831
N of Items	30	7	11	7	5

Table 3
Importance index and ranking of factors affecting healthy building.

Stage	Code	Factor	Importance index and ranking										
			Designer		Contractor		Occupant		Professional		All		
Design	F111	Site plan	82.27	3	79.52	2	84.49	2	85.63	1	82.87	2	KIF
	F112	Structural design (Optimization of design)	83.64	1	80.95	1	82.86	3	85.00	2	82.99	1	KIF
	F113	Architectural design (Optimization of design)	83.64	1	78.10	3	86.12	1	82.50	3	82.75	3	KIF
	F114	Cost plan	77.73	7	75.24	6	73.06	7	76.25	7	75.45	7	
	F115	Building envelope	82.27	3	75.71	4	75.92	6	82.50	3	78.80	6	
	F116	Renewable energy and material recycling	78.64	6	75.71	4	81.63	4	80.63	6	79.16	5	
	F117	Ecological protection	80.45	5	75.24	6	80.41	5	82.50	3	85.27	4	KIF
Construction	F121	Construction safety	77.73	11	84.76	1	77.14	8	74.38	11	78.68	9	
	F122	Project objectives (Time, Cost, Quality)	83.64	2	83.81	2	82.04	5	78.13	8	82.16	6	KIF
	F123	Air pollution	85.45	1	82.86	3	87.35	1	87.50	3	85.75	1	KIF
	F124	Waste water	82.27	5	80.95	5	84.90	4	88.13	1	83.83	3	KIF
	F125	Solid waste	82.27	5	79.05	8	81.22	6	88.13	1	82.28	5	KIF
	F126	Noise pollution	81.36	7	81.43	4	85.71	2	86.25	5	83.59	4	KIF
	F127	Light pollution	78.18	10	80.00	7	77.14	8	80.00	7	78.68	9	
	F128	Radioactive contamination of materials	82.73	4	80.95	5	85.71	2	86.88	4	83.95	2	KIF
	F129	Vibration	81.36	7	76.19	10	80.82	7	75.63	10	78.80	8	
	F1210	Workload of construction workers	83.64	2	77.14	9	76.33	10	83.13	6	79.76	7	
	F1211	Mental health of construction workers	78.64	9	74.76	11	70.61	11	77.50	9	75.09	11	
Operation	F131	Living environment (Natural environment, neighborhood and community facilities)	80.45	6	77.62	3	77.14	5	78.13	7	78.32	5	
	F132	Safety performance	80.91	5	77.62	3	81.22	2	80.63	5	80.12	3	KIF
	F133	Energy performance	75.91	7	72.38	7	72.24	7	78.75	6	74.49	7	
	F134	Light pollution	81.36	3	74.29	5	72.65	6	81.25	4	77.01	6	
	F135	Toxic pollutants from building materials	86.36	1	80.95	1	88.16	1	88.75	1	85.99	1	KIF
	F136	Occupant satisfaction with indoor environment quality	81.36	3	80.00	2	79.59	3	81.88	3	80.60	2	KIF
	F137	Indoor environmental quality (thermal, lighting, acoustic and air)	82.73	2	74.29	5	77.55	4	82.50	2	79.04	4	
Demolition	F141	Dust & air pollution	81.36	3	79.05	4	82.86	1	85.00	1	81.92	2	KIF
	F142	Contamination of water	82.73	1	80.00	2	82.86	1	84.38	2	82.40	1	KIF
	F143	Demolition waste (solid or semi-solid)	79.09	4	79.52	3	80.00	4	79.38	5	79.52	4	
	F144	Vibration & explosion	76.82	5	78.10	5	78.78	5	80.63	4	78.44	5	
	F145	Noise pollution from demolition	82.27	2	80.95	1	81.63	3	81.25	3	81.56	3	KIF

During the design stage, site plan, structural design (optimization of design), and architectural design (optimization of design) are regarded as the top three key factors, as shown in Table 3. It indicates that the health of building itself is considered more important than other factors. On the contrary, cost plan is considered less important by all respondents.

During the construction stage, safety is taken as the first important factor by contractors due to high accident costs and negative impacts on their images (John and Peter, 1996). As direct participants in construction, designers and contractors pay close attention to project objectives (time, cost, quality) than occupants and professionals. It is well known that heavy construction machinery causes much air and noise pollution (Guggemos and Horvath, 2006). Therefore, air pollution is considered as a key factor for all respondents. Experts take waste water and solid waste as top two factors because the pollution caused by them has great impacts on the health of buildings, and more effort should be made to reduce construction waste (Safiuddin et al., 2010). The occupants fail to concern about air pollution, noise pollution, and radioactive contamination of materials which affect workers, residents, or passengers near construction sites. The light pollution is considered less important to some extent. The importance of the indices of vibration, workload, and the mental health of construction workers are ranking at the bottom. Their indices reflect the poor working conditions like overload work and less healthcare. Workers are overburdened because there is no free psychological counseling for them (Love et al., 2010).

At operation stage, toxic pollutants from building materials, occupant satisfaction with indoor environment quality and safety performance are top three essential factors. It indicates that toxic pollutants from building materials are the major concern of people because they directly affect peoples' health. The importance of indoor environment has reached a consensus among many researchers (El Asmar et al., 2014). For office buildings, the satisfaction with indoor environment quality and air quality is of great benefit to working efficiency (Jazizadeh et al., 2013). Occupants put safety performance in the second place because any accident may get them in trouble (Chu, 2013). Energy performance, whose index reflects huge amounts of power consumption at the building operation stage, is listed at the bottom from Table 3. In fact, energy saving is pretty important for healthy development (Chwieduk, 2003).

At demolition stage, dust pollution, air pollution, noise pollution and water pollution are all considered as top important factors because these factors have direct effects on residents nearby. Demolition waste (solid or semi-solid), vibration and explosion are ranking at the bottom because many people think they are unavoidable at demolition stage (Poon et al., 2014).

From the importance index sequenced above, it can be seen that designers, contractors, occupants, and professionals have different views on the importance of factors affecting healthy building. They rank the factors based on their individual perspectives and interests. Some factors, however, such as cost at design stage (Jiang et al., 2014), health of construction workers (Chan et al., 2013) are unexpectedly removed from the responses.

5.3. Factor analysis

Before performing factor analysis, the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity are generally used to examine the correlations among variables to determine their suitability for factor analysis (Chen and Huang, 2009). In this study, the KMO and Bartlett's test were carried out, and the results are shown in Table 4. It can be seen that all KMO values are above 0.7, indicating a mediocre degree of common variance (Field, 2005). Therefore, the collected data in this study is adequate for factor analysis.

The principal component analysis was carried out by SPSS 20.0. There are two common factors extracted at the design stage, with eigenvalues greater than 1, i.e. 2.811 and 1.041. The two common factors explain 55.027% of the variance in the data. Factor 1 explains 40.157%, and Factor 2 explains 14.870%. Similarly, there are three common factors extracted at construction stage, two at operation stage and one at demolition stage. The percentages of accumulated contribution of variances are 60.793%, 58.002% and 60.070% respectively.

Factor rotation is used to make the factor loading explainable (Zhang, 2004). The varimax rotation was applied in this study. All 30 factors at four stages are grouped into three principle factors by PCA to find internal relationships, shown in Table 5.

Principal Factor 1: Health of building. There are five KIFs in this category. Healthy buildings have to meet the application requirements. The main function of a building is to provide space for people working or living in it. A healthy building needs to make people safe inside. With rapid economic development, people have higher requirements on buildings. A healthy building should provide comfortable space for people to meet the increasing demand for public places, leisure facilities, and living environments (natural environment, neighborhood and community facilities) (F131) (Bluyssen, 2010). Besides, as a special construction project, healthy building should meet some traditional objectives, such as cost plan (F114), project objectives (Time, Cost, Quality) (F122). Efficient cost control is the focus of healthy construction and a critical part of keeping buildings healthy (Na et al., 2016).

Principal Factor 2: Health of environment. Rapid economic development has caused many environmental problems. In recent years, with increasing emissions of greenhouse gas, people realized that buildings play an important role in economic development. On the contrary, they consume large amounts of natural resources and energy. At construction stage, lots of solid waste (F125) and demolition waste (solid or semi-solid) (F143) will be produced with negative impacts on surrounding environments (Wang and Lee, 2014). It is imperative to take effective measures to reduce the pollution during the construction stage, such as air pollution (F123), water pollution (F124) and noise pollution (F126, F145). Additionally, renewable energy and recycling materials should be made full use of at operation stage (F116) to minimize the impact on the environment.

Principal Factor 3: Health of people. There are two KIFs included in this category. Occupants tend to have the closest relationship with the building because they may spend the most time working or living in the building. Therefore, the physical and mental health of occupants seems to be greatly influenced by space layout and visual environment indoors. A healthy building must provide a comfortable internal environment for occupants (F136), which makes them healthy, both physically and psychologically (Grawitch and Ballard, 2016). Furthermore, building exerts an impact on the health of construction workers. In the construction process, the synergistic effect of noise and high temperature do great harm to the circulatory systems of workers and result in increased prevalence of hypertension, arrhythmia and myocardial ischemia (Gomes et al., 2002). Therefore, a healthy building should provide a good working condition to protect workers from high temperatures, dust and noise. In addition, workers often feel stressed (F1211) with work overload (F1210).

5.4. Framework of factors affecting healthy building

Based on PCA, all impact factors during the whole building life cycle are classified into three principle factors with respect to building itself, environment and humans separately, in accordance with the term *healthy building* we proposed. For instance, a healthy building is one that can maintain its health itself, minimize adverse impacts on its surroundings, and ensure the physical and psychological health of both construction workers and occupants. Above all, a framework integrating all these impact factors of a healthy building during its life cycle is established, shown in Fig. 4. This framework helps various stakeholders to have a better understanding of the impact factors of healthy building.

Table 4
KMO and Bartlett's test.

	Design Stage	Construction Stage	Operation Stage	Demolition Stage
Kaiser-Meyer-Olkin Measure of Sampling Adequacy	0.727	0.847	0.770	0.797
Bartlett's Test of Sphericity (Sig.)	0.000	0.000	0.000	0.000

Table 5
The classification of the impact factors in life cycle of healthy buildings.

Principal factor 1 Health of building	Principal factor 2 Health of environment	Principal factor 3 Health of people
F111 Site plan(KIF)	F115 Building envelope	F129 Vibration
F112 Structural design (Optimization of design)(KIF)	F116 Renewable energy and material recycling	F1210 Workload of construction workers
F113 Architectural design (Optimization of design) (KIF)	F117 Ecological protection(KIF)	F1211 Mental health of construction workers
F114 Cost plan	F123 Air pollution(KIF)	F134 Light pollution
F121 Construction safety	F124 Waste water (KIF)	F135 Toxic pollutants from building materials(KIF)
F122 Project objectives (Time, Cost, Quality)(KIF)	F125 Solid waste(KIF)	F136 Occupant satisfaction with indoor environment quality(KIF)
F131 Living environment (Natural environment, neighborhood and community facilities)	F126 Noise pollution(KIF)	F137 Indoor environmental quality (thermal, lighting, acoustic and air)
F132 Safety performance(KIF)	F127 Light pollution	
F133 Energy performance	F128 Radioactive contamination of materials(KIF)	
	F141 Dust & air pollution(KIF)	
	F142 Contamination of water(KIF)	
	F143 Demolition waste (solid or semi-solid)	
	F144 Vibration & explosion	
	F145 Noise pollution from demolition(KIF)	

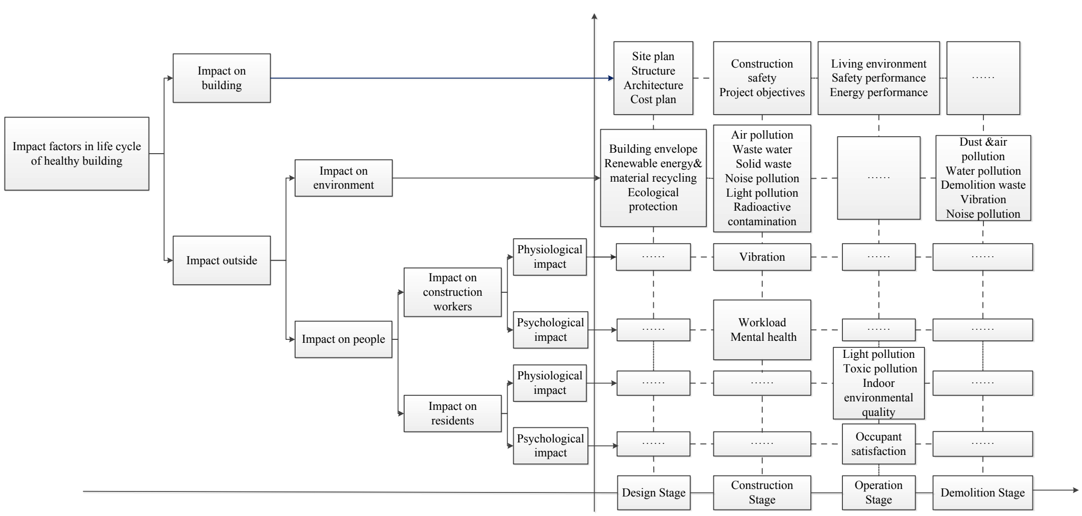

Fig. 4. Framework of impact factors in life cycle of healthy building.

5.5. Connotation of healthy building

The traditional concept of health was defined from a physical point of view; a person is considered healthy only if all requirements on physical, psychological and social dimensions can be satisfied, based on which, the paper annotated the health of building in the sense of architectural discourse. There is still a lack of existing research studies on building's health regarding its life cycle stages and diverse impacts. Hence, this research redefined what a healthy building is based on the reviews and compliments of previous relevant concepts. The 30 impact factors examined during building life cycle were classified into three categories based on PCA, including impacts on the health of the building itself, the environment and humans. It finally demonstrated the connotation of healthy building we proposed. Specifically speaking, healthy building in this research is a building which plays a multi-role in meeting the functional requirements itself, minimizing adverse effects on surroundings as well as keeping construction workers and indoor occupants healthy, both physically and mentally, in the whole building life cycle.

6. Conclusions

Buildings play major roles in economic, social, and environmental activities in the development of construction industry. Their health status should be properly examined when considering implementation. In fact, the health of building involves many complicated impact factors during its life cycle, and on the contrary, relevant comprehensive research studies are still unavailable, which leads to an ambiguous connotation of healthy building in these days. It is of great significance to make an examination of its impact factors in each life cycle stage. This paper, therefore, identified 30 impact factors affecting healthy buildings in the whole life cycle, 16 of which were listed as KIFs sequenced by importance index. Then all the 30 ones were classified into three categories by PCA, based on which, a systematic framework incorporating all impact factors was finally established. Furthermore, this paper redefined a comprehensive connotation of healthy building from a view of building life cycle. The research aims to provide useful theoretic support and practical guidance, with which to improve the health status of building, enrich healthy building theories as well as promote sustainable construction and operation management levels in its whole life cycle. While the framework of impact factors developed in this paper would put forward a new thought to examine healthy buildings, some limitations are appreciated. The comprehensiveness of the framework still needs additional discussion, and the factors in the framework should also be analyzed further in the light of their influencing ways and degrees. Future research studies, therefore, are recommended to refine this framework and improve it with more case studies.

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