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The potential influence of building optimization and passive design strategies on natural ventilation systems in underground buildings: The state of the art

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ABSTRACT

Most of the underground buildings rely on mechanical ventilation system for achieving an acceptable indoor thermal comfort level. In order to alleviate the greenhouse effect, it is essential to incorporate a passive system in an underground building to reduce the overall building energy consumption. From the perspective of the indoor occupant, the Indoor Environmental Quality (IEQ) should be maintained at a reasonable level as well if the passive system is used in a building ventilation system. The above problem could be addressed by devising an integrated design procedure that combines both underground building simulation and design optimization methods. The review of this topic, however, is rather scarce in the open literature. Thus, this review paper assesses existing scientific literatures that address the potential influence of building optimization and passive design strategy on the control of IEQ level. The topics covered in this review paper are histories and design considerations of underground buildings, consideration factors required, concept of building ventilation system, IEQ level assessments reported by buildings' occupants, critical element in building optimization and passive design strategy in the underground building. From the current review, we have found that integrating both optimization approach and passive design strategy into building performance simulation is a promising technique in improving the IEQ level of the underground building. Moreover, the adoptions of soil and natural ventilation can effectively reduce the energy consumption in underground conditioning system. Indeed, there are several important factors that should be taken into account while designing an underground building. Also, there are a few passive designs that can improve thermal comfort and reduce energy consumption in underground buildings. All in all, the primary target of this paper is to assist building engineers and designers in designing an energy-efficient underground building. Meanwhile, the acceptable IEQ level could be maintained.

1. Introduction

One of the pertinent topics in building technology nowadays is the implementation of natural ventilation. Basically, natural ventilation is the process of supplying fresh air into the building and removing moist indoor air from the building with the help of wind pressure, thermal buoyancy or a combination of both. Besides that, natural ventilation is an efficient passive cooling method that can provide a pleasant and comfortable living environment. Natural ventilation is not a new building technology as it was discovered since 15–18 decades ago, before the implementation of mechanical ventilation systems in buildings.

In general, natural ventilation systems can reduce up to 25% of energy consumption in a mechanically ventilated building. Khan et al. (2008) and Bayoumi (2017) have highlighted that heating, ventilation and air-conditioning (HVAC) systems alone consume about 60–70% of the total energy consumption of non-industrial buildings (i.e. domestic buildings). About 30–50% of the total energy is consumed by mechanical ventilation systems. Undoubtedly, a well-designed ventilation system can ensure proper circulation of fresh air within a building and maintain the desired humidity level. Zhang et al. (2016) reported that moderate concentration of bioeffluents with CO_2 were causative agents which were detrimental to the occupant's health. These bioeffluents could be removed by employing a well-designed ventilation system.

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A good ventilation system is essential in underground building. However, there are many design issues associated with underground buildings. Designing a natural ventilation system for an underground building is difficult because even on windy days, the amount of air that can travel through the vertical entry (inlet) via external forcing mechanisms (e.g. gravity or fan) is limited. Instead of relying on natural ventilation, most underground buildings are equipped with mechanical devices (Goel et al., 2012) for better ventilation. Recently, researchers have found that geothermal energy coupled with optimal insulation is the best approach in maximising the energy saving for a building during heating and cooling operations (Al-Temeemi and Harris, 2004; Gan, 2015; Shan et al., 2017; Van Dronkelaar et al., 2014). In addition, the underground building construction type is one of the most innovative passive thermal comfort systems in history (Hassan et al., 2016). Compared to a conventional building that is above ground, Shan et al. (2017) and Anselm (2012) have proven that underground buildings can reduce annual heating/cooling loads and keep indoor temperatures stable in different climates. Therefore, a comprehensive approach is necessary while designing the ventilation system in an underground building in order to satisfy the IEQ and to meet the requirements of building regulations.

This study reviews the literature related to the potential influence of optimization approach and passive design strategy on natural ventilation systems in underground buildings. Moreover, extensive references on the subject of design requirements of underground buildings, concept of ventilation systems, and assessment of IEQ for practitioners are provided. Furthermore, by examining the processes involved in building optimization and summarizing passive building design strategies, readers can have an overview of the current research and development works related to underground buildings.

2. Underground buildings

Underground buildings refer to buildings that are located below ground level. Here, ground level is defined as the natural elevation of the earth surface (Rönkä et al., 1998). The demand for underground buildings has been increasing due to the growing provision of living space environment especially in urban areas (e.g. compact cities). The idea of having an underground buildings is inspired by many reasons. Certain underground buildings have been developed in a multi-layered and large-scale manner in order to meet the current needs (Goel et al., 2012; Xu et al., 2014). Thus, the structure of an underground building has become more complicated and diversified in order to satisfy different requirements. Compared to above ground buildings, underground buildings rely on mechanical ventilation systems due to insufficient openings for natural ventilation. In fact, developing underground building is one of the traditional methods used to reduce temperature fluctuation and energy consumption (Goudarzi and Mostafaeipour, 2017; Hassan et al., 2016). Al-Mumin (2001) has reported that the sunken courtyard (located 3 m below ground level) could reduce annual energy consumption by 35%. This finding was consistent with that reported by Kumar et al. (2007) and (Hassan and Sumiyoshi, 2017). In other words, the underground building has a high potential for energy saving.

As reported in most literature, underground buildings offer several advantages such as space saving, good thermal efficiency, minimal visual impact, lower noise, lower maintenance cost and high security (Alkaff et al., 2016; Anselm, 2012, 2008; Erdem, 2008; Hassan et al., 2012; Shan et al., 2017; Yang et al., 2014). However, the shortcomings of underground buildings are high construction costs, limited access to natural lighting, poor ventilation, lack of public acceptance and safety issues (Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Anselm, 2012, 2008; Benardos et al., 2014; Erdem, 2008; Hassan and El Kotory, 2019; Kaliampakos et al., 2016a, 2016b; Roberts et al., 2016; Shan et al., 2017). The possible advantages and disadvantages of underground buildings are summarized in Table 1.

Recently, due to the advantages of underground building, there is an increasing demand for developing underground facilities such as underground parking, metro and subway, underground storage (i.e. cold and oil), bunkers (underground shelters), etc. in developed countries (Langer, 1993).

3. Underground building principles from ancient times to the present

In ancient times (∼3000 BCE), underground buildings were used as shelters from natural hazard threats and animal attacks, and spaces for providing warm, etc. (Alkaff et al., 2016; Cusido et al., 1987). During those times, underground buildings existed in the form of cave dwellings (Goel et al., 2012). In the 1990s, the technology used for constructing underground buildings was quite developed (Watanabe, 1990). Some of the earliest underground dwellings and houses could be seen around the world (i.e. the Miyagi prefecture in Japan, the Indian village of Mesa Verde in Colorado, the Yaodong cave houses in China, the Kandovan Rock in Iran, the mined houses of Coober Pedy in Australia, the underground cities in Turkey, Iran and Scotland, the Guadix cave in Spain, the Sassi di Matera dwellings in Italy, the traditional underground houses in Greece and Tunisia, the cave dwellings and homes in Turkey and Iran, and finally the Kashmir's underground in India) (Alkaff et al., 2016; Benardos et al., 2014; Goel et al., 2012). As seen, most of the ancient models mentioned above are located in arid countries.

Underground buildings in ancient times were mainly built for living and security purposes without considering the energy demand. However, in the current modern era, the development of underground building is one of the strategies in promoting low-energy buildings (Alkaff et al., 2016; Benardos et al., 2014) and in providing better lifestyles for occupants (Goel et al., 2012).

4. Design classification of underground buildings

As explained in Section 2, underground buildings offer many advantages. In fact, the usage of underground building is quite extensive (Goel et al., 2012). Therefore, it is common to organize underground buildings into various categories such as function, usage and design typology. This classification is beneficial for building designers.

4.1. Categories of underground buildings

Depending on the usage, an underground building could be divided into four main categories: (a) residential, (b) non-residential, (c) infrastructure and (d) military usage (Carmody and Sterling, 1984; Goel et al., 2012; Rönkä et al., 1998) as listed in Table 2. However, Zaini et al. (2012) argued that the classification of underground buildings should be based on other factors such as economic, legal and administrative, social and health, technical and geo-environmental issues. Thus, these arguments should be considered as well when considering the development of underground buildings.

4.2. Construction typology of underground buildings

The energy efficiency and structural integrity of an underground building is dependent on its construction type (Anselm, 2012). Boyer (1982) has found that underground building structures could be classified into several classes such as building section, plan type and building elevation. The third class could be further separated into two dominant types which are Berm and Subgrade/Chamber, similar to those reported by Labs (1976) and Anselm (2012). However, Alkaff et al. (2016) classified underground building designs into three types: (a) Atrium/Courtyard (b) Elevation (c) Berm. As shown in Fig. 1, we have classified the design concept into two types. This classification is discussed further in the next section.

Table 1
A summary of advantages and disadvantages of underground building.

Advantages and disadvantages		References
Advantages	Space saving	(Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Liu et al., 2015; Shan et al., 2017)
Advantages	Good thermal efficiency (i.e. isolated from harsh climate, better thermal comfort, lower indoor temperature)	(Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Anselm, 2012, 2008; Goel et al., 2012; Goudarzi and Mostafaeipour, 2017; Hassan et al., 2012; Mukhtar et al., 2017c)
Advantages	Minimum visual impact and high privacy level	(Al-Temeemi and Harris, 2004; Goel et al., 2012; Shan et al., 2017)
Advantages	Resistant to external noise. (Note, the noise transmission in soil is slower than that in liquid or gas)	(Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Liu et al., 2015; Shan et al., 2017)
Advantages	Low maintenance and operating costs	(Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Goel et al., 2012; He et al., 2005; Yang et al., 2014)
Advantages	High security. It offers protection from natural disaster	(Alkaff et al., 2016; Erdem, 2008; Hassan et al., 2012; Shan et al., 2017)
Disadvantages	High construction cost	(Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Goel et al., 2012; Kaliampakos et al., 2016a)
Disadvantages	Limited access to natural light and outside views	(Alkaff et al., 2016; Benardos et al., 2014; Goel et al., 2012; Nakhaei et al., 2016)
Disadvantages	Poor air circulation if the ventilation system is not properly designed	(Alkaff et al., 2016; Benardos et al., 2014; Goel et al., 2012; Hassan et al., 2012; Mukhtar et al., 2018a, 2018b)
Disadvantages	Safety issue	(Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Goel et al., 2012)
Disadvantages	Lack of public acceptance	(Al-Temeemi and Harris, 2004; Alkaff et al., 2016; Goel et al., 2012; Kaliampakos et al., 2016a; Roberts et al., 2016; Shan et al., 2017)

4.2.1. *Bermed*

This type of construction uses earth soil as principal building material. Therefore, the building structural integrity is dependent on the soil strength. Technically, the earth soil is loaded up against the exterior walls and piled to incline downwards away from the building (Alkaff et al., 2016; Anselm, 2012). It could be shaped easily, thus facilitating on-grade access and window exposure (when used with retaining walls; see Labs (1976)). This type of construction can overcome high water tables, clays soils, rock strata and flat rural sites (Boyer, 1982). Moreover, moisture-related problems occur less commonly when compared to other construction plans (Alkaff et al., 2016). The Bermed type is normally accompanied with elevation and in-hill to provide maximum solar radiation during cold seasons (Anselm, 2012). Fig. 2 shows an example of ground Bermed house construction.

4.2.2. *Subgrade*

In this type of construction, the entire building structure is fully submerged into the ground and is in direct contact with the landscape. Moreover, it is most suitable for flat terrain sites containing permeable, dry or well-drained soils which are far from groundwater sources (Alkaff et al., 2016). It is suitable to implement natural ventilation in this type of construction. The building is also able to capture natural lighting (Anselm, 2012; Chenari et al., 2016). Khan et al. (2008) have pointed out that the subgrade can create sufficient airflow (natural ventilation) due to large openings. Atriums and courtyards are commonly found in this type of construction to promote cross-ventilation (Anselm, 2012) and natural lighting (Labs, 1976). Fig. 3 shows an example of a ground-atrium house construction. Besides the differences in concept and structural integrity as discussed in Section 4.2, Table 3 indicates that the building's energy consumption is dependent on the climate and physical characteristics of each typology (Anselm, 2012). Table 4 summarizes the underground buildings developed around the world.

5. Consideration factors needed

The consideration factors in the development of underground buildings are somewhat limited in the current literature. However, various underground infrastructures (e.g. underground transport interchange buildings, underground storages, ancient tombs, subways, underground mines, underground wine cellars and ground heat exchangers (GHE)) have been developed (Domingo et al., 2011; Gribble, 2009; Huang et al., 2011; Juraeva et al., 2014; Khalil, 2006; Mihalakakou et al., 1994; Onder and Cevik, 2008; Park et al., 2016; Pfafferott, 2003; Sasmito et al., 2013; Stefopoulos and Damigos, 2007; Xu et al., 2015; Yuan and You, 2007). These information are indeed valuable for the current study. In fact, the consideration factors for the construction of an underground building may differ (Goel et al., 2012). These factors are discussed in the following section.

5.1. *Construction typologies*

Hait (1983) has discussed about the thermodynamic cycles in underground buildings. Heat flows into the ground during summer and vice versa during winter. As shown in Fig. 4, the soil temperature is almost constant (hovering at the average annual air temperature) at a ground depth of 20 feet. Therefore, the construction typology would affect the heat modulation of underground buildings (Alkaff et al., 2016). In fact, it has been proven in Section 4.2 that the construction typology plays a dominant role at depth below the ground level and at the contact surface between the building and the ground. Anselm (2008) has investigated the effects of Passive Annual Heat Storage (PAHS) on two types of underground buildings. They argued that the thermal performance was mainly influenced by the construction typology. Thus, PAHS is one of the most significant factors in determining the energy efficiency of an underground building.

Table 2
Classification of underground building (by usage) retrieved from literatures (Carmody and Sterling, 1984; Goel et al., 2012; Rönkä et al., 1998).

Categories	Subcategories of usage	
	People-oriented use	Product-oriented use
Residential	Single-family, multiple-family	–
Non-residential	Religious, recreational, institutional and commercial	Industrial (i.e. storage, production, treatment plant), parking, traffic tunnel, agriculture.
Infrastructure	Transportation of passengers (i.e. metro, subway.)	Utilities, energy, disposal, mine, transportation of goods
Military	Civil defence (i.e. military bunker)	Military facilities (i.e. ammunition storage)

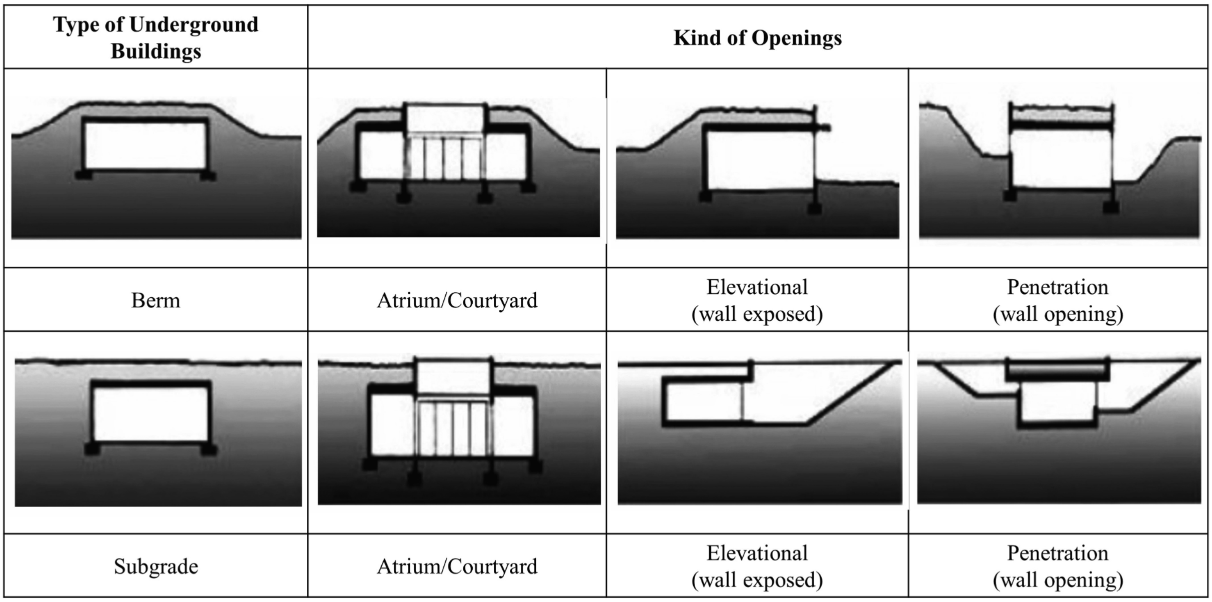

Fig. 1. A different typology of underground building.

5.2. Geological features

The number of underground buildings is increasing in industrial countries (Langer, 1993). However, the complex geological condition is still the major problem encountered during the development of underground buildings. As reported by a few researchers (Goel et al., 2012; Sterling and Nelson, 1982; Watanabe, 1990), the structural integrity of any underground building relies heavily on geological conditions. Therefore, a geological assessment should be carried out to determine soil properties such as thermal conductivity, density, diversity, soil strength, bedrock depth, groundwater table and soil nature (Kaushal, 2017). For instance, Goel et al. (2012) stated that rocks with uniform physical properties are commonly used as construction material for the foundation. In addition, geological features such as groundwater play a dominant role as well. Sterling and Godard (2000) have identified the effects of groundwater quality and groundwater table on the development of underground buildings. They argued that both the pressure and inflow of groundwater can affect the stability of excavation faces and the strength of the support structures. Moreover, the movement of groundwater can affect the settlement of the surrounding ground. Therefore, the local geological features should be taken into account while designing an underground building.

5.3. Potential of psychological and physiological problems

Humans are used to staying above ground. Most people consider underground buildings to be dark, damp, confined, and poorly ventilated. Also, these buildings are commonly treated as burial places and occupants feel uneasy due to the potential of structural collapse (Alkaff et al., 2016; Goel et al., 2012; Shan et al., 2017). Hughey and Tye (1984) and Hassan et al. (2013) have outlined many negative reactions associated with underground buildings. It is interesting to note that both psychological and physiological problems are not conclusive and sometimes contradictory. As stated by Carmody and Sterling (1987, 1984) and Goel et al. (2012), physiological effects are associated with the lack of natural lighting and poor ventilation. Meanwhile, the psychological effects are related to indirect disease or response. The conditions contributing to the negative psychological and physiological effects in underground buildings are shown in Table 5. In order to resolve the negative psychological and physiological problems related to

Fig. 2. An example of the ground Bermed house.
Reproduced from https://homedesignfree.com/berm-home-designs.html/

Fig. 3. An example of the ground Atrium house.
Reproduced from http://rehberlik.site/underground-home-designs-plans/underground-home-designs-plans-image-result-for-underground-houses-underground-house-designs-plans/

Table 3
Comparing efficiency values of construction typology for underground buildings retrieved from Anselm (2012).

Factors	Types of underground building	
	Bermed	Subgrade
Visual disruption of landscape	Excellent	Less effective
The potential for passive-solar heating	Excellent	Poor
Thermal stability	Good	Excellent
Protection from wind	Good	Excellent
Views	Excellent (one directional view)	Poor (allow only open sky)
Protection from noise	Less effective	Excellent
Potential for natural lighting	Excellent	Less effective
Structural cost	Less expensive	Most expensive

underground buildings, Al-Temeemi and Harris (2004) and Goel et al. (2012) have recommended an appropriate design solution as summarized in Table 6. In short, both the psychological and physiological aspects of the planned structure should be prioritized in order to offset the negative perceptions of residents about underground buildings.

6. Ventilation systems and indoor environmental quality (IEQ)

The need for ventilation systems has been recognized for a long time (Almesri et al., 2012; Awbi, 2015). In fact, it has been aggressively explored by some researchers (Chen, 2009; Etheridge, 2012; Li and Nielsen, 2011) in order to provide better thermal comfort and indoor air quality (IAQ). A good ventilation system can ensure proper circulation of fresh air inside a building and maintain the desired humidity level. Moreover, in line with Omer (2008) and Daghigh (2015), the ventilation system plays a dominant role in controlling the IAQ. The IAQ could be represented by the impact of desirable or unfavourable movement of air inside the building structure. Factors such as temperature, humidity and air velocity could affect the IAQ levels as well. Thus, they should be considered by building engineers in the design stage. In addition to providing a comfortable environment to avoid Sick Building Syndrome (SBS) (Fanger, 2000; Fisk et al., 2009; Sundell et al., 2011), the ventilation system is associated with the total building energy consumption (Alkaff et al., 2016). The importance of ventilation systems has been stated in the ASHRAE Standard 62.1-2004 codes.

As mentioned in Section 1, the ventilation system for an underground building is equally important as that for an aboveground building. Both ventilation systems should be able to provide ample ventilation rate for good thermal comfort. In fact, the design process for ventilation system in underground building is very challenging (Likar and Čadež, 2000). Most underground buildings are equipped with a mechanical ventilation system (Chestert, 1981; Goel et al., 2012) to dilute and remove pollutants from the buildings. It is also used to stabilize the indoor temperature. Meanwhile, it is recommended to rely on an emergency ventilation system when the mechanical system fails. Scholars such as Holthusen (2013), Barber et al. (1972) and King, (1965) have insisted on the use of natural ventilation systems as an alternative. Technically, natural ventilation systems are recognized as

Table 4
A summary of an underground building's category.

Building name	Year	Location	Category	Description	References
Kandovan Rock Houses	800,000 years B.P	Kandovan, Iran	Residential	Archaeological evidence for human history against the harsh environment	(Alkaff et al., 2016; Benardos et al., 2014; Hazbei et al., 2015)
Kaymaakli Underground City	8th – 7th Centuries B.C	Anatolia, Turkey	Residential/ Storage/Stables/ Cellars	The design is dependent on the feasibility of ventilation	(Erdem, 2008)
Mesa Verde Cliff Dwelling	7500B.C	Colorado, US	Residential/ Storage/Cellars	There are many problems associated with the shelter, i.e. improper sunlight and sanitation, inadequate ventilation, etc.	(Alkaff et al., 2016; Benardos et al., 2014; Hazbei et al., 2015)
Ancient Underground City	7th Centuries B.C	Derinkuyu, Turkey	Residential Quarters/Schools/ Stores/Cemeteries	It contains facilities such as ventilation shafts, residential quarters, schools, stores, cemeteries, etc.	(Alkaff et al., 2016)
Petra Historical City	6th Centuries B.C	Petra, Jordan	Water Storage/Control Floods	It is able to get rid from flash flooding, Water could be stored for use in prolonged period of drought	(Alkaff et al., 2016)
Edinburgh's South Bridge and Vaults	1788	Edinburgh, Scotland	Multi-function/ Residential	The structure is poorly ventilated and it has damp which is unsuitable for human residence	(Alkaff et al., 2016)
Opal Mine Homes	1915	Coober Pedy, Australia	Residential/ Religious Place	It offers higher thermal comfort level to occupants as compared to above-ground building. It was built from an abandoned mine	(Benardos et al., 2014; Hazbei et al., 2015)
RAF Holmpton Nuclear bunker	1951	Holmpton, England	Military	Shelter used during warfare. However, its energy performance was not provided	(Alkaff et al., 2016)
Kölner Philharmonie	1980	Köln, Germany	Recreational/ Musician hall	The room acoustics system was well designed to eliminate unwanted echo	(Alkaff et al., 2016)
Itäkeskus Swimming Hall	1993	City of Helsinki, Finland	Recreational/ Multi-Purpose Building	It was used as multipurpose building and former bomb shelter during the 19th century	(Alkaff et al., 2016)
Underground skyscraper of FIFA headquarters	2007	Zurich, Switzerland	Football Association	2/3 of the building is below the ground level. It is a low-energy building	(Alkaff et al., 2016)
Traditional Underground Wine Cellars	unknown	Central-Spain	Food Preservation	Various aspects such as ventilation, annual thermal performance and energy efficiency were investigated	(Mazarrón et al., 2015; Mazarrón and Cañas, 2009; Porras-amores et al., 2011)
Shovadan House	unknown	Iran	Residential	The heating & cooling operations, energy consumption and augmentations of ventilation and heat transfer performances were reported	(Mohammadshahi et al., 2016; Moradi and Eskandari, 2012; Vaezizadeh and Kazemzade, 2013)

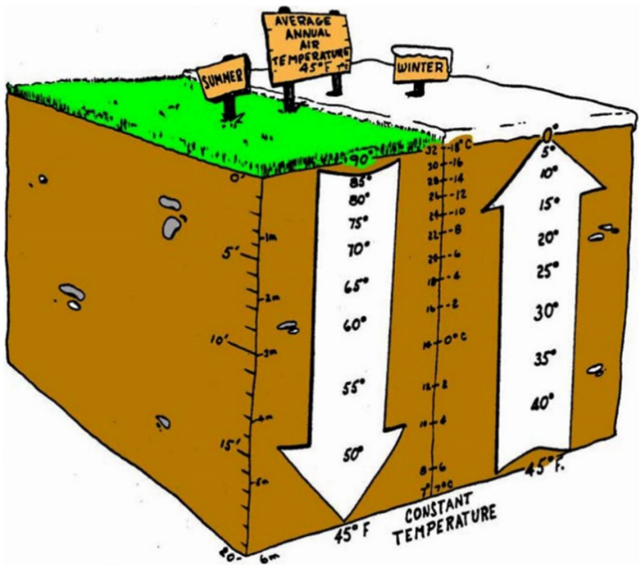

Fig. 4. The soil temperature equals to the average annual air temperature at depth of 20 ft.
Reproduced from Hait (1983).

traditional and well-accepted passive cooling techniques particularly in hot and humid countries (Toe and Kubota, 2013). It is interesting to discover that ancient underground buildings are normally integrated with natural ventilation systems (Alkaff et al., 2016) due to its low maintenance cost and energy consumption (Dehghan et al., 2014). Nevertheless, a natural ventilation system should be properly designed in order to supply adequate air flow during all conditions.

6.1. Indoor environmental quality (IEQ)

The building sector (e.g. residential building) is the most prominent energy consumer amongst all industrial sectors (Chenari et al., 2016). In general, the primary function of a building is to provide acceptable Indoor Environmental Quality (IEQ) to building occupants. It seems that the IEQ is an integral part of the building performance approach. Omer (2008) has categorised the IEQ of building services into three main categories: (a) space conditioning for thermal comfort (b) lighting for visual comfort and (c) ventilation for IAQ. However, this argument has been contended by Omrani et al. (2017) who indicated that the main environmental conditions influencing the IEQ were thermal, acoustic and visual comforts as well as IAQ. This claim was fully supported by other researchers (see Frontczak and Wargocki (2011), Sarbu and Sebarchievici (2013) and Wong et al. (2008)). Fig. 5 highlights the survey performed by Frontczak and Wargocki (2011) about the importance of environmental conditions on the overall satisfaction in IEQ. They have utilized seven references (e.g. Astolfi and Pellerey (2008), Choi et al. (2009), Humphreys (2005), Lai et al. (2009), Lai and Yik (2009, 2007) and Wong et al. (2008)) to explore the importance of environmental conditions with regards to the subjective evaluations of the occupants. As shown in Fig. 5, thermal comfort has been ranked as the most important category by the occupants, followed by IAQ, acoustic and visual comfort. Therefore, in this paper, we have assessed the two most important conditions stated in the literature (i.e. thermal

Table 5
Potential of psychological and physiological problems associated with underground building.

Psychological and physiological problems		Explanation	References
Potential psychological	Lack of natural light	The lack of natural light is one of the typical negative perspectives. Access to natural lighting is indeed essential for indoor occupants even though the ratio of daylight to artificial lighting could be relatively low in underground buildings. Nevertheless, excessive natural lighting would degrade the thermal comfort level as well	(Al-Temeemi and Harris, 2004; Carmody and Sterling, 1987, 1984; Goel et al., 2012)
Potential psychological	Lack of visibility from the exterior	Occupants could observe weather conditions and establish a sense of connection with outdoors through windows. Some studies have revealed that occupants put more concerns on the view effect than the natural lighting effect (sunlight)	(Carmody and Sterling, 1987, 1984; Goel et al., 2012; Labs, 1976)
Potential psychological	Location of underground	Underground location is still one of the major psychological problems even though the interior space of underground building is similar to that of conventional building (above ground). Occupants tend to associate underground with fear and uneasiness (e.g. structural collapse, immobilised during fire or flooding, etc.)	(Benardos et al., 2014; Carmody and Sterling, 1987, 1984; Goel et al., 2012; Labs, 1976)
Potential psychological	Undesirable internal conditions	Complaints on poor indoor temperature, ventilation and humidity control in underground building are common. However, the aforementioned problems (except poor ventilation) are frequently encountered in conventional building as well. In fact, the development of underground building could reduce the annual heating/cooling loads and keep the indoor temperature stable in different climates. Therefore, the problem of poor ventilation in underground building should be properly addressed	(Anselm, 2012; Carmody and Sterling, 1987, 1984)
Potential physiological	Lack of natural light	The primary physiological concerns are lack of natural lighting and poor ventilation. It seems that lighting is the key factor in designing underground building. Note, sunlight provides vitamin D to occupants	(Carmody and Sterling, 1987, 1984)
Potential physiological	Lack of fresh air and indoor air pollution	Most studies have indicated that underground buildings are associated with poor ventilation and inadequate Indoor Air Quality (IAQ). In fact, underground building has limited rooms for window, thus limiting the potential of natural ventilation. Adequate ventilation is essential to remove bioeffluents with CO_2, heat, and moistures released by occupants	(Carmody and Sterling, 1984, 1987; Goel et al., 2012; Labs, 1976; Mukhtar et al., 2017b; Mukhtar et al., 2018a, 2018b; Zhang et al., 2016)
Potential physiological	High humidity	High humidity level in underground buildings (those which are lack of maintenance) is detrimental to human health. Therefore, periodic maintenance on underground building should be regularly performed	(Carmody and Sterling, 1987, 1984; Goel et al., 2012; Labs, 1976)

Table 6
Techniques to alleviate psychological and physiological problems retrieved from Goel et al. (2012).

Serial	Categories	Techniques and strategies to alleviate
1.	Entrance and exit design	a. The designs of entrance and exit should be easily recognisable (connected to the surface naturally). b. An entrance area that is spacious with high ceilings. c. Supply the maximum natural lighting at the entrance. d. The design should look interesting to attract occupants.
2.	The sense of space, view and orientation	a. Maximize the usage of glass partition between spaces. b. Develop high-ceilinged space in most area. c. Use multilevel spaces whenever possible. d. Utilize an atrium which is extended from the surface to the ground. e. Provide a fibre scope to visualize the outside view. f. Use different columns (e.g. carved, designed, etc.) to enhance occupant's senses of viewing and hearing. g. Use creative visual designs.
3.	Natural lighting	a. Utilize an atrium which is extended from the surface to the deep space. b. Maximize the application of artificial light inside the buildings for physiological benefits. c. Use beamed daylight systems that rely on mirrors and lenses to distribute light from the surface.
4.	Interior design elements	a. Use warmer and brighter colour to create a positive interior environment. b. Extensive usage of green plants. c. Allocate pools or fountains in appropriate areas. d. Make an artwork (mural) to create emotion of happiness. e. Encourage lighting variation, i.e. use very bright lights in plant-filled area, or spotlights in showing artwork.
5.	Ventilation systems	a. Provide proper temperature, humidity controls and ventilation to the occupants. b. Use a flexible mechanical system to control humidity and thermal comfort. Poor ventilation affects IAQ and it is detrimental to the health of occupant. c. Provide a backup ventilation system in the event of malfunctioning of mechanical system.

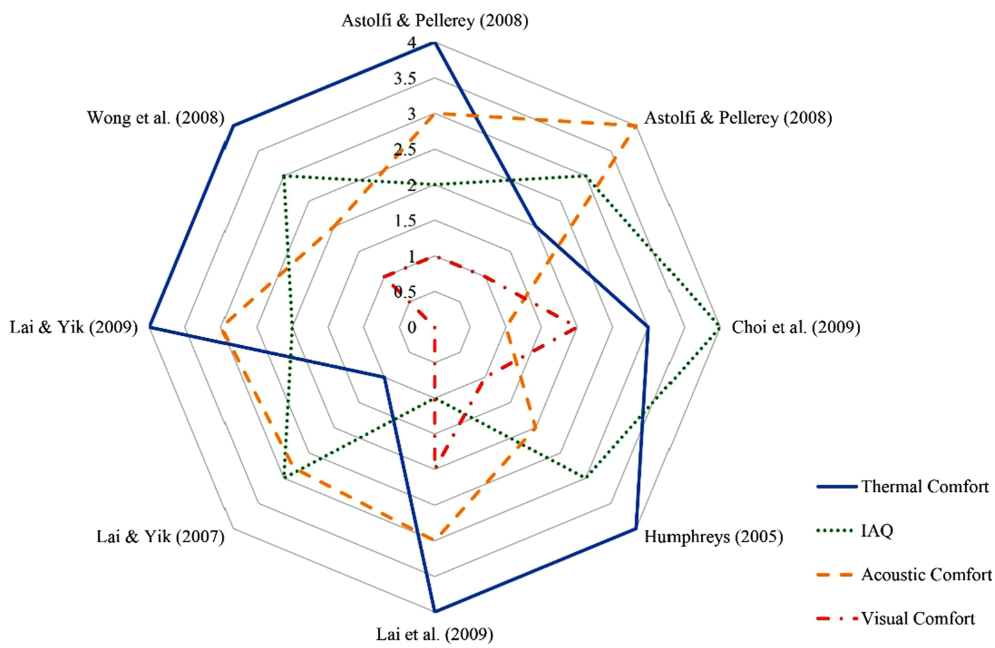

Fig. 5. Ranking of the importance of environmental conditions for overall satisfaction with IEQ retrieved from Frontczak and Wargocki (2011).

comfort and IAQ). In fact, thermal comfort and IAQ are closely linked to the health levels of indoor occupants. According to building occupants, these two factors are more important than visual and acoustic comforts (Frontczak and Wargocki, 2011). For instance, a lack of fresh air supply can badly affect the IAQ whereas excessive air supply can cause discomfort (draught). Thus, it is necessary to look into thermal comfort and IAQ issues separately. Table 7 summarizes several IEQ concerns about thermal comfort and IAQ.

Table 7
Issue of IEQ concern for thermal comfort and IAQ.

Thermal comfort	Indoor air quality
Issue related to heat load (e.g. lighting, solar shading and daylight)	a. Issue related to pollution sources (e.g. building material and local exhaust)
Issue related to cooling load (e.g. thermal mass and night ventilation)	b. Issues related to heating and cooling energies (e.g. passive heating and cooling)
Space conditioning (e.g. thermal comfort requirement)	c. Ventilation system (e.g. minimum ventilation rate requirement)
Air supply to occupants (e.g. high-temperature efficiency)	d. Air supply to occupants and removal of pollutants (e.g. high ventilation efficiency)

6.1.1. Thermal comfort

Thermal comfort refers to the satisfaction with the thermal environment (ASHRAE Standard 55-2004). In practice, it is difficult to provide a perfect thermal environment that would satisfy all indoor occupants in a building as each occupant has unique clothing and metabolism rates. Therefore, a thermal comfort level that is acceptable to the majority of occupants should be provided (Chenari et al., 2016). The Predicted Mean Vote (PMV) and the Percentage People Dissatisfied (PPD) model (Fanger, 1970) could be used to predict the required indoor temperature. Although the PMV/PPD standards have been used in the building design process (Roaf et al., 2010), the model does not work well for naturally-ventilated buildings (Clements-Croome, 2002). Therefore, a new adaptive thermal comfort model which relates indoor and outdoor temperatures has been developed by Nicol and Humphreys (2010) and de Dear and G.S. Brager (2002). They have proposed a regression formula for estimating the comfort temperature in the naturally-ventilated building (Yang et al., 2014). Consequently, several studies have been performed to evaluate the reliability of thermal comfort model and additional parameters related to the requirements of building occupants have been considered. For instance, Hazbei et al. (2015) studied the reduction of energy consumption in Shavadoon buildings by utilizing earth temperatures and natural ventilation. They highlighted that the proper use of natural air movement, heat conduction and air displacement could meet the thermal comfort requirements of indoor occupants. Mochida et al. (2005) have proposed a new method for controlling the natural ventilation around building in order to enhance the thermal comfort. The results indicate that by controlling the window openings appropriately, the indoor thermal comfort could be improved during the summer time. Mukhtar et al. (2018a) have utilized statistical data-based analysis for the improvement of ventilation rates and thermal comfort in naturally-ventilated underground shelters. The results indicated that the optimized design meets the comfort temperature requirement.

6.1.2. Indoor air quality (IAQ)

A good IAQ is related to a pollutant-free air condition (Omer, 2008). In other words, IAQ is closely linked to the dilution of outdoor air pollutants through adequate ventilation rates. In accordance with the ASHRAE Standard 62.1-2004, a good IAQ is achieved when "*there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction*". However, the sensitivity level of IAQ may vary amongst occupants. Thus, occupants who are vulnerable would feel dissatisfied easily (Chenari et al., 2016). The IAQ level could be measured via Percentage Dissatisfied (PD). As noted, ventilation rate is the primary parameter in IAQ. According to Linden (1999), the main component in controlling IAQ is the air movement used to transport contaminant, heat as well as the building material. Many works have been performed to understand the physics of ventilation (e.g. wind pressure and thermal buoyancy), the airflow characteristics of ventilated and air-conditioned building, and the effects of position, arrangement, shape and spacing of the opening on the ventilation performance in order to develop an air distribution index in thermal environment (Almesri et al. (2012), Cheung and Liu (2011), Gribble (2009), Huang et al. (2011), Khalil (2006), Mazarrón et al. (2015), Mukhtar et al. (2018b), Shetabivash (2015), Stefopoulos and Damigos (2007)).

6.2. The concept of natural ventilation systems

Natural ventilation systems had been employed to ventilate indoor spaces for many years (Clifford et al., 1997). It is also one of the most effective passive cooling strategies to reduce energy consumption and greenhouse gas emission (Zhai, 2006). Natural ventilation relies on wind speeds and temperature differences between a building and its environment as a natural driving force. Its effectiveness is dependent on

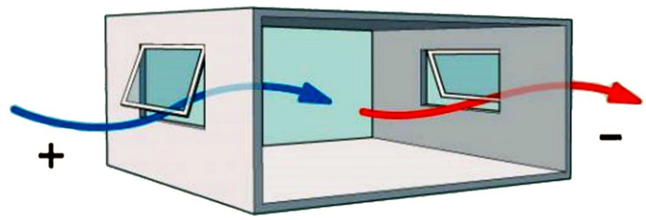

Fig. 6. Schematic diagram of the cross-ventilation approach. Reproduce from https://www.tealproducts.com/natural-ventilation-control

climate, building design and human behaviour. There are two fundamental approaches for designing natural ventilation systems: (a) cross-ventilation driven by wind pressure difference and (b) stack ventilation driven by temperature difference between outdoor and indoor environments (e.g. thermal buoyancy) (Dehghan et al., 2014; Gładyszewska-Fiedoruk and Gajewski, 2012; Khan et al., 2008). These two approaches are further described in the next section.

6.2.1. Wind pressure differential (cross-ventilation)

With cross-ventilation, the airflow is driven by pressure differentials (Kuo and Lai, 2005). Typically, positive pressure is built on the building side facing the wind (windward side) and negative pressure is established on the leeward side (Khan et al., 2008). As shown in Fig. 6, air travels through the opening at the windward side and exits through the opening at the leeward side. Cross-ventilation is sometimes produced as air enters from one side of the space and leaves from the opposite side. It is recommended to use cross-ventilation when the speed and wind direction are known (Chenari et al., 2016). Therefore, it is essential to not place any obstacles between the windward (inlet) and the leeward (exhaust) openings. To date, the performance of cross-ventilation systems (Karava et al. (2011)), the design optimization (Gilkeson et al. (2014), Hajdukiewicz et al. (2013a) Stavrakakis et al. (2012) and Zhou et al. (2014)), the assessments of flow characteristics (Kato et al. (1992), Stavrakakis et al. (2008) and van Hooff et al. (2016)) and the positions of inlets and exhausts (Montazeri and Montazeri (2018), Shetabivash (2015) and Tominaga and Blocken (2016)) have been investigated.

6.2.2. Thermal buoyancy (stack ventilation)

Stack ventilation (thermal buoyancy) is driven by the difference between indoor and outdoor temperatures (Linden, 1999). The difference in air density creates a pressure differential that promotes air movement within the building. As indicated in Fig. 7, when the indoor temperature is higher than the outdoor temperature, the hot indoor air would rise, exit through the windows at the top and be replaced by colder air from the bottom. Technically, stack ventilation is dominant during low wind periods and ineffective in summer periods (i.e. when the difference between indoor and outdoor temperatures is minimal (Khan et al., 2008)). Although Wong and Heryanto, (2004) have reported that stack ventilation is one of the important elements in low-energy buildings, it is less popular than cross-ventilation. So far, studies

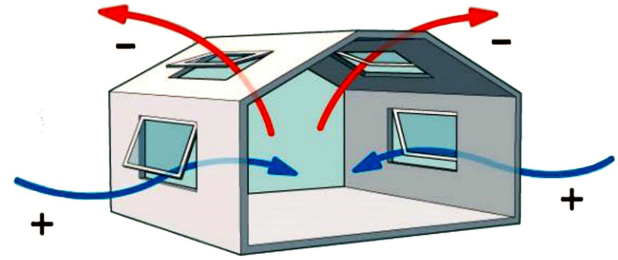

Fig. 7. Schematic diagram of the stack ventilation approach. Reproduce from https://www.tealproducts.com/natural-ventilation-control

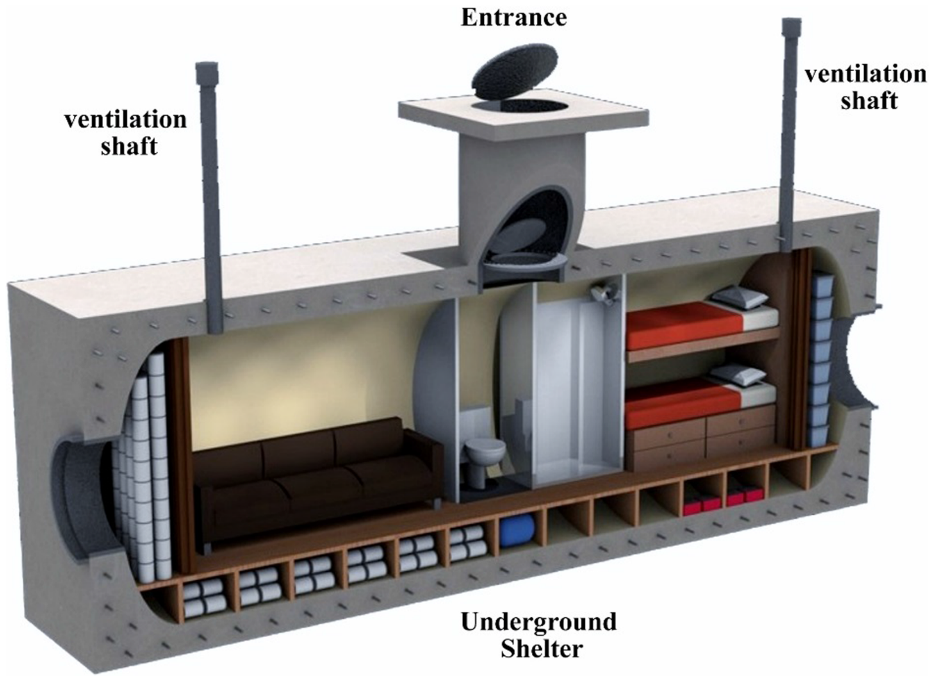

Fig. 8. The use of vertical ventilation shaft for the ventilation system in an underground shelter. Reproduce from https://bornprepper.com/build-underground-bunker/

related to stack ventilation focusing on natural driving forces (Andersen, 2003; Gładyszewska-Fiedoruk and Gajewski, 2012; Ray and Glicksman, 2013; Wahab and Ismail, 2012; Wong and Heryanto, 2004; Yang et al., 2005), effects of ventilation modes on flow characteristics (Jiang and Chen, 2003; Li, 2000; Wang and Li, 2010) and building applications (e.g. passive stack systems) (Bansal et al., 1994, 1993; Dong et al., 2012; Yusoff et al., 2010) have been reported extensively in the current literature.

6.2.3. The use of vertical shaft

The ventilation shaft is one of the primary components of natural ventilation systems as recently pointed out by Aflaki et al. (2015) and Chenari et al. (2016). As illustrated in Fig. 8, the ventilation shaft could serve as a supply or exhaust shaft in underground buildings (Kleiven, 2003). Huang et al., (2011) simulated the effect of vertical shafts on the ventilation performance in a subway tunnel. In practice, the vertical shaft is used in underground buildings to channel smoke during fire. Takeuchi et al. (2017) investigated the performance of natural ventilation in an underground road tunnel using six vertical shafts. They developed a simple model for predicting smoke temperatures based on the patterns of smoke exhausted from many vertical shafts. Fan et al. (2014) have numerically investigated the influence of vertical shaft arrangements on natural ventilation performance during fire with and without longitudinal wind. They highlighted that the best ventilation performance was attained when the longitudinal wind velocity was small and the number of vertical shafts was large. Furthermore, they found that natural ventilation using vertical shafts could restrain the longitudinal smoke propagation and the vertical sedimentation in the tunnel. Wang et al. (2017) studied experimentally and theoretically the effects of vertical shaft geometry and arrangement on the maximum smoke temperature beneath the ceiling of a tunnel during fire. Design parameters such as the number of shafts, the distance between two shafts, the shaft height and the shaft width were optimised in order to maximize the exhaust efficiency. The results demonstrated that the theoretical results agreed well with the experimental data. To summarize, it seems that the vertical ventilation shaft is an instrumental element that should be considered in the design of natural ventilation systems.

6.2.4. Application for energy consumption aspect

The promising energy efficiency and cost-effectiveness of natural ventilation systems have been well recognized (Heiselberg, 2004; Omrani et al., 2017). If a natural ventilation system is appropriately designed, it could provide good IAQ level. As noted, natural ventilation is capable of decreasing the building's energy consumption. These findings were consistent with those reported by previous researchers (Aflaki et al., 2015; Shafiei Fini and Moosavi, 2016; Siew et al., 2011). Conforming to Seppänen and Fisk (2002), fewer SBS symptoms are reported in buildings integrated with natural ventilation systems when compared to building equipped with mechanical ventilation systems. Nevertheless, the humidity levels in buildings ventilated via natural ventilation systems are relatively high due to the low ventilation rates (Yaglou, 1961; Yang and Clements-Croome, 2012). In order to address this problem, natural ventilation systems should be combined with conventional air-conditioning systems. Thus, a natural ventilation system should be properly designed and analysed before it is implemented. Therefore, extensive information about the interactions between underground building characteristics and natural ventilation systems are required.

7. Building optimization

Building simulation models are often employed to analyse the thermal energy behaviours in buildings in order to reduce energy consumption and to improve IEQ (Nguyen et al., 2014). However, most of the analyses focus on single variable as outlined in the One-Factor-At-A-Time (OFAT) design approach. In this method, each input variable is varied and the variation in design objective is checked while fixing other variables. Sometimes, the behaviour of design objective is ignored when multiple input variables are varied simultaneously (Ng et al., 2008). Undoubtedly, this approach is time-consuming and the best optimal design is hardly attainable (Norton et al., 2010). To address this issue, numerical optimization (Khan et al., 2012) or simulation-based optimization (Yang et al., 2016) could be used to study the correlation between input variables and design objectives. Therefore, different optimization methods should be used in order to meet different design objectives (Machairas et al., 2014).

Table 8
Major phases in simulation-based optimization modified from Nguyen et al. (2014).

Phase	Major task
Pre-processing	a. Selection of building performance simulation tool and creation of building model. b. Identification of design variables and their relevant constraints. c. Selection of objective function. d. Selection of optimization algorithm (e.g. DOE with surrogate model). e. Coupling between the optimization tool and the building simulation program. f. Screening out unimportant variable (optional). g. Diagnostic (e.g. model satisfied, fit & adequate).
Running optimization	a. Monitoring convergence. b. Controlling termination criteria. c. Detecting error or simulation failures.
Post-processing	a. Interpreting optimization results. b. Verification (e.g. error check by simulation). c. Comparing optimization results with real models for reliability purpose (optional). d. Performing sensitivity analysis on the results (optional). e. Presenting the results.

Optimization is a procedure used to obtain the minimum or maximum value of a function by manipulating several variables subjected to some constraints. In other words, optimization is the process of finding the best solution from a set of variables. Conventional building optimization methods tend to combine building simulation models and optimization tools which may involve one or more optimization algorithms (Nguyen et al., 2014). Additionally, this method could be used to assess different building design issues such as thermal comfort, IAQ, natural lighting, energy consumption and IEQ-related problems. Nowadays, simulation-based optimization has become an efficient tool for building optimizations (Immonen (2015), Juraeva et al. (2014), Mukhtar et al. (2018b, 2018a, 2017b), Shen et al. (2013a) and Sofotasiou et al. (2016)). An optimization process could be divided into 3 phases. Table 8 shows the optimization phases and the potential tasks associated with each phase.

7.1. Building simulation programs and optimization tools

Based on the literature reviews reported by Crawleya et al. (2008) and Nguyen et al. (2014), there are about 20 major building simulation programs currently employed by building energy communities. Fig. 9 indicates an estimated usage of these major building simulation programs from year 2000 to year 2013. From the chart, EneryPlus and TRNSYS are the most popular choices, followed by DOE-2, ESP-r and CFD. Software relying on text-based input and output formats could facilitate the coupling between optimization tools. Recently, CFD has become a potent and favoured building simulation program. It has been widely used to model indoor and outdoor airflows, heat transfer, contaminant transport, natural ventilation, HVAC system designs as well as pollution dispersion and control (Hajdukiewicz et al., 2013a; Passe and Battaglia, 2015; Zhai, 2006). In agreement with Chen (2009), about 70% of published research works in 2008 (e.g. ventilation performance in the building) have utilized CFD as the main simulation tool. Thus, it appears that the CFD could be used to simulate flow in naturally ventilated spaces, which is difficult to perform using other building simulation tools. The most critical challenge in CFD modelling is the reliability of the flow results.

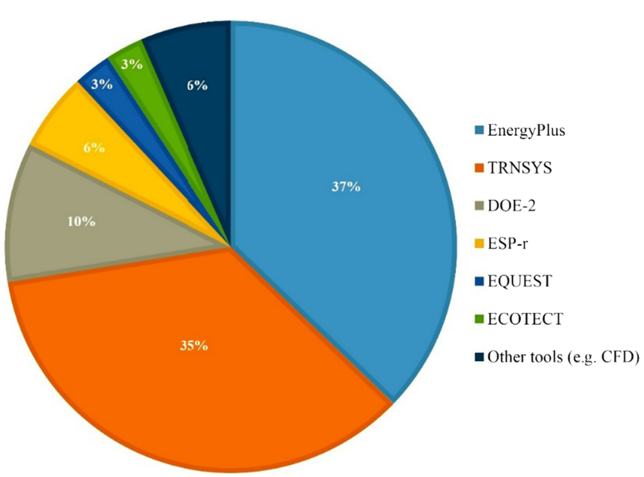

Fig. 9. Estimated usage of building simulation programs for period 2000–2013. Retrieved from Nguyen et al. (2014).

Machairas et al. (2014) have separated the optimization tool into three categories: (a) custom programmed algorithms; (b) general optimization packages; and (c) special optimization tools coupled with building simulation software. The fully flexible custom programmed algorithms undoubtedly require advanced programming skills. Due to the complex programming, only a few researchers (e.g. Bouchlaghem (2000), Adamski (2007) and D'Cruz and Radford (1987)) have applied this method in their analyses. GenOpt (Wetter, 2001) and MATLAB (The Mathworks Inc., 2016) are more widely used in building optimization. These two software could be regarded as general optimization packages. GenOpt is a generic optimization program used for minimizing cost functions and it is evaluated by an external simulation program. It accepts both continuous and discrete (or a combination of both) for the independent variables and is used when the gradient function is not available. While, MATLAB has a graphical user interface and it contains useful optimization algorithms and post-processing functions. Recently, MATLAB has been coupled with different building energy simulation tools to optimize building energy consumption. Furthermore, available toolboxes developed for different optimization methods have made the function of MATLAB more convenient in optimization problems. Some authors have also recommended *mode*FRONTIER (ESTESCO, 2012) for building optimization. *mode*FRONTIER is a multi-objective optimization environment which can be coupled with engineering tools, in this case, building energy simulation tools. It encompasses both response surface methods and direct optimizations and accepts both discrete and continuous variables. The various algorithms that can be chosen is an advantage of the *mode*FRONTIER. One is able to find related works employing general optimization packages from Asadi et al. (2012), Rapone and Saro (2012), Shi (2011) and Tuhus-Dubrow and Krarti (2010).

For the third category, Genetic Algorithms (GA) have been coupled with building simulation programs. Generally, GA is a population-based algorithm, classified as a global-optimum finding algorithm that includes operations to search for the optimum and improve the solutions. The iterative process of GA will converge to better solutions based on the breeding of the parents with higher performance. One of examples in a similar case, Tuhus-Dubrow and Krarti (2010) utilized GA coupled with DOE-2. Lee (2007) has developed optimal design tools using GA and CFD. Charron and Athienitis (2006) have combined GA and TRNSYS in the early design stage. However, most of the optimization tools mentioned above are computationally expensive. This problem could be addressed by implementing surrogate models such as Design of Experiment (DOE) method and approximating computation functions (Park and Dang, 2010).

7.2. Building performance surrogate models

A surrogate model is a statistical model used to speed up the optimization process by using surrogates for the objective and constraint functions (Ong et al., 2003; Queipo et al., 2005). It usually mimics the behaviour of the original model in order to produce model responses at reduced computational cost. Primarily, the surrogate technique involves four steps: (a) choosing the DOE to produce data, (b) selecting a model to present the data, (c) fitting the model to the observed data and (d) validating the model. There are numerous surrogate models available nowadays (Simpson et al., 2001). Amongst these models, the Response Surface Methodology (RSM) (Mukhtar et al., 2018b; Mukhtar et al., 2018c; Myers et al., 2009) and the Kriging-based Models (Booker, 1998; Mukhtar et al., 2017a; Sacks et al., 1989) are the popular ones in engineering (Goel et al., 2009; Wang and Shan, 2007). More information regarding the application of surrogate models in building design optimization could be found in Simpson et al. (2001) and Wang and Shan (2007).

Lately, there are a number of researchers that employ surrogate model techniques in optimizing building performance problems. In this approach, each variable could be simultaneously varied in a controllable or uncontrollable manner and meanwhile produces an accurate result. Some authors (Hajdukiewicz et al., 2013b, 2013a; Ng et al., 2008; Norton et al., 2010; Shen et al., 2013a, 2013b; Sofotasiou et al., 2016; Stavrakakis et al., 2012) discussed issues related to meta-modelling such as suitability of data sampling, type of meta-model, model fitting technique, model verification and optimization method.

For instance, Shen et al. (2013a) estimated the ventilation rate in a naturally-ventilated livestock building. They conducted the assessment with multiple DOEs and three factors in order to develop a mathematical model of the ventilation rate. The quadratic RSM was used as a meta-model and the results demonstrated that the Box-Behnken Design (BBD) method had the best performance while the Space Filling Design (SFD) method had the best accuracy in developing the quadratic RSM model. In a separate paper, Shen et al. (2013b) estimated the ventilation rate in dairy buildings in order to develop a model-based control to reduce gas emission. They applied the Optimal Design (OD) method coupled with the quadratic RSM. Meanwhile, Shen et al. (2013b) used controllable (e.g. vent size) and uncontrollable factors (e.g. wind speed and direction) as the design variables. The findings indicated that the sidewall opening of the dairy building influenced the air change rate of the building significantly.

Hajdukiewicz et al. (2013a, 2013b) performed a parametric analysis using CCD. They used 8 input variables to measure the indoor air speed and indoor air temperatures. The output variable was subsequently employed to evaluate the IAQ and the thermal comfort in a highly-glazed, naturally-ventilated office. The result indicated that the average air temperatures were close to the comfort value recommended by the occupants. Moreover, the air speed value met the design requirement of offices during summer seasons. From these related work, it appears that a statistical data-based analysis could be implemented when solving building performance problems (e.g. IEQ).

7.3. Optimization of design variables and objective function

From Table 8, the pre-processing phase plays a substantial part in optimization studies. In this phase, the essential tasks are: (a) selection of a building performance simulation tool and creation of a building model, (b) identification of the design variables and their relevant constraints, (c) selection of an appropriate objective function and (d) selection of an appropriate optimization algorithm (e.g. DOE with a surrogate model). Both simulation tools and optimization algorithms have been discussed in the previous section. In this section, design variables and objective functions are discussed.

Typically, design variables play a significant role in building design optimization. It could be expressed in either quantitative (e.g. length, weight and temperature) or qualitative (e.g. aesthetics and manufacturability) measures. Parameters such as number, nature, permissible value and mutual dependency of design variables can affect the overall performance of the optimization task (Roy et al., 2008). There is no limitation on the number of design variables in an optimization task. However, according to Wetter (2001), they should be limited in the order of 10. Technically, the number of design variables is dependent on the capability of the optimization algorithm and the complexity of the objective function (problem). There are two types of design variables in building optimization, i.e. continuous (e.g. design parameter) and discrete (e.g. building components). Both types are constrained within the lower and upper bounds. Some examples of design variables used in building optimization are orientation and shape of the building, position and dimension of opening (window), HVAC system size, wall dimensions, outdoor conditions, air tightness and others (Hajdukiewicz et al., 2013b; Juraeva et al., 2014; Mukhtar et al., 2018a, 2018b; Ng et al., 2008; Norton et al., 2010; Shen et al., 2012, 2013a; Sofotasiou et al., 2016). The constraint of the design variables, on the other hand, is specified as a functional limit of the design. Roy et al. (2008) have classified the constraint into two types, i.e. non-equality and equality. For example, in the non-equality type, the temperature of the fan blade must be less than the melting point of the material, i.e. $T(x) < T_{max}$ where x is the vector of design variables: $(x_1, x_2, \cdots.., x_i)$. For the equality type, the constraint must be satisfied, e.g. $F = ma$. In consonance to Coello (2002), the number of constraints and their developments are factors that would affect the optimization procedure significantly.

The selection of objective function depends on the nature of the design variables and their constraints. The model presumes that certain aspects of the design are fixed (denoted as design parameters). The design parameters are frequently applied to reduce the number of design spaces (Roy et al., 2008). Thus, the objective function could be mathematically represented as follows:

$$Minimize/Maximize \quad F_j(x, p), \ j = 1, 2, \cdots\cdots, j \tag{1}$$

where variables x_i is bounded within $x_i^{min} \leq x_i \leq x_i^{max}$ and subjected to constraint:

$$g_k(x) \geq 0 \quad \text{and} \quad h_m(x) = 0 \tag{2}$$

In this case$k = 1, 2, \cdots, k$ and $m = 1, 2, \cdots, m$. Here, $F_j(x, p)$ is the objective function. The minimization of $F_j(x, p)$is equivalent to the maximization of$- F_j(x, p)$. In accordance with Roy et al. (2008), objective functions are used to access a design solution within the optimization context. It could be classified as single-objective or multi-objective functional optimization. In real life, most of the optimization problems are multi-objective. Such objective functions were reported in (Hajdukiewicz et al., 2013b; Juraeva et al., 2014; Mukhtar et al., 2018a, 2018b; Ng et al., 2008; Norton et al., 2010; Shen et al., 2012, 2013a; Sofotasiou et al., 2016). In addition, the objective functions in building design optimization problems do not utilize any constraint. In summary, the identification of design variables and their relevant constraints as well as the selection of an appropriate objective function play a crucial role in an optimization study. However, the identification of design variables and the selection of objective function should not be solely performed based on the data obtained from open literature.

8. Passive building designs

The building sector has contributed to about 20%-40% of the total energy consumption in the world and the consumption percentage is expected to increase by 50% by year 2050 (Pérez-Lombard et al., 2008). The use of passive systems could reduce energy consumption and greenhouse gas emissions (Pacheco et al., 2012). In addition, passive building design could reduce the daily and annual indoor temperature fluctuations as well as increase thermal comfort (Souayfane et al., 2016). Some examples of passive building designs are phase change materials (PCM) (Raj and Velraj, 2010), thermal energy storage (TES) (Heier et al., 2015), underground buildings (Mukhtar et al., 2017a, 2017b; Mukhtar et al., 2018b, 2018a), wind catchers/scoops (Jomehzadeh et al., 2017), earth to air heat exchangers (EATHE) (Benhammou and Draoui, 2015), green roofs (Coma et al., 2016), roof ponds (Sharifi and Yamagata, 2015), trombe walls (Saadatian et al.,

2012) and green walls (Saadatian et al., 2012). Nevertheless, we have restricted the current review to only three passive techniques (i.e. underground buildings, wind scoops and EATHE).

8.1. Applications of underground buildings

As discussed in Section 2, developing underground buildings is one of the traditional methods for reducing temperature fluctuations and energy consumption. Recently, solution such as promoting underground heat transfer has been proposed in the construction of low-energy building in harsh climates. Researchers have found that geothermal energy coupled with optimal insulation is the best approach to maximising the energy savings in a building during heating and cooling operations (Al-Temeemi and Harris, 2004; Gan, 2015; Hassan and Sumiyoshi, 2017; Van Dronkelaar et al., 2014). Compared to conventional buildings (above ground), Anselm (2012) has proven that underground buildings can reduce annual heating/cooling loads and keep the indoor temperatures stable in different climates. Similar observations have been reported by Anselm (2008) and Kumar et al. (2007). Van Dronkelaar et al. (2014) have calculated the annual energy demand of above ground and underground buildings based on the EN-ISO 13790 standard. Their study took into consideration various climates, building functions and depths. They claimed that underground buildings would consume less energy as the soil could act as a natural insulator. Moradi and Eskandari (2012) estimated the heating and cooling performances of Shavadoons (underground space dug) in Dezful, Iran. Their numerical results deviated from the experimental results by 6% and 36% during the cold and hot months, respectively. Additionally, the authors highlighted that the Shavadoons were capable of providing a warm/cold space during the cold/warm season at minimal energy consumption. Hazbei et al. (2015) have studied the passive heating and cooling systems of Shavadoons separately. The simulation was conducted via Ansys Fluent by using the annual climatic data of Dezful. They highlighted that the proper use of natural air movements, heat conduction and air displacement could meet the thermal comfort requirements of indoor occupants. Mukhtar et al. (2018b) analyzed the thermal performance of a naturally-ventilated underground shelter in a hot and humid country such as Malaysia. They found that the room temperature of the shelter was significantly lower than the outdoor temperature during the hottest month and vice-versa during the coldest month. Moreover, Givoni (2011) found that the soil moisture and earth (avoid direct sunlight) could reduce the soil temperature. Even at lower depth, the soil temperature rarely reaches the outdoor temperature (Benardos et al., 2014; Mukhtar et al., 2017c). In short, soil possesses a high thermal capacity and it is excellent in terms of energy preservation.

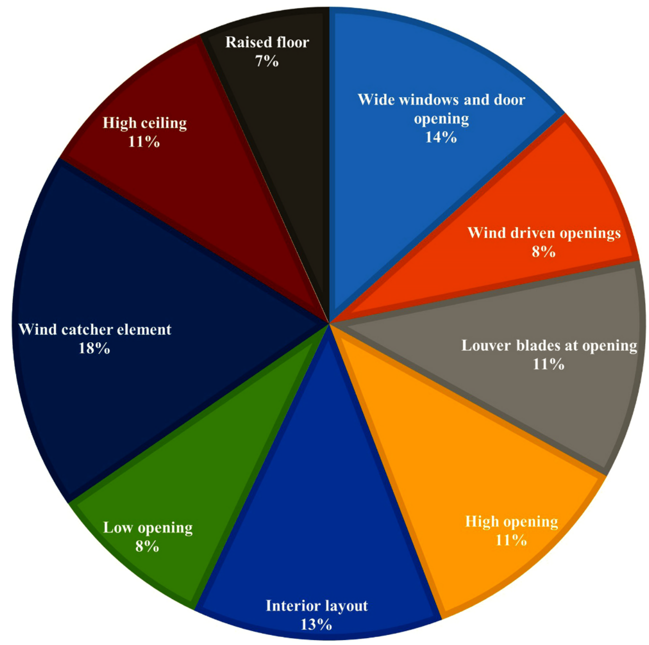

Fig. 11. Frequency of attributes presence in good natural performance spaces retrieved from Wahab et al. (2018).

8.2. Applications of wind scoops

In the Middle East, wind scoops have been traditionally used for centuries as a passive ventilation element in buildings. It is designed to capture the wind so that ambient air could be used to ventilate the indoor space when leaving the ventilation shaft (Chenari et al., 2016; Etheridge, 2012). It is sometimes known as a wind cowl (Khan et al., 2008). When the wind scoop opening faces the wind direction, fresh air would enter the building via the opening. Having said that, when the opening is located at the opposite side of the wind direction, ambient air would be drawn (or induced) into the opening, as shown in Fig. 10. In fact, most researchers have defined wind scoop as a one-sided wind

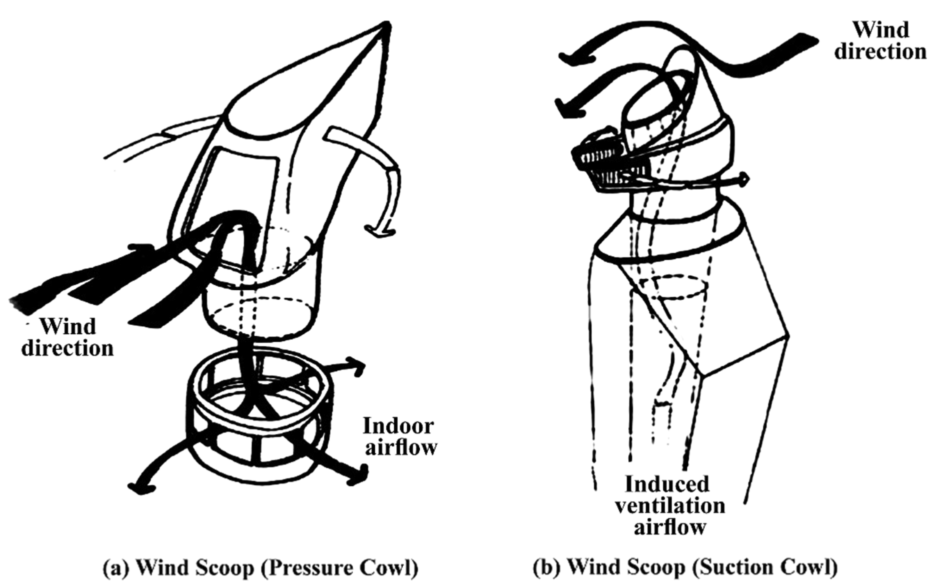

Fig. 10. Schematic examples of pressure cowl and suction cowl retrieved from Khan et al. (2008).

catcher. As discussed by Chenari et al. (2016), a wind catcher is a popular and sustainable passive technology used for cooling and ventilation in recent decades. Also, wind catcher was found as the most significant attribute in natural ventilation areas, as presented in Fig. 11 (Wahab et al., 2018). Wind catchers could be categorized based on their openings such as one-sided, two-sided, four-sided, hexahedral and octahedral types. The opening could be unidirectional or omnidirectional (Hughes et al., 2012). Unidirectional wind scoops are commonly found in buildings whereby the facades are not specifically designed for natural ventilation. Wind catchers could be applied as supply and exhaust systems. However, wind scoops can only be applied as supply systems. Wind scoops integrated with ventilation shafts could seemingly be adopted in the design of ventilation systems in underground buildings. Typically, wind scoops are commonly found in old-time ships in order to ventilate the space under the deck (Kleiven, 2003).

Although the study of wind catcher has been extensively reported in recent years, the number of studies related to wind scoops (one-sided wind catchers) is quite limited. Esfeh et al. (2012) used the smoke visualization approach to determine the airflow characteristics in one-sided wind catchers with flat, inclined and curved roofs. Dehghan et al. (2013) reported the influence of wind speed and wind direction on the ventilation performance of one-sided wind catchers using the analytical method and wind tunnel experiments. Finally, Montazeri and Azizian (2011) have evaluated the pressure coefficient of a scaled-down one-sided wind-catcher model in a wind tunnel. In order to discern the flow pattern in the vicinity of the wind-catcher model, a few smoke visualization experiments were carried out. In short, wind scoops (one-sided wind catchers) could be an effective passive design strategy for underground buildings.

8.3. Applications of earth to air heat exchangers (EATHE)

Apart from the applications of underground buildings and wind scoops discussed in the previous sections, there is another promising passive cooling technology. This is the earth to air heat exchanger (EATHE) which has the potential to improve natural ventilation through cooling effect (Maerefat and Haghighi, 2010). This application is proven to improve the building's thermal comfort and meanwhile reduce the energy demand. Technically, EATHE uses soil as a heat source or sink and air as the medium of heat exchange. An EATHE system consists of a long horizontal pipe (or several pipes) buried below the ground. As illustrated in Fig. 12, one end of the pipe acts as an inlet (induces the outdoor air), while the other end acts as an outlet (releases air to the building) (Al-Ajmi et al., 2006). According to Benhammou and Draoui (2015), the air supply is drawn through the pipes, and the temperature difference between the pipe surface and the air leads to the cooling/heating operation. This difference, however, is dependent on several factors such as the outdoor air temperature, soil temperature, depth of the burial pipe, soil and pipe thermal properties, ventilation rate, pipe length and dimension as well as pipe material (Kaushal, 2017). Several works have been conducted on this system and a consensus has been reached that this strategy can provide a good indoor comfort condition according to the adaptive thermal comfort criterion specified for estimating the comfort temperature (Yang et al., 2014). Thiers and Peuportier (2008) have reported a technical solution for EATHE. Their aim was to reduce the energy consumption while providing a satisfactory thermal comfort level in buildings. They highlighted that the EATHE system appeared to be an adequate solution to improve the environmental performance of building from a French context. Al-Ajmi et al. (2006) has developed a theoretical model of an EATHE for predicting the outlet air temperature and cooling potential in Kuwait (a hot and arid climate). Their numerical result showed a reduction of 1700 W in the peak cooling load with an indoor temperature reduction up to 2.8 °C. From this result, they claimed that the EATHE has the potential for reducing the cooling energy during summer season. Similar observations were reported by Ahmed et al. (2015) who studied the performance assessment (room cooling) of EATHE for low energy buildings. They also found that the temperature reduction of around 2 °C (indoor temperature) could lead to energy saving of up to 866.54 kW per year. Also, from this study, we have found that certain works on the hybrid systems for the EATHE have been conducted, which are very beneficial to the society. Maerefat and Haghighi (2010) have introduced the hybrid systems for EATHE with a solar chimney in order to investigate the cooling and ventilation performances in a solar house. They found that the solar chimney was a perfect tool in powering the underground cooling system during daytime and in providing a thermally comfortable indoor environment for long period during summer time. Moreover, Benhammou et al. (2015) have proposed a new EATHE design (with a wind tower) as a summer time cooling system in Algeria. They found that the wind tower dimension does not result in any significant impact as compared to the pipe dimension. However, the outdoor air passing through the wind tower coupled with EATHE is much colder than that of using the conventional wind tower. Finally, Jakhar et al. (2016) estimated the heating potential for the EATHE coupled with the solar air heating ducts (SAHD). This model was developed using the TRNSYS 17 simulation tool and validated with the experimental data obtained from Ajmer, India. They claimed that the increase in flow velocity would

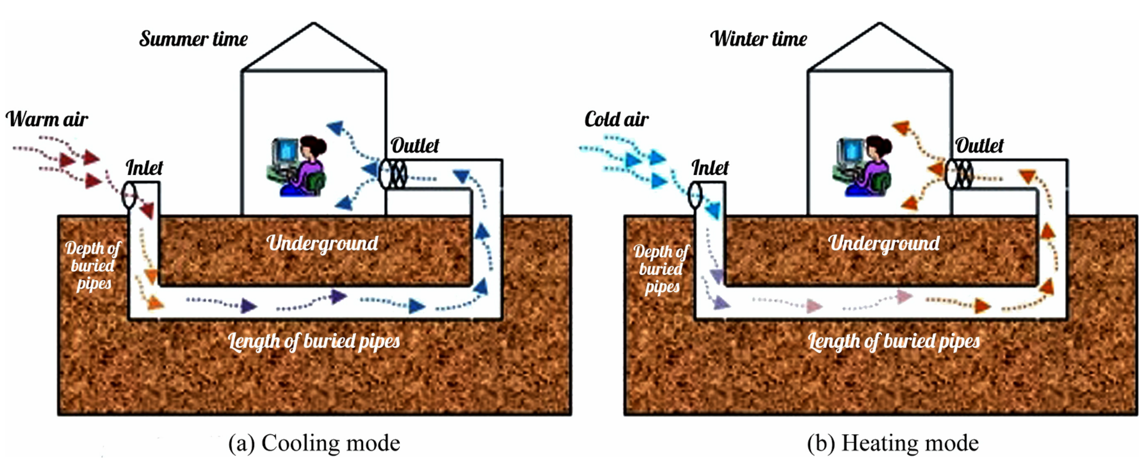

Fig. 12. Conceptual view of (a) cooling and (b) heating modes of EATHE. Reproduced from Singh et al. (2018).

reduce the EAHE outlet temperature, while room temperature increased at higher velocity (5 m/s). In short, an EATHE system can reduce the energy consumption and it can also be coupled with other passive designs (especially with wind scoop) to improve the performance of a stand-alone passive design.

9. Conclusion

A detailed literature review on the potential of building optimization and passive design strategy in promoting natural ventilation in underground buildings has been carried out. Based on the literature review, the following conclusions have been drawn:

- The literature shows that integrating both optimization approach and passive design strategy into building performance simulation is a promising technique in improving the IEQ level of underground building.
- The adoptions of soil and natural ventilation can effectively reduce the energy consumption in underground conditioning system. In fact, underground building is one of the most efficient ways in reducing the cooling/heating loads and in stabilizing the indoor temperature at different climates. However, there are some important factors that should be taken into account while designing an underground building such as construction typologies, geological features, psychological and physiological issues as well as ventilation systems.
- Building simulation models are often used to analyse the thermal energy behaviours in buildings. Nevertheless, most analyses focus on a single variable (e.g. OFAT design). This approach is time-consuming and the best optimal design is hardly attainable. In order to address this issue, building design optimization could be employed to study the correlation between the input and response variables.
- Additionally, the literature shows that there are a few passive designs associated with underground buildings which can improve the thermal comfort and reduce the energy consumption. These passive designs are viable options in mechanical air-conditioning systems in underground buildings. Furthermore, these strategies could be coupled in order to improve the performance of the stand-alone passive design concept.

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Appendix A. Supplementary material

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